

## **Energy Literacy in STEM: Opportunities for Interdisciplinary Integration in Higher Education**

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Energy literacy is increasingly vital for understanding energy flows, managing resources, and addressing global environmental challenges. Initiatives such as the European Green Deal and the United Nations Sustainable Development Goals target climate change, biodiversity loss, and pollution. However, studies indicate that current higher education curricula often fall short in preparing graduates for these challenges. This research conducted a document analysis of the curricula for the Physics, Mathematics, and Civil Engineering study programs at the University of Maribor to identify opportunities for integrating energy literacy. Emphasizing an interdisciplinary approach, we propose an example where students optimize energy efficiency by combining physics, mathematics, and engineering concepts. Students study the energy balance of a building by connecting thermodynamic principles, such as heat transfer, with mathematical techniques, including partial derivatives and differential equations. Measurements using infrared cameras provide hands-on experience in analyzing real-world data. Additionally, students develop models and program simulations to explore energy-efficient design options. Activities also address ecological and economic impacts, encouraging sustainability discussions. The research highlights that significant changes or the introduction of new content in educational curricula are not strictly necessary; rather, the focus should be on innovative teaching methods and the application of established problem-solving approaches.

*Keywords:* energy literacy, STEM, sustainable development, interdisciplinarity, higher education

### **Introduction**

Integrating sustainability and digital transformation into STEM education is one of the most important challenges in the 21st century. We are witnessing the effects of climate change, biodiversity loss, and environmental degradation, issues that the United Nations Environment Programme (UNEP, 2021) refers to as the “triple planetary crisis”. These urgent problems highlight the need for systemic solutions and a new generation of critically engaged, sustainability-literate graduates. This also implies the importance of knowledge leadership and knowledge sharing as core components of sustainable educational transformation (Rahman et al., 2025).

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In this context, energy literacy emerges not only as a foundational skill but also as a concrete and integrative entry point for embedding sustainability into STEM education. Unlike broader sustainability frameworks, energy literacy directly links scientific principles, technological applications, and societal impacts. It enables learners to contextualize theoretical knowledge, such as thermodynamics or mathematical modeling, within real-world issues like building efficiency, renewable energy systems, and climate change mitigation.

Energy literacy is broadly defined as the ability to understand energy systems, evaluate the implications of energy choices, and apply this understanding in personal, societal, and professional contexts (US Department of Energy, 2014). It is more than just knowing about different energy sources or how to improve efficiency. Energy literacy involves a comprehensive understanding of energy systems as a whole, including various factors such as socio-economic and environmental trade-offs, and making informed and responsible decisions (DeWaters & Powers, 2011; Cotton et al., 2015). These dimensions align closely with GreenComp's competence-based approaches to sustainability education (European Commission, 2022). GreenComp suggests that sustainability-related skills need to cover cognitive, socio-emotional, and behavioral aspects to truly make an impact. Despite these evolving demands, most STEM curricula remain discipline-specific and content-driven, often failing to address how foundational knowledge in physics, mathematics, or engineering connects to real-world sustainability challenges (UNESCO, 2017; Filho et al., 2018). As a result, graduates may be technically proficient but lack the broader systems thinking, policy awareness, and digital skills required to address the green transition effectively.

Furthermore, the ongoing digital transformation of society, including the big data analysis, and artificial intelligence, requires students to do more than just consume information. They must actively co-create solutions using digital technologies (Vuorikari et al., 2022). In energy-related fields, this means developing competences in modeling, interpreting sensor data, visualizing energy flows, and communicating findings. This calls for integrative learning approaches that merge sustainability, technical, and digital competences.

In response to these challenges, this study explores how energy literacy can be meaningfully embedded into existing STEM curricula through interdisciplinary teaching strategies and digital technologies, without requiring major structural changes. We begin with a document analysis and faculty interviews to assess current curriculum content and identify points of potential disciplinary intersections. Based on these insights, we develop an interdisciplinary teaching module that combines physics, mathematical modeling, and civil engineering practices. The module is grounded in project-based learning (PBL), chosen for its potential to foster system thinking, student engagement, and real-world problem solving (Barth et al., 2007; Corvers et al., 2016; Repko & Szostak, 2020).

## Literature Review

To support the global shift toward sustainability and the green transition, a variety of frameworks have been developed, each emphasizing different aspects of sustainability education. These frameworks emphasize a broad range of knowledge, values, and skills essential for navigating environmental complexity and driving systemic change (Shephard, 2008).

The UNESCO (2017) Framework for Education for Sustainable Development promotes a holistic approach to education that aims to strengthen learners' abilities to respond to the challenges of sustainability through critical thinking, systems thinking, self-awareness and integrated problem solving. The framework defines eight key competences:

- (1) Systems thinking
- (2) Anticipatory thinking
- (3) Normative competence
- (4) Strategic competence
- (5) Collaboration
- (6) Critical thinking
- (7) Self-awareness
- (8) Integrated problem-solving

While on one hand this framework emphasizes dispositions and mindsets necessary for sustainability leadership content, it remains relatively high-level and conceptual, offering limited operational guidance.

The European GreenComp Framework (2022) further builds on UNESCO's foundation by providing a structured, actionable model of sustainability competences. It organizes 12 competences into four thematic areas:

- (1) Embodying sustainability values (appreciating sustainability, supporting fairness, promoting nature),
- (2) Embracing complexity (systems thinking, critical thinking, problem framing),
- (3) Visualizing a sustainable future (future literacy, adaptability, exploratory thinking),
- (4) Acting for sustainability (political action, collective action, individual initiative).

GreenComp offers concrete descriptors and can be adapted across all levels of education and training, making it particularly suitable for policy alignment and curricular development in European contexts.

These frameworks not only promote education for sustainability but are also in line with the broader goals of global citizenship. By developing skills like critical thinking, collaboration, and system thinking, we prepare learners to tackle global challenges that go beyond national borders. In addition, the increasing complexity of sustainability issues requires interdisciplinary and international collaboration, particularly in STEM fields where innovative problem-solving relies on a variety of

expertise and open intercultural dialogue. Embedding Global Citizenship Education within the framework of sustainability ensures that learners are equipped not only with technical knowledge, but also with intercultural understanding and ethical responsibility. Research by Chierichetti et al. (2025) further highlights the potential of both curriculum design and extracurricular activities in shaping students as global citizens. Integrating such opportunities into STEM education supports the development of socially responsible graduates, prepared to work in diverse teams and contributing to solving global sustainability challenges.

## **Energy Literacy**

While UNESCO and GreenComp frameworks provide comprehensive visions for sustainability education, they remain relatively high-level and abstract in their guidance. One promising domain through which these competences can be applied in a tangible, disciplinary context is energy literacy.

The North American Association for Environmental Education (NAAEE, n.d.) provides a framework that focuses on environmental and energy education through a set of core concepts and best practices. The framework includes:

- (1) Understanding energy sources and systems,
- (2) Recognizing human impacts on the environment,
- (3) Evaluating actions for environmental and energy sustainability.

The NAAEE approach emphasizes lifelong learning and real-world application, supporting educators in designing programs that engage learners in energy-related problem-solving and community action. However, its U.S.-centric policy grounding may limit its integration into higher education curricula.

DeWaters and Powers (2011) propose a three-dimensional model of energy literacy encompassing:

- (1) Cognitive (knowledge about energy systems),
- (2) Affective (attitudes and values toward energy use),
- (3) Behavioral (capacity to take informed action).

This framework provides a holistic perspective on energy literacy, advocating for education that connects technical understanding with ethical responsibility and behavioral change. It is particularly valuable for developing comprehensive learning outcomes that go beyond factual knowledge. However, it lacks detailed competence progression levels and discipline-specific applications.

The US Department of Energy (2014) defines energy literacy as the ability to understand energy's role in the universe and everyday life and to apply that understanding in problem-solving and decision-making. It outlines seven essential principles:

- (1) Energy is governed by natural laws
- (2) Energy drives Earth's systems
- (3) All living systems require energy
- (4) Humans use various energy sources, each with costs and benefits
- (5) Energy decisions involve multiple factors
- (6) Societal energy use is influenced by numerous variables
- (7) Energy choices affect quality of life

This framework offers a strong foundational structure for science-based energy education, making it especially useful for integrating into physics and engineering curricula. However, it does not include skill-level progression or interdisciplinary dimensions like policy, biodiversity, or circular economy, areas increasingly critical to the green transition.

Klemencic et al. (2025) propose a comprehensive competency framework tailored to natural sciences and mathematics education. Grounded in the context of the green transition, the framework aims to foster critical competences in energy literacy, sustainability, and biodiversity awareness. The framework organizes 12 competences into five thematic domains, each spanning three proficiency levels. Each level includes detailed descriptors to guide educators in curriculum development and to support assessment of student progress. Five thematic domains are the following:

- (1) Systems Thinking of Energy Systems (Understanding systemic interactions in environmental and biological energy flows, recognizing cause-effect relationships, feedback loops, and long-term sustainability implications),
- (2) Biodiversity (Understanding the role of biodiversity in ecological and energy systems, developing and implementing biodiversity management strategies across contexts),
- (3) Resource Management Skills (Applying principles of resource conservation, circular economy, and life-cycle analysis, planning for efficient energy use and sustainable infrastructure),
- (4) Technological Competence (mastering the fundamentals of renewable energy technologies and green innovations, designing and optimizing sustainable technical solutions, from materials to systems),
- (5) Policies and Regulation Awareness (Understanding environmental and energy policy frameworks, developing strategies for green entrepreneurship and participating in policy design).

Inclusion of biodiversity and policy reflects a systemic view of sustainability aligned with the "triple planetary crisis" of climate change, biodiversity loss, and pollution. This competency framework was applied to students studying physics, mathematics, and those pursuing degrees in educational physics and educational mathematics at the University of Maribor (IICE 2025). Findings indicated that students generally align well with market requirements; however, there are gaps in their knowledge of policy and competencies related to biodiversity across all programs. Its structured progression across proficiency levels enables educators to

define measurable learning outcomes in sustainability domains often perceived as abstract, offering practical support for curriculum design and assessment.

While each of the discussed frameworks contributes valuable perspectives, a clear gap remains in integrating them into discipline-specific and actionable curricular design. This study draws particularly on the Klemencic et al. (2025) framework due to its alignment with STEM disciplines and its potential for guiding curriculum integration at both the cognitive and practical levels.

### **Aim of the Study**

This study aims to explore how energy literacy can be effectively integrated into STEM higher education through interdisciplinary teaching approaches and digital technologies, without requiring major structural reforms. Drawing on the presented frameworks, we seek to operationalize these conceptual foundations into a concrete, competence-based educational intervention. The study specifically investigates:

1. To what extent energy literacy and sustainability competences are currently embedded in physics, mathematics, and civil engineering curricula.
2. How interdisciplinary connections across STEM disciplines can be leveraged to develop a cohesive and practical teaching module.
3. How project-based learning, supported by digital tools, can enhance students' understanding of energy systems, sustainability, and real-world problem solving.

By analyzing curricula, interviewing lecturers, and designing a project-based interdisciplinary module, this study contributes a pedagogical model for embedding energy literacy in STEM education, aligned with 21st-century sustainability and digital competence goals. While focused on the University of Maribor, the study offers a transferable model that can inform curriculum redesigns across European higher education institutions.

### **Methodology**

Our study was conducted in three parts. First, we conducted in-depth analysis of relevant curricula documents of bachelor's study programs Physics (P), Mathematics (M) and Civil Engineering (CE) at the University of Maribor. The selection of study programs was informed by their foundational role in STEM education and their potential for cross-disciplinary integration. Additionally, researchers from those study programs collaborate within a pilot project at University of Maribor. Secondly, as teaching practices in classroom can differ slightly from written curricula, we interviewed professors teaching specific subjects. Finally, based on our findings, we developed a specific interdisciplinary teaching module.

## Document Analysis

The curricula of three study programs were analyzed through document analysis and interviews with lecturers. Combining document analysis and interviews enhances the depth of research. To enhance transparency and replicability, the qualitative content analysis used a coding framework based on the key dimensions of energy literacy (US Department of Energy, 2014; DeWaters & Powers, 2011) and sustainability competence frameworks (European Commission, 2022; Klemencic et al. 2025). The coding framework was mapped against cognitive, behavioral, and policy-related domains, allowing for a systematic comparison between existing curricula and the targeted sustainability competences. The cognitive domain captures knowledge-based outcomes, such as understanding of energy systems and sustainability principles, the behavioral domain reflects practical application and problem-solving in real-world contexts, and the policy-related domain addresses awareness of institutional, societal, and regulatory dimensions of energy and sustainability. We selected relevant curriculum documents for analysis. First, we analyzed the list of graduates' competences for the Physics, Mathematics, and Civil Engineering Study Programs at the University of Maribor. This was followed by a document analysis of 18 courses: Numerical methods (M), Introduction to differential equations (M), Mathematical modeling (M), Mechanics (P), Electromagnetism (P), System Thinking (P), Oscillation and waves (P), Modern physics (P), Applied Physics (P), Thermodynamics (P), Environmental physics (P), Building physics (CE), Civil engineering materials (CE), Geometric modeling and descriptive geometry (CE), Timber structures (CE), Steel structures (CE), Foundation engineering (CE), and Concrete structures (CE). Representative courses were selected based on their relevance to energy-related topics and their potential to support interdisciplinary teaching. Each course was coded for explicit references to energy-related concepts using selected keywords: energy sources, energy conservation, energy efficiency, energy policy, climate change, sustainability, environmental impact, circular economy. We also search for implicit sustainability competences (e.g. systems thinking, critical thinking, ethical reasoning) and opportunities for interdisciplinary learning and the use of digital tools.

The course outline includes general information about the subject (course type, lecturer, hours), prerequisites, syllabus outline, readings, objectives and competences, intended learning outcomes (knowledge and understanding, and transferable/key skills and other attributes), learning and teaching methods, assessment, lecturer's references. The goal of the analysis was to determine the extent to which current curricula integrate energy literacy. Our focus was on syllabus outline, objectives and competences and learning outcomes. Two researchers independently coded each course and then compared results. Possible discrepancies were discussed until consensus was reached.

While document analysis cannot be influenced by the research process and remain consistent over time (Bowen, 2009), interviews offer firsthand perspective and can clarify ambiguities. Semi-structured interviews were conducted with professors, who lecture the above-mentioned courses. Participation was voluntary, and interviews were not audio-recorded in order to create more comfortable and open atmosphere. Detailed notes taken during the interviews were analyzed

thematically using an inductive approach. The interview protocols included the following questions relevant to this study:

- Q1. Do you include content from the field of energy literacy in the pedagogical process? If so, in what way?
- Q2. Is energy literacy included among the goals and competences? If so, in what way?
- Q3. Is the development of energy literacy foreseen among the study results? If so, in what way?

### **Interdisciplinary Teaching Module Design**

Based on curricula analysis, we designed an interdisciplinary teaching module that connects the theoretical foundations of physics, mathematics, and civil engineering for students at the University of Maribor. The design process began by identifying a thematic focus that would provide meaningful contexts for all three disciplines. We selected energy-efficient building analysis, given its strong relevance to climate change mitigation, urban sustainability, and everyday energy use. Next, we outline connections to each discipline, to emphasize interdisciplinarity:

- (1) **Physics:** Students explore the thermodynamics principles of heat transfer, conduction, convection, and radiation in the context of building insulation and envelope performance. Emphasis is placed on interpreting physical laws (Fourier's law) within applied systems.
- (2) **Mathematics:** Concepts such as differential equations, partial derivatives, and numerical approximations are used in mathematical modelling of heat flow, optimization of insulation strategies, and interpretation of energy profiles over time.
- (3) **Civil Engineering:** Students are introduced to civil engineering considerations, including material properties, structural thermal bridging, and regulatory standards related to energy efficiency. Energy audits are contextualized as multidisciplinary tasks requiring both measurement and interpretation.

Additionally, we incorporated digital technologies such as infrared cameras, analysis of measurements data and simulation software, as well as a collaborative platform to support interactive learning. As a pedagogical approach, we adopted project-based learning, a learner-centered method known to promote higher-order thinking, collaboration, and real-world problem-solving (Cörvers et al., 2016; Kurt & Akoglu, 2023).

## **Results**

### **Integration of Energy Literacy in Curricula**

We began by analyzing the list of graduates' competences of selected study programs. Our focus was on identifying how well energy literacy, sustainability, and green transition competences are integrated. The findings reveal a significant

imbalance: energy-related competences are notably underrepresented across all programs when compared to computational skills and digital literacy. Among the examined study programs, the Civil Engineering Study Program demonstrates the highest integration, with approximately 38% (8 out of 21) of its core competences aligning with energy literacy. The Physics Study Program follows with 33 % (7 out of 21), indicating some level of integration. In contrast, the Mathematics Study Program shows no alignment at all between its core objectives and energy literacy.

As the initial analysis focused solely on the key objectives and competences a graduate will obtain by completion of a study program, we proceeded with a more detailed document analysis of 18 individual courses to gain a deeper understanding of how energy literacy and sustainability are represented within the curricula. The analysis revealed that energy literacy is not explicitly addressed in most of the examined courses. For all three courses in the Mathematics Study Program, we identified potential opportunities to integrate energy literacy by applying theoretical knowledge to the problem-solving of authentic, energy-related issues. Tables 1, 2 and 3 present a summary of the findings for each study program, including direct excerpts from curricula in sections where energy literacy could potentially be integrated.

*Table 1.* Summarized findings of Curricula Analysis of Mathematics Study Program

Course	Syllabus outline	Objectives and competences	Learning outcomes
Numerical methods	/	/	Critical Thinking Skills (problem solving): solving more demanding numerical tasks and practical problems.
Intro to differential equations	Ordinary differential equations: ... applications in geometry and physics Modeling changes with differential equations.	/	Critical Thinking Skills (problem solving): solving more demanding physical tasks and practical problems based on the acquired knowledge
Mathematical modeling	Modeling changes with difference and differential equations. Mathematical behavior of dynamic systems. Applications of math models in science and engineering.	Apply knowledge from other mathematical areas in analysis of practical problems. Gain experience in developing a mathematical model, useful in their future career	To deepen the knowledge of applications of mathematical modelling in research and practice. Direct applications in ... numerous other social and natural sciences.

Source: own

Within the Physics Study program, few courses support the development of energy literacy through key knowledge areas such as energy, energy conversion and storage,

particularly in courses Mechanics, Thermodynamics, Oscillations and Waves, Electromagnetism, and Modern Physics (see Table 2). A more comprehensive focus on energy literacy is evident in only one course, Environmental Physics, offered as an elective. In this course, energy literacy is framed as a transferable skill, as reflected in the learning objective: *"The student is aware of the importance of protecting the environment and is ready to work on physics projects in the field of environmental protection."* This unit introduces students to physical processes in various environments, technical applications, energy sources, waste management, and eco-remediation techniques. This content directly supports the development of knowledge relevant to energy literacy and sustainable practices. Additionally, two compulsory courses, Applied physics and System thinking, offer opportunities to integrate energy literacy and sustainability. System thinking aligns with the GreenComp framework, emphasizing the importance of understanding complex system dynamics. In Applied physics, the focus is on transferring theoretical knowledge to real-world problem-solving, which supports the development of practical skills relevant to energy and sustainability.

Table 2. Summarized findings of Curricula Analysis of Physics Study Program

Course	Syllabus outline	Objectives and competences	Learning outcomes
Mechanics	Kinetic energy and work, potential energy, conservative and dissipative forces, conservation of mechanical energy, conservation of energy.	Define a physical system, the elements in the surrounding that affect the system and qualitatively and quantitatively predict changes of the system	Use modern computer software for quantitative calculations and for plotting dependencies among variables at different values of parameters
Electro-magnetism	Capacitors, energy, semiconductors, superconductors, electric circuits, voltage sources	Students acquire basic theoretical knowledge in electromagnetism and can use the knowledge to solve problems with the use of mathematical tools.	Understanding basic processes in nature giving rise to electromagnetic phenomena and gained global approach to solving problems
Oscillation and Waves	Electro-magnetic waves: spectrum, source, radiation pressure, polarization.	/	/
Thermo-dynamics	Heat transfer Heat engines and second law of thermodynamics	/	Apply the principles of thermodynamics to analyze the phenomena associated with heat transfer

			Use modern computer software for quantitative calculations
Modern Physics	Atomic Nucleus. Models, radioactivity, nuclear reactions	Acquire basic theoretical knowledge in modern physics, use knowledge to solve problems with the use of mathematical tools.	Understanding of basic processes in nature and gained global approach to solving problems
Applied Physics	Application of physics in different fields of economy and everyday living	Solving real physical problems in different fields of activities and in applications	Recognizes opportunities to apply theoretical knowledge of physics. Plans and conducts transfer of theoretical knowledge. Connects theoretical knowledge of physics with contents of other research or professional areas. Understands the meaning of application of theoretical knowledge.
System Thinking	Structure, dynamics and evolution of natural, technical and social complex systems System Thinking and System Dynamics Modelling. Applications in Physics and in other fields: population dynamics, environmental systems, biological systems.	Transfer of using general methods for the analysis of physical systems to other fields, e.g., population dynamics, environment, biological systems	Implement methods for qualitative analysis of system dynamics for simple physical systems. Better communicate in the field of natural sciences. Effectively solve problems: problem solving with the modelling of systems dynamics
Environmental Physics	Physical processes and phenomena in different environments and technical applications	Students acquire knowledge that is necessary for complex understanding of	Understands complex physical phenomena and processes in the environment, energetics, and waste

	<p>Physics of energy sources Physics of dealing with waste</p>	<p>physical phenomena and processes in environment. On different examples from natural or technical environments they understand importance and kinds of energy sources and energy transitions. They understand different types of waste and how to safely transport and store them.</p>	<p>management. Describe environmental systems, phenomena, and processes with physical models. Able to measure physical parameters in the environment and interpret the obtained measurements. Analytically and numerically solves physical models of environmental systems.</p>
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Source: own

In the Civil Engineering Study Program, energy literacy is explicitly incorporated in the compulsory course Building Physics, which plays a central role in connecting foundational engineering principles with sustainable practices. The unit's learning goals state: "...*understanding professional procedures for improving energy efficiency in buildings, acoustics and lighting, and controlling moisture and noise.*" The syllabus covers key topics such as thermodynamics, heat transfer, and heat behavior in building components. Although Building Physics is the only unit with an explicit emphasis on energy literacy, other courses offer indirect opportunities to support its development. For example, Civil Engineering Materials includes content on materials for insulation and protection, which are relevant to energy efficiency in construction. However, this potential is not fully realized, as the objectives and learning outcomes do not explicitly connect to energy or sustainability. Similarly, units such as Concrete Structures and Geometric Modeling and Descriptive Geometry develop essential engineering skills but lack direct references to energy-related competencies. This indicates that while the program includes valuable foundational knowledge, there is room to integrate energy literacy more systematically across the curriculum. Table 3 provides a summary of these findings, including curriculum excerpts and a mapping of relevant objectives and learning outcomes.

Table 3. Summarized findings of Curricula Analysis of Civil Engineering Study Program

Course	Syllabus outline	Objectives and competences	Learning outcomes
Civil Engineering Materials	Materials for isolation and protection.	/	Understanding of principles of material property determination and principles of material design for engineering applications Given a civil engineering material, to be able to select appropriate testing method.
Timber Structures	/	/	/
Steel Structures	/	/	/
Concrete Structures	/	/	Ability of structural analysis, design and assemble of single reinforced concrete structural elements.
Building Physics	Basics of thermodynamics Heat transfer Heat transfer in building components	Good understanding of heat and moisture transfer. Study related international standards and to learn professional best practices for improving energy efficiency	Explain the mechanisms of heat transfer and connect them into a structure. Qualitatively predict and quantitatively determine heat losses. Choose professionally suitable civil engineering solutions regarding heat transfer. Identify the reasons for excessive heat transfers
Foundation Engineering	/	Understand the philosophy of geotechnical design, design situations, ultimate limit states and serviceability limit states,	/

		determination of project loads and project bearing capacity in all types of foundation and other geotechnical structures	
Geometric Modeling and Descriptive Geometry	/	/	Use geometric modeling to present engineering information.

Source: own

In addition to document analysis, semi-structured interviews with professors were conducted to gain insight into actual classroom practices. In the Physics Study Program, energy literacy is integrated primarily through problem-solving activities. For instance, students engage in comparing energy outputs from different types of power plants in Mechanics, analyzing the efficiency of various heating, cooling, and engine systems in Thermodynamics, and evaluating modern "green" technologies, such as LED lighting, electric vehicles, and renewable energy sources, in Applied Physics. Modern Physics addresses nuclear fission and fusion with an emphasis on their relevance to energy production, while Environmental Physics highlights the environmental impacts of energy systems and the link between energy use and climate change. In the Mathematics Study Program, the unit Mathematical Modelling was identified as a key opportunity for integrating energy literacy, as it involves solving real-world problems that can include energy-related challenges. Within the Civil Engineering study Program, interviews revealed that energy literacy is partially included in Concrete Structures and Steel Structures, where students are expected to understand energy-related concepts and apply this knowledge in structural design. However, although energy issues are introduced during initial lectures, the instructional focus tends to shift toward material optimization, with limited sustained attention to energy efficiency or broader sustainability considerations.

The results of the curriculum analysis and interviews are summarized in Table 4, which compares the integration of energy literacy and related competences across the Physics, Mathematics, and Civil Engineering study programs.

Table 4. Summary of Energy Literacy Integration Across Study Programs

Study Program	Explicit Energy Content	Sustainability Competences	Interdisciplinary Opportunities	Digital Tools
Physics	Present in Applied Physics, Environmental Physics, System Thinking	Moderate – supports systems thinking	Strong – links to environmental contexts	Moderate (simulation, programming, lab tools)
Mathematics	None	Low – mainly cognitive dimensions	Weak – abstract focus	Limited use (modelling tools)
Civil Engineering	Strong in Building Physics	Moderate – focused on efficiency, materials	Strong – project-based potential	Moderate (design tools)

Source: own

### Interdisciplinary Teaching Module "Optimizing Energy Efficiency in Buildings"

The teaching module is designed for bachelor's degree students in STEM fields and is structured into five sessions, each lasting two hours: (1) Introduction to Energy in Buildings, (2) Thermodynamics and Modeling, (3) Measurement and Data Collection, (4) Simulation and Optimization, (5) Presentation and Reflection. The proposed teaching method is project-based learning, implemented through collaborative group work. Table 5 outlines the planned student activities alongside the corresponding roles and responsibilities of the instructor – lecturer.

Table 5. Sessions Overview

Session	Students Activities	Lecturer Role
1	<ul style="list-style-type: none"> <li>- Learn about key thermodynamics principles</li> <li>- Discuss the importance of energy in buildings (analyze a case study)</li> <li>- Formation of project teams</li> <li>- Brainstorm initial ideas</li> </ul>	<ul style="list-style-type: none"> <li>- Lecture on project context (theoretical background and)</li> <li>- Present project goals</li> <li>- Facilitate discussion</li> <li>- Assign teams</li> <li>- Help to define research question</li> </ul>
2	<ul style="list-style-type: none"> <li>- Learn about heat transfer types</li> <li>- Apply Fourier's law and basic differential equations</li> <li>- Calculate heat loss</li> <li>- Discuss real-world relevance</li> </ul>	<ul style="list-style-type: none"> <li>- Lecture on physics and mathematics principles</li> <li>- Support application in building context</li> <li>- Guide students through modelling tasks</li> </ul>
3	<ul style="list-style-type: none"> <li>- Use IR camera and sensors</li> <li>- Measure building envelope (windows, walls, etc.)</li> <li>- Log and interpret temperature data</li> </ul>	<ul style="list-style-type: none"> <li>- Demonstrate tools</li> <li>- Ensure safety</li> <li>- Supervise measurements</li> <li>- Guide data organization and analysis</li> </ul>

4	<ul style="list-style-type: none"> <li>- Input data into simulation or modeling tool</li> <li>- Explore effects of different materials or insulation</li> <li>- Plan improvement strategies</li> </ul>	<ul style="list-style-type: none"> <li>- Provide instructions on tools/software</li> <li>- Support modeling</li> <li>- Guide cost/sustainability analysis</li> </ul>
5	<ul style="list-style-type: none"> <li>- Present findings and design solutions</li> <li>- Engage in peer feedback</li> <li>- Reflect on interdisciplinary learning</li> </ul>	<ul style="list-style-type: none"> <li>- Facilitate presentations and feedback</li> <li>- Assess learning outcomes</li> </ul>

Source: own

### Detailed Sessions Plan

The teaching module begins in Session 1 with an introduction to energy use in buildings. Students learn key thermodynamic principles, focusing on heat transfer, insulation, and energy loss, while exploring the importance of energy efficiency through group discussions. They form project teams and brainstorm possible factors that influence building energy efficiency. Each group defines a specific research question, for example “How can we improve building efficiency, if the building’s exterior envelope cannot be changed?”.

The second session focuses on mathematical modelling. Students study heat transfer mechanisms, use formulas for heat conduction, apply derivatives and build basic models. Depending on their prior knowledge, they may also work with transient heat transfer described by Fourier’s law using partial differential equations.

Session 3 shifts to hands-on data collection. Students use infrared cameras and sensors to measure surface temperatures of walls, windows, and insulation points, aiming to detect so-called hot spots, thermal bridges and areas of heat loss. They log, organize, and begin to interpret the data to identify thermal weaknesses in the structure. Various software options can be used for analysis; for example, the FLIR Thermal Studio software provides a user-friendly platform when using FLIR infrared cameras.

In Session 4, students build simple simulation models using digital tools to evaluate different insulation materials and energy solutions. Based on their programming skills, they may use digital tools, such as Excel, Python, C++, Wolfram Mathematica, or AI-based applications. In this session, it is important they analyze the environmental and economic impacts of their proposed improvements and begin preparing their final design strategies.

Finally, in the last session, each team presents its findings and solutions, supported by data and simulations. The session includes peer feedback, group reflection on interdisciplinary learning, and a discussion on how the knowledge gained applies to real-world sustainability and engineering challenges.

### Objectives, Competences and Learning Outcomes

After successful completion of the teaching module, students will be able to (1) analyze the energy balance of a building using thermodynamic principles, (2) apply mathematical tools such as differential equations and derivatives to model heat flow,

(3) evaluate and suggest improvements to building design for better energy efficiency (4) use tools like infrared cameras and simulation software to collect and interpret data, (5) understand ecological and economic implications of energy inefficiency, and (6) communicate findings through technical presentations or reports. Key competences developed are the following:

- Critical thinking and problem-solving
- Systems thinking and sustainability awareness
- Digital literacy and data analysis
- Interdisciplinary collaboration

### Assessment

We suggest the following assessment presented in Table 6, with which students are acquainted beforehand.

Table 6. Assessment Rubric

Criteria	Need improvement	Satisfactory	Good	Excellent
Scientific and mathematical accuracy	Significant misconceptions	Conceptual understanding present	Minor errors	Accurate modelling and correct use of physics/math tools
Practical application and design	Lacking real-world relevance	Generic or partially applicable	Reasonable and realistic	Creative, feasible, sustainable
Use of tools and data	Poor integration of tools	Basic usage	Some support needed	Effective use
Collaboration and presentation	Disorganized or unclear	Adequate	Mostly clear, some improvements need	Clear, engaging, well-structured

Source: own

### Discussion

The curriculum analysis revealed varying degrees of energy literacy integration across the three examined STEM programs. The Civil Engineering Study Program demonstrates the most explicit alignment, particularly through the Building Physics course, which directly addresses energy efficiency in buildings. However, the program still tends to prioritize material performance and structural optimization over broader sustainability considerations. Institutional commitment to sustainability and curriculum innovation is essential for scaling such initiatives, suggesting that top-down support may significantly enhance adoption.

In the Physics Study Program, while energy literacy is not always explicitly named in course objectives, students develop key knowledge and skills essential to it, particularly in the System Thinking, Applied Physics, and Environmental Physics courses. These provide students with a comprehensive understanding of energy systems, encourage interdisciplinary thinking, and explore real-world applications such as energy efficiency technologies, power generation methods, and environmental impacts. This suggests that the Physics Study Program already offers a strong foundation for energy literacy, albeit under different conceptual framings.

In contrast, the Mathematics Study Program lacks direct references to energy or sustainability. Nevertheless, courses such as Mathematical Modelling offer valuable opportunities for integration, particularly through applied problem-solving tasks that can be adapted to energy-related challenges. Recent studies confirm that mathematics education often emphasizes abstract modelling rather than real-world applications (Vasquez et al., 2023, Makramalla et al., 2025). In higher education, study by Naidoo (2023) shows that integration of digital tools and authentic contexts can enhance sustainable mathematics embedding and critical thinking.

These findings confirm earlier observations (Barth et al., 2007; Filho et al., 2018) that sustainability competences in higher education often remain implicit or fragmented rather than systematically embedded. Similar to Corvers et al. (2016), our results highlight that rigid curricula and limited institutional incentives can restrict interdisciplinary collaboration. At the same time, this initiative in Physics and Civil Engineering supports Green Comp's (European Commission, 2022) argument, that STEM disciplines can provide entry points to integrate sustainability competences. The document analysis across three programs also supports findings of DeWaters and Powers (2011) that depending on disciplinary focus development of different aspects of energy literacy is uneven. These patterns suggest that fostering energy literacy requires not only curricular alignment but also professional development for lecturers and institutional support for interdisciplinary collaborations.

Overall, the findings underscore the importance of recognizing and building on existing disciplinary strengths. Energy literacy, as defined by current frameworks, is a multidimensional competence that includes technical understanding, systems thinking, ethical reasoning, and the ability to act. The interdisciplinary teaching module proposed in this study leverages these principles by connecting disciplinary content with real-world applications, supported by digital tools and collaborative learning. While the module has not yet been piloted, its implementation is planned for the upcoming academic year. Unlike previous research that has primarily examined sustainability integration from a policy or curricular design perspective, this study provides an operational model for embedding energy literacy directly within existing STEM courses through interdisciplinary and digital approaches. The pilot will adopt a mixed-methods evaluation, combining quantitative pre- and post-module assessments with qualitative feedback from student reflections and focus groups. Evaluation will focus on measuring students gain in energy literacy using instruments aligned with the Klemencic et al. (2025) framework. The outcomes of this pilot will guide the refinement of the module and contribute to institutional strategies for scaling interdisciplinary sustainability education.

## Conclusion

This study demonstrates that energy literacy can be meaningfully embedded into STEM higher education through interdisciplinary teaching approaches and without the need for extensive curricular reform. Curriculum analysis and faculty interviews across Physics, Mathematics, and Civil Engineering study programs revealed varying degrees of alignment with energy literacy competences. Notably, Physics courses such as System Thinking, Applied Physics, and Environmental Physics support the development of relevant knowledge and skills, while Civil Engineering includes explicit content in Building Physics. Furthermore, Mathematics presents potential for integration, particularly through applied modeling in courses such as Mathematical modelling.

Our findings resonate with gaps identified in other disciplines. For example, a recent content analysis of studies on sustainability leadership in police education (Fagerland et al., 2025) revealed that only two out of eight studies directly addressed core sustainability leadership competencies or policy awareness. This highlights a broader challenge in higher education: sustainability-related policy knowledge remains underdeveloped even in fields where they are crucial.

The findings of this study underscore the importance of pedagogical redesign, particularly project-based learning and digital tools, in supporting systems thinking and interdisciplinary application (Barth et al., 2007; Kurt & Akoglu, 2023). The teaching module proposed in this study reflects these strategies and aligns with established sustainability frameworks, including GreenComp (European Commission, 2022) and the Klemenčič et al. (2025) framework, which provides discipline-specific descriptors across cognitive, behavioral, and policy-related domains relevant to the green transition. Effective integration of sustainability into education relies more on the redesign of existing pedagogical structures than on adding new content, as it facilitates connections between disciplinary knowledge and real-world sustainability challenges.

However, this study is limited by its focus on two faculties within a single university, which may restrict the generalizability of the findings to other higher education contexts with different curricula or national policy frameworks. Additionally, the focus is on three specific study programs, Physics, Mathematics and Civil Engineering. Although these are representative STEM disciplines, they do not capture the full diversity of approaches in areas such as computer science, chemistry, biology or environmental engineering. Future research should include comparative studies to assess the applicability and the transferability to other STEM disciplines and combine qualitative and quantitative measures of students learning once the module is piloted.

From a methodological perspective, this study is also limited by its reliance on documents analysis and faculty perspectives, as students' perceptions were not examined. This restricts the ability to assess the actual impact of current teaching practices on the development of energy literacy competences. Longitudinal studies would also be beneficial in determining whether such interdisciplinary approaches have long-term effects in energy literacy and sustainability competences development. Furthermore, future research should explore how participation in such interdisciplinary

modules influences students' career readiness and their engagement with sustainability beyond academia.

To support meaningful integration, universities could establish cross-faculty teaching clusters, shared digital repositories of sustainability-related case studies, and targeted professional development programs in interdisciplinary pedagogy and digital competence. Higher education institutions can support such transformations by offering professional development for educators in relevant topics and by enabling collaborative, interdisciplinary learning. By embedding energy literacy as a transversal competence, STEM education can not only align with global policy frameworks but also enhance its societal relevance in addressing complex energy challenges and advancing sustainable development (UNESCO, 2020; Cotton et al., 2015). In doing so, higher education can play a pivotal role in preparing graduates who are not only technically proficient but also critically aware, ethically responsible, and ready to address the complex energy and sustainability challenges of the 21st century.

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