

Sustainability-Oriented Science, Technology, Engineering, and Math Teacher Education in Transnational Contexts: Design and Evaluation of an Energy Sustainability Module in Estonia, Finland, and Croatia

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ABSTRACT

This article reports the design and post-only transnational evaluation of the role of energy in sustainability, a module developed in the acaSTEMy teacher academy project for pre-service and in-service Science, Technology, Engineering, and Mathematics (STEM) teachers. Grounded in education for sustainable development, sustainability competence, energy literacy, systems thinking, circular economy, regenerative agriculture, transformative learning, and teacher professional development, the module aimed to make sustainability an integrative framework for STEM teaching. The study does not test pedagogical effectiveness or learning gains; it examines teachers' perceived acceptability, usefulness, satisfaction, and applicability after implementation. Quantitative ratings and open-ended responses from heterogeneous participant profiles in Estonia, Finland, and Croatia show broadly positive perceptions, with differences concentrated especially in organization and applicability. Estonia's in-service science teachers emphasize practical classroom transfer, Finland's pre-service education students emphasize dialogic learning and atmosphere while requesting clearer structure, and Croatia's in-service STEM teachers emphasize systems-oriented reflection together with the need for local examples and conceptual scaffolding. The findings are interpreted as implementation evidence for sustainability-oriented STEM teacher education guidelines: retaining a common theoretical core while adapting examples, terminology, pacing, coordination, and classroom applications to participant profiles and local contexts.

KEY WORDS: Education for sustainable development, energy literacy, implementation guidelines, perceived usefulness, science, technology, engineering, and mathematics teacher education, sustainability competence, teacher professional development

INTRODUCTION

Sustainability challenges require teachers to connect scientific knowledge with values, uncertainty, and action. In Science, Technology, Engineering, and Mathematics (STEM) education, energy systems, food systems, climate change, biodiversity loss, resource use, and circular economy cannot be addressed through isolated disciplinary content alone; they call for systems thinking, evidence-based reasoning, ethical reflection, and collaborative problem-solving (Bianchi et al., 2022; UNESCO, 2017; 2020).

Education for sustainable development (ESD) places teacher education at the center of this work because teachers translate global sustainability goals into classroom learning. For STEM teachers, the task is not simply to add sustainability examples to existing lessons but to design learning that connects scientific concepts with everyday life, local contexts, social responsibility, and future-oriented decision-making.

This article examines the design and evaluation of the Role of Energy in Sustainability, a transnational acaSTEMy

Teacher Academy module for pre-service and in-service STEM teachers (acaSTEMy Teacher Academy, 2025). The module addresses energy in sustainable development through agriculture, regenerative and sustainable food systems, circular economy, and energy efficiency, treating sustainability as an integrative lens for STEM teaching (Bybee, 2013; National Academy of Engineering and National Research Council, 2014; UNESCO, 2017).

The article outlines the theoretical principles behind the module, explains how they were translated into content and pedagogy, and reports post-questionnaire and open-response findings from Estonia, Finland, and Croatia. The aim is evaluative rather than causal: To examine whether the design is perceived by participating teachers and teacher candidates as acceptable, useful, satisfying, applicable, and transferable. The study therefore avoids claims about measured pedagogical impact or training effectiveness.

The transnational contribution is comparative rather than merely geographic. By examining a shared module across professionally different participant groups and implementation

contexts, the study can distinguish features that appeared acceptable across settings from those that required local adaptation. Because the groups differ by professional status, subject background, and proximity to classroom practice, differences are interpreted as participant-profile and implementation differences rather than as national characteristics.

The study addresses four research questions:

1. What theoretical principles underpinned the design of the sustainability education module for STEM teachers?
2. How were these principles translated into module content and pedagogy?
3. How did participants in the three teacher-profile groups evaluate the module after implementation?
4. What implementation guidelines could be drawn for the further development of sustainability-oriented STEM teacher education?

THEORETICAL BACKGROUND AND MODULE CONTEXT

ESD and Sustainability Competence

ESD provides the module's overarching basis. It emphasizes interdependence among ecological, economic, social, and cultural dimensions of development and supports pedagogies that move beyond transmitting sustainability facts toward reflection, participation, and action (UNESCO, 2017; 2020).

The module also draws on sustainability competence frameworks. UNESCO (2017) highlights systems thinking, anticipatory thinking, normative and strategic competence, collaboration, critical thinking, self-awareness, and integrated problem-solving; GreenComp similarly frames sustainability competence through values, complexity, futures, and action (Bianchi et al., 2022). These ideas shape the module's focus on interconnected themes, collaboration, reflection, and transfer to practice.

For evaluation, these competencies were translated into teacher-oriented indicators such as analyzing information, decision-making, collaboration, planning, purposeful use of digital tools, and inclusive pedagogical design.

STEM Education, Energy Literacy, and Interdisciplinary Integration

Energy and sustainability are inherently interdisciplinary, which makes them suitable for integrated STEM education. Integrated STEM connects scientific, technological, engineering, and mathematical knowledge with real-world problems, while sustainability education adds ecological, social, economic, and cultural dimensions to problem-solving (Bybee, 2013; National Academy of Engineering and National Research Council, 2014).

Energy literacy is therefore central. Energy-literate citizens understand energy concepts, recognize social and environmental consequences, and make informed energy decisions (DeWaters

and Powers, 2011; U.S. Department of Energy, 2017). The module broadened energy literacy beyond energy sources to include agriculture, soil energy, food systems, circular economy, and efficient energy use.

Circular Economy, Regenerative Agriculture, and Sustainable Food Systems

Circular economy, regenerative agriculture, and sustainable food systems are included because they make energy visible within wider systems of production, consumption, waste, soil health, biodiversity, resource use, and everyday decision-making (Geissdoerfer et al., 2017; Kirchherr et al., 2017).

Regenerative agriculture can support pedagogical links to school gardens, composting, local farms, food waste, water retention, soil organisms, and sustainable consumption, but the concept requires careful clarification because definitions and intended outcomes vary (Giller et al., 2021; Newton et al., 2020).

Transformative Learning and Teacher Professional Development

The pedagogical design also draws on transformative learning, which emphasizes reflection on assumptions and shifts in frames of reference (Mezirow, 1997). In sustainability education, such learning engages cognitive, emotional, and practical dimensions of complex real-world issues (Sipos et al., 2008; Sterling, 2001). In science and STEM education, Sjöström and Eilks (2018) connect transformative learning with a critical, praxis-oriented Vision III of scientific literacy, while Sjöström (2025) further develops this orientation around ethico-socio-political and relational-existential dimensions of science education.

Teacher professional development research points to content focus, active learning, coherence with teachers' work, sustained engagement, collective participation, situated practice, and practical value (Borko, 2004; Desimone, 2009; Guskey, 2002). The module seeks to operationalize these principles through vignettes, discussions, online tasks, group work, concept mapping, peer feedback, and teaching-oriented applications.

Module Design as Study Context

In the present study, the module is treated as the study context and object of evaluation rather than as a methodological procedure. It has a dual function: As a teacher-education activity for participating pre-service and in-service teachers, its content and activities are also designed for transfer into school STEM teaching. The participants in this study do not take part in designing or developing the module; their role is to participate in the implemented module and subsequently evaluate their experiences through the post-module questionnaire and open-ended responses. Accordingly, the analysis evaluates implementation and perceived transfer rather than a co-design process.

The transnational module was developed from ESD, sustainability competence frameworks, STEM integration,

energy literacy, systems thinking, transformative learning, and teacher professional development research. These criteria guided the content, activities, and evaluation dimensions summarized in Table 1.

Constructive Alignment and Module-Design Logic

The module followed constructive alignment: Aims, outcomes, content, activities, assessment, and evaluation criteria were designed to support the same learning goals (Biggs, 1996). The overall aim was to help teachers understand energy as a sustainability issue and apply this understanding in STEM teaching.

Learning moved between face-to-face and online phases, from conceptual input to reflection, application, and pedagogical transfer. Activities included lectures, vignettes, discussions, role play, group work, concept mapping, readings, videos, experiments, homework, and feedback.

Assessment combined formative participation, role play, and peer feedback with summative development and presentation of teaching materials, evaluated for clarity, scientific accuracy, and classroom applicability.

METHODOLOGY

Research Design

This study used a mixed-methods, post-only evaluation design to examine how pre-service and in-service teachers perceived the already developed transnational module on the role of

energy in sustainability. Quantitative post-questionnaire data were combined with qualitative open-ended responses to compare ratings across implementation groups and to explain how different teacher profiles experienced the module. The design supported conclusions about perceived acceptability, satisfaction, usefulness, and applicability, but not causal claims about learning gains or pedagogical effectiveness.

The questionnaire used a 1–6 agreement scale, where 1 represented strong disagreement and 6 strong agreement. It measured perceptions of transferable skills, module-related learning, and organization/applicability. Because the data were ordinal, bounded, strongly tied, and collected from small non-equivalent groups, non-parametric procedures were used (Sullivan and Artino, 2013). Distribution diagnostics were added to make this decision explicit.

Open-ended responses were analyzed through qualitative content analysis and a qualitative comparative analysis (QCA)-style configurational comparison to identify recurring patterns in perceived value, pedagogical usefulness, and improvement needs (Braun and Clarke, 2006; Ragin, 1987).

Sample

Participates who piloted the module were in-service or pre-service teachers from Estonia, Finland and Croatia. The samples differed in professional status, teaching experience, and subject background (Tables 2 and 3). For this reason, the analysis was framed as an evaluation across different teacher

Table 1: Theoretical criteria for developing the transnational module

Theoretical criterion	Theoretical basis	Application in the transnational module
Education for sustainable development orientation	ESD emphasizes interdependence among environmental, economic, social, and cultural dimensions and supports transformative action (UNESCO, 2017; 2020).	Sustainability was treated as an integrative framework for STEM teaching rather than as an additional topic.
Sustainability competence development	Sustainability competence includes systems thinking, critical thinking, collaboration, self-awareness, and action for sustainability (Bianchi et al., 2022; UNESCO, 2017).	The module aimed to strengthen transferable teacher competencies such as analysis, decision-making, collaboration, planning, and inclusive pedagogical design.
Interdisciplinary STEM integration	Integrated STEM connects disciplinary knowledge with real-world problems and authentic contexts (Bybee, 2013; National Academy of Engineering and National Research Council, 2014).	Energy, agriculture, circular economy, and food systems were connected through interdisciplinary examples and learning tasks.
Energy literacy	Energy literacy includes understanding energy concepts, their societal and environmental implications, and informed decision-making (DeWaters and Powers, 2011).	The module addressed renewable energy, energy efficiency, soil energy, food systems, and energy in the circular economy.
Systems thinking	Systems thinking supports understanding complexity, interconnections, consequences, and feedback in sustainability issues (Bianchi et al., 2022; UNESCO, 2017).	Concept mapping, holistic case discussions, and comparison of energy and resource-use consequences were used.
Transformative learning	Transformative learning emphasizes reflection on assumptions and changes in perspectives (Mezirow, 1997; Sipos et al., 2008). In STEM/science education, Vision III connects transformative learning with critical, praxis-oriented scientific literacy (Sjöström and Eilks, 2018; Sjöström, 2025).	Vignettes, dilemmas, reflective tasks, and discussions were used to support critical thinking and perspective change.
Teacher professional development relevance	Effective professional development is content-focused, active, coherent with teachers' work, collaborative, and practice-oriented (Borko, 2004; Desimone, 2009; Guskey, 2002).	The module combined conceptual input with practical activities, peer discussion, lesson-oriented applications, and feedback.
Inclusive and participatory pedagogy	Sustainability-oriented education benefits from collaborative, inclusive, and learner-centered approaches (UNESCO, 2017; 2020).	Group work, role play, feedback, interactive learning, and student-centered methods were included.

STEM: Science, Technology, Engineering, and Mathematics, ESD: Education for sustainable development

Table 2: Constructive alignment and module-design logic of the transnational sustainability module

Design component	Module design translation	Intended outcome
Overall aim	Sustainability was used as an integrative lens for STEM teaching, with emphasis on the role of energy in sustainable development.	Teachers understand sustainability as a systemic and interdisciplinary educational issue.
Learning objectives	The module focused on sustainable development, energy in sustainability, circular economy, agriculture, food systems, and energy efficiency.	Teachers develop conceptual understanding of sustainability-related STEM content.
Learning outcomes	Participants were expected to connect sustainability themes to teaching, apply student-centered methods, promote systems thinking, and support school culture for sustainability.	Teachers can translate sustainability content into classroom practice.
Content structure	Content included sustainable development, food systems and food security, circular economy, sustainable agriculture, and energy efficiency.	Teachers gain an interdisciplinary perspective on energy sustainability.
Pedagogical methods	Vignettes, lectures, discussions, group work, role play, concept mapping, readings, quizzes, essays, experiments, videos, brainstorming, and feedback were used.	Teachers engage cognitively, socially, and practically with sustainability issues.
Learning phases	Day 1 face-to-face introduction; Days 2–3 online learning; Day 4 face-to-face consolidation.	Teachers move from conceptual input to reflection, application, and synthesis.
Transfer to teaching	Teaching-material development, classroom examples, and lesson-oriented applications were included.	Teachers can adapt module ideas to their own teaching contexts.
Assessment logic	Formative assessment included participation, role play, and peer feedback; summative assessment included teaching-material development and presentation.	Assessment supports reflection, scientific accuracy, and classroom applicability.

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Table 3: Participant sample by implementation group

Implementation group	N	Professional status	Subject/Specialization detail available	Interpretation for analysis
Estonia	25	In-service primary and upper-secondary science teachers	Biology and geography teachers; individual subject-count detail was not available in the supplied analysis file	Experienced classroom teachers could judge classroom transfer directly
Finland	24	Pre-service education students	16 students from design and technology/primary teacher education programmes and 8 from an international master's programme in education; all had prior pedagogical studies	Prospective-teacher group; ratings reflected future-use and academic perspectives
Croatia	22	In-service primary and upper-secondary STEM teachers	Different STEM subject areas; exact counts by mathematics, physics, primary school, etc., were not available in the supplied analysis file	Heterogeneous in-service group; score differences should be interpreted cautiously

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profiles and implementation contexts rather than as a direct test of national differences.

The Estonian and Croatian samples comprised in-service teachers who could assess transfer to classroom practice based on their current professional experience, whereas the Finnish sample comprised pre-service teacher education students with prior pedagogical studies and an emphasis on sustainability pedagogy. These profile differences likely shaped how participants judged classroom applicability, organization, pacing, and the need for local examples or conceptual scaffolding. Exact subject-by-subject counts for the Croatian group were not available.

The qualitative data included 13 Estonian, 19 Finnish, and 16 Croatian substantive response profiles after repeated, near-repeated, or blank responses were accounted for. These responses were used to contextualize the rating patterns, not to make statistically generalizable claims about national populations.

Questionnaire Development and Quantitative Analysis

The post-module questionnaire reflected the module's learning outcomes and cross-group implementation evaluation needs (Table 4).

It included 25 items in three sections: Transferable skills (Q1–Q8), module reflections (Q9–Q15), and organization/applicability (Q16–Q25). The full item wording and open-ended qualitative questions are provided in Appendix A.

The sample sizes differed by implementation group. Estonia included 25 respondents, Finland 24 respondents, and Croatia 22 respondents, with some missing item responses. The available respondent-level data were used for descriptive statistics, exploratory reliability checks, and distribution diagnostics; where data were incomplete, analyses used the valid responses available for the relevant item or section.

Descriptive statistics were calculated for each item and section. Between-group rating differences were tested with Kruskal–

Table 4: Questionnaire-development criteria and structure of the post-module questionnaire

Questionnaire criterion	Rationale	Operationalization in the questionnaire
Alignment with module learning outcomes	Evaluation should reflect the intended learning outcomes of the module.	The questionnaire assessed transferable skills, module-related reflections, and organization/applicability.
Coverage of sustainability competence	The instrument needed to capture transversal competencies relevant to sustainability education.	Section 1: Transferable skills included Q1–Q8 and assessed teachers' self-evaluated skills after the module, including analysis, decision-making, collaboration, planning, digital tool use, and inclusive activity design.
Coverage of perceived learning and relevance	The questionnaire needed to capture participants' reflections on sustainability-related content and teaching value.	Section 2: Module reflections included Q9–Q15 and focused on sustainability, energy, circular economy, and teaching-related reflections.
Coverage of implementation quality	The evaluation needed to examine how participants perceived the structure, usefulness, and applicability of the module.	Section 3: Organization/applicability included Q16–Q25 and assessed organization, structure, online materials, usefulness, and applicability in teaching practice.
Cross-group comparability	The study compared responses across different teacher-profile and implementation groups.	The same 25-item structure was used for all three implementation groups.
Practicality of administration	The instrument needed to be usable immediately after the module in different implementation contexts.	A short 1–6 Likert-type scale was used for all quantitative items.
Suitability for small samples	The national samples were relatively small and Likert-type responses were ordinal.	Item-level and section-level analyses were conducted using non-parametric statistics.
Integration with qualitative feedback	Numeric ratings alone would not explain why country differences appeared.	Open-ended responses were analyzed alongside the Likert-scale results.

Wallis H tests; significant results were followed by pairwise Mann–Whitney U-tests with Holm-adjusted p-values (Holm, 1979; Kruskal and Wallis, 1952; Mann and Whitney, 1947). The statistical comparisons are interpreted as differences among teacher-profile and implementation groups, not as estimates of national effects.

Effect sizes were reported as epsilon squared for Kruskal–Wallis tests for pairwise comparisons. Content-validity evidence was based on alignment among the module aims, learning outcomes, questionnaire sections, and qualitative coding frame; the instrument was therefore treated as a context-specific evaluation instrument rather than as an externally validated psychometric scale.

Exploratory internal-consistency checks were conducted on the available respondent-level item files using Cronbach's alpha (Cronbach, 1951). Section-level alpha values were high for Estonia ($\alpha = 0.941$ – 0.947) and Croatia ($\alpha = 0.941$ – 0.955). Finland showed acceptable values for transferable skills ($\alpha = 0.805$) and module reflections ($\alpha = 0.770$), but lower internal consistency for organization/applicability ($\alpha = 0.545$), which was seen as consistent with the more varied Finnish responses to structure, online materials, and theoretical balance. Overall alpha values were 0.948 for Estonia, 0.884 for Finland, and 0.949 for Croatia. These values were reported as exploratory checks because the samples were small and the items used an ordinal response format.

Qualitative Content Analysis and QCA-Style Comparison

The qualitative analysis used a shared coding frame for open-ended responses from the three countries. Its purpose was to identify recurring patterns in what participants valued and what improvements they requested, not to produce statistical generalization.

Responses were read repeatedly, coded thematically, and compared across implementation groups using the eight codes, as shown in Table 5.

Codes were applied as present when responses contained clear evidence. Given the small and partly incomplete datasets, the analysis did not use formal Boolean minimization; QCA logic was used descriptively to identify dominant configurations such as practical materials with hands-on methods and clear structure, or dialogic learning with a positive atmosphere.

RESULTS

Evaluation across Participant Profiles and Implementation Contexts

The qualitative and quantitative findings were integrated to compare how the three participant groups experienced the module, what they valued most, and where statistically meaningful rating differences appeared. Because the groups were heterogeneous, the results were interpreted through teacher profile and implementation context rather than through country membership alone.

Overall Quantitative Pattern

As summarized in Table 6, the Estonian implementation group had the highest ratings, the Croatian group showed an intermediate positive profile, and the Finnish group had the lowest but still positive profile. This pattern was interpreted as a difference in perceived fit, clarity, and applicability across participant profiles rather than as evidence that the module was more effective in one country than another.

The overall Kruskal–Wallis test yielded a significant between-group rating difference, $H = 306.88$, $p < 0.001$,

Table 5: Qualitative coding scheme used for cross-group comparison

Code	Condition	Meaning	Illustrative example from data
D	Dialogic learning	Discussions, peer learning, feedback, listening to others	Valuing discussion, peer feedback, and opportunities to hear different perspectives.
P	Practical examples/materials	Concrete examples, classroom materials, local examples, real-life cases	Valuing ready-to-use teaching materials and requesting more concrete or locally relevant examples.
A	Positive atmosphere	Supportive, calm, pleasant learning environment	Describing the learning environment as supportive and positive.
H	Hands-on/interactive learning	Role-play, group tasks, mapping, demonstrations, self-assessment	Valuing role play, group work, mapping, and other active application tasks.
S	Adequate structure	Clear, logical, well-organized, manageable module design	Describing the module as clearly structured and manageable.
C	Clarity/coordination need	Need for clearer instructions, concepts, deadlines, or explanations	Requesting clearer instructions, better coordination, or clearer explanations of concepts.
T	Time/pace/scheduling issue	Rushed pace, busy timing, need for more time	Requesting slower pacing, less repetition, or more time for activities.
V	Variety/extension need	More examples, longer course, follow-up, more local or level-specific cases	Requesting follow-up activities, greater differentiation, additional examples, or more applied work.

The illustrative examples are paraphrased from the open-ended response patterns reported in the dataset and are not verbatim quotations

Table 6: Overall Likert-scale evaluation by implementation group

Implementation group	Overall mean	Median	Ratings 5–6 (%)	General pattern	Interpretation for analysis
Estonia	5.35	6	85.3	Highest perceived fit/acceptability	In-service science teachers reported the strongest perceived fit and applicability.
Croatia	4.92	5	69.7	Positive, between Estonia and Finland	Heterogeneous in-service STEM group reported positive perceptions with localization and scaffolding needs.
Finland	4.34	4	48.1	Lowest but still positive perceived fit	Pre-service education students reported weaker organization/applicability but positive dialogic learning.

STEM: Science, Technology, Engineering, and Mathematics

$\epsilon^2 = 0.175$. Pairwise comparisons yielded higher scores for Estonia than for Finland and Croatia, and higher scores for Croatia than for Finland. These results indicated perceived evaluation differences among the implementation groups; they did not establish pedagogical impact or causal module effectiveness.

Section-Level and Item-Level Comparison

At the section level (Table 7 and Figure 1), the largest group differences occurred in organization/applicability. Estonia rated this dimension very highly, Croatia positively, and Finland clearly lower. This pattern was seen as important because organization/applicability was the section most directly affected by local scheduling, clarity of instructions, online-material design, and participants' proximity to classroom practice.

Item-level means (Figure 2) followed the same general pattern across the three questionnaire sections. Variation was greatest in the Finnish ratings, with the lowest scores especially for online materials and the item asking whether the course was not too theoretical. This supported the qualitative interpretation that Finnish participants did not reject the module, but experienced a weaker fit between the module structure and their needs as pre-service students.

Pairwise Item-Level Differences between Implementation Groups

Pairwise Mann–Whitney U-tests with Holm correction were used to locate item-level group differences after significant Kruskal–Wallis tests.

Figure 3 showed that the Estonian and Finnish groups differed on 17 of 25 items, Estonia and Croatia on 10 items, and Finland and Croatia on 9 items.

Thus, the strongest contrast was between the Estonian in-service science-teacher group and the Finnish pre-service education-student group, while Croatia occupied a moderate position with similarities to both. This supported the interpretation that participant profile and implementation conditions shaped the rating pattern.

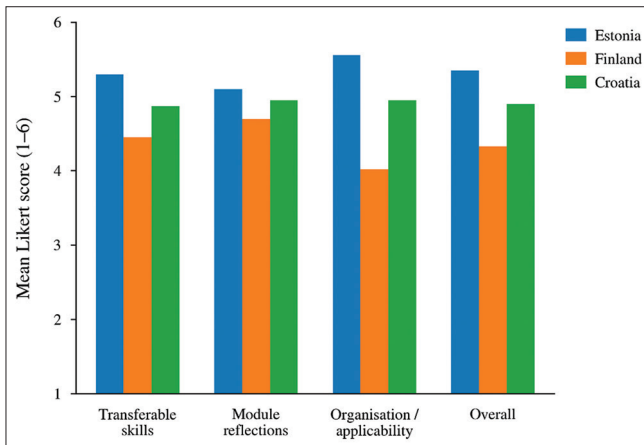
Integrated Participant-Profile Patterns

Profile-specific qualitative patterns were evident in the coded responses. In Estonia, practical examples and materials, hands-on activities, and clear structure were especially prominent; this combination indicates a strong orientation toward classroom transfer and immediate applicability among in-service science teachers. Finnish responses more often emphasized dialogic learning and a positive learning atmosphere; comments concerning clarity, coordination, and pacing indicated a need for more explicit

Table 7: Section-level comparison of Likert-scale ratings by implementation group

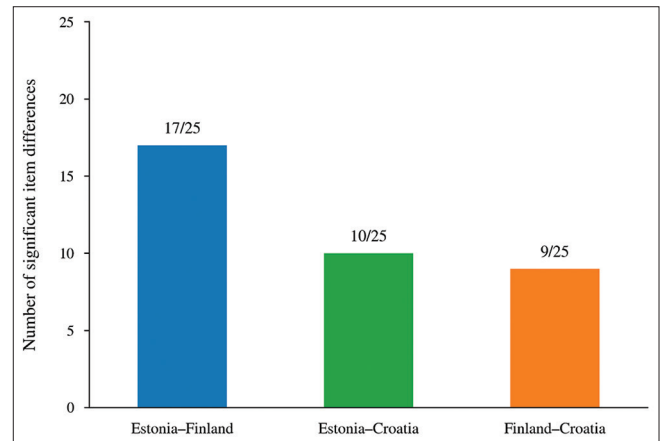
Section	Estonia M	Finland M	Croatia M	H	p-value	ϵ^2
1. Transferable skills	5.30	4.46	4.86	78.43	<0.001	0.141
2. Module reflections	5.10	4.70	4.94	27.26	<0.001	0.056
3. Organization/applicability	5.57	4.01	4.95	224.81	<0.001	0.320
Overall	5.35	4.34	4.92	306.88	<0.001	0.175

M: Mean, H: Kruskal–Wallis test statistic, ϵ^2 : Epsilon-squared effect size

**Figure 1: Mean Likert ratings by section and implementation group****Figure 2: Item-level mean Likert ratings by implementation group across questionnaire sections**

structure and classroom-facing scaffolding for pre-service participants. Croatian responses emphasized the complexity of energy-sustainability issues and included requests for practical and locally relevant examples, conceptual clarification, and further opportunities for active application. Across the three groups, the qualitative evidence therefore pointed to different implementation needs within a shared module: practical transfer in Estonia, dialogic learning and learning atmosphere in Finland, and contextualization and conceptual scaffolding in Croatia.

For Estonia, the qualitative pattern centered on practical teaching transfer. Teachers valued vignettes, real-life examples, videos, numerical data, role play, group work, and ready-to-use teaching materials. The dominant pattern of Estonia was:

**Figure 3: Significant pairwise item differences between implementation groups after Holm correction**

- Practical materials + hands-on methods + clear structure → teaching transfer

This profile was consistent with Estonia's participants highest overall score ($M = 5.35$) and organization/applicability score ($M = 5.57$). Participants suggested follow-up activities, grade-level differentiation, hybrid access, and more applied or laboratory-based work. The high ratings should be read as perceived suitability for this in-service teacher group, not as measured improvement in teacher competence.

For Finland, the qualitative pattern centered on dialogic learning. Participants emphasized discussion, peer learning, feedback, others' perspectives, and study atmosphere. The dominant pattern of Finland was:

- Dialogic learning + positive atmosphere → positive learning experience

Finnish participants had the lowest overall score ($M = 4.34$) and organization/applicability score ($M = 4.01$). In the qualitative responses, participants valued collaboration but wanted clearer instructions, better coordination, less repetition, and slower pacing. This pattern was consistent with a pre-service group evaluating the module partly from a future-teaching perspective, where classroom applicability might be less immediately visible.

For Croatia, the quantitative ratings were moderately positive, while the qualitative responses emphasized systems understanding. Teachers engaged with energy sustainability as a complex issue involving production, consumption,

economy, society, climate, communities, and personal habits. Specific examples named in the qualitative responses included renewable energy, affordability, transport, hydropower, agrivoltaics, nuclear energy, and personal habits. The dominant pattern of Croatia was:

- Practical/local examples + conceptual clarity + extension needs → localized, scaffolded application

Croatian teachers occupied an intermediate quantitative position ($M = 4.92$). Participants valued the module but requested more local examples, clearer technical explanations, and more active application tasks. Requests for clarification particularly concerned technically or conceptually dense topics such as circular economy, regenerative agriculture, agrivoltaics, and energy efficiency. Because the Croatian group included in-service STEM teachers from varied subject areas, these requests were interpreted as needs for localization and conceptual scaffolding across a heterogeneous professional audience.

Integrated Qualitative-Quantitative Comparison

Table 8 summarized the integrated participant-profile patterns. The magnitude and pattern of the differences were quantified using the rating data, while the qualitative responses were used to contextualize participants' descriptions of value and improvement needs.

The same module therefore produced complementary implementation profiles: practical transfer in Estonia, dialogic learning in Finland, and systems-oriented reflection in Croatia. These profiles supported a design-guideline interpretation: A shared sustainability core could be retained, but examples, pacing, scaffolding, and classroom applications needed to be adapted to the participant group.

Influence of Sample Composition on the Results

The sample composition was central to interpreting the results. Estonia's high ratings might reflect experienced in-service science teachers who could judge classroom transfer directly; Finland's lower organization/applicability ratings might reflect pre-service students evaluating the module from future-teaching and academic perspectives; Croatia's intermediate profile might reflect a diverse in-service group of primary and upper secondary STEM teachers from different subject areas that valued broad systems thinking but needed more local and technical scaffolding. The observed score variations therefore could not be attributed to the module alone.

DISCUSSION

Across the three implementations, the module was positively received as a teacher-education experience, but participants' evaluations varied according to how the common design aligned with their professional contexts. Estonia emphasized practical transfer, Finland dialogic learning, and Croatia systems-oriented understanding of energy sustainability across primary and upper secondary STEM teaching contexts.

Comparing the three implementations provided information that a single-context evaluation could not provide: The same common module was valued for different reasons, while applicability, pacing, coordination, and localization varied with participant profiles and implementation contexts. For this reason, the study did not propose or empirically validate a formal common-core and local-adaptation model. It instead derived implementation guidelines for sustainability-oriented STEM teacher education, while treating between-group differences as profile and implementation differences rather than national effects.

Viewed against the four research questions, each question could be answered within the limits of a post-only evaluation. Regarding RQ1, the module was underpinned by ESD, sustainability competence, STEM integration, energy literacy, systems thinking, transformative learning, and teacher professional development. Regarding RQ2, these principles were translated into content, activities, constructive alignment, assessment, and teaching-oriented transfer. Regarding RQ3, participants across all three implementations reported positive perceived usefulness and satisfaction, although the statistical analyses detected significant between-group differences, particularly in organization/applicability. Regarding RQ4, the evidence supports implementation guidelines rather than a validated model: shared sustainability principles could be retained, while examples, scaffolding, coordination, pacing, and classroom applications should be adapted to participant profiles and implementation contexts.

The largest quantitative differences appeared in organization and applicability, which indicated that perceived acceptability of transnational sustainability modules depended not only on theoretical coherence but also on clarity, pacing, local relevance, and visible classroom use.

The Estonian profile aligned with professional development research because teachers valued content focus, active learning,

Table 8: Integrated qualitative-quantitative comparison of participant-profile patterns

Dimension	Estonia group	Finland group	Croatia group
Dominant qualitative profile	Practical teaching transfer	Dialogic learning and atmosphere	Systems understanding and reflection
Quantitative profile	Highest ratings	Lowest ratings	Intermediate positive ratings
Strongest feature	Applicability and structure	Discussion and peer learning	Energy-sustainability complexity
Main weakness	Need for more extension and differentiation	Need for clearer coordination and pacing	Need for local examples and conceptual scaffolding
Main improvement direction	Extend and differentiate	Clarify and coordinate	Localize and scaffold

coherent structure, collaboration, and practical relevance (Borko, 2004; Desimone, 2009; Guskey, 2002).

Finnish participants valued dialogue and a supportive atmosphere but also requested clearer task structure and classroom scaffolding. This combination was consistent with scholarship on transformative sustainability learning that emphasized both dialogic engagement and structured support for transfer (Mezirow, 1997; Sipos et al., 2008; Sterling, 2001; UNESCO, 2017; 2020).

Croatian participants engaged with a broad range of energy-literacy dimensions across varied STEM subject areas, including production, consumption, renewable energy, affordability, resource use, local communities, transport, hydropower, agrivoltaics, nuclear energy, and personal habits (DeWaters and Powers, 2011; U.S. Department of Energy, 2017).

At the same time, Croatian participants requested more local examples and clearer explanations of complex concepts such as circular economy, regenerative agriculture, agrivoltaics, and energy efficiency. This need was particularly relevant because definitions, practices, and outcomes varied and because these topics might be insufficiently incorporated into curricula as part of teachers' everyday professional work (Geissdoerfer et al., 2017; Giller et al., 2021; Kirchherr et al., 2017; Newton et al., 2020).

Overall, the combined evidence could be interpreted as supporting an integrated STEM and ESD approach, in which scientific knowledge was connected with systems thinking, ethical reflection, collaboration, and action-oriented pedagogy (Bianchi et al., 2022; Bybee, 2013; National Academy of Engineering and National Research Council, 2014; UNESCO, 2017; 2020).

The between-group differences should therefore be read primarily as implementation and participant-profile differences. Professional status, teaching experience, subject background, and proximity to classroom practice shaped how participants evaluated the same module.

Further development should follow implementation guidelines based on a common core and local adaptation: keep the shared sustainability framework, but adapt examples, scaffolding, terminology, activities, and classroom applications to curricula, teacher needs, and participant profiles.

Implications for Sustainability-Oriented STEM Teacher Education

The main implication was that sustainability-oriented STEM modules should combine five design features: Systems-level content, practical pedagogical tools, structured dialogue, local examples, and active application tasks. The balance should vary by participant profile and implementation context: The Estonian implementation pointed to extension and differentiation as the main development priorities; Finnish participants' feedback pointed to clearer coordination and practical classroom examples; and Croatian participants' feedback pointed to stronger localization and conceptual scaffolding.

Limitations

Several limitations should be acknowledged. The datasets were not fully equivalent: Estonian and Finnish qualitative responses addressed general module evaluation, Croatian responses focused more specifically on energy and sustainability, and Finnish data contained limited information about intended classroom application. Because the quantitative analysis used post-questionnaire data only, the study assessed perceived acceptability, satisfaction, usefulness, and applicability rather than measured learning gains, classroom transfer, student outcomes, or pedagogical effectiveness.

Participant groups were also non-equivalent: Estonia and Croatia involved in-service teachers, while Finland involved pre-service education students with prior pedagogical studies and sustainability-pedagogy emphasis. The available files did not provide a full subject-by-subject breakdown for all groups, especially the Croatian group, so the present study could not disentangle country, subject specialization, teaching tenure, and implementation conditions. Future studies should use more equivalent samples or analyze professional status, teaching experience, subject specialization, prior sustainability education, and current classroom responsibilities as moderating variables.

A further limitation concerned the evaluation instrument and statistical assumptions. The questionnaire was aligned with the module aims and showed acceptable exploratory internal consistency in most sections, but it was not externally validated and should be interpreted as a context-specific evaluation tool. Distribution diagnostics showed ceiling effects and non-normal tendencies in some participant-level section means; together with the ordinal response scale and small heterogeneous samples, this supported the use of non-parametric tests. Finally, the module was a bounded, one-off intervention and should not be interpreted as sufficient to establish sustainability competences or to resolve broader educational challenges. Competence development was cumulative and required sustained exposure to varied content, learning experiences, and pedagogical approaches across teacher education and continuing professional learning (UNESCO, 2017; 2020).

Within these limitations, a coherent pattern emerged across the mixed-methods analyses: Participants' perceived evaluations were broadly consistent with key aims of sustainability-oriented STEM teacher education, and context-sensitive implementation was necessary to account for the observed between-group differences.

CONCLUSION

Across the integrated analysis, the transnational sustainability module was positively evaluated as a teacher-education experience in Estonia, Finland, and Croatia, but participants emphasized different aspects of its perceived value. Estonian in-service science teachers emphasized practical transfer, Finland's pre-service teachers highlighted dialogic professional learning, and Croatian in-service primary and upper secondary

STEM teachers engaged with energy sustainability in systems-oriented ways.

The main conclusion is that a common international sustainability module can be perceived as useful and acceptable when its implementation remains flexible. It needs to combine clear structure, practical classroom relevance, dialog, local examples, and active application tasks, while adapting the balance of these elements to participant profiles and teaching contexts. The specific transnational contribution is the evidence that a shared design does not produce a uniform experience: Comparison across the three implementations makes it possible to distinguish which elements can remain common and which require adaptation to participant profiles and local teaching contexts.

Ethics Statement

Participation was voluntary, responses were anonymised, and results were reported only at group level. No sensitive personal data were collected, no pupils or minors participated, and the study was treated as low-risk educational research. Likert-type responses were used only for statistical comparison and were not reported as identifiable participant profiles. Data were handled confidentially and used only for research and module-development purposes.

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Appendix A: Evaluation Questionnaire and Open-ended Questions

Likert-scale items were rated from 1 to 6, where 1 = Strong disagreement and 6 = Strong agreement.

Item	Wording
Q1	After the module I can better analyse information (e.g., think critically and draw conclusions about holistic approaches to energy or circular economy).
Q2	After the module I can better make informed decisions on sustainability education issues.
Q3	After the module I can better experiment with different problem-solving approaches and evaluate them.
Q4	After the module I can better collaborate effectively and respect others' opinions.
Q5	After the module I can better plan time effectively to achieve goals.
Q6	After the module I can better manage and complete diverse tasks.
Q7	After the module I can better integrate digital tools into teaching and learning for their intended purpose.
Q8	After the module, I can better design learning activities that follow inclusive education principles.
Q9	I have a deeper understanding of the role of energy in sustainable development, especially in agriculture and circular economy.
Q10	I feel I can participate more constructively in discussions on sustainable development, smarter resource use and the impact of the economy on ecology.
Q11	I believe the module provided new insights into presenting sustainability and circular economy issues in direct teaching.
Q12	I believe the module effectively connected ecological, economic, social, and cultural aspects and enabled me to apply them in teaching.
Q13	I believe the module prepared me to start discussions with students on sustainability issues (e.g., the impact of sustainability in agriculture and how current actions affect the future) and gave me insights into interactive lesson organization.
Q14	I believe the module introduced me to new teaching methods and expanded my digital competencies.
Q15	I believe the module encouraged me to promote sustainable development in everyday life and school culture.
Q16	The module was appropriate and useful.
Q17	The structure of the module (2 days face-to-face and 2 days online) was suitable for me.
Q18	Online learning materials were well-designed and easy to use for self-study.
Q19	Online research, reading and problem-solving activities were appropriate for me.
Q20	I gained new knowledge by attending this modular course.
Q21	I will recommend this modular course to my colleagues.
Q22	I would like to participate in similar professional development methods.
Q23	The course gave me ideas for applying new issues in teaching.
Q24	I did not find the course too theoretical.
Q25	Overall, I am satisfied with this modular course.

Open-ended Questions

No.	Question
1	In your own words, how do you define critical thinking?
2	In your own words, how do you define sustainable development?
3	In your own words, how do you define circular economy?
4	In your own words, how do you define food systems?
5	What was the most valuable aspect of this module for you?
6	How would you evaluate the structure and organization of the module?
7	Which topics or methods were particularly useful or inspiring?
8	How did you plan to apply the knowledge and skills gained in your teaching practice?
9	Was there anything that could be improved next time?