

Interdisciplinary Teaching in the Field of Resilient Energy Systems: Experiences with Expert Lecture Series Combined with Workshops

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Abstract

The increased complexity of renewable energy systems derives in uncertain and vulnerable systems behavior, making necessary for energy experts to understand and apply resilience studies with interdisciplinary approaches. With this aim, we have designed a postgraduate course on resilience of energy systems, pursuing an “exchange interdisciplinarity” level that enables students to (i) become aware of competing approaches in terms of methods and theories stemming from different disciplines, and (ii) to critically argue on the suitability of presented concepts for energy systems design and management. The course aimed at achieving a sound level of exchange interdisciplinarity as defined in relevant literature. We chose the following specific teaching methods and didactic items to facilitate this aim and address the different challenges of interdisciplinary education identified from the literature: fundamental introduction (FI), expert interviews and deepening workshops. The FI aimed at providing a sound common basis for understanding the perspectives and approaches from different disciplines. The expert lecture series exposed students to the broadness of state-of-the-art approaches existing in resilience research for energy systems, while the deepening workshops allowed students to develop a deep and critical appraisal of the disciplinary approaches and their relations. The course impact is evaluated through the standard questionnaire for teaching evaluation from the University of Oldenburg. The evaluation shows that the course fostered a critical and interdisciplinary thinking, with a high and interactive participation through the use of multiple didactic measures. This is supported by the high satisfaction of the students, the high level of engagement and academic performance and the qualitative perception from the lecturers. Topics of similar complexity or interdisciplinarity in energy higher education, such as sustainability, technology assessment or energy systems analysis could also benefit from such a course design.

Keywords: resilience energy research, interdisciplinary teaching, higher education

1. Introduction

Renewable energy systems have evolved from a niche technology following a “small is beautiful” approach (Schuhmacher, 1999; Bortman, 1976) to largely complex systems (Labanca, 2017), involving a great number of technology interactions and a great variety of stakeholders. Nowadays, its design and control is a complex task: bidirectional networks, prosumers, sector-coupling approaches, the development of energy markets, or the increasing use of digital communication technologies for monitoring, control and forecasting the behavior of the energy system are just some of the fields that exemplify this complexity. The energy system is becoming more decentralized and networked and complex at the same time. Higher complexity is strongly related to higher uncertainty in the system behavior and may lead to increased vulnerability. In this context, designing, monitoring and operating the energy system so as to maximize its adaptability to unforeseeable and drastic changes is necessary (Selina Byfield, 2017). The resilience approach is devoted exactly to this aim (Ruth and Goessling-Reisemann, 2019).

This is why experts working on energy systems management and design should be able to strengthen the resilience of current energy systems, as well as to develop and implement strategies fostering it. For postgraduate students on their way to become such energy experts knowledge and proficiency on the resilient behavior of energy systems is of significant importance (B. D. S. Walker, 2012): “We live in a complex world. Anyone with a stake in managing some aspect of that world will benefit from a richer understanding of resilience and its implications.”

In recent years, several disciplines are applying resilience concepts to energy system analysis [7-16]. Currently, resilience research on energy systems engages perspectives from environmental modelling (Kim et al., 2018), physics (Haehne et al., 2019), cyber-resilience and informatics (Fischer et al. 2018), or social sciences (B. Walker et al., 2004; Goldthau, 2014). There exists neither a widely accepted homogeneous procedure or framework nor a standardized set of metrics for quantifying the resilience of a given system from those different perspectives. Several researchers have recently done significant efforts on trying to define an appraisal method for operationalizing the concept and applying it to energy systems analysis. The developed approaches range from defining resilience as a guiding-concept for systems design and operation (Göbbling-Reisemann, 2016), (Brand and von Gleich, 2015), to establishing a comprehensive set of metrics (Roegel et al. 2014), appraisal methods (Wyss, Mühlemeier, and Binder, 2018) or following an epistemological approach aiming at making obvious incompatibilities in different resilience approaches (Hamborg et al., 2019). Incompatibilities range from: the mode of inquiry, following either a positivistic and analytical or a constructivist and descriptive approach; the relevant time scales, ranging from milliseconds as applied to grid stability or years when applied to system transformation; or the methodology proposed for applying the concept to energy systems analysis, which goes from a descriptive and qualitative approach found in the social sciences and systems analysis (Stefan Göbbling-Reisemann, 2016), (Brand and von Gleich, 2015; Hamborg et al., 2019), to quantitative and management-oriented methods applied more often in the natural sciences (Roegel et al., 2014; Wyss, Mühlemeier, and Binder 2018).

For all stated above, a postgraduate course on resilience for energy systems, should enable students to (i) become aware of competing approaches in terms of methods and theories stemming from different disciplines, and (ii) be capable to critically argue on the suitability of the presented concepts for energy systems design and management. Particularly for the second goal, two conditions are of fundamental importance: (a) a broad introduction to available approaches with relevance for energy systems analysis; (b) a sound understanding of different disciplinary approaches existing for resilience research applied to energy systems. Such a course is deeply confronted with the main challenges in interdisciplinary teaching (Sarah Falcus, Christopher Cameron, 2019), (Bradbeer, 1999): (i) student's difficulties in moving across disciplines; (ii) lack of understanding of new disciplinary approaches; (iii) difficulties in synthesizing different disciplinary views. Interdisciplinarity in higher education is a contested field of discussion, with contrasting views on whether specific modules and teaching methods are required for it, whether it is the responsibility of students to achieve it by integrating the knowledge from the different disciplinary courses or it should be focus of targeted teaching actions and courses promoting it (Lyall et al., 2015). Interdisciplinary competences, such as the ability to synthesize, appreciate different perspectives and develop a critical and innovative thinking, are highly valuable in a competence-oriented higher education (Lyall et al., 2015). There are different didactical settings, pedagogical methods and teaching tools for promoting interdisciplinarity, but there is no one single design or approach that is proved to foster a high level of integrating interdisciplinarity (DeZure, 2017). In this context, showing best practice examples and case studies of fruitful integration of a sound interdisciplinarity level in higher education is expected to foster the implementation of such teaching methods and the subsequent development of those competences (Lyall et al., 2015).

In the present paper, we show the design of a postgraduate course developed to promote a sound interdisciplinary understanding of resilience research for energy systems analysis, explicitly addressing the challenges mentioned above. In section 2, we characterize the nature of interdisciplinarity in the context of resilience research for energy systems, we outline the main challenges for higher education in this field and we define the level of interdisciplinarity intended to achieve in the developed course. Section 3 presents the main methods and didactic approaches and elements integrated within the course, as well as the aims intended by their use. Section 4 shows results from the evaluation of the students attending the course. Finally, in section 5, a discussion on the results achieved and the approaches we followed in the course is given.

2. Interdisciplinarity in Energy Systems Resilience Research and Teaching

2.1 Resilience as an Interdisciplinary Concept

The concept of resilience has evolved over the last decades from a narrow concept within the realm of physics, material science and engineering, to a multidisciplinary concept able to engage perspectives from different disciplines and to act as a "unifying concept" (Göbbling-Reisemann and Thier, 2018). This process involved several transfers and methodological and theory driven shifts engaging approaches from different disciplines such as physics, mechanics, physiology, psychology, biology and ecology (Stefan Göbbling-Reisemann and Thier 2018). Particularly important for the application of the concept to broader disciplinary fields are the transfers in the context physiology and ecology. The transfer to physiology occurred around 1926 (see Figure 1) with the work from Cannon, and introduced "homeostasis", with a strong focus on self-regulation as stabilization mechanism, as a key concept within the resilience framework. Resilience gained thereby the capacity of being transferred to other

disciplines, such as psychology, social-sciences or biology, since all these different systems employ self-regulation strategies (Stefan Gößling-Reisemann and Thier 2018). Thereby it retained a strong focus on stability and equilibrium conditions. This higher transfer potential can be seen clearly in Figure 1, where the frequency in the use of the terms “resilience”, “robustness”, “homeostasis” and “sustainability” in books written between 1800 and 2000 is shown. The number of mentions shown in Figure 1 is obtained by searching the mentioned terms in Google N-gram.

The transfer to ecology, greatly fostered by the work “Resilience and Stability of ecological Systems” (C. S. Holling 1973), shifted the focus to disequilibrium theories and the process of change itself. It introduced the idea of multiple-equilibria and the management of the system behavior between these different equilibrium states, and thereby paved the way to a transfer to systems science. The corresponding terms from the social science domain would be system approach, complexity, contingency and risk. The resulting increase in the use of the terms due to this transfer can be seen on Figure 1.

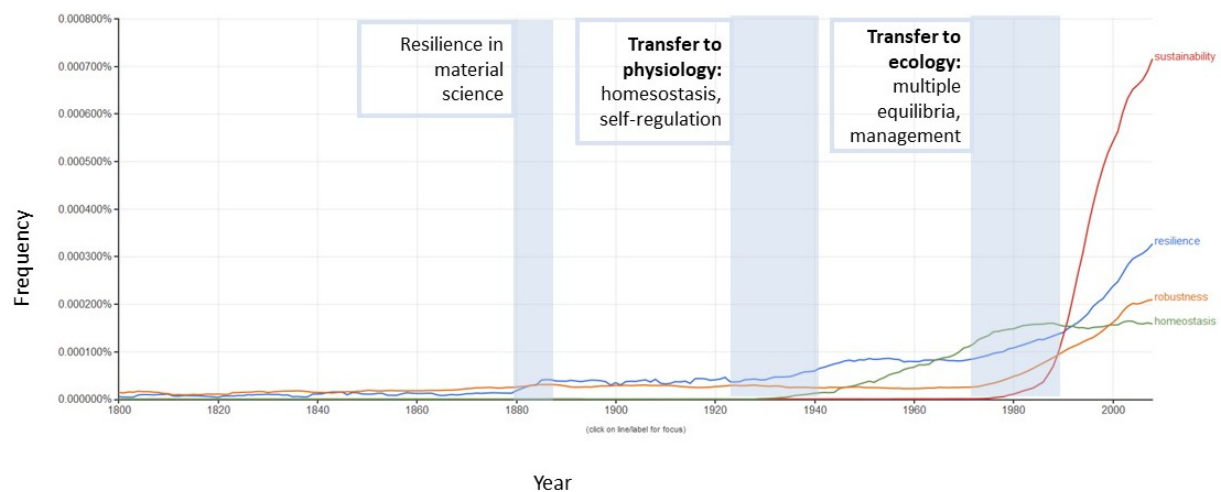


Figure 1. Frequency in the use of the term sustainability, resilience, robustness and homeostasis in printed books between 1800 and 2018 against the background of the resilience concept

As a result of these transfers a state-of-the-art and working definition of resilience can be given as the ability of coping (absorbing) a strike or stressor effect and utilize it or even benefit from change (Crawford S Holling, 2001). This definition retains a strong focus to change processes, the aim of managing the system’s behavior as well as the idea of multiple possible equilibria. It is broad enough to allow applications in different disciplinary realms and still allows divergent interpretations. This has led to different approaches in the context of energy systems analysis (Hamborg et al., 2019; Roege et al., 2014; Haehne et al., 2019), (B. Walker et al. 2004; Goldthau, 2014).

Walker et al. (B. Walker et al., 2004) define resilience as the ability of a system to re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks. Other authors (Folke, 2006; B. Walker et al., 2004), (Carpenter et al. 2001) include, besides the absorption of disturbances while retaining a given system domain, a strong focus to the self-organization and transformation processes fostered by the adaptive capacity within the system. In their approaches maintaining a given structure or function is only one possibility for resilient behavior. Roege et al. (Roege et al., 2014) define resilience for critical infrastructures focusing in the ability to withstand and recover (i.e. maintaining its function) after stressors. They see an urgent need for developing metrics for quantifying the resilience of energy systems and develop a set of metrics for this purpose. In this sense, the authors see resilience as a real and objectifiable property of the system. In turn, U. Brand and A. v. Gleich (Brand and von Gleich, 2015) conceptualize resilience as a “guiding principle” able to give orientation on suitable development directions for the design and operation of the energy system. Their definition of resilience is based on Holling (Crawford S Holling, 2001), but they concretize it giving a strong focus to two main specific characteristics: i) resilience is oriented to preserve system services. The system structure may instead significantly change as a result of stressors and changing conditions; ii) it follows a qualitative or descriptive approach, separating itself from (analytical) approaches intended to measure or quantify the resilience of an energy system. Related approaches can be found in (Stefan Gößling-Reisemann, 2016). Fischer et al. (Fischer et al., 2018) define resilience also on the basis of retaining system performance and not the system structure. But they operationalize it as an analytical and quantitative concept in the realm of cyber-resilience of the energy system.

The authors focus on the management process of the system performance, including the phases of planning, absorption and adaptation and analyze the system state with approaches from agent-based models and gaming theory. Hamborg et al. (Hamborg et al., 2019) conceptualize resilience as a “bridging concept” able to “span communicative gaps between different social and natural sciences”. The authors review different approaches for resilience research in the context of energy systems, showing the different quantitative and qualitative approaches, those defining resilience as a real quantity of systems and those seeing it as a matter of interpretation and description. As an attempt to facilitate the dialogue and integration of these significantly different resilience approaches, the authors develop a cross-epistemic resilience (CER) framework. They analyze the differences and underlying modes of knowledge in the different approaches and make them explicit with their framework as a way to foster dialogue among the different disciplines and researchers.

2.2 Types of Interdisciplinarity

In order to characterize the forms of interdisciplinarity found in different resilience approaches in the context of energy systems we first need to introduce a framework which allows us to map and distinguish them. Here we follow the approach from Davies and Delvin (Davies & Devlin, 2010). They see interdisciplinarity as “the emergence of insight and understanding of a problem domain through the integration or derivation of different concepts, methods and epistemologies from different disciplines in a novel way” (Davies & Devlin, 2010) p.11). Following this definition, interdisciplinarity is significantly different from multi-disciplinarity, where different disciplines work on a joint research programme without being aware of the contributions from other disciplines and cross-disciplinarity, where a discipline works on a problem from another disciplinary field with its traditional disciplinary methods without adapting or developing different methodological approaches (Davies & Devlin, 2010).

Davies and Delvin define three different types of interdisciplinary work (Davies and Devlin, 2010):

- **Relational interdisciplinarity:** in this approach separate disciplinary contributions to a common research object take place with explicit acknowledgement of the work from the other disciplines. There is, however, no modification of each of the disciplinary approaches as a result of the reciprocal knowledge of the others work.
- **Exchange interdisciplinarity:** this “implies a critical exchange of views and methods while maintaining robust disciplinary integrity” (Davies & Devlin, 2010), p.13). Modification of each disciplinary approach is not intended. As a result, novel approaches are often not developed. Awareness of the limits and backdrops of each perspective can be identified and highlighted.
- **Modification interdisciplinarity:** its aim is the integration and modification of each of the disciplinary contributions to create a novel and consistent approach.

2.3 Intended Level of Interdisciplinarity Education in the Presented Module

Given the disciplinary, methodological and theory diversity of resilience concepts in the context of energy systems research (see section 2.1) we intended at making it obvious and reflecting on the current status of resilience research. For making obvious the different approaches the relational level of interdisciplinary exchange, also called “curriculum mix up” by some authors ((Davies & Devlin, 2010), p.13), would be enough. However, a critical reflection on the status and meaningful understanding of possible future developments and applications of the resilience concept would be out of scope with only relational interdisciplinary approaches. Instead, the exchange interdisciplinarity would be a fruitful basis for such a critical dialogue among participating disciplines and students. Modification interdisciplinarity, in turn, would be a desirable approach for a research-based module on the topic but would require proficient knowledge in the different disciplinary approaches and their interlinkages. Since previous knowledge in the field is not requested, exchange interdisciplinarity was out of scope within the presented course.

For all stated above, we aimed at achieving a sound exchange interdisciplinarity in the course presented here. We chose specific teaching methods and didactic items to facilitate this aim.

3. Research Design

The research conducted on the development and evaluation of a postgraduate course with the aim of promoting a sound interdisciplinary understanding of resilience research for energy systems analysis follows a Mixed Method approach (Creswell, 2003). After a literature review on the main challenges of interdisciplinary education and existing methods for fostering and addressing them, a course design is developed. The course is then evaluated via a quantitative assessment through a standardized questionnaire to understand the student’s perception and their self-perceived level of achievement. Additionally, qualitative estimations from lecturers and open answers from

students give insight on the adequateness of the proposed methods for effectively tackling the challenges intended to be addressed.

The learning outcomes defined for the course were transparently communicated to the students during the course of the seminar and reflect the aim of achieving an “exchange interdisciplinarity” within the course in the learning process of the students. The main goal of the course was to give a sound introduction to the concept of resilience, its scientific origins and related concepts and approaches from different disciplines. The main learning outcomes of the course derived from this overall goal were: to understand different resilience approaches in the context of RE systems design; to understand strengths and blackspots in the application of resilience and related concepts (e.g. robustness, vulnerability) to the energy system; to understand interdisciplinary dependencies and concepts required to design resilient RE systems; to address technical and non-technical dimensions of resiliency assessment (economy, participation, etc.); to get to know different (modelling) methods and metrics for assessing/quantifying the concept of resilience for RE systems design; to understand and critically argue on the suitability of methods for resilience assessment in the context of RE systems. These learning outcomes were discussed with the students in the first week of the semester and it was referred to them frequently during the discussions within the seminars.

In this section we introduce the main didactic items that were part of the course (sections 3.1 to 3.4). In section their relation with challenges and different modes identified in interdisciplinary education is discussed.

3.1 Fundamental Introduction

The Fundamental Introduction (FI) comprised the first three weeks of the semester. Its main aim was to provide a sound common basis for understanding the perspectives and approaches from different disciplines. For that purpose, we introduced fundamental concepts and assessment approaches that represent a common ground for resilience research in several disciplinary fields (such as risk, normativity, complexity or adaptive cycles).

All concepts and approaches were firstly presented from a theoretical point of view. After the theoretical introduction, students worked in interactive workshops with the introduced theoretical content. Each workshop was based on two or three relevant scientific publications, including guiding questions related to them. Students were given one week to work with the provided literature on their statements, assessments and responses. Moderated discussions during the workshop helped the students to work on a reflected understanding of the presented concepts and to achieve a differentiated understanding of the introduced concepts.

3.2 Expert Lecture Series

After the first three weeks (FI) the **expert lecture series** began. Each week one invited expert introduced its research perspective, methods, theoretical approaches, questions, and outcomes from resilience research. The diversity of experts and research fields exposed students to the broadness of state-of-the-art approaches existing in resilience research for energy systems and provided a sound basis for grasping the relations among them.

3.3 Deepening Workshops

A deepening workshop/seminar on each expert lecture topic followed one week after the corresponding lecture. Two **scientific papers** provided by each expert lecturer were the basis for each workshop. Again, students were given one week to read the papers and prepare for the workshop, developing a deep and critical appraisal of the disciplinary approaches and their relations. For each workshop we provided a set of **guiding questions** that should be answered or discussed during the seminar, fostering a reflective discussion of the scientific papers and the expert lectures. The questions main focus was on the links between different disciplines approaches or related concepts, as well as on the transfer of knowledge and its applicability to energy systems resilience.

The workshops were prepared to be **highly interactive**, involving numerous didactic methods and a research-based and -oriented approach: World-Cafes, Brain-walking or collaborative mind-map creation were some of the methods we used for this aim.

3.4 Portfolio as Assessment and Examination Tool

The students' participation in the course was evaluated by a portfolio, a set of work elements distributed along te course time. The elements, explained in detail below, were research question(s), impulse presentation and a thesis paper.

- **Research question(s):** after the FI, students, paired in groups of two, had to develop 1-2 research questions and 2-3 related hypotheses on the field of resilient energy systems. The research questions were refined by each group of students over the course of the semester with the aid of expert presentations and workshops. The self-developed questions provided a singular motivation and perspective for each group of students to engage with the content presented each week in the lectures and seminars. The questions developed were the basis for the thesis paper,

which was the last part of their portfolio.

- **Impulse presentation:** each group of two students prepared an impulse presentation of 15 minutes for one of the workshops, by preference related with their research question. Using the scientific papers and the related lecture as basis, students worked out a sound theoretical framing for the given approach. The impulse presentation aimed at sharing the interest and perspective of the students with the group, and gave the students preparing it the opportunity of deepening the links between one disciplinary perspective and the rest of the topics presented until the moment of their presentation.

- **Thesis paper:** in a 3 to 4 pages essay, students answered their self-developed research question(s) either by applying one of the proposed methodologies or a combination of several of them or by arguing with concepts from the different disciplinary views previously introduced. In some cases, answering the research questions proposed would have required a research project on its own. Therefore, preliminary answers well supported by literature or a sound proposal for a research methodology applicable for answering the proposed questions were also accepted as part of their thesis paper.

3.5 Course Design and Interdisciplinarity Challenges

Each of the item within the course design fulfilled different aims. Their different characteristics aimed at addressing the three main challenges of interdisciplinary higher education presented above in a suitable manner. Table 1 shows the relation of the main items of the course with the main challenge they were addressing. A brief explanation on how we expected each item to contribute positively to the mentioned challenge is also given.

Table 1. Relation of the course design items (Didactic measures and Examination Portfolio elements) with the challenges in interdisciplinary higher education that they addressed.

Challenges	Didactic measures	Examination portfolio elements
Student's difficulties in moving across disciplines	<p>Fundamental Introduction: provided a sound basis for understanding the approaches from the different disciplines.</p> <p>Moderated discussions /Workshops: provided an empowering environment for encouraging students to discuss critically on the presented approaches and their understanding of them.</p>	<p>Research question(s): provided a personal perspective from which students could engage in a discussion with expert lecturers and question the different approaches presented throughout the course.</p>
Lack of understanding of new disciplinary approaches	<p>Expert lectures: provided cutting-edge and state of the art knowledge on resilience research from different perspectives</p> <p>Scientific papers: provided deep knowledge basis on the application and context of a particular approach. The literature allowed students to work with the presented contents and understand them at their own pace.</p> <p>Guiding questions: they gave the focus of the workshops and discussions within them, enabling to focus on developing a sound understanding of the presented approaches as well as the links and criticisms between them.</p>	<p>Impulse presentation: motivated students to work and understand deeper on a given approach.</p> <p>Thesis paper: the students answered their self-developed research question(s) either by applying one of the proposed methodologies or a combination of several of them or by arguing with concepts from the different disciplinary views previously introduced.</p>
Difficulties in synthesizing different disciplinary views	<p>Impulse presentation: motivated students to analyze and present a specific disciplinary approach, bringing in perspective theory from previous sessions and opening question.</p>	<p>Thesis paper: as part of their essay, students argued on which methods and approaches to use and its main flaws and blind spots, grounding their statements with literature.</p>

4. Obtained Results: Evaluation

At the end of the semester, the students evaluated the course within a standardized procedure from the University of Oldenburg. The questionnaire addresses questions about the following items: course design, content, structure, lecturers and students learning experience. Besides students have the opportunity to give personal but anonymous comments to the lecturers within the questionnaire.

A total of 9 students attended regularly to the course. Out of the 9 students attending regularly to the course, 7 fulfilled the questionnaire. All answers are issued on a Likert scale ranging from 1 (fully agree) to 4 (fully disagree). Figure 2 shows the results for the four questions addressing the course design. Student responses show a high level of satisfaction regarding the course structure and organization. Remarkable is that 100% of the students fully agreed that the course encouraged critical analysis.

Additionally, the lines under the bars show the average score and standard deviation achieved for each of the questions for the course (black lines) and the average values of all courses offered in the Physics department of the University of Oldenburg (grey lines). In all fields the course lead to a better performance (average values) and lower standard deviation than the average results in the Physics Department.

2. General Questions

The course...

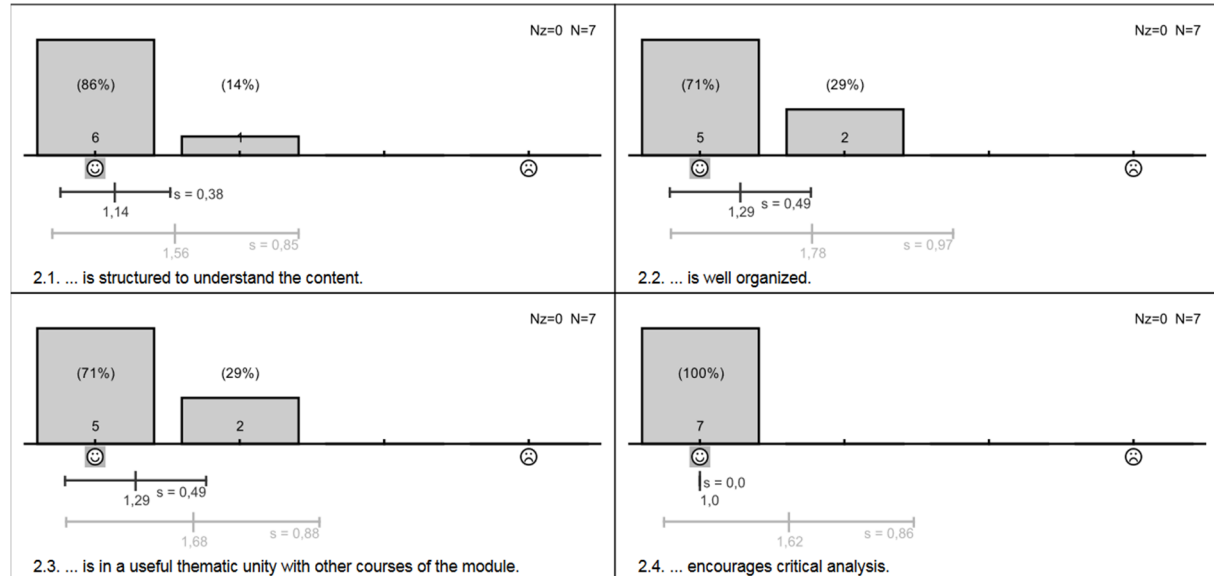


Figure 2. Results for the four questions addressing the course design

3. Entire Module

In relation to the entire module...

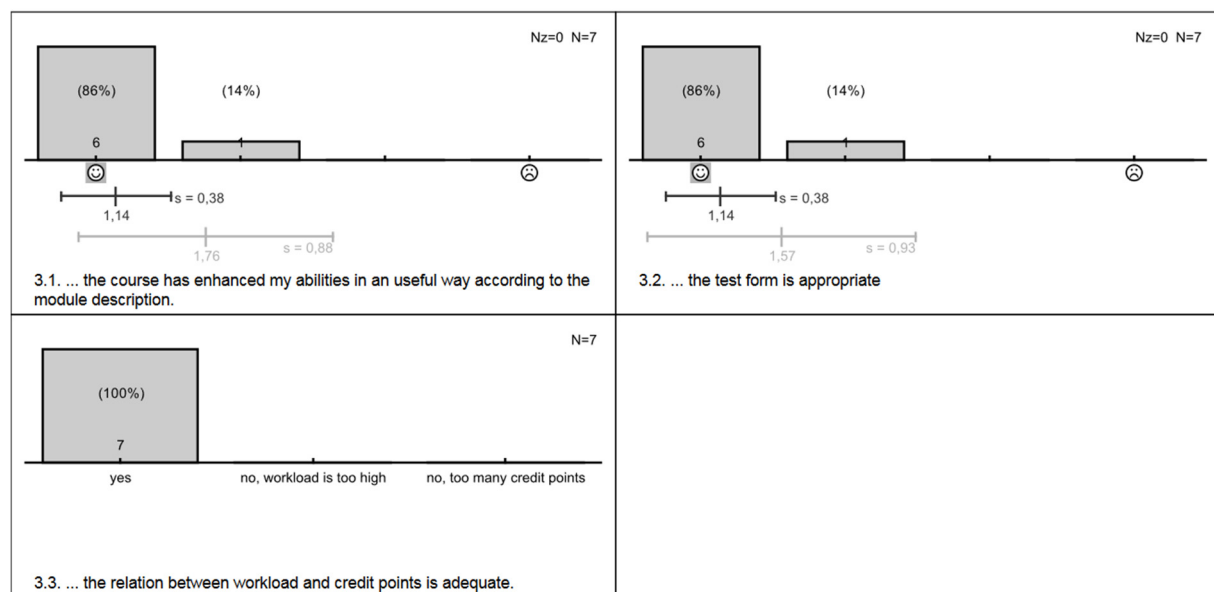


Figure 3. Scores for the questions concerning the overall estimation on the learning outcomes, the examination form and the workload

Figure 3 shows the scores for the questions concerning the overall estimation on the learning outcomes, the examination form and the workload. Again, scores are very positive, with more than 80% of the answers being very positive. The average values are clearly higher and standard deviations lower than those representative for the Physics Department.

Figure 4 shows the scores obtained for the organization of the students self-learning process and their participation within the course. Students participated very actively on the course, as can be seen on the 71% fully agreeing on preparing to and follow up the course progress. Students also estimated the workload related to the course to be rather high, being above the average estimated workload in the Physics Department.

5. Questions concerning own learning

I...

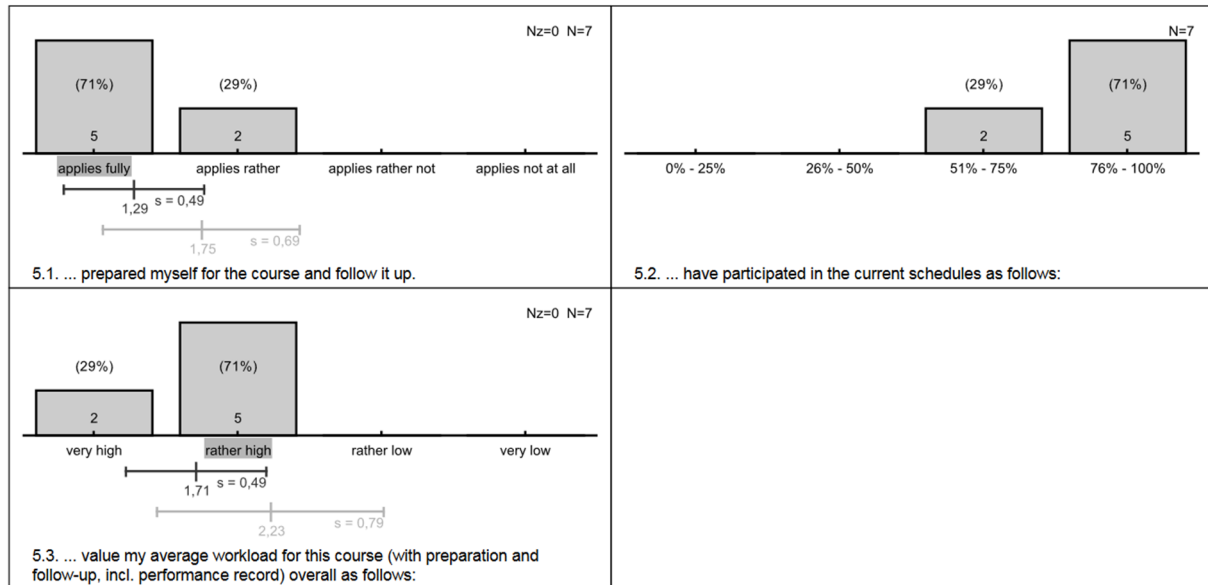


Figure 4. Scores for the organization of the students self-learning process and their participation within the course

6. Overall assessment

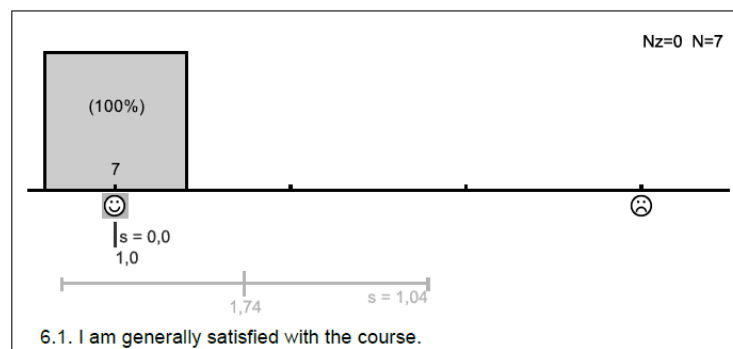


Figure 5. Scores for the organization

Figure 5 shows students' satisfaction with the whole course. 100% of them were fully satisfied with the course, despite the higher workload as the average of the Physics Department. Several comments also support this result. The following statements are quotations from students in the evaluation sheets:

- "...not I liked - I loved the course design. The variety fields of the lecturers invited was very nice and I certainly gained a lot of insights into a lot of facets of resilience. It encouraged me to consider a possible career outside the pure engineering/natural sciences".
- "Good organization, interesting topics, well-educated and friendly teachers. Best course I have taken at the

University of Oldenburg so far!”.

- *“Nice, nice outline; nice, nice setup (lectures (introductory & external) + seminars + group work + papers + research questions & hypothesis); Nice methods in the beginning (group finding with time, resilience concepts discussion for 1.5h, literature; defined learning outcomes”.*
- *“... Thank you very much for this course. I think it is one of the best courses from my entire learning time so far; didactically and content-wise. I really enjoyed it and am very grateful for having all three of you as my "professors". I appreciate a lot the effort you put in the course and also the time you take for answering and listening to our/my questions”.*
- *“The experience of the different experts has been really valuable for the course; The different fields this lecture touch has also increased the level of the course. The seminar is also really valuable owing to let the students can contribute to the development of the lecture”.*
- *“The structure, the discussions and the way they were done. The guest lecturers were something where I could really learn a lot and that I think that my colleagues, even though they are not part of the class, may take advantage of this lectures. Critical analysis is something that this lecture really encourages and is something that is going to be needed when facing renewable energy issues that we might find when coming to working life”.*

5. Discussion and Conclusions

Both results from the questionnaire-based evaluation and the comments of the students show that the course design was suitable to tackle the main challenges of interdisciplinary education in a suitable manner.

Quantitative answers from the students show that the course managed in a great manner to encourage critical analysis. Six students fully agreed that the course is structured appropriately as to understand the content (see Figure 2 upper left picture). One student agreed with this statement. The overall score concerning this issue is clearly very positive, with 1,14 as score (being 1 “I fully agree” and 2 “I agree”). Thus, the course managed to make the disciplinary approaches, despite their great variety, understandable to the students. This supports the statement that we achieved a positive contribution through the course design to address the challenge “Lack of understanding of new disciplinary approaches” (see Table 1).

A highly positive score, with a value of 1,29, can be observed for the statement of the course representing a good thematic unity. From this statement we infer that students were able to find and work out the links between the different disciplinary approaches presented. The course was, thus, able to introduce all presented approaches in the context of resilience of energy systems as an overarching topic. All students fully agreed with this statement (see Figure 2, lower left picture). Thereby, we state that the course managed to contribute positively to address the challenge “*Student’s difficulties in moving across disciplines*” (see Table 1) identified previously in the literature.

All students fully agreed that the course managed to encourage critical thinking. The answer to this question achieved a score of 1,0 (see Figure 2, lower right picture). Critical thinking is one of the core competences in interdisciplinary education (see section 1, or (Lyall et al. 2015)). The ability to synthesize the different disciplinary views soundly is a fundamental prerequisite for performing a sound critical analysis. Thus, we infer that the course from the student’s perspective managed to contribute positively to the third challenge identified from the literature, namely “*Difficulties in synthesizing different disciplinary views*” (see Table 1). Furthermore, for synthesizing and critically appraising different approaches both moving across disciplines, i.e. getting to know them, and soundly understanding them are required and necessary steps. Thus, student answers give the picture that the course managed to address positively the challenges identified.

Qualitative perception from the lecturers also supports the above stated conclusion. Students showed a high level of engagement during the discussions within the deepening workshops and also in their weekly literature reading as preparation for the moderated discussion sessions. The academic performance of all student groups was between “outstanding” and “very good”, making obvious the good level of understanding achieved by the students. Students chose rather complex research questions for their final thesis papers. Examples of their research questions are (i) mechanisms to enhance the resilience of companies to climate change, (ii) the influence of the battery production supply chain in the resilience of mobility or (iii) the resilience of the grid with 100% e-mobility. Students managed to work out either a sound theoretical interlink between several concepts to elaborate on a literature-supported arguing on a particular method, strategies or conclusions, or other cases, students set up suitable research methods for answering their proposed questions.

Despite the variety of disciplinary views engaged in the course, students achieved a sound understanding of the introduced concepts and underlying theoretical frames, moving comfortably across the disciplinary

boundaries. Despite the challenging aim of achieving “exchange interdisciplinarity” and the ambitious learning outcomes defined, the learning process was satisfactory according to the students’ evaluation and the perception of the lecturers.

According to the students’ comments, the didactic elements chosen for the course design provided a suitable balance between theoretical depth, sound understanding of the concepts and their links between, together with critical reflection and appraisal on the interdisciplinary views. The moderated discussions provided a good frame for reflecting on the students understanding and open questions on each presented topic. They enabled to connect the concepts and theories presented on each expert lecture and were a fundamental basis to achieve a critical understanding of the resilience research in the context of renewable energy systems.

The presented course is an example of a successful implementation of interdisciplinary education on a complex field of renewable energy systems. Through several didactic measures complementing each other and designed to foster an active learning process in the students, it suitably provided a sound basis for addressing the main challenges faced in interdisciplinary higher education. It could be useful for encouraging lecturers of courses dealing with topics of similar complexity or interdisciplinarity in energy higher education, such as sustainability, technology assessment or energy systems analysis from broader perspectives than the technical realm.

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