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Pedagogical Perspectives of Interdisciplinary Teaching and Research: An Energy System Modelling Outlook in Relation to Energy Informatics

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Abstract: The purpose of this paper is to present and discuss pedagogical frameworks and approaches to developing, delivering, and evaluating a new interdisciplinary course within the domain of energy informatics at both Master's and PhD levels. This study is needed because many papers on sustainable energy engineering education concentrate on course content but provide very little information on the pedagogical methods employed to deliver that content. The proposed new course is called "smart energy and power systems modelling" and is aimed at discussing how mathematical optimization, in the context of computer science, can contribute to more effectively managing smart energy and power systems. Different pedagogical frameworks are discussed and adapted for the specific domain of energy informatics. An ASSURE model coupled with Bloom's taxonomy is presented for the design of the course and identification of learning objectives; self-regulated learning strategies are discussed to enhance the learning process; a novel model called GPD (Gaussian Progression of Difficulty) for lecture planning was proposed; a teaching-research nexus is discussed for the course planning and enhancement. Adopting qualitative analyses and an inductive approach, this paper offers a thorough reflection on the strengths and weaknesses of the new course, together with improvement possibilities based on fieldwork and direct experience with the students and colleagues. Opportunities and challenges of interdisciplinary teaching are presented in light of real-world experience, with a particular focus on the interaction between mathematics and computer science to study the specific application of energy and power systems.

Keywords: energy systems modelling; energy informatics; interdisciplinary STEM education; Bloom's taxonomy; ASSURE model; self-regulated learning; teaching-research nexus; qualitative research; inductive approach; pedagogy in higher education

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1. Introduction

The development of new university courses in higher education is a challenging task that combines many aspects together. This is especially true when it comes to novel domains that are not usually addressed in higher education, and where emerging subjects are going to be taught such as energy informatics. Energy informatics is an emerging interdisciplinary domain that lies at the intersection of energy systems, power systems, economics, computer engineering, and computer science.

The objective of this paper was to reflect on best practices and approaches to developing, delivering, and evaluating a new course within the domain of energy informatics at both Master's and PhD levels. This was accomplished by putting together the personal experience and the lessons learned during the implementation and evaluation phases of the course, in light of the established literature in the pedagogical field. Indeed, the development of a new course is not only a matter of "technical choices" (in terms of sub-topics to teach within certain subjects), but it is also a matter of "pedagogical choices". Pedagogical choices should take the perspective of the student's needs and aim at generating solutions that are beneficial for all the parties involved at different levels (the students, the lecturers, and the department as a whole) such that the whole system can, in the end, be stronger together.

Figure 1 summarizes the main pedagogical dimensions that can be identified within the energy informatics domain. As an interdisciplinary domain, energy informatics comprehends a wide variety of subjects among mathematics, economics, engineering, computer science, and power systems as further elaborated in [1]. Here, smart energy and power systems modelling is identified as a key subject lying at the heart of the energy informatics domain and creates strategic links between the other subjects. As such, there is a need to teach both fundamental and more advanced specialized subjects in order to educate future energy informatics specialists [2] that will be able to address the sustainability needs [3] of modern society using holistic and interdisciplinary socio-techno-economic approaches. Education should cover subjects at different levels, from introductory courses at the Master's level to more advanced courses at PhD level. This motivates and explains the two key dimensions of lecturing undergraduates and lecturing PhDs that are shown in Figure 1. Another important pedagogical dimension that is strictly connected to teaching is supervision at both Master's level and PhD level. In both cases, the objective is to work on wider projects with some degree of novelty for Master's students, and with full research content for PhD candidates. Novelty is intrinsic in research, therefore a Master's level thesis can be considered as smaller sub-projects of wider research projects that are tackled at PhD level. From this point of view, smart energy and power systems modelling is an advanced subject that offers many research opportunities, as it can be noted by the active scientific community that consistently and continuously works in this field [4]. At a wider level, the supervision of large groups of Master's students and PhD candidates requires additional pedagogical skills in terms of team leadership. Therefore, supervision and research teams' leadership are tightly interconnected as pedagogical dimensions, since they require complementary pedagogical skills, as shown in Figure 1. Broadly speaking, on top of the leadership role and technical competencies required for supervision, coaching skills are also necessary for those managing large groups, to provide more holistic support that goes beyond pure technical knowledge but considers the students and researchers as human beings that need to be motivated and guided throughout their career. That is why the coaching dimension is embracing the other three dimensions of supervision and leadership in Figure 1, to identify the additional set of pedagogical skills that can enhance the quality of the tasks performed within the other dimensions.

This paper focuses on the "lecturing" dimension of Figure 1, with regard to lecturing both undergraduates and PhD students. The other dimensions will be tackled in future follow-up papers. In particular, this paper describes the design of an interdisciplinary course within the Energy Informatics domain (smart energy and power systems modelling) and how teaching and research can be linked in such courses accessible to both master's level and PhD level students. Three central aspects of the course were investigated and are discussed: the interdisciplinary aspects of the course; the course design; the teaching-research (T-R) nexus within the course.

We then explored how the students experienced learning in this kind of framework, with a particular emphasis on how students experienced assignments, guest lectures, course progression of difficulty, and overall course content and relevance. The overall students' performance is also discussed in light of the interdisciplinary background of the course participants. Data were collected through a survey, reflective writing, interviews, and using a general inductive approach for qualitative analysis.

In light of the inductive and qualitative analysis results we discuss opportunities for improvements, with a particular focus on the T-R nexus that will be introduced in the following sections.

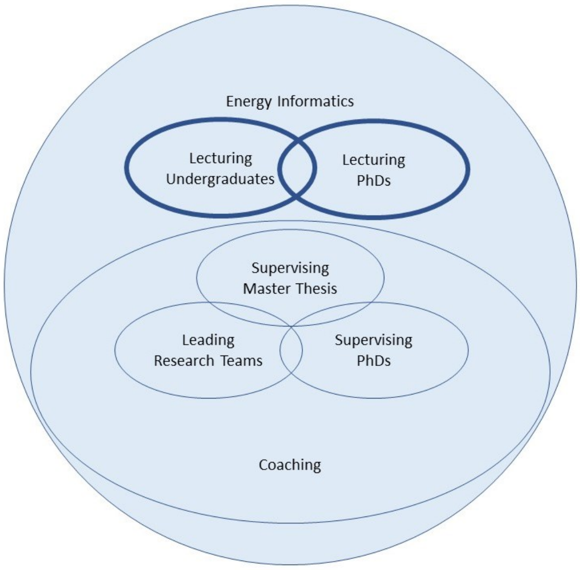


Figure 1. The main pedagogical dimensions of energy informatics. The dimensions tackled in this article are highlighted in bold.

The course is titled "Energy Informatics: Smart Energy and Power Systems Modelling". It has been designed, developed, and delivered at UiT, The Arctic University of Norway, and is currently proposed as an optional Master's [5] and PhD level [6] course offered by the computer science department, open to students coming from different study programs [7].

The remainder of this paper is organized as follows. Section 2 introduces the theoretical background, describing the main pedagogical frameworks discussed in this paper. Afterward, the key contribution of the paper is discussed in Section 3. The study design is introduced in Section 4, outlining the concept of qualitative research and the inductive approach that characterizes this paper. The interdisciplinary aspects and scope of the course are outlined in Section 5 where the broad energy informatics domain is introduced together with the specialized subject of smart energy and power systems modelling. The development of a course within the energy informatics domain is described in Section 6 where the ASSURE model, Bloom's taxonomy, and self-regulated learning strategies are discussed and implemented for the specific course of interest, and a novel GPD model for teaching and learning is also introduced. The T-R nexus within the course is discussed in Section 7, while Section 8 proposes a course evaluation based on experience and observation. Improvements to the course are discussed in Section 9 in light of the T-R nexus. Section 10 summarizes opportunities and challenges of interdisciplinary teaching by putting the specific experience discussed in the paper into a broader perspective. Finally, conclusions are drawn in Section 11.

2. Background—Pedagogical Frameworks and Approaches

Several pedagogical frameworks exist and have been developed and discussed in the literature for decades. This paper revolves around four main frameworks and approaches that have been picked as the most suitable ones to design interdisciplinary courses like those within the energy informatics domain, such as smart energy and power systems modelling: the ASSURE model for course design, Bloom's taxonomy for learning goals definition, self-regulated learning strategies to improve the learning experience of the students. On top of that, the T-R nexus was investigated to better understand the relation between teaching and research that exist within the course, and identify a balanced set of tasks to be performed within the course.

The ASSURE model, developed by Heinich, Molenda, and Russel in 1993, is an instructional design paradigm used by designers to create more successful training programs that incorporate integrated technology. The ASSURE model focuses on the student and the total result of meeting learning objectives. It has been successfully utilized for educational purposes in general and proved to be an effective model also for interdisciplinary STEM education [8] (where STEM stands for Science, Technology, Engineering, Mathematics). Therefore, the ASSURE model is also particularly suitable for tackling interdisciplinary domains such as the energy informatics domain and the related key subject of smart energy and power systems modelling.

Benjamin Bloom and his colleagues published Bloom's taxonomy [9] for the first time in 1956 as a way to help teachers organize learning goals. The original version of the framework had six parts: knowledge, understanding, application, analysis, synthesis, and evaluation. The categories that come after knowledge were called "abilities and skills" because people thought that knowledge was needed before these abilities and skills could be used in real life. Bloom's taxonomy is a widely used educational learning theory [10] that has been further expanded towards a so-called Bloom's Digital Taxonomy, inspired by informational and technical advancements as a means of expanding student access to knowledge. As outlined in [11], Bloom's taxonomy's congruence principle could help engineering, technology, science, and math teachers create a multidisciplinary STEM course. This motivates the adoption of such a framework to identify the learning objectives within the interdisciplinary course development discussed in this paper for the specific case of the energy informatics domain and the subject of smart energy and power systems modelling.

Self-regulated learning strategies are ways of teaching that are based on research and help students keep track of and control their own learning habits and skills. There are three sequential steps to self-regulated learning, according to [12]: forethought, performance, and self-reflection. The forethought phase aims at analyzing the learning tasks and setting goals towards completing the tasks; the performance phase employs strategies to make progress on the learning task and monitor the effectiveness of the strategies employed; the self-reflection phase aims at evaluating the performance of the learning tasks and manages the emotional responses related to the outcome of the learning experience. Self-regulated learning is a valid learning strategy in higher education [13] and it is an approach that improves students' self-efficacy and self-regulation, which in turn helps students to learn STEM skills effectively [14]. Therefore, self-regulated learning strategies are worth to be discussed within the development of energy informatics-related courses.

Mick Healey created a T-R nexus paradigm in 2005 to map diverse activities along two dimensions: learning content (what students learn) and learning process (how students participate in learning). The learning content can be centered on research findings or research procedures and abilities, and students can be involved as participants or as an audience. Based on these two dimensions, four distinct approaches to establishing the T-R nexus can be distinguished as shown in Figure 2: research-led, in which students learn about current research; research-tutored, in which students participate in research discussions; research-based, in which students conduct research and inquiry; and research-oriented, in which students learn about research methods and techniques.

International interest exists in the integration of research and education since teaching and research are core tasks of university faculty [15,16]. The connections can take many forms and can be found in any type of higher education institution. Many research-intensive universities and departments aim at "research-led" teaching and learning in their undergraduate programs, where research and teaching are brought together. Attention must be given to the design of the curriculum and how students learn in order for students to benefit the most from the teaching-research links. It has been argued that the discipline is an important mediator in enhancing the links between research and teaching to benefit student learning, both because the nature of knowledge creation and research approaches differ across disciplines and because, practically disciplines often act as distinct academic tribes or communities of practice. Studies of the link in multiple publications support a discipline-based approach to exploring the T-R nexus [17]. From this perspective, the domain of energy informatics together with the specific subject of smart energy and power systems modelling represent an ideal opportunity for the implementation of the T-R nexus paradigm. This is due to the intrinsic research component that lies within such fields, demonstrated by the active research community that revolves around energy systems modelling. Such a community is composed of researchers with a wide interdisciplinary background ranging from computer science, mathematics, power systems, economics, and engineering; in sum, an energy informatics community.

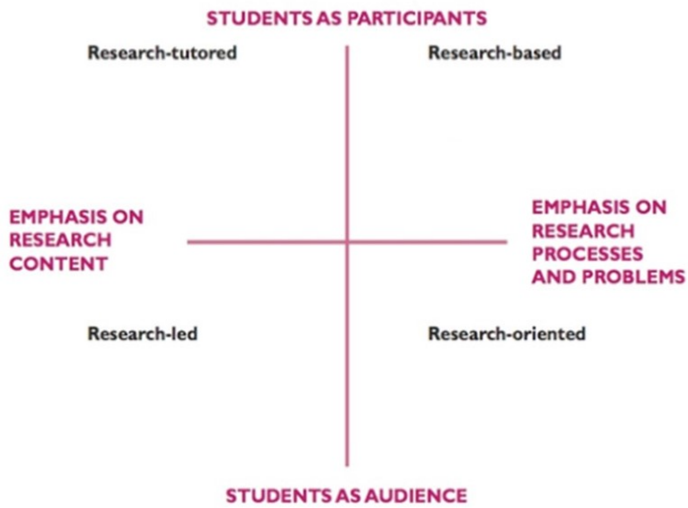


Figure 2. A framework for linking teaching and research.

3. Novelty and Key Contribution

Interdisciplinary approaches to tackling energy and environmental challenges are becoming pivotal in the modern world, and the intrinsic interdisciplinarity of energy informatics is gaining increasing attention both among the academic community and within the industrial world [18]. Novel concepts such as education-energy nexus are arising in response to such a trend, to address the need for energy-oriented interdisciplinary education [19,20]. Indeed, in order to contribute to the achievement of long-term, sustainable goals, higher education needs to equip itself with the essential skills and competencies [21]. To meet the growing demand for professionals in the sustainable energy industry on a global scale, educational institutions must urgently produce graduates with the necessary skills [22]. Moreover, there is a need for a wider education of CEOs of companies that are directly or indirectly related to the energy field [23], such that their qualifications can support decision-making within energy-related activities. Indeed, CEO education affects firm performance. education creates knowledge, vision, and the ability to understand diverse views of management and business.

However, many papers on sustainable energy engineering education concentrate on course content but provide very little information on the pedagogical methods employed to deliver that content [22].

While several pedagogical frameworks for teaching (i.e., ASSURE model, constructive alignment, didactic relational model, Bloom's taxonomy) and research (i.e., T-R nexus) exist, none of them is discussed and adapted for the specific domain of energy informatics. In this modern interconnected and interdisciplinary world, there is a need to adapt and expand broad existing frameworks and put them into more specialized scopes of certain key domains and specific disciplines. This paper addresses such a need with a focus on the key domain of energy informatics and the specific discipline of energy and power systems modelling. This is motivated by the fact that energy is currently one of the major concerns at national and international levels [24], and computer science coupled with mathematical modelling are among the key disciplines to address the energy problems with an interdisciplinary approach [1].

The key contributions of this paper can be summarized as follows.

- An ASSURE model coupled with Bloom's taxonomy for the design of energy informatics courses and the identification of learning goals;
- Self-regulated learning strategies to enhance the learning process within energy informatics courses;
- A novel GPD (Gaussian Progression of Difficulty) model for lectures planning;
- A T-R nexus for the specific case of energy informatics;
- A thorough discussion on strengths and weaknesses of the new course, as well as the improvement of opportunities based on fieldwork and direct experience with the students and colleagues.

Since energy informatics is a broad domain, the scope is narrowed towards the key discipline of smart energy and power systems modelling, as was outlined in the previous paragraph, and as will be further discussed in the following sections.

4. Research Method and Study Design

Qualitative analysis is a research method that explores the understanding of social phenomena by examining textual, visual, or audio data. Contrary to quantitative analysis, which is centralized on numerical data and statistical reasoning, qualitative analysis aims to identify patterns, themes, and insights in data. Such analysis often uses methods including content analysis, discourse analysis, and grounded theory. Qualitative analysis and research are two related but distinct concepts in social science research. Qualitative analysis is based on a set of principles and methods that is more oriented toward researchers' interpretation of the data, contrary to measuring variables.

Broadly speaking, a process could begin with a hypothesis and then a method is applied to reach a conclusion. From this perspective, the process is research, and based on the method applied it could be qualitative or quantitative. Qualitative methods may also include quantitative methods to explain the dataset but often a conclusion is drawn through interpretation [25–29].

Qualitative analysis is often used to explore complex and likely subjective topics where quantitative methods are not suitable or incomplete. Take for example, attitudes, beliefs, behaviors, and experiences. It is important to localize or contextualize the qualitative results as it is applied or derived from a specific group that may have divergence in terms of patterns even with the same group in another circumstance. Although parallels can be drawn they are distinct. That is to say, qualitative analysis often involves a small sample size and results may not be generalized but could be useful to know. Qualitative analysis often involves iterative and flexible research designs, where the research questions and methods may evolve throughout the research process. However, it could also be based on standardized approaches and structures. What qualitative analysis misses on the wide-ness or generalization it makes up for it in the form of in-depth exploration of a specific topic or phenomenon. This leads to a higher degree of interpretation and conceptualization of the results of a study. Qualitative research typically involves detailed analysis of individual cases, which could be time-consuming and resource intensive. For instance, collecting rich and detailed information (like interviews, transcripts, and observation notes) is voluminous and therefore difficult to manage with large sample sizes. Adding to that, some patterns that may exist in small sample sizes might fade away as the sample size increases which amounts to another challenge. Qualitative data analysis software like NVivo [30] can be used to prepare interview data for analysis, find and choose important themes through open coding of interviews, and organize the results for publication. Qualitative research also involves purposive and theoretical sampling as in selecting participants based on relevance to the research questions rather than random sampling which could over-complicate the study. Data gathering in a qualitative study has a saturation point, meaning that new data does not add to the understanding of the topic or phenomenon. Also, such research is focused on collecting rich and nuanced data which may not require large sample sizes to identify patterns and themes. The source of such data are often hard to reach, time-critical, or vulnerable populations, which then raises accessibility or ethical considerations. Such data requires a deep analysis with close attention to individual cases rather than aggregation [31–36].

Criteria and quality indicators for good qualitative research are discussed in [37,38]. A key element in qualitative research is good listening [39], which is an important part of the data-gathering process, especially when interviews are involved. From this perspective, the interaction between the interviewer and the interviewee is of great importance in establishing good levels of trustworthiness and therefore gathering realistic information that communicates the actual thoughts of the participants. From this perspective, qualitative researchers are also "listening researchers"; the act of "listening" is not limited to formal situations like interviews, but it should be intended in a more holistic way, as listening to the whole research environment consistently and paying attention to feedback that can be provided at any point in time (i.e., during informal conversations).

The inductive approach is a qualitative research method that is based on developing themes, categories, and theories from the data, rather than identifying existing hypotheses or otherwise deductive approach. It is typically applied in exploratory or descriptive studies where research questions are broad and undefined, focusing on generating new insights or understanding about a particular phenomenon. The process starts with an open and flexible data-gathering process in a non-directed and non-judgmental way. Afterward, the researchers review the data in detail, looking for patterns, themes, or other meaningful features that emerge from the data. Then the data are coded, grouping similar themes or categories, and refined. Finally, the researchers systematically synthesize the categories into broader themes or theories, drawing conclusions about the phenomenon under study. Such a study is particularly useful for exploring complex and poorly understood phenomena, where the researchers need to be flexible to new insights which may not comply with existing understanding. Fields such as anthropology, sociology, psychology, and education utilize inductive approaches to explore human behavior, experiences, and perceptions [25,27,31,40,41].

This paper is based on qualitative research and an inductive approach as outlined above. The main source of information were course participants, as well as colleagues and collaborators directly or indirectly involved in the course.

The course participants included 23 Master's students and 2 PhD students. In addition, 6 persons among researchers and guest lecturers were invited to interact with the students during some parts of the course. Finally, 4 student advisors were also included as part of the course staff. In total, a sample of 35 people was available from which to gather and discuss qualitative information on different aspects of the course.

Information was gathered from course participants through student input received from informal talks in small groups and one-to-one, notes from colloquium meetings, their own reflections, notes from feedback received during and after the lectures, discussions with other faculty members, feedback from visiting researchers and guest lecturers involved in some parts of the course, as well as a few consultations with students' advisors. A small anonymous survey was also proposed to gather additional insights into some of the most relevant aspects that were raised during the various interactions outlined above.

The survey included both multiple-choice questions and open questions about the course structure, the quality of lectures, the teaching approach, the student's background, and the potential challenges encountered throughout the course. It is important to mention that the survey was just one of the many ways adopted to gather information and it cannot be utilized alone. Indeed, it was mainly the holistic informal dialogue with various actors that provided most of the reflective material, which was combined with a few pieces of information gathered from the survey for further insights. An inviting, informal, and open dialogue has been proven to be a better approach to receiving more open-hearted and genuine feedback than one provided in a more formal setting [42].

A general inductive approach for qualitative analyses was adopted to analyze the information gathered. As discussed in [40], such an inductive approach can produce reliable and valid findings.

5. Interdisciplinary Aspects and Scope of the Course

5.1. The Energy Informatics Domain

Energy informatics researches ways to more efficiently manage fossil and renewable energy resources using information and communication technology. Smart (power) grids, smart meters, demand response, smart buildings, plug-in electric vehicles, energy storage, energy policy, energy markets, and market mechanisms, etc. are some of the issues covered by energy informatics [1]. As discussed in [2], energy informatics is a broad domain that is neither about being an expert in power/energy systems nor about being an expert in computer science. It is more about developing connections between sectors. Most importantly, energy informatics is an interdisciplinary field; hence, a relevant course should cover issues that connect and integrate the two key subjects of energy and informatics. The main opportunity behind this domain is to create connections between different fields, enhance skills and allow research tasks that would not be possible without interdisciplinary knowledge. The main challenge is that students coming from different study programs will always be weaker on one side or the other. For instance, computer science students will need to pick up some broad energy and power systems knowledge, while students coming from energy-related study programs, might have to pick up and reinforce some computer science knowledge, with particular regard to programming skills. The teaching approach should therefore provide the right tools to tackle Energy "and" Informatics topics in a holistic, high-level way, that is approachable to students with different backgrounds.

5.2. Narrowing the Scope: Smart Energy and Power Systems Modelling

As discussed in [2], the other challenge hidden behind the wide, broad, and interdisciplinary character of energy informatics is that a selection of topics must be made in order to communicate the subject. Given the breadth and depth of the energy and informatics disciplines, it is necessary to pick a subset of pertinent topics for an energy informatics course. Prior to narrowing the scope of an energy informatics course, it is necessary to establish what is required and fundamental. This might be referred to as the energy informatics course's "basic framework". The second step is to discover "distinctive features" that can be added to the fundamental structure. These differentiating characteristics are intended to reflect the specific relevant research interests and experience of the lecturers teaching the course. Obviously, distinguishing characteristics must be relevant to the energy informatics discipline as a whole. A key emerging subject within the broad energy informatics domain is represented by "smart energy and power systems modelling", which is the chosen specialization for the course that is discussed in this paper. By incorporating components like renewable energy sources, storage technologies, electric vehicles, smart grids, and smart buildings, as well as social aspects like nudging and demand response, it focuses on the best design, expansion, management, and operation of energy and power systems. It is crucial to provide a comprehensive understanding of the problems with energy and power systems.

In particular, the proposed course covers the energy informatics discipline through the use of mathematical optimization as a background. The objective of the course is to discuss how mathematical optimization, in the context of computer science, can contribute to more effectively managing smart energy and power systems. The course also aims at discussing various optimization applications to power and energy systems problems, as well as the links between optimization and computer science within the Energy Informatics domain.

Optimization models can be used to analyze optimal energy resource investment decisions as well as optimal operational management of energy and power systems [43].

Starting with broad high-level models of the entire European Energy system [44], for example, it is possible to progress to local models for smart microgrids design [45] or thermal network design [46], and then to more detailed optimal power flow models for network restructuring and reconfiguration [47,48] or for virtual power plants [49]. The level of detail can then be increased by investigating more detailed models for smaller systems such as charging stations [50] and demand response [51], or buildings [52], and then moving down to detailed and specialized models of single generating units [53] or specific storage technologies [54]. Nuclear energy [55] can also be included in large energy system models to evaluate its long-term impact under different future scenarios. There may be no limit to what can be modelled and studied with such tools, both on the thermal and electrical sides. The above examples are already an indication of the wide research opportunities that lie behind the energy and power systems modelling discipline. They also show the strong applied implications that are of high interest not only to academia but also to the industrial world. This motivates the need to educate students in such a direction and develop specialized courses focused on this discipline so that the students of today will become the researchers and industrial leaders of tomorrow.

6. The Development of a Course within the Energy Informatics Domain

As outlined in the previous section, an energy informatics course with a focus on smart energy and power systems modelling has been developed. Two versions of the course were designed, a Master's level version and a PhD level version. As will be further expanded in the following paragraphs, the lectures for the two versions are the same, but the learning outcome, the examination form, and the grade scale are different.

6.1. The ASSURE Model

The ASSURE model and concepts have been used as an instructional design model to develop the energy informatics course in smart energy and power systems modelling. As summarized within the ASSURE model, the principal elements that make teaching and learning possible and attainable are: the teachers, the learners, and a conducive learning environment. The teacher is the primary mover of the educational cycle. The learners are the most important people in the learning process. The favourable environment provides critical aspects and components that could help guide the processes and methodologies required for a seamless link between the teachers and the learners.

The ASSURE model can be summarized as follows:

- A: Analyze learners and teachers;
- S: State standards and objectives;
- S: Select strategies, technology, media, and materials;
- U: Utilize technology, media, and materials;
- R: Require learner participation;
- E: Evaluate and revise.

6.1.1. A: Analyze Learners and Teachers

The main questions to answer within this key point are: who should learn and who should teach? The energy informatics course is supposed to be part of the master courses provided within the computer science study program at UiT, The Arctic University of Norway. As such, the target learners will be the master students of the computer science study program. The course is also supposed to be offered to PhD students, interested in energy and power systems modelling topics. Due to its intrinsic interdisciplinarity, the energy informatics course is also considered a strategic one for the computer science department, since it has the potential to create bridges with other departments and attract students from other study programs. This refers in particular to students from the so-called "Energy Climate and Environment" study program, as well as students from the "Renewable Energy", "Electrical Engineering" and "Industrial Engineering" study programs.

In terms of teaching, the main responsible for the course should be a professor or associate professor actively working in the field of energy informatics, with a background in mathematical optimization in the context of computer science applied to energy and power systems. From this point of view, as already outlined in the previous sections, the "distinguishing feature" of the course will be smart energy and power systems modelling, which represents a versatile and interdisciplinary subject that couples both energy and informatics. This will respond to the need to narrow the scope of the broad energy informatics discipline, as well as tailoring the course to the teacher's main research focus and expertise. In addition, by proposing mathematical optimization as a fundamental subject to build on, the course has the potential to reach a wider type of learners, for instance, also those from study programs in mathematics.

6.1.2. S: State Standards and Objectives

All study programs must have learning outcome descriptions that define what the students must have achieved in terms of knowledge, skills, and general competence after completing their education. Learning outcome descriptions are seen as part of the transition from teacher- to student-centered teaching. With learning outcome descriptions, emphasis is shifted from the content (what is taught) to the result (what the student is able to perform after completing the course).

As already outlined in previous sections, the original version of Bloom's taxonomy framework consisted of six categories: knowledge, understanding, application, analysis, synthesis, and evaluation. The categories that come after knowledge were collectively referred to as "abilities and skills", based on the perception of knowledge as a necessary prerequisite for these abilities and skills to be applied in practice. Based on the student-centered approach and on Bloom's taxonomy, the learning outcomes have been identified for Master's students and PhD students, as shown in Figures 3 and 4.

Objectives of the course - Master

Knowledge - the student can ...

- Understand the role of Smart Energy and Power systems modelling and optimization within the Energy Informatics domain.
- Understand the theory of operations research, mathematical modelling and optimization, as well as the specific applications to the energy and power systems.
- Understand the principles underlying the energy optimization tools.

Skills - the student can ...

- Develop mathematical optimization models and manipulate dataset to analyse relevant applied problems within energy and power systems, both on the investment side and on the operational side.
- Utilize an interdisciplinary approach to perform techno-economic analyses of sustainable energy systems. Adopt a practical approach for model building through concrete energy problems that have been addressed in literature in different energy sectors.

General competences - the student can ...

- Understand the overall concept of Energy Informatics and the interconnections between the fundamental subjects and the real-world energy problems.
- Understand the challenges and opportunities of interdisciplinary approaches to address Energy and power systems problems both at a research level and at an industrial level.
- Read scientific literature in the field of smart energy and power systems modelling, and extract relevant information from it.

Figure 3. Objectives and learning outcomes for Master's level students.

Figure 4 shows the learning outcomes for PhD level students and highlights in yellow the additional expectations as compared to the learning outcomes for Master's level students listed in Figure 3.

In addition to the fundamental learning outcomes that are common for both Master's and PhD level students, there are higher expectations for PhD level students in terms of research-related knowledge building, as well as critical thinking, independent learning, and more advanced abilities to read and understand scientific literature. These higher expectations will be mostly embedded in the semester-long project that is assigned to PhD level students, and that is also supposed to show a certain degree of novelty and originality, as it will be further discussed in the following paragraphs.

Objectives of the course - PhD

Knowledge - the student can ...

- Understand the role of Smart Energy and Power systems modelling and optimization within the Energy Informatics domain.
- Understand the theory of operations research, mathematical modelling and optimization, as well as the specific applications to the energy and power systems.
- Understand the principles underlying the energy optimization tools.
- Acquire knowledge needed to perform research within the smart energy and power systems modelling field.

Skills - the student can ...

- Develop mathematical optimization models and manipulate dataset in order to analyse advanced relevant research questions within energy and power systems, both on the investment side and on the operational side.
- Utilize an interdisciplinary approach to perform techno-economic analyses of sustainable energy systems. Adopt a practical approach for model building through concrete energy problems that have been addressed in literature in different energy sectors.
- Refine skills to perform research within the smart energy and power systems modelling field.

General competences - the student can ...

- Understand the overall concept of Energy Informatics and the interconnections between the fundamental subjects and the real-world energy problems.
- Understand the challenges and opportunities of interdisciplinary approaches to address Energy and power systems problems both at a research level and at an industrial level.
- Read advanced scientific literature in the field of smart energy and power systems modelling, and extract relevant information from it.
- Develop critical thinking on Energy Informatics research directions and on industrial innovation driven by Energy Informatics.
- Develop research and independent learning within the Energy Informatics domain.

Figure 4. Objectives and learning outcomes for PhD level students. The additional expectations for PhD level students, as compared to the learning outcomes for Master's level students, are highlighted in yellow.

6.1.3. S, U: Select/Use Strategies, Technology, Media, and Materials

Given its intrinsic interdisciplinarity, the course should reach out to students with different backgrounds and from different study programs. The main strategy to achieve this is to organize the course such that it will be as much self-contained as possible. All the most important background material in terms of energy and informatics should be broadly touched on such that students from different backgrounds will be able to understand and follow it. Therefore, the lectures to be given within this course have been organized into three main chunks. The first group of lectures introduces the main topics of energy systems and power systems and provides a broad overview of areas where the most relevant energy/power systems problems and opportunities can be identified. The second group of lectures provides the relevant background of operations research and mathematical modelling, with a focus on applications for energy and power systems, as well as programming skills to develop the models in different programming languages and modelling tools. The last group of lectures will take the basic optimization knowledge developed in the previous part and will put it into the broader perspective of energy informatics, by discussing the relevant links that exist at the intersection of energy systems, power systems, economics, computer engineering, and computer science.

The above chunks use instructor-centered strategies (lectures, demonstrations, etc.). In parallel, student-centered strategies such as group work are also proposed (see Section 6.1.4). In addition, guest lectures from industry and researchers, outlining the most recent research and development that has led to successful real-world applications, are proposed to keep the course modern, fresh, and up to date.

6.1.4. R: Require Learner Participation

The course is available for both Master's-level students and PhD students. The following strategies are adopted to engage the students and promote participation: guest lectures for both Master's level and PhD level students, assignments for Master's level students, and a semester-long project characterized by a certain degree of originality for PhD level students.

Guest lectures are organized such that key speakers (both from industry and academia) are invited to present interesting applications of the subject in the real world or to present some more specialized topics that can add a more in-depth understanding of certain aspects of the subject. Guest lectures have the purpose of providing the students an arena to discuss how concretely the knowledge acquired in this course can be used in the real world. The other objective is for the students to gain awareness of the job opportunities in the field of energy informatics that are available in the job market.

The Master's-level students are asked to work on two assignments graded pass/non-pass that give access to the final written exam at the end of the course. For both assignments, the students can choose to work alone or in small groups.

The first assignment consists of identifying an energy or power system optimization problem of interest, finding two papers in the literature that address such a problem using two different approaches, and writing a 3–5 page "compare and contrast" report. As further elaborated in [56], the objective of this report is to find points of comparison between two selected scientific works. This activity can enhance comparative thinking and strengthen student learning. An example is given by two papers that address the same energy optimization problem by utilizing different methodologies or focusing on different aspects. Another example is given by two papers when the second paper is more recent and is presenting an improved algorithm built on top of the first original paper. For this purpose, the students are provided some guidance in terms of web links and study material explaining what a compare and contrast essay is, and how it can be addressed. There are usually two main ways to tackle a compare and contrast essay. The so-called point-by-point method alternates discussions about the two papers that are compared. In this case, each similarity and difference between the works is discussed next to each other. The so-called block method first presents all relevant points related to the first selected paper and then compares and/or contrasts them to all relevant points related to the second paper.

The second assignment is an essay in which the students have to discuss a few given points based on what they learned during the course and based on additional research that they can make online. The points for discussion are broad topics related to the value of modelling within the energy informatics domain, the future research directions that should be pursued in light of the existing literature, and the EU's sustainability goals, as well as reflections on opportunities and challenges of interdisciplinary work and a portfolio of skills required to work within an energy informatics domain both in industry and research.

For the PhD students, a semester-long project (graded pass/non-pass) with some degree of novelty is required to pass the course. The semester-long project consists of a literature review, a compare and contrast exercise, and a model development. All these points should be linked to the PhD project so that the learning outcome throughout the semester-long project can actually be relevant and contribute to the research of the student.

6.1.5. E: Evaluate and Revise

The evaluation phase is crucial for identifying areas for improvement, especially considering that the course discussed in this paper was developed and provided for the first time in the autumn semester of 2022. This phase is further expanded in Section 8 where a broad evaluation is made based on the participant's feedback and experience, observations from the lecturer and guest lecturers, as well as discussions with colleagues and students' advisors. Possibilities for improvement are discussed in Section 9 with a particular focus on enhancing the T-R nexus within the course.

6.2. A Novel GPD Model: Gaussian Progression of Difficulty

Traditional pedagogical principles are built on the basis of the so-called linear pedagogy, which assumes that all learners need to progress "from easy to hard" or "from simple to complex" topics. Existing studies in the literature have already discussed how learning processes seem to be more successful when teaching processes deviate from a linear approach [57]. Non-linear approaches to course structure that improve learning have been recently discussed in [58]. In general, the focus of nonlinear pedagogy is on the individual learner and clearly, student-centered.

A novel non-linear Gaussian approach to tackle the course progression of difficulty was introduced and tested during the course. Such an approach is defined as a GPD model, which stands for Gaussian Progression of Difficulty. A graphical representation to better understand the fundamental concept behind the GPD model is shown in Figure 5.

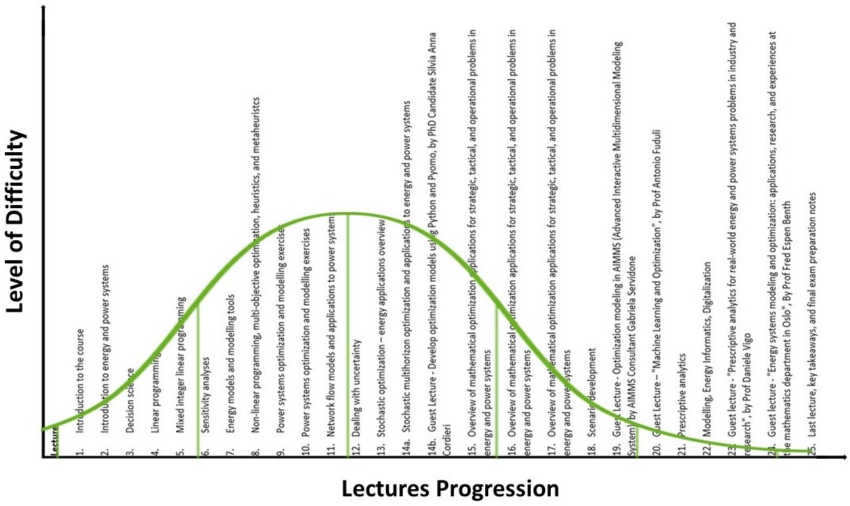


Figure 5. A novel Gaussian progression of difficulty model (GPD) for lectures planning that improves and facilitates learning.

The figure shows a list of lecture topics, on a cartesian diagram, where the horizontal axis shows a temporal progression, while the vertical axis shows the level of difficulty. As can be observed, the lecture progression has a Gaussian shape, with a peak level of difficulty more or less at the center (as opposed to the traditional linear approaches with a mostly linear increase of difficulty from the beginning to the end of the course). Clearly, for the first half of the semester, the lecture topics are progressing from simple to complex (as in a traditional linear pedagogy approach). However, once a peak level of difficulty has been reached (about in the middle of the semester), the lecture topics are no longer becoming even more complex, but they are rather turning into a "complex to simple" progression. The reason is that the students should be given the time to delve deeper into the more challenging topics presented in the first half of the semester. Therefore new less demanding (but still complementary) lectures are continuously added during the second half of the semester, to enhance the understanding of the more challenging topics that were previously introduced. Indeed, the second half of the lectures is mostly dedicated to guest lectures discussing the practical implications of the theoretical topics introduced within the first half of the semester. Beyond guest lectures, also traditional lectures on broader applications with a less demanding theoretical background are proposed.

The proposed GPD model has two main potential benefits.

It allows "repeating without repetition", meaning that the teaching content can be repeatedly revised throughout the duration of the course, by proposing it from different angles. This means that during the second part of the semester, students will have the opportunity to revise certain challenging concepts by focusing on less demanding collateral tasks (such as guest lectures) that tackle the earlier concepts from different perspectives (for instance, applied implications) that are smoother to grasp and contribute to an enhanced and more holistic understanding of the subject.

The GPD model can also positively affect the students' motivation. Once the top level of difficulty is reached, a portion of students may have lost part of their initial motivation due to the challenges they encounter in understanding certain concepts. Indeed, motivation is likely to decrease substantially as the students move from easier to harder topics. At this stage, continuously adding more difficult topics can be detrimental and negatively affect the students' self-motivation. A GPD model gives an opportunity to less motivated students to catch up and not quit the course. At the same time, more motivated students can still identify new challenges and hints through the additional study material that is proposed in the second half of the lectures and take the opportunity to delve deeper into the material that was proposed within the first half of the lectures.

These potential benefits will be further expanded later in Section 8 where observations of the student's feedback and behavior will be discussed.

6.3. Self-Regulated Learning Strategies

Self-regulated learning strategies are research-based instructional techniques to help learners monitor and manage their own learning skills and habits. Self-regulated learning has three phases [12]—forethought, performance, and self-reflection. These steps are sequential. Self-regulated learning is implemented through the course works as follows.

The forethought phase is implemented for Master's students by asking them to select and propose two relevant energy/power system problems/areas that are of interest to them. Once approved, the selected problems will be utilized as a starting point to identify scientific papers for the first assignment. This phase will encourage the students to familiarize with the course material and topics upfront, while also searching themselves for additional information online. For PhD students, the forethought phase is implemented in a similar way, by asking them to identify a relevant optimization problem in energy that is somewhat linked to the research that they are performing for their PhD.

The performance phase for Master's level students is implemented through the two assignments whose content is described in the previous sections, while for PhD level students this phase is represented by the core semester-long project that they develop throughout the course.

The self-reflection phase for Master's students will be facilitated by the second assignment, where students are encouraged to reflect on some key aspects of the course and discuss them in a written report in the form of a summary text. For PhD level students, the semester-long project includes a final section in which they are supposed to discuss the limitations of their work and research directions that they are planning to pursue.

6.4. Course Modules and Lectures

Based on the reflections outlined above, the final course structure is presented below. The course has been divided into three main modules: fundamental theory, energy and power systems applications, and guest lectures.

- MODULE 01—Fundamental Theory
  - Introduction to energy and power systems;
  - Introduction to decision science;
  - Linear programming;
  - Mixed integer linear programming;
  - Sensitivity analyses;
  - Non-linear programming, multi-objective optimization;

  - Heuristics and metaheuristics algorithms;
  - Dealing with uncertainty.
- MODULE 02—Energy and Power Systems Applications
  - Energy models and modelling tools;
  - Power systems optimization and modelling exercises;
  - Network flow models and applications to power systems;
  - Stochastic optimization—energy applications overview;
  - Scenario development;
  - Overview of mathematical optimization applications for strategic, tactical, and operational problems in energy and power systems;
  - Modelling, energy informatics, digitalization.
- MODULE 03—Guest Lectures
  - Develop optimization models using Python and Pyomo;
  - Optimization modeling in AIMMS;
  - Prescriptive Analytics to Optimize Power Grid Operations and Planning Based On Energy Storages and Human Energy Behaviour in Northern Norway;
  - Machine Learning and Optimization;
  - Prescriptive analytics for real-world energy and power systems problems in industry and research;
  - Energy systems modeling and optimization: applications, research, and experiences at the mathematics department in Oslo.

A variety of study material has been proposed as a mix of book chapters, a selection of relevant scientific articles, and slides. Sometimes relevant short videos were also proposed during lectures. Book chapters were proposed for the fundamental theory discussed in the first module. For the second module, a mix of slides and scientific papers was proposed. During the third module, slides from the guest lecturers were made available for the students to revise the content.

7. The Teaching-Research Nexus within the Course

When research is built into the design and implementation of a course then it is referred to as intrinsic research. Intrinsic research aspects could be summarized as follows: learning outcomes, curriculum design, instructional strategies, assessment practices, student engagement, faculty development, and gradual development [59–67].

- Learning outcomes: learning outcomes reflect the knowledge, skills, and competencies that the course provides to the students when they successfully complete it.
- Curriculum design: The curriculum is to be designed for a structured and coherent progression of the information. The sequence and contents of the topics are two important aspects of the design of a course.
- Instructional strategies: How the content is delivered in a class matters in promoting the learning outcomes. Some well-established methods include active learning, problem-based learning, or inquiry-based learning.
- Assessment practices: Aligning with the learning outcomes and instruction strategies, constructive feedback to the students on their development is important. Assessments could be in the form of assignments, exams, or oral to list some widely used ones.
- Student engagement: Motivation and satisfaction of the student throughout the course leads to successful completion.
- Gradual development: Gradually updating the course with feedback and current research development is important to keep the course and learning relevant to the times.

The above six key points are part of the intrinsic research aspects of the course that motivate the adoption of a T-R nexus framework to achieve better course development.

The main tasks performed during the course are summarized in Table 1. The content of the assignments and guest lectures is further expanded in the previous sections.

Table 1. Main tasks within the course

Task	Acronym	Description	Target
Assignment 01	A1	Compare and contrast report	Masters
Assignment 02	A2	Essay, summary text	Masters
Semester-long project	SP	Research project with some degree of originality	PhDs
Traditional lectures	TL	Lectures discussing the main theoretical aspects	Masters and PhDs
Guest lectures	GL	Lectures with invited speakers from industry or accademia	Masters and PhDs

Figure 6 shows how the different tasks mentioned in the previous paragraphs are positioned on a T-R map. As shown in pink, the T-R map is characterized by four main dimensions. Two dimensions identify the role of the students (students as participants versus students as audience). The other two dimensions identify the type of research emphasis (emphasis on research content versus emphasis on research processes and problems).

The tasks mentioned in Table 1 are spread on the T-R map of Figure 6 in the form of green circles. These circles are positioned based on how much each task satisfies one or more of the four dimensions. Assignment A1 is characterized by a high level of student participation since the students have to be actively involved in the different aspects of the assignment (namely identify a topic of interest, identify two relevant papers, study the papers, and write a report based on a compare and contrast analyses). Moreover, since this assignment involves the selection and understanding of scientific papers, it is characterized by a high emphasis on research content, which explains its position on the top left corner of the T-R map.

Similar to assignment A1, assignment A2 is also characterized by a high level of student participation since it requires active search and writing tasks to develop the final essay. However, due to the intrinsic content of the essay that is broader and less research-focused, assignment A2 has a lower emphasis on research content.

The semester-long project SP for PhD students has the highest level of student participation and also a very high emphasis on research processes and problems since the PhD students are supposed to actively work on literature review and model development for specific applications of interest. This explains the position of the SP green circle on the top left corner of the T-R map.

Finally, both traditional lectures TL and guest lectures GL are characterized by students as audience. Traditional lectures TL have a low emphasis on research content since they are more focused on introducing the foundations and theoretical aspects of the subject. While guest lectures have a high emphasis on research processes and problems since the invited speakers are supposed to present applications of the subject in research or real-world industrial problems.

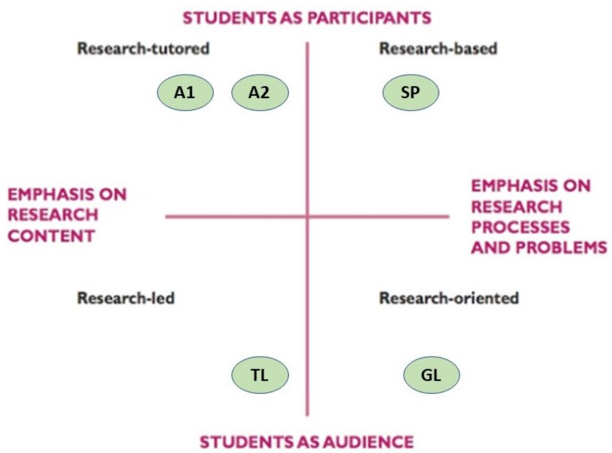


Figure 6. Different tasks performed by the students during the energy informatics course and their position on the T-R map.

8. Experience, Observations, and Discussion

The course was a success, with 20 students passing, of which eighteen were Master's students and two were PhD candidates. In addition to that, one Master's student failed the final exam, and two Master's students dropped out during the first half of the course.

Students at different stages of various Master's programs and diverse academic backgrounds participated. This was an excellent result, both academically and in terms of new connections between study programs and departments. Master's students came from the following study programs:

- Master Civil Engineering—Energy, Climate, and Environment—five students;
- Master Civil Engineering—Computer Science (five years)—six students;
- Master Computer Science (two years)—seven students;
- Master Physics—three students;
- Single course—one student;
- Master exchange students—one student.

The main difference between the 5 years and the 2 years computer science study programs is that students enrolled in the 5 years study program typically have a broader overview with deeper insights into fundamental subjects, such as more math and physics-related exams to prepare.

The single course is related to external students who are not enrolled in a study program but can take the course as a single specialization course as part of their job.

Finally, Master's exchange students are students coming from abroad and joining single courses as part of their exchange study program, such as Erasmus students

The list above clearly shows the variety of students' backgrounds, which represented both an opportunity and a challenge for the course delivery. The opportunity lies in the possibility to reach out to a diverse group of students, popularize the subject within different study programs, and create bridges among different departments and research groups. The challenge lies in the need for delivering lectures to students that have different backgrounds and therefore different foundations. A typical challenge here is that students have very different knowledge of the different disciplines involved in the course, namely energy and power systems, computer science, mathematics, and engineering. Typically, students from computer science will be weaker in the power and energy systems' related subjects, while students from physics or energy, climate, and environment study program may be weaker in their programming skills as compared to computer scientists. The advantage anyway is that such a diverse mix of skills may create informal self-help groups among the students so that, for instance, exchanging knowledge during group work, will enhance the overall understanding of the different methodological, analytical, and applied aspects of the subject.

Despite the fact that the course was new, it received a positive response and it was followed by a relatively high number of students considering that optional courses usually have less than 10 students on average at the Department of Computer Science.

The students enjoyed the overall lecture structure and the proposed topics; they appreciated the course assignments to help them understand the subject better; and they enjoyed the proposed guest lectures. Several students said that they will utilize what they have learned during the course for future activities such as thesis, projects, papers, etc.

This is a positive response, confirming the practical implications and applicability of the course topics.

Throughout the course, there was a good degree of attendance at both formal lectures and guest lectures.

8.1. Feedback on the Assignments

Assignment 1 (scientific papers comparative analyses) was considered very interesting by the students since it provided a very good understanding of the subject chosen by each group. Students commented positively on this type of assignment because they were given the time to focus on a specific part of the curriculum which they found very helpful and engaging. One comment was that it could have been a good idea to have each group give a short presentation to give other students the opportunity to learn what other groups have worked on. This will be further discussed in the following section where potential improvements to the course will be presented. Assignment 2 (summary and reflection text) was considered by some students to be a bit less engaging. However, while Assignment 1 was about reading and discussing somebody else's work, Assignment 2 was about writing down one's own thoughts and understanding from scratch. Assignment 2 required additional abilities to synthesize concepts and gather relevant information from online sources. Several students suggested that the course could have included one or more practical assignments so that the theoretical understanding of the tools and concepts used in energy informatics could be coupled with the actual knowledge of how to use the tools and give students a good insight into what they are trying to learn.

However, it is important to note that, on an optional basis, students were actually given the opportunity to experiment with coding exercises, that were presented and proposed during the lectures. Even though several students reported that they indeed engaged themselves in such optional modelling exercises, still some students reported that they would have preferred more mandatory hands-on coding in this course, to be actually motivated into investing their time in more practical tasks.

The feedback received highlighted that, while Assignment 1 turned out to be very useful, Assignment 2 may need to be revised, and replaced by a more practical assignment, or a third practical assignment could be included on top of the two existing assignments.

8.2. Feedback on the Guest Lectures

A wide variety of guest lectures was proposed towards the second half of the course. Some guest lectures were more rigorous and methodological, while others were more applied. Most of the students appreciated the more practical guest lectures where lecturers explained how modeling was applied to real-world problems. A few guest lectures were more focused on the mathematical aspects of the subject and were considered by the students harder to follow. The overall feedback was positive and students considered the guest lectures as a nice addition to better understand the applied implications of the course. The type of student background (coming mainly from engineering and computer science) partly explains why the applied lectures had more success than the more methodological ones.

The mixed feelings regarding the guest lectures highlighted that it is beneficial to offer diversified topics from diversified guest lectures so that various students' needs are met.

8.3. Feedback on the Course Progression of Difficulty

As outlined in the previous sections, the course was organized following a novel GPD model that consists of a non-linear approach with a peak level of difficulty towards the middle of the course. The lecture difficulty increased throughout the first half of the course, and it decreased over the second half. This means that the most difficult material was introduced to the students within the first half of the semester.

Master's students appreciated that, after the peak level of difficulty reached in the first half of the course, there was a second half of the lectures with lower difficulty. Indeed, this gave them time to better digest the most difficult topics while consistently adding new knowledge through the additional lectures. On the other hand, one PhD student would have rather preferred a more traditional linear model and felt he could have tolerated more difficulty after the peak. It is relevant to note that two Master's students dropped out right in the middle of the course, which corresponded to the peak level of difficulty. If more complex content was added after the peak, more may have dropped out later on. However, the following observation should also be mentioned. It has been observed by the administrative staff throughout the years, that a small number of students often signup for a few optional courses at the same time without the ambition of necessarily concluding them, but just to "put eggs in different baskets" and finally pursue something that can be passed with the minimum effort. In such instances, a GPD model is unlikely to be effective, because such students' motivation is already low from the start of the course. Indeed, a GPD model is intended to "keep" students' motivation high and minimize motivation loss during the course, particularly in courses with tough topics. From this perspective, there is little that can be done for students whose attitude is not proactive from the outset. However, more qualitative research should be performed to further investigate these aspects.

Master's students appreciated how the second half of the lectures were still adding new "relevant" content, but not new "more difficult" content. Indeed, the additional content was new but still complementary to a better understanding of the content presented in the first half of the course. This gave the students time and peace of mind to revisit some chunks of the more difficult topics of the previous lectures, while still adding new relevant knowledge as the course was progressing. This also positively affected the overall motivation of the students so that nobody dropped out during the second half of the course.

During the course, a constant very good attendance to lectures was also observed in the second part of the course (where normally in many other courses we rather observe a reduction in the number of students that show up during lectures). An average of 15–17 students were always attending the lectures. Here it is important to mention that several students chose to work in groups of a maximum of three people for their course assignments and some of them were helping each other with lecture attendance and note sharing.

The different perspectives offered by Master's students and PhD students highlighted that it may be necessary to further differentiate the two curricula such that PhD students can receive more challenges and choose between a GPD model and a more traditional linear model with regard to the lectures' progression of difficulty.

8.4. Feedback on the Course Content and Relevance

All students gave positive feedback on the overall lecture content and structure, confirming that the overall plan and organization gave them a good understanding of the different topics involved and prepared them very well for the final exam. Another comment concerned the speed of the lectures. Because there were so many topics to cover, some students thought some of the lectures went a bit too fast.

This feedback highlighted that certain topics may need to be presented at a slower pace in the future.

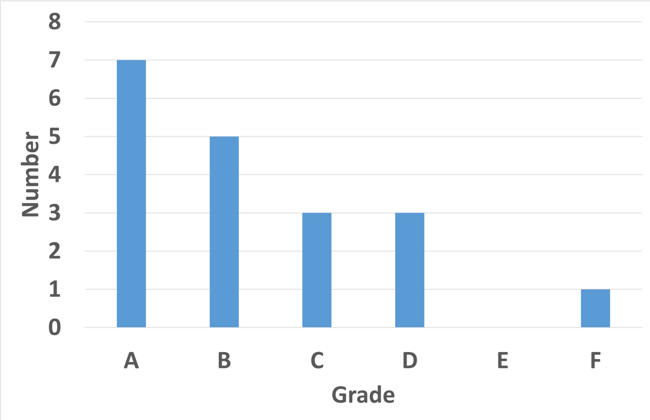
8.5. Overall Student Performance

The Master's students' performance during the assignments was satisfactory and all the students submitted good-quality reports and were admitted to the final written exam.

The overall performance of Master's students at the final written exam (four hours of school written exam without aids) is summarized in Figure 7 where the qualitative description of the graded scale is also included for completeness. The Norwegian grading system consists of two grading scales: one scale with the grades pass or fail and one graded scale from A to E for pass and F for fail. In terms of performance, it was observed that informatics students with engineering backgrounds outperformed the others on average in the final written exam.

It is important to highlight that the course was an optional one, and therefore it was mostly selected by students who were already interested and motivated by the broad learning objectives. This partly explains the high number of students who got an A grade, followed by a relatively high number who got a B. Students performed particularly well also because the course was actually "chosen" by them based on their interests and learning desires. This, together with good quality lectures, contributed to the overall success in terms of final performance.

The two PhD candidates were graded with a pass or fail assessment and they both passed the course, submitting good quality projects.



Symbol	Description	General, qualitative description of valuation criteria
A	Excellent	An excellent performance, clearly outstanding. The candidate demonstrates excellent judgement and a high degree of independent thinking.
B	Very good	A very good performance. The candidate demonstrates sound judgement and a very good degree of independent thinking.
C	Good	A good performance in most areas. The candidate demonstrates a reasonable degree of judgement and independent thinking in the most important areas.
D	Satisfactory	A satisfactory performance, but with significant shortcomings. The candidate demonstrates a limited degree of judgement and independent thinking.
E	Sufficient	A performance that meets the minimum criteria, but no more. The candidate demonstrates a very limited degree of judgement and independent thinking.
F	Fail	A performance that does not meet the minimum academic criteria. The candidate demonstrates an absence of both judgement and independent thinking.

Figure 7. Performance at the final written exam for Master's students and qualitative description of valuation criteria.

8.6. Post-Course Positive Effects

The course was well received by the students with overall very positive feedback. Moreover, the course had positive effects during the following months. Indeed, five Master's students in their last year contacted the lecturer to discuss master thesis proposals inspired by the topics proposed during the course. In addition, both PhD students remained in touch to further develop their semester-long project and produce a scientific publication from it. In sum, 40% of the course participants asked for further supervision after the course in relation to Master's thesis projects and doctoral scientific publications. This is a very positive outcome and promising feedback on the overall quality and relevance of the topics proposed throughout the course.

9. Enhancing the Course

This section discusses improved choices when it comes to lecture planning, laboratory experiences, and examination approaches, based on the feedback received by the students.

In light of the inductive and qualitative analysis results we discuss opportunities for improvements.

The main possibilities for improvements can be summarized as follows: improve the research-based content through the inclusion of a third research-based assignment, improve the learner participation (R part of the ASSURE model) through the inclusion of laboratory experiences for model building exercises, improve the self-reflection phase of the Bloom's taxonomy through the inclusion of students' presentations throughout the course.

All the above developments will enhance the overall T-R nexus of the course as it will be further expanded in the following subsections.

9.1. Improve the Research-Based Content

A potential development to improve the research-based content of the course might be the inclusion of an additional optional assignment A3 for the master students who are interested in working on more research-based projects. It may also be possible to include the possibility for master students and PhD students to cooperate within a subset of the semester-long project SP. This would give a unique opportunity to the master students who may engage in more research-based discussions with more advanced PhD students. It would also give a good opportunity to the PhD students who may receive some help for a few tasks within their semester-long project so that they could also experience a little bit of a leading role while guiding the master students in a few subtasks.

Such a project-based assignment will better address the "apply", "understand", and "remember" fields of Bloom's taxonomy, as well as further reinforce the performance phase of self-regulated learning. This will consist of two parts:

(1) A main modelling and programming task: develop a prototype of a mathematical model to address a relevant energy or power system problem that is of interest to the student.
(2) A report (in the form of a conference paper) describing the chosen energy or power system problem, a well-founded description of the developed model, and a discussion of the performed sensitivity analyses.

Figure 8 shows how the T-R map would change if such a development would be included. The new tasks are shown in light blue.

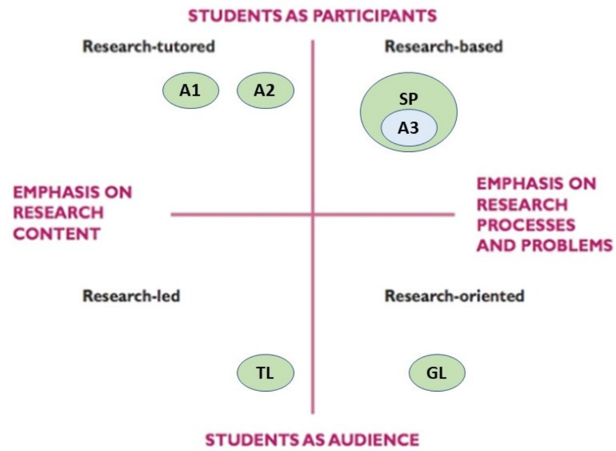


Figure 8. A variation of different tasks performed by the students during the energy informatics course and their position on the T-R map: additional assignment A3.

9.2. Improve the Learner's Participation

The "R part" of the assure model (require learner participation) proposed in Section 6 can be further enhanced through the inclusion of laboratory experiences LE. This will refer to model-building exercises for energy and power systems by using a chosen programming language to formulate optimization problems and run analyses.

Laboratory experiences where the students implement the models and learn how to interface with modelling tools and solvers can be included in a T-R map too. In this case, the laboratory experience is characterized by a low emphasis on research since the students would develop modelling exercises that are simplified and not necessarily research-based (the focus here is learning to use modelling tools) and also a low level of students participation since the student would implement given mathematical models, they will not be asked to develop their own model to solve a certain problem. Hence this would be a pure implementation task that would not require much critical thinking in terms of solving an existing problem.

Figure 9 shows how the T-R map would change if such a development would be included. The new tasks LE are shown in light blue.

The laboratory experiences, together with the required course work for Master's students and the semester-long project for PhD students, will reflect the key aspects of the Bloom taxonomy framework (remember, understand, apply, analyze, evaluate, create) as discussed in [9], as well as touch upon the concepts of self-regulated learning.

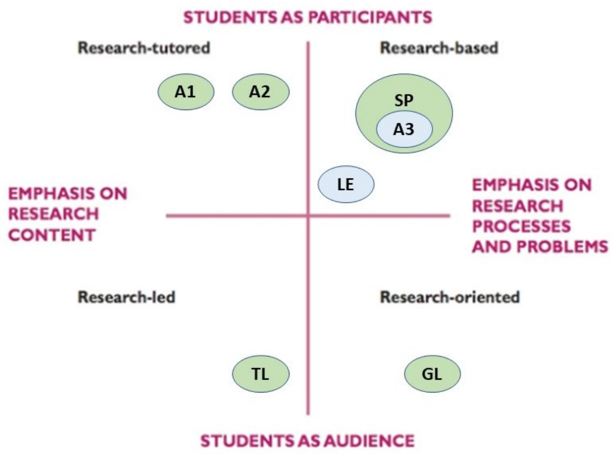


Figure 9. A variation of different tasks performed by the students during the energy informatics course and their position on the T-R map: additional laboratory experiences LE.

9.3. Improve the Self-Reflection Phase

As introduced in Section 6.3, self-regulated learning has 3 sequential phases: Forethought, Performance, and Self-reflection. The self-reflection phase can be enhanced through the inclusion of an additional task in the form of a 10 min presentation P of the outcome of the first assignment to give in front of the other course participants. A presentation should adhere to the IMRAD format [68]. This format was originally developed for structuring a scientific paper, but can successfully be utilized also as a basis for a good presentation structure [69,70]. This refers to four main sections: Introduction, Methods, Results, and Discussion. While the introduction and discussion are presented at a broader level, the methods and results are usually more specialized and focused.

The self-reflection phase will be facilitated by such live 10 min presentations since the students will receive feedback from others and will be engaged in short discussions afterward. The above tasks will also touch upon the "create", "evaluate", and "analyze" fields of Bloom's taxonomy [9].

Figure 10 shows how the T-R map would change if such a development would be included.

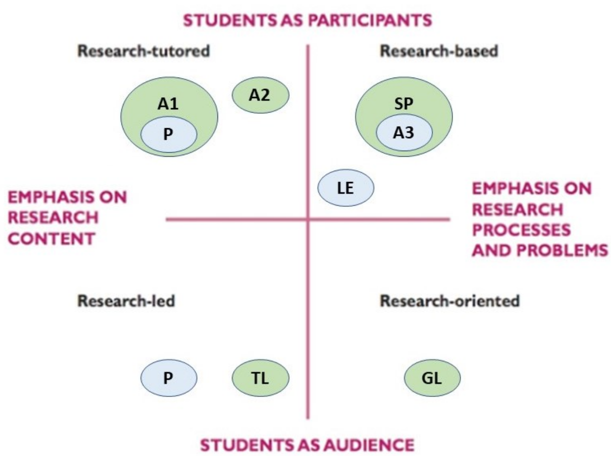


Figure 10. A variation of different tasks performed by the students during the energy informatics course and their position on the T-R map: additional presentation tasks P.

The new tasks P are shown in light blue. The opportunity to present the work to their peers would put the students both as participants (when they are giving a presentation to their peers) and as an audience (when they are attending the presentation of their peers). This is the reason why the new task P is visible in two quadrants simultaneously.

Presentation P is an extension of the first assignment A1 when students are delivering it, and it has a high level of student participation as well as a high emphasis on research content due to the intrinsic requirements of assignment A1 that are strictly connected to existing scientific research papers. This explains the position of task P in the research-tutored quadrant, embedded in task A1 of Figure 10. The presentation P puts also students as the audience, while still maintaining a high emphasis on research content. This explains the simultaneous position of task P in the second research-led quadrant.

10. Interdisciplinary Teaching: Challenges and Opportunities

Lecturers often have their backgrounds rooted in a particular discipline or scientific area. In the course, guest lecturers had a variety of backgrounds, including mathematics and statistics. We share in this subsection some experiences and views gained in interdisciplinary teaching (and research) seen from the lecturers' point of view.

Meeting a rather heterogeneous group of students demands careful preparation by the lecturer. The students have very different knowledge as well as expectations and interests. As a lecturer, one aims at motivating the students, as well as introduce knowledge and develop skills. Preparations for lectures in a multidisciplinary course often require careful re-thinking of the teaching material compared with "standard courses", which may, in fact, provoke new questions and ideas for research.

One may claim that scientific disciplines are comparable to silos, with deep knowledge in a specific area and very limited knowledge in neighboring areas. Disciplines have their own scientific notions and ways of communicating science. This can cause confusion among students, and be a pedagogical barrier. However, being aware of such barriers may give students first-hand experience with the challenges of interdisciplinary work. In fact, in our experience, this may be a point where the lecturer learns from the students through classroom discussions across disciplines.

Mathematics enters into energy informatics through data analysis, systems modeling, and optimization. Sometimes, for example when teaching finance and energy markets (being important for the functioning of the energy systems), rather specific knowledge is required to grasp the problem. To what extent should one spend time on introducing such material, and what compromises does the lecturer need to make? As the students' interests also differ, spending too much time on background material may be a risky road toward the loss of the student's attention. Needless to say, the progression of the course is also harmed by the need for background material, which is not an uncommon problem in the linear teaching of courses in mathematics.

Energy informatics involves questions from social sciences on the perceptions of society on energy fairness, say, or questions from the law on land use. However, frequently, the questions from these sciences (and others) are not in focus, but rather more quantitative problems dwelling around the mathematical optimization of a stylized model. Only constraints that can be quantified mathematically are accounted for in a cost minimization of an energy system, say, whereas other "soft" constraints like human rights are ignored. However, in practice, such rights may in policy-making be determining the system to a much larger extent than costs, say, and seemingly sub-optimal decisions are taken. This confronts the students with the interplay between model and reality, where a careful critical awareness must be built up toward what such idealized theoretical frameworks actually tell us.

Furthermore, many questions raised and answers found are heavily influenced by the methods and knowledge we have available. For example, often in both computations and mathematics, the curse of dimensionality puts severe limits on what can be analyzed. Sometimes researchers jokingly say they have the hammer (i.e., the method) but in search for a nail (i.e., problem) in despair. Closer to the truth, at least to some degree in energy systems design, is that one has a toy hammer, which one avoids using on the big poles (i.e., real problem) but rather aims for the small nails (i.e., toy problem). In mathematics, say, there may be a long scientific path that must be laid before being able to solve the real problem. This may often be circumvented by numerical solutions, however, sometimes without a rigorous foundation or understanding. In climate and energy research one also observes sometimes that computer-based methods (like simulations) have been used to analyze huge sets of data, where known statistical methods could have provided a rigorous answer. Thus, knowledge beyond the silo may result in more insight and knowledge than that resulting from excessive and unnecessary use of computers. These aspects pose a challenge in research-oriented courses, but, also an opportunity to convey the limitations and current borders of science to young and aspiring future researchers.

11. Conclusions

This paper presented approaches to developing, delivering, and evaluating a new interdisciplinary course called "smart energy and power systems modelling" at both Masters's and PhD levels, in the context of energy informatics. Pedagogical perspectives of interdisciplinary teaching and research have been discussed based on different pedagogical frameworks, utilizing qualitative research and an inductive approach.

The study and the successful real-world implementation demonstrated the value of the selected pedagogical frameworks and models with regard to interdisciplinary STEM education in general, and the energy informatics domain in particular. It has been observed how the ASSURE model, Bloom's taxonomy, and self-regulated learning strategies can be successfully adapted to specific interdisciplinary domains to tackle the challenges of interdisciplinary teaching.

The T-R nexus has also proved to be a powerful tool to design, analyze, and enhance interdisciplinary courses within the energy informatics domain, such that more research-based content can be included in ways suitable to both educate Master's students toward research-based pathways and enhance the PhD student's research skills.

The novel proposed GPD model was implemented and tested. It has proved to be an appropriate strategy to handle the course progression of difficulty such that the student's motivation is positively affected, especially throughout the second half of the course. More research and observations should be carried out to better understand the effects of such a model and how to improve it when both Master's students and PhD students are involved in the same course.

The observations performed and feedback received highlighted the importance of differentiating the curricula and the course's tasks when courses are open to both Master's and PhD students. The most critical aspect is providing a common fundamental learning material, but at the same time differentiating the learning pathways according to the different students' levels and learning objectives. From this perspective, a wider portfolio of mandatory and optional assignments could be a key aspect. This leads to the challenge of gathering additional teaching resources in terms of researchers and assistants. These can follow the students' assignments, perform laboratory, and guide the most motivated students through potential additional course material. The challenge here is two-fold, since this is both a financial problem (funds are needed to assign more human resources to a course) and a recruitment problem (since it is vital to identify resources that are qualified for such roles). The financial problem can be addressed by a better popularization of interdisciplinary courses for energy applications, such that faculties gain a deeper understanding of the value that such disciplines have to tackle modern society's environmental and sustainability challenges. This way, strategic funds could be devoted to the development of courses and study programs in the energy informatics domain. The recruitment problem can be addressed in a similar way since devoting strategic funds to the development of the energy informatics domain will widen the opportunities to educate specialists that can become the human resources of tomorrow.

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