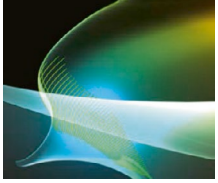
MRS Energy & Sustainability (2022) 9:64–78

doi:10.1557/s43581-021-00019-3



ORIGINAL RESEARCH

Active learning as enabler of sustainability learning outcomes: Capturing the perceptions of learners during a materials education workshop

Vasiliki Kioupi, Centre for Environmental Policy, Imperial College, London, UK

Tatiana V. Vakhitova, Ansys UK Ltd, Cambridge, UK

Katherine A. Whalen, RISE Research Institutes of Sweden AB, Göteborg, Sweden

Address all correspondence to Vasiliki Kioupi at v.kioupi17@imperial.ac.uk

(Received: 9 August 2021; accepted: 29 October 2021;
published online: 6 December 2021)

ABSTRACT

This study confirms the potential of using active learning for empowering students with knowledge and skills for sustainability during a materials education workshop.

Active learning is a promising teaching approach that can develop sustainability competences in learners. In this paper, we investigate the potential of active-learning pedagogies such as serious games and active-learning toolkits to deliver sustainability knowledge and skills in materials education. We organised a workshop for 20 participants from UK Universities where they played the serious game In the Loop around critical materials and circular economy and engaged in the Active-Learning ToolKit Sustainable Development (Granta Design/now Ansys UK Ltd.) to assess the sustainability of a proposed policy intervention around the use of electric cars. We used a self-assessment questionnaire and reflection sessions to deduce the level of sustainability skill developed by the participants as well as importance and performance analysis (IPA) to help the educators understand crucial components they should concentrate their teaching and learning efforts on in the future. Finally, we provide recommendations for educators on how to implement active learning in materials education in order to empower students with skills for sustainability.

Keywords sustainability · education · society · outreach · circular economy · critical materials

Discussion

- Assessing sustainability knowledge and skills in university students is receiving a lot of attention in the scientific literature and here we attempted to link knowledge and skill development with active-learning methodologies applying it in a materials education workshop for the first time.
- We used a serious game and active-learning toolkit to teach critical materials and the circular economy as well as to assess the sustainability of policy interventions.
- We placed the students at the centre of learning allowing interactivity, collaboration and direct experience of a sustainability challenge.
- We assessed the development of sustainability knowledge and skill using a self-assessment questionnaire and reflection sessions and analysed the results using importance/performance analysis.

Introduction

Higher Education (HE) Institutions have a renewed mission under the UNESCO Roadmap on Education for Sustainable Development (ESD) for 2030[1] and that is to provide learners with opportunities to develop sustainability competences in order to navigate the socio-ecological and economic complexities of our VUCA (volatile, uncertain, complex and ambiguous) world.[2] This educational imperative is also necessitated by international agreements such as the Sustainable Development Goals (SDGs) aiming to achieve collective sustainability commitments and a better future for all.[3] Higher Education community representatives highly recommend the design of ESD into curricula and provide specific guidelines, as in the newly developed Quality Assurance Agency and Advance HE ESD guidance.[4] Higher Education Institutions already have at their disposal tools to align learning outcomes (LOs) towards sustainability,[5] and also assessment frameworks to measure sustainability competences in students.[6] However, there is need to explore further the relationship between assessment of competence performance and the learning approach used in an educational environment.

Active-learning approaches such as project and problem-based learning, are very well studied pedagogies that have been found to enable all sustainability competences in learners.[7, 8] This is because they enable the student to actively engage with problematic or complex situations that require critical analysis of the context and available viewpoints and order to make decisions on what action to pursue. Very often, they also require students to work in groups, thus enhancing their collaborative capacities and conflict resolution abilities, which are important skills in professional settings. Serious games are defined as games that have a purpose beyond entertainment in that they convey ideas, values and facilitate learning and skills.[9] Serious games, although suggested in the literature as part of active learning, have not been adequately investigated for their potential to develop sustainability competences in learners.[10] In addition, assessing proposed sustainability policies on the basis of criteria as case studies is another approach that has been suggested as yielding benefits in terms of student learning outcomes (LOs).

A literature review of assessment methodologies around sustainability LOs and competences, reveals that although the integration of the various components of competence is addressed; the independent and authentic learning components of the assessment are missing.[11] Most assessment tools take a generalist view of competences that is neither related to the educational context applied nor to the pedagogies used. Ploum et al.[12] based on previous work by Lans et al.[13] offer a validated framework for sustainable entrepreneurship competences assessment based on student perceived levels of competence questionnaires that comprises six constructs. Trencher et al. developed a comparative assessment tool to evaluate environmental and sustainability masters programs on their effectiveness to deliver sustainability competences using the Wiek et al.[14] competences framework. Another study conducted in German secondary education schools by Waltner et al.[15] provides a validated paper-pencil questionnaire for assessing sustainability competences and their socio-demographic, cognitive, affective, behavioural, application and curriculum aspects based on the frame model of sustainability competences.

PISA the OECD's Programme for International Student Assessment started to incorporate the evaluation of cross-cutting skills such as complex and collaborative problem-solving and in their latest assessment of 2018 they included global competence which consists of transversal competences related to sustainable development, citizenship and intercultural understanding.[16] One study shows how vignette questions can be used to assess LOs related to sustainability awareness and responsibility in actions,[17] another study highlights the potential of measuring knowledge about sustainable development issues and knowledge of skills related to sustainable development through a multiple choice test–SULITEST.[18] Lastly, there are some studies that are focusing on affective LOs such as attitudes towards sustainable development measured through the New Ecological Paradigm Scale[19] or values related to sustainable development using a new instrument considering Freedom, Equality, Solidarity, Tolerance, Respect for nature and Shared responsibility.[20]

All the previous assessment methods may provide some benefits to educators or other education and sustainability stakeholders in terms of giving them information on the level of students' knowledge, skills, attitudes or values, a snapshot of students' performance toward a generalist view of sustainability. In all cases, there is no link between competence development and evaluation and the actual practice of teaching and learning.

In this study, we aim to demonstrate how an assessment of sustainability competences can be performed as part of an educational workshop for materials education for sustainability in a UK University. Specifically we aim to investigate the potential of serious games and active-learning case studies to enable the development of sustainability LOs as our hypothesis and use as measure of competence development, a self-assessment questionnaire and reflection sessions.

Educational conditions that enable sustainability competence development

Competences have complex conceptualisation as they refer to both performance ability to deliver a task and willingness to engage in the task, and this has direct links with motivation, worldview and values.[21] This, in turn, has implications for the educational process. On the one hand, the curriculum content, pedagogy and assessment should ensure the defined LOs are met, which is largely reflected in the notion of constructive alignment.[22,23] The consistency between competences, defined LOs, ways to teach and assess them, is a significant indicator that the curriculum engages students in authentic learning about sustainability.[19,24] On the other hand, if an assessment is to capture

concrete learning and competence development, it needs to see the students assessed in ways that allow them to demonstrate the competences developed.[6]

Moreover, the aspirational component of sustainability competences, related to the willingness to act and showcase the capability embedded in knowledge and skills, is manifested when the appropriate conditions are present.[25] When designing an educational intervention to enable competences, a practitioner should divert from solely focusing on academic knowledge acquisition,[26] skills and excellence,[27] and low order thinking skills.[26] Instead, they should focus on providing learning that can be applied in real world settings, such as community *problem-solving and stakeholder projects*.[27,28] Both have been found to equip learners with sustainability change agent skills and higher order thinking skills.[29-31]

Content focus and rote memorisation[26]; theoretical teaching, unrelated to context[32] are not conducive to competence development. On the contrary, prioritising *student learning experience*, which is meaningful, fosters in-depth study and critical approach,[26] promotes engagement and participation in local, regional and global contexts.[33] The latter enables *transformative learning,* focuses on active and collaborative engagement and competences development.[34] The educator is not the source of all knowledge that delivers the course in a linear fashion with the students being passive recipients of that knowledge.[26] Instead, the *educator is a facilitator* that supports, guides and monitors learning processes, enables an open and interactive-learning environment, includes practical activities and the engages students as active contributors[26] that develop discipline-specific and transversal sustainability-related skills.[35] Lastly but most importantly, the assessment of learning is not about traditional summative strategies (exams, multiple choice tests) with objectives low in Bloom's taxonomy[26]; nor about achievement.[23] It aims on, hard to assess but crucial, competences[15] and thus it employs an integrated approach[36] with a variety of *authentic assessment* formats; both formative and summative. Furthermore, it provides meaningful feedback to the learners[26] as it emphasises growth and mastery[36]; assesses performance and provides clear expectations for the students[23, 37] and assists them to improve their learning.

Potential and limitations of active-learning approaches to enable sustainability competences

Serious games and active-learning toolkits have been suggested to enable sustainability competences in learners and enhance the learning environment when used as pedagogical tools as they enable students to immerse in real world experiences and active problem-solving.[38–40] Social simulation or simulation games, are games that recreate real world problematic situations and allow players to explore key elements of the situation[41] by becoming immersed in the game play.[42] According to some authors, serious games and social simulations have the potential to transform the classroom into an experiential learning setting[43] that enables students to better understand concepts, develop their individual and team working skills.[38] Similarly, active-learning interventions show promising results not only in terms of fundamental cognitive gains, such as retention,[44] but also in terms of sustainability competences.[45]

A recent literature review revealed that most serious games for sustainability in particular, focus on its environmental dimension and in terms of topics they engage users on climate change issues.[46] Moreover, they aim to raise awareness of environmental issues rather than enable the user to propose solutions and lastly they engage the user as a citizen who has to make sustainable decisions to improve their personal performance, rather than a decision maker who influences policy.[9] Simulations have been especially used in the context of management education, where they have been found to enhance cognitive and affective LOs.[47] On the other hand, in the context of political science and international policy education, studies report educational gains[38] as well as student difficulties to deal with the complexities of scenarios and inability to appropriately manage risk.[48]

Criteria for active-learning approaches such as serious games, simulations and toolkits to address sustainability competences in Higher Education

When using serious games or simulations for teaching sustainability in materials education, the educator should prioritise open-ended options with no right solutions. This way they contribute to pluralism and encourage various opinions to be articulated and perspectives to be explored.[21] Students should face challenging and problematic situations that require understanding stakeholders conflicting views and trying to address them through critical analysis.[49] These situations should be relevant to real world decision making and policy processes.[50] They should engage students in experiential learning and more specifically, in active experimentation, concrete experience, reflective observation and abstract conceptualisation,[51] as normal classroom teaching only enhances the latter two.

In experiential learning, the student has an active role in individually constructing knowledge by comparing experiences with existing mental models and adapting them to the new evidence (constructivism).[52] Furthermore, the student is better able to develop competence through social interaction with peers, professionals, academics and others (social constructivism) expanding their zone of proximal development.[53] Experiential learning strongly relates with the concept of flow in which learners are immersed in the experience and operate in a state of optimal competence.[54] In that state, their skill level is in balance with the challenge they are facing and are highly concentrated, motivated and so they are leveraging their competence to address it. Learning happens when students are in the arousal phase, when in other words they are pushed beyond their comfort zone (challenge is a little higher than their skills)[55] to achieve flow. Flow

has been found to increase in collaborative settings thus further supporting social constructivism premises that students learn better in interactive environments.

An important component of enabling students to showcase competence through a serious game or simulation is dialogue, which is different to discussion and debate as it allows learners to see the whole, seek connection between the parts of the problem, question their assumptions, learn by exploring and find shared meaning without judging other's views and by respecting differences. Considering the limitations of serious games identified in the literature, games that allow all three aspects of sustainability to become visible (the environmental, social and economic) as well as their interconnections are desirable. Moreover, aiming at a positive vision of the future and engaging students emotionally in the situation at hand so that they can clarify values as the root causes of issues have been advocated for.[39]

During the serious games, students should be engaged in heterogeneous groups (could be various achievement levels, gender, age and ethnic diversity or disciplinary backgrounds). This is not only important for mixing knowledge and skills levels so that lower performing students can become more motivated and engaged but in HE contexts working in interdisciplinary groups is essential for addressing complex sustainability challenges.[56]

Lastly, regarding the use of digital tools in the educational activities, they are crucially important because students are already using these technologies in their everyday lives so much that they are considered digital natives and so possess enhanced digital skills.[57] These skills can be further developed and applied in creative ways to tackle sustainability issues in a world increasingly influenced by digital interactions.[58]

In this paper, we developed an active-learning educational intervention around materials education for sustainability in which the participants played a serious game on circular economy and participated in an active-learning session around sustainability assessment of a proposed technology. The participants self-assessed both the importance of and their performance in the intended competences they would develop from the activity and then engaged in reflection activities.

The serious game in the loop

The serious game "In the Loop" is a board game that deals with material criticality and circular economy (CE) concepts. Both are important aspects of sustainability, as material criticality is influenced by material availability, supply chain risk and socio-environmental implications (around human rights and toxicity) and CE is an alternative to the resource depleting and waste generating model of the linear economy.[59] In the game, each player or group takes on the role of a manufacturing company CEO and aims to be the first company to reach seven 'Progress Points'. These points are awarded by producing products and making strategic decisions. Even to produce high tech sustainability enabling products (e.g. photovoltaics, electric vehicle batteries), players must first mine and bid for certain materials (e.g. neodymium, tungsten, gallium). After production, products and materials are immediately confined to the 'Junkyard' as players begin the game with linear business models. As play progresses, players face competition over the same materials and struggle to collect enough materials in order to produce products and earn Progress Points. In light of this, players may choose to purchase 'Strategy Cards', which also award Progress Points, and provide players with alternatives to their linear business models. For example, players may obtain materials from the Junkyard or retain their materials after production. Other socio-political changes, in the form of 'Event Cards' may affect gameplay and provide players with additional motivation to invest in business strategies. As such, interlinkages between the players' decisions, available resources, Event Cards, and Strategy Cards emerge throughout the game and make it a complex, dynamic system with various inputs and output possibilities.

The game was selected to challenge the views of participants regarding the use of technology to address sustainability problems and because materials criticality and sustainability is not adequately addressed in the University Department's Postgraduate Research Programme.

The active-learning sustainable development toolkit

The Active-learning Sustainable Development ToolKit is used to facilitate teaching around assessing the sustainability of proposed technological solutions in University programmes.[60] The ToolKit consists of a five-step methodology for tackling complex sustainability problems that have no obvious right solutions.[61] Students are confronted with a challenging proposal and then they follow the five-step methodology for assessment of sustainability. The steps include problem definition, identifying stakeholders and their concerns, which includes analysing stakeholders, researching facts around materials, energy, society, regulation and economics with the use of educational software (Ansys Granta EduPack), forming a judgement by first analysing facts on the basis of natural, manufactured, human and social capital, making reflections, and assessing alternative solutions, including long-term scenarios. The specific proposal we analysed using the toolkit was: "*Half of all new cars must be electric by 2030 to meet EU emission targets*"–The Times, 26 November (2015).

Materials and methods

We ran a one-day workshop with 20 participants, 16 doctoral students of the Centre for Environmental Policy (CEP), two doctoral students from the Dyson School of Design Engineering of Imperial College London, one Master's student from Queen Mary University and a member of Teaching Staff from CEP. The workshop comprised playing the serious game In the Loop, and using the Active-learning ToolKit Sustainable Development.

The format of the workshop was such that allowed for active learning. During the first half of the day, the instructors introduced the serious game and its rules and then the players played in groups. After the end of the game there was a group reflection session and an individual reflection session on the experience with the aim to help the participants consolidate their learning and think of how they can apply what they have learnt in their own research contexts. The workshop with the use of Active-learning ToolKit took place on the second half of the day.

First, the instructors introduced the topic of the project and the participants worked in groups to identify stakeholders involved and then discussed in the classroom. They then discovered data, using Ansys Granta EduPack, regarding the policy target and had a class debate around the various environmental, social, financial and legal implications they uncovered. In the end, they had to synthesise their findings of the proposed intervention. After the end of the activity, the participants had a final round of reflection on the project outcomes in small groups and a group discussion. We provide more information about the outcomes from the sessions and the reflections in the results section of the paper.

To assess the development of competence in the participating students we developed a self-assessment survey based on the competence model designed for the MSc programme Environmental Technology of CEP, as the doctoral programme did not have specified Intended LOs. The eight main types of competence in the master's program are systems thinking, anticipatory thinking, normative thinking, strategic thinking, critical thinking, collaboration, digital skills and self-awareness.[6] The students were asked to assess the importance/criticality of 46 statements of competence related to sustainability (Table 1) on a scale from zero (not important) to five (highly important). On a separate table, they had to assess their performance in these 46 competence statements (application of the competences) on a scale from zero (no evidence of application) to three (plenty of evidence for application) during participation in the active-learning workshop.

The results were analysed using Importance Performance analysis (IPA). IPA has been used before as an evaluative tool in adult education and can give insight into the factors that the trainees deem critical as educational outcomes in a specific educational setting as well as their performance with regards to the pedagogy/teaching approach used.[62] In our case, we wanted to understand which competences the students thought were critical for achieving sustainability and of these, which they thought, they experienced/applied during the active-learning workshop. We analysed the results individually for all the participants to get some insight into the effect the activities have on student development of competence.

Results

Results from the self-assessment questionnaire

The participants perceived all competences to be important for sustainability, assigning lower scores to self-awareness and digital skills and higher scores to critical, strategic thinking and collaboration (Table 2). In terms of their self-assessed performance during the workshop, they assign some evidence of competence application during the active-learning workshop, with lower scores assigned for normative thinking and self-awareness and higher scores assigned to systems and critical thinking and collaboration (Table 2).

We plotted the data for the perceived importance of competence versus the data for the perceived performance of participants in these competences during the workshop to perform an importance-performance analysis and the results are shown in Fig. 1.

Based on the questionnaire design, the importance is considered high or very high when the assigned value is 4 or higher and the performance is acceptable when the assigned value is 1 or higher. Consequently, we divided the graph in Fig. 1 into 4 sections based on these thresholds and colour-coded the data according to which quadrant they belong. Thus, Q1 includes the blue points which represent high importance-low performance and indicate "Concentrate here", Q2 includes the green points which represent high importance–high performance and indicate "Good job", Q3 includes the orange points which represent low importance–high performance and indicate "Possible Overkill" and Q4 includes the red points which represent low importance–low performance and indicate "Low Priority". We conducted the analysis based on Fig. 1 and we present the results for the 46 competence statements in Table 3.

According to the analysis in Table 3, 26 competence statements received "good job," indicating the toolkit has met LOs for these competences.

The competence statements to which the attention should be paid in the "Concentrate here" quadrant, are the following six:

- Include the needs of present and future generations
- Examine the norms, values, assumptions and attitudes that underlie the problem
- Use criteria to assess alternative ideas, options, plans and solutions
- Resolve conflict that may arise from competing worldviews, priorities and values
- Promote a culture of peace, solidarity and equality
- Evaluate the extent to which the goal/task has been achieved

Most of them have a normative element, which is considered important, but the active-learning session did not enable the participants to apply it and perform well.

Table 1. Competence statements included in the students' questionnaire and their coding for the analysis of the results.

Competence statements	Competence coding
1. Identify systems related to the problem in various scales, their components and relationships	Systems thinking, SYS1
2. Investigate how history influences the problem	Anticipatory thinking, ANT1
3. Examine the norms, values, assumptions and attitudes that underlie the problem	Normative thinking, NOR1
4. Know about political, social, economic and environmental concepts, conditions, institutions and functions relevant to the problem	Systems thinking, SYS2
5. Use standards for collecting information such as accuracy, relevance, clarity and precision	Critical thinking, CRI1
6. Determine knowledge, skills and method for dealing with the problem	Strategic thinking, STR1
7. Use (digital or other) tools effectively to search for, collect and visualise information	Digital skills, DIS1
8. Form effective teams as variety of knowledge, skills and perspectives is needed	Collaboration, COL1
9. Communicate with team-members to establish shared understanding and responsibility about the problem	Collaboration, COL2
10. Identify strengths of and assign roles to team-members accordingly	Strategic thinking, STR2
11. Show respect to both people and nature	Normative thinking, NOR2
12. Build a conceptual model of the problem (consisting of elements, interactions, cause-effect, feedback, flows)	Systems thinking, SYS3
13. Include the needs of present and future generations	Anticipatory thinking, ANT2
14. Consider all involved stakeholders and identify their perspectives, needs and concerns	Systems thinking, SYS4
15. Interpret information correctly in order to reason and produce robust and transparent judgements	Critical thinking, CRI2
16. Identify tasks, set goals, describe steps, challenges, success factors, existing solutions and their evidence to addressing the problem	Strategic thinking, STR3
17. Show appreciation and understanding of differences between value systems and worldviews of different groups	Normative thinking, NOR3
18. Encourage and motivate oneself and others to proceed through tasks and fulfil roles	Self-awareness, SeaA1
19. Understand and respect other peoples' needs and show empathy	Collaboration, COL3
20. Promote intra and inter-generational equity and justice	Normative thinking, NOR4
21. Identify leverage points in the system to make interventions	Systems thinking, SYS5
22. Craft scenarios (possible future), make predictions (probable future) and envision (desirable and sustainable future)	Anticipatory thinking, ANT3
23. Generate multiple ideas, options, alternatives and solutions and elaborate on them	Anticipatory thinking, ANT4
24. Develop effective strategies and plans to address the problem	Strategic thinking, STR4
25. Engage in well-thought action to solve the problem	Strategic thinking, STR5
26. Consider the implications of future scenarios	Anticipatory thinking, ANT5
27. Use criteria to assess alternative ideas, options, plans and solutions	Critical thinking, CRI3
28. Weigh different values and consider trade-offs to reach a sustainable decision	Normative thinking, NOR5
29. Use (digital or other) tools effectively to support creativity, innovation and collaboration between team-members	Digital skills, DIS2
30. Use media to communicate messages and actions regarding the problem	Digital skills, DIS3
31. Resolve conflict that may arise from competing worldviews, priorities and values	Collaboration, COL4
32. Promote a culture of peace, solidarity and equality	Normative thinking, NOR6
33. Negotiate between members to reach sustainable decision	Collaboration, COL5
34. Communicate with team-members about task progress, rules of engagement and maintain shared understanding and commitment to the task and roles	Collaboration, COL6
35. Manage personal emotions and persevere in the face of challenge, uncertainty or ambiguity	Self-awareness, SeaA2
36. Consider the effect of time delays, conflicting goals and policy resistance on the outcome of the decision	Systems thinking, SYS6
37. Consider for whom the future scenario is desirable, which and whose values it incorporates	Anticipatory thinking, ANT6
38. Evaluate the extent to which the goal/task has been achieved	Strategic thinking, STR6
39. Think open-mindedly to clarify assumptions, biases, inferences, distortion and superficialities	Critical thinking, CRI4
40. Discern meaningful signal by learning to exclude fear, emotional attachment and any other restriction	Self-awareness, SeaA3
41. Give and receive constructive feedback	Self-awareness, SeaA4
42. Use (digital or other) tools effectively to produce innovative outcomes (products, technologies, policies)	Digital skills, DIS4
43. Monitor shared understanding of problem, roles, tasks, actions, results and success	Critical thinking, CRI5
44. Monitor understanding of difference in communication styles, values and perspectives	Self-awareness, SeaA5
45. Reflect on personal and collective way of thinking and action processes to improve	Self-awareness, SeaA6
46. Reflect on group strategies, processes and solutions in the face of evidence and adjust if needed	Critical thinking, CRI6

Table 2. Criticality and Performance descriptive statistics from analysing the self-assessment questionnaires on the intended competences for the participants.

	Importance (0–5)			Performance (0–2)		
Competence	**Mean**	**St. deviation**	**Variance**	**Mean**	**St. deviation**	**Variance**
Systems thinking	4.15	0.31	0.09	1.22	0.24	0.06
Anticipatory thinking	4.02	0.34	0.11	1.00	0.28	0.08
Normative thinking	4.13	0.27	0.07	0.91	0.22	0.05
Critical thinking	4.21	0.28	0.08	1.18	0.15	0.02
Strategic thinking	4.22	0.16	0.03	1.16	0.21	0.04
Collaboration	4.19	0.34	0.12	1.19	0.30	0.09
Self-awareness	3.63	0.64	0.41	0.97	0.25	0.06
Digital skills	3.94	0.13	0.02	1.05	0.36	0.13

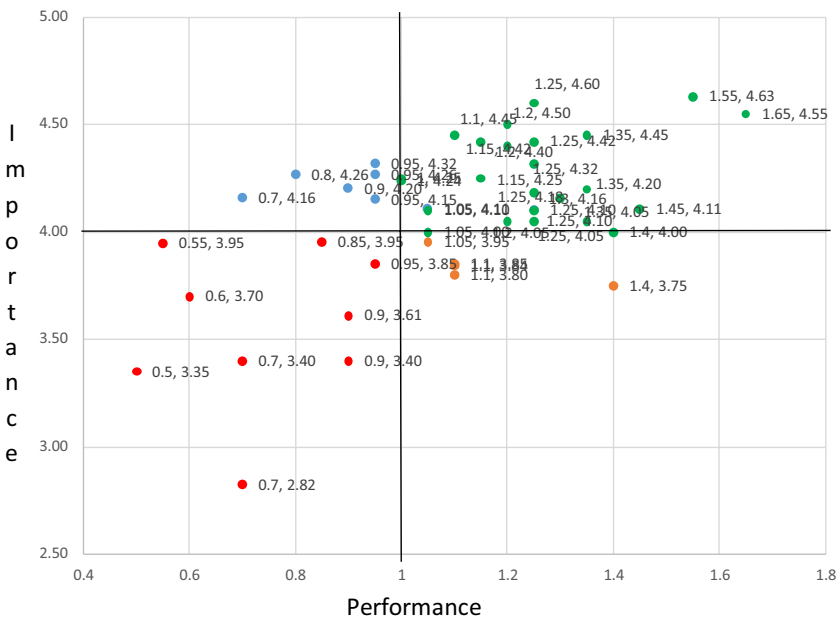


Figure 1. Importance (I)–performance (P) analysis of the individual results of the statements of perceived sustainability competence in the participant questionnaire (Q1 includes results with $I \geq 4$ and $P < 1$ in blue, Q2 includes results with $I \geq 4$ and $P \geq 1$ in green, Q3 includes results $I < 4$ and $P > 1$ in orange and Q4 includes results with $I < 4$ and $P < 1$ in red).

Results from the reflection sessions

We asked the groups of participants to reflect on playing the serious game and think why some teams won and others did not. The members of the winning teams mentioned they invested early on strategies that included collecting the materials they needed or using the junkyard for used material, pushing market prices up for materials they did not need and also making wise choices about strategy cards. As the teams played the game for an hour and a half teams who focused on short-term strategies won.

The teams who did not win, invested in longer-term and more expensive strategies, by selecting the relevant cards and paying a lot for materials later in the gameplay. This resulted in loss

Table 3. Competence statements categorised to typologies according the Importance Performance analysis (IPA).

Competence	Code	Category	Code	Category	Code	Category
Systems Thinking	SYS1,2,3,4	Good Job	SYS5	Low Priority	SYS6	Possible Overkill
Anticipatory Thinking	ANT3,4,5,6	Good Job	ANT1	Low Priority	ANT2	Concentrate Here
Normative Thinking	NOR2,5	Good Job	NOR1,6	Concentrate Here	NOR3	Possible Overkill
Critical Thinking	CRI2,4,5,6	Good Job	CRI1	Possible Overkill	CRI3	Concentrate Here
Strategic Thinking	STRT1,3,4,5	Good Job	STR2	Low Priority	STR6	Concentrate Here
Collaboration	COL1,2,5,6	Good Job	COL3	Low Priority	COL4	Concentrate Here
Self-awareness	SeA4,5	Good Job	SeA1,2,3	Low Priority	SeA6	Possible Overkill
Digital skills	DIC1,2	Good Job	DIC3	Low Priority	DIC4	Possible Overkill

of money in the short-term. Their motivation was to think for the long-term and keep collecting materials that other teams would need in the future, as they would become unavailable. They invested in specific strategies cards (called 'private warehouses´ in the game) to retain product ownership and implement circular economy when the competition would be unable to mine or resources would become unavailable due to supply disruptions.

After, we asked them to think of aspects for companies to consider when designing products or technologies; aspects that policymakers should consider when developing policies for products or technologies and to reflect on trade-offs in developing sustainable solutions for products and technologies. The results are presented in Table 4.

During the Active-learning ToolKit session, the students used the active-learning methodology developed by Granta Design (now Ansys UK Ltd.) and the University of Cambridge, whereby they had to try and map the steps from the current state to the desired future in order to meet 2030 EU emission targets by the introduction of electric vehicles.

As a first step, they developed a stakeholder diagram and considered the concerns of those stakeholders, which are shown in Fig. 2.

Then they researched the facts around the environmental impact of electric vehicles in terms of total energy use and CO_2 emissions as well as the material needs in terms of Li-ion batteries using the Ansys Granta EduPack programme, which are presented in Fig. 3.

Lastly, they assessed the proposal based on the concept of three capitals, the natural, the manufactured and the human and social capital. The natural capital includes natural resources such as clean atmosphere, productive land fresh water, oceans, bio-sphere, and material and energy resources; the manufactured capital includes the built environment, industrial capacity, and financial health of a social system; and the human and social capital includes the knowledge, education, culture, human health, skills and happiness and the values that a prosperous society relies on. All three capitals are interconnected and contribute to sustainable development. The participants' assessment showed that in the short-term (in 5 years) the objective would not be achieved, as the infrastructure is doubtful, material supply is not guaranteed and recycling of the batteries is not in place. In the longer-term (> 15 years) if the decarbonisation of the energy grid had happened as well as the battery recycling was available then there would be chances of achieving the proposal. The participants also thought about alternatives so they would rethink car use and redefine mobility to achieve more sustainable cities in terms of emissions.

After the Active-learning ToolKit session was over, we asked the participants to reflect on the most important aspects of their experience and how they would apply what they learnt in the future. Below we present some significant quotes. In general, participants commented on the use of systems thinking throughout the session and how it would help them solve problems in their own research or teaching (Box 1).

Table 4. Results from the reflection session on aspects for companies and policymakers to consider when designing products and technologies for sustainability as well as the foreseen trade-offs.

Aspects of product design for companies	Aspects of product design for policy	Trade-offs for sustainability
1. Keep control of resources (leasing, warehouse) 2. Sourcing from waste 3. Collaborate with other companies in the sector 4. Market competition/race for materials 5. External factors (socio-political and environmental) that might produce benefits or cause damage/useful to do forecasting 6. Availability of materials (raw material reserve, market dynamics, and geopolitics) 7. Long-term investment in circular economy 8. Cash flow implications of products and investment 9. Origin and availability of materials 10. Amount of material needed for product development 11. Whole lifecycle of product/ End of product life 12. Cost of production 13. Willingness to pay based on materials scarcity	1. Regional conflict 2. Environmental/Ecological footprint/impact of material 3. Labour conditions 4. Social aspects (consideration for local communities living close to extraction/mining sites) 5. Sustainability 6. Long-term impact 7. Make products recyclable (disassembly after use) 8. Incentives for low-carbon green tech 9. Policies for incorporating social & environmental capital, internalising wider value/impact rather than just GDP/economic perspective 10. Cap price for raw materials 11. Availability of materials/ regulate mining cost 12. Demand for products 13. Minimising waste 14. Protect material resources from becoming exhausted 15. Avoid hoarding of resources 16. Align consumption of resources between companies 17. Variation in policies they develop 18. Competition between companies	1. Time 2. Socio-political and environmental events 3. Initial investment 4. More expensive in theory because parties will have to take responsibility 5. Consume less virgin resources/raw materials 6. Materials will cost more so more expensive to produce 7. Need to be more creative because of shortage of materials 8. You still extract finite materials to produce them. Some resources might be used for different products. Those that get produced sell at the highest price 9. Decreased shareholder returns 10. May limit local employment and economic prosperity 11. Sustainable solutions may not benefit the buyer of the solution, moving beyond the tragedy of the commons 12. Politics/desire for higher income 13. The wide opinion that more money makes us happier 14. Design to last (longer life) 15. To arrange a sustainable operation may cause further investment (cost) 16. Short-term benefits may be compromised 17. Availability (use of material from the junkyard)

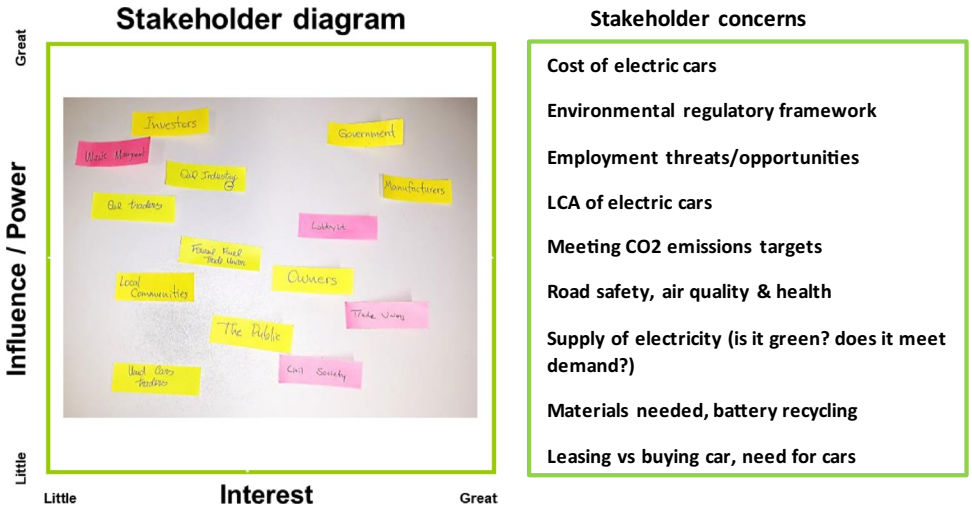


Figure 2. Stakeholder diagram and concerns identified during the implementation of the Active-learning ToolKit during the workshop.

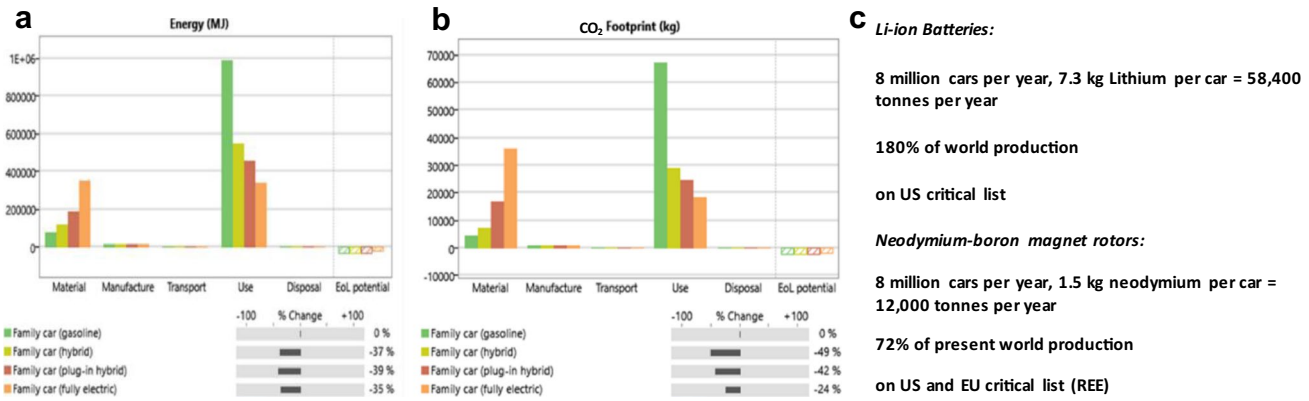


Figure 3. (a) Total energy use, (b) CO_2 footprint and c. materials needs calculated with the participants during the Active-learning ToolKit implementation (Ansys Granta EduPack 2018).

Box 1: Participant reflections

"It was the first time we heard about the concept of critical materials and included the political perspectives of resources. We were given the opportunity to look at other dimensions of sustainability and not only carbon emissions mitigation."

"For the sake of dealing with a very complex problem we reduce our outcomes or outputs to very specific kinds of metrics. If we are all to improve sustainability, we should be aware of unintended outcomes or consequences. So it is great for me to say yes it is good to transition to wind energy in terms of CO_2 emissions but if there is a limit to how many turbines we can comfortably produce within the EU because of materials criticality then policies are limited."

"I think it highlights our selfish approach. What my country needs in terms of resources to develop may affect other countries. Taking reserves from them or dumping waste on them and polluting them. It is like I want to be green but at the expense of other countries' wellbeing."

"If the countries have both the resources (raw materials) and the technology to exploit them and produce innovative and green products then this may cause industry to be transferred to these emerging economies. So instead of creating green jobs, we are losing jobs or transferring them elsewhere."

Discussion and conclusions

The aim of the workshop was to demonstrate the potential of active-learning educational interventions to develop sustainability competences in learners and measure these in the participants of the workshop we organised. We developed a self-assessment questionnaire and asked the participants to reflect on their experiences. Both these tools for self-assessing competence have been found effective in measuring sustainability competences in previous studies.[63] The self-assessment questionnaire was developed based on a competence model developed for the evaluation of sustainability competences in the MSc Environmental Technology[6] and helped us collect the data about the participants' view on the importance of the competences selected for sustainability as well as on how they

performed during the workshop. Most self-assessment questionnaires used in the literature use only the self-assessment of performance and not how important the competence is for participants. By including the importance component of sustainability competence in the questionnaire, learners participated in the process of forming the LOs of the session instead of being assessed on criteria selected only by the educators and became engaged as they took ownership and felt motivated to achieve what is crucial for them.[64]

The reflection sessions offered the participants an opportunity to consolidate their experience in both the serious game and the Active-learning ToolKit, draw insights and link the learning from both. They managed to provide more information on the competences they developed not by being directly asked about them, but by demonstrating it through answering questions around how they would apply their experiences in their own educational, professional or other settings. They also benefited from having discussions with the other participants reflecting on the workshop sessions and building on other's views and perspectives, sometimes debating the gameplay of the serious game and how to make it more inclusive of all sustainability dimensions or critiquing the policy options to achieve sustainable development through the use of electric cars and what alternatives they could explore for sustainable mobility. Reflection sessions as part of active-learning activities that require participants to confront challenging and open-ended situations have been found to produce positive outcomes in terms of competence development.[65]

Workshop participants considered all eight competences to be critical or highly critical for sustainability and they thought they were given at least some opportunities to develop those. This is in accordance with literature around sustainability competences that highlights systems thinking, anticipatory thinking, critical thinking, strategic thinking, collaboration and self-awareness as important for solving sustainability challenges.[14, 66–68] Digital skills and self-awareness received lower scores, which contradicts claims in the literature around the importance of navigating digital and online environments for tackling twenty-first century challenges and the importance of reflection and understanding of one's role in sustainability as well as how to achieve it.[4, 69, 70] The latter finding supports that experiential learning and active learning can foster the development of sustainability competences in learners in accordance with the published literature.[71, 72]

According to the results of the IPA on individual data, participants consider six competence statements to be low priority. It is interesting that three of them belong to the self-awareness competence as maybe the participants think they are not that crucial and they did not have opportunity to develop them. According to recent research,[73] self-awareness is an important competence for sustainability practitioners as it enables them to make decisions when these are needed on the spot, it helps them become transformative leaders and also helps them evaluate the effectiveness of their actions. Furthermore, self-awareness has links with systems thinking, anticipatory thinking and strategic thinking that make it highly interconnected with the other competences.[73] The most critical aspects of self-awareness and those the workshop did a good job in developing were giving and receiving feedback and monitoring understanding of differences in perspectives, worldviews and values. It seems that the active-learning workshop offered opportunities for students to develop the most critical dimensions of systems, anticipatory, strategic and critical thinking and collaboration, while it also covered some of the dimensions of normative, self-awareness and digital skills competences.

This is supported by the reflective sessions as well. Participants after the end of the first session on the serious game explained that it was strategic thinking that helped some teams win the game, because they focused on short-term strategies that generated income. However, longer-term strategies were selected by others who thought they could overcome material scarcity and invest in circular economy. In the reflection questionnaire, we asked them for considerations for companies and policy makers and to identify the trade-offs that may influence the former in pursuing sustainable solutions. They talked a lot about considering and anticipating future events such as shortages of materials, cost of limited resources and future investments that link with anticipatory thinking. Anticipatory thinking is important not only for setting the future vision of sustainability for a society to achieve but also to make projections and predictions on how current decisions, plans and actions can affect the future.[74] They also mentioned holistic consideration of factors, such as socio-political, environmental and economic, when dealing with sustainability challenges, whole life cycle assessment of products and unintended consequences of policies such as use of electric cars can result in material shortages and unemployment, which align with systems thinking. They also criticised the values that permeate our society, such as the throwaway human attitudes, selfishness, the motto "money equates to happiness" and making choices that benefit ourselves but harming others (lack of empathy), which align with normative thinking. Collaboration as well as minimising competition and achieving conflict resolution were mentioned in response to how companies can navigate the changing landscape of material availability and move to circular economy, but also as obstacles they would have to overcome with the help of policy to achieve more sustainable operations. Critical thinking is evident in reflections around factors that affect the availability of materials, the priorities when designing policies and the impact of sustainable solutions on different parts of the population. Self-awareness and digital skills are still not clearly demonstrated through the reflective sessions.

What has more interest for the active-learning workshop is that some critical dimensions of normative, critical, strategic thinking and collaboration were not covered even though they we deemed crucial in the opinion of participants. Those dimensions have to do with the intergenerational nature of sustainability, the normative (value systems, beliefs and norms) underpinnings of sustainability issues as well as the values that guide sustainability visions. According to the iceberg model of systems thinking, those normative underpinnings (or alternatively mental models) are the root causes of unsustainability and in order

to achieve whole systems change they need to be redefined for sustainability.[75] This may have to do with the format of the workshop that was time restrained so the participants were not given enough time to delve deeper into those issues. Lastly, some dimensions of collaboration such as resolving conflict were not adequately addressed mainly in the serious game session. This again may have been as participants did not have enough time to develop their long-term strategies which would have brought them in situations where they would compete heavily for the critical materials needed. Last but not least, one dimension of strategic competence, evaluation of the extent to which the goal of the strategy has been achieved was not adequately covered. One possible reason is again that the scenarios the participants had to actively pursue would have been achieved with long-term strategies in both the serious game and the Active-learning ToolKit and so evaluation could not be entirely completed.

Regarding the six competences that the organisers of the workshop need to pay attention to, for the first one "Include the needs of present and future generations", the serious game could have lasted longer so that the participants would have been faced with challenging situations and have been required to plan for the long-term. The same would have been included in the Active-learning Toolkit as a criterion on which to assess the proposed policy measure around electric vehicles not only in terms the materials and energy needed for their manufacturing and use but on sustainable mobility as a concept for future generations.

In terms of competence indicator "examine the norms, values, assumptions and attitudes that underlie the problem" the participants could spend more time conducting stakeholder analysis and delving deeper into their mentalities. This could be further enhanced by including it in the reflection section of the serious game to discuss what the various stakeholders of companies, government and civil society think and feel about linear versus circular economy. Another activity that could be included in the toolkit would be a role-playing game of stakeholders involved in the electric cars case study as this has been found to engage participants to think more systemically in materials science education.[76]

Regarding the "use of criteria to assess alternative ideas, options, plans and solutions" the participants could gain more hands-on experience of generating assessment criteria aligned to the three capitals and apply them to evaluate a proposed sustainable development during the Active-learning ToolKit or come up with criteria for companies or policy makers around navigating materials' criticality. For the competence statement "resolve conflict that may arise from competing worldviews, priorities and values" one way to tweak the serious game would be to ask companies to collaborate to achieve common sustainability goals such as sustainable development goal (SDG) 12 sustainable consumption and production and SDG17 partnership for the goals.[57] For "promoting a culture of peace, solidarity and equality" the participants could be engaged in broader participatory visioning exercise at the start of the workshop around what sustainable development would look like and how can these attributes be enacted.[68] Lastly and importantly, regarding the competence statement "evaluate the extent to which the goal/task has been achieved" the serious game session can be adapted to require participants to set a goal initially for their company and then after the game is over reflect on it and if it was achieved. For the Active-learning ToolKit session after participants assess their options in terms of aligning with sustainable development, could investigate data on its current achievement and assess the gap that remains or suggest future action.

Considering the active-learning workshop in its entirety and how it can be improved to enhance the development of the crucial competences for sustainability, it would be worth holding the serious game and Active-learning Toolkit as part of the same educational intervention in the future. The analysis of the reflection questions shows that the participants developed their competences in both sessions and worked to explore some of the concepts they encountered in the first session, more in-depth in the second session as they provided links between the two. However, because of the time constraints of holding both sessions in one-day it is important to consider them as part of the same educational activity but hold them on separate but consecutive days so that participants have enough time to engage with both and reflect deeply.

Finally, we suggest to materials and sustainability educators to implement active-learning interventions in their teaching as they help learners develop sustainability competences. Moreover, they should include their learners' views in the development of the LOs and the format of the activities so that they can be more aligned with their views of what is crucial for sustainability as well as with assessment of performance in the selected competences. Assessment of LOs can be done through self-assessment and reflection sessions and both ways can offer rich data to the educator to understand the needs of learners as well as to deduce their learning progress.

Author contributions

VK conceived, prepared and wrote the article, performed the research, collected and analysed the data, KAW facilitated the serious game session of the workshop, assisted data collection and writing of the article, TVV facilitated the Active-learning ToolKit session of the workshop, assisted in data collection and reviewed the article.

Funding

The authors wish to acknowledge funding from the Graduate School of Imperial College London for organising the materials education workshop for sustainability.

Data availability

Data available on request due to privacy/ethical restrictions. The data that support the findings of this study are available on request from the corresponding author, VK. The data are not publicly available due to containing information that could compromise the privacy of research participants.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval

This research has received ethics approval by the Imperial College Research Ethics Committee (ICREC) as it involves the participation of human subjects and handling their data. The ICREC approval reference is 18IC4498, dated 14 May 2018.

Open Access

REFERENCES

1. UNESCO Education sector, Education for sustainable development: A roadmap. Paris (2020)
2. C. Fadel, J.S. Groff, Four-dimensional education for sustainable societies. In: Sustainability, Human Well-Being, and the Future of Education (2018)
3. R. Wade, H. Atkinson, The role of education for sustainability in the sustainable development goals—changing policy and practice? In: World Sustainability Series (2017)
4. QAA, Education for sustainable development guidance—draft for consultation (2020)
5. V. Kioupi, N. Voulvoulis, Sustainable development goals (SDGs): Assessing the contribution of higher education programmes, vol 2019 (2020)
6. V. Kioupi, Sustainability education: A systemic framework for evaluating educational outcomes towards the Sustainable Development Goals, PhD thesis. Imperial College London (2021)
7. R. Donnelly, M. Fitzmaurice, Collaborative project-based learning and problem-based learning in higher education: A consideration of tutor and student role in learner-focused strategies, pp 0–20 (2005)
8. W. Leal Filho, C. Shiel, A. Paço, Implementing and operationalising integrative approaches to sustainability in higher education. J. Clean. Prod. **133**, 126–135 (2016)
9. T. Ouariachi, M.D. Olvera-Lobo, J. Gutiérrez-Pérez, Serious games and sustainability. In: Encyclopedia of Sustainability in Higher Education (2019)
10. R. Lozano, M.Y. Merrill, K. Sammalisto, K. Ceulemans, F.J. Lozano, Connecting competences and pedagogical approaches for sustainable development in higher education: A literature review and framework proposal. Sustain **9**(10), 1–15 (2017)
11. W. Lambrechts, P. Van Petegem, The interrelations between competences for sustainable development and research competences. Int. J. Sustain. High. Educ. **17**, 776 (2016)
12. L. Ploum, V. Blok, T. Lans, O. Omta, Toward a validated competence framework for sustainable entrepreneurship. Organ. Environ. **31**(2), 113–132 (2018)
13. T. Lans, V. Blok, R. Wesselink, Learning apart and together: Towards an integrated competence framework for sustainable entrepreneurship in higher education. J. Clean. Prod. **62**, 37–47 (2014)
14. A. Wiek, L. Withycombe, C.L. Redman, Key competencies in sustainability: A reference framework for academic program development. Sustain. Sci. **6**(2), 203–218 (2011)
15. E.M. Waltner, W. Rieß, C. Mischo, Development and validation of an instrument for measuring student sustainability competencies. Sustain. **11**(6), 1–20 (2019)
16. OECD, Preparing our youth for an inclusive and sustainable world illustrative examples of scenarios for the cognitive assessment of global understanding the assessment of global competence in Pisa (2018)
17. O. Sandri, S. Holdsworth, I. Thomas, Vignette question design for the assessment of graduate sustainability learning outcomes. Environ. Educ. Res. **24**(3), 406–426 (2018)
18. A. Décamps, G. Barbat, J.C. Carteron, V. Hands, C. Parkes, Sulitest: A collaborative initiative to support and assess sustainability literacy in higher education. Int. J. Manag. Educ. **15**(2), 138–152 (2017)
19. K. Shephard et al., Seeking learning outcomes appropriate for 'education for sustainable development' and for higher education. Assess. Eval. High. Educ. **40**(6), 855–866 (2015)
20. D.A. Shepherd, V. Kuskova, H. Patzelt, Measuring the values that underlie sustainable development: The development of a valid scale. J. Econ. Psychol. **30**(2), 246–256 (2009)
21. K. Shephard, M. Barth, M. Rieckmann, Seeking sustainability competency and capability in the ESD literature, no. October, pp. 1–23 (2018)
22. J.B. Biggs, Teaching for quality learning at University. Open Univ. Press. Res. into High. Educ. Second Ed. (2003)
23. K. Casey, C. Sturgis, Levers and logic models: A framework to guide research and design of high-quality competency-based education systems, p. 55 (2018)
24. A.I. Starcic, M. Terlevic, L. Lin, M. Lebenicnik, Designing learning for sustainable development: Digital practices as boundary crossers and predictors of sustainable lifestyles. Sustain (2018)
25. T. Holm, T. Vuorisalo, K. Sammalisto, Integrated management systems for enhancing education for sustainable development in universities: A memetic approach. J. Clean. Prod. (2015)
26. J. Dlouhá, S. Burandt, Design and evaluation of learning processes in an international sustainability oriented study programme. In search of a new educational quality and assessment method. J. Clean. Prod. **106**, 247–258 (2015)
27. W. Leal Filho et al., The role of planning in implementing sustainable development in a higher education context. J. Clean. Prod. **235**, 678–687 (2019)
28. K. Ceulemans, I. Molderez, L. Van Liedekerke, Sustainability reporting in higher education: A comprehensive review of the recent literature and paths for further research. J. Clean. Prod. **106**, 127–143 (2015)
29. K. vanPoeck, J. Læssøe, T. Block, An exploration of sustainability change agents as facilitators of nonformal learning: Mapping a moving and intertwined landscape. Ecol. Soc. **22**(2), 12 (2017)
30. S. Wilhelm, R. Förster, A.B. Zimmermann, Implementing competence orientation: Towards constructively aligned education for sustainable development in university-level teaching-and-learning. Sustain **11**, 1891 (2019)

31. G. Trencher, S. Vincent, K. Bahr, S. Kudo, K. Markham, Y. Yamanaka, Evaluating core competencies development in sustainability and environmental master's programs: An empirical analysis. J. Clean. Prod. **181**, 829–841 (2018)
32. A. López-Alcarria, A. Olivares-Vicente, F. Poza-Vilches, A systematic review of the use of Agile methodologies in education to foster sustainability competencies. Sustainability (Switzerland) **11**(10), 2915 (2019)
33. G. Caniglia et al., The glocal curriculum: A model for transnational collaboration in higher education for sustainable development. J. Clean. Prod. **171**, 368–376 (2018)
34. L. Probst et al., A transformative university learning experience contributes to sustainability attitudes, skills and agency. J. Clean. Prod. **232**, 648–656 (2019)
35. S. Holdsworth, O. Sandri, I. Thomas, P. Wong, A. Chester, P. McLaughlin, The assessment of graduate sustainability attributes in the workplace: Potential advantages of using the theory of planned behaviour (TPB). J. Clean. Prod. **238**, 117929 (2019)
36. J.W. Cook, *Sustainability, Human Well-Being, and the Future of Education* (Springer, Cham, 2018)
37. E. Bergsmann, M.T. Schultes, P. Winter, B. Schober, C. Spiel, Evaluation of competence-based teaching in higher education: From theory to practice. Eval. Program Plann. **52**, 1–9 (2015)
38. S. Kröger, Realising the potential of EU simulations - practical guidance for beginners. Eur. Polit. Sci. **17**(1), 161 (2018)
39. G. Liarakou, E. Sakka, C. Gavrilakis, Evaluation of serious games, as a tool for education for sustainable development. Eur. J. Open Distance E learning **15**(2), 20 (2012)
40. K.A. Whalen, T.V. Vakhitova, How to approach experimental learning for sustainable development in materials education? In: 10th International Materials Education Symposium, no. 12–13 April, pp. 1–3 (2018)
41. S. Usherwood, Constructing effective simulations of the European Union for teaching: Realising the potential. Eur. Polit. Sci. **13**(1), 53–60 (2014)
42. J. Jozwiak, Vegelate and Greece: Teaching the EU through simulations. Eur. Polit. Sci. **12**(2), 215 (2013)
43. E.E. Zeff, Negotiating in the European council: A model European union format for individual classes. Int. Stud. Perspect. **4**(3), 265 (2003)
44. S. Freeman et al., Active learning increases student performance in science, engineering, and mathematics. Proc. Natl. Acad. Sci. USA **111**(23), 8410 (2014)
45. J. Segalàs, D. Ferrer-Balas, K.F. Mulder, What do engineering students learn in sustainability courses? The effect of the pedagogical approach. J. Clean. Prod. **18**, 275 (2010)
46. K. Whalen, G. Kijne, Game-based approaches to sustainable innovation, in *Palgrave Studies in Sustainable Business in Association with Future Earth*. ed. by N. Bocken, P. Ritala, L. Albareda, R. Verburg (Springer, Cham, 2019)
47. J. Sierra, The potential of simulations for developing multiple learning outcomes: The student perspective. Int. J. Manag. Educ. **18**, 100361 (2020)
48. N. Matzner, R. Herrenbrück, Simulating a climate engineering crisis: Climate politics simulated by students in model United Nations. Simul. Gaming **48**(2), 268 (2017)
49. I. Thomas, Critical thinking, transformative learning, sustainable education, and problem-based learning in universities. J. Transform. Educ. **7**(3), 245–264 (2009)
50. S. Zhang et al., Serious games: Improving public policy through game-based learning and simulation. Environ. Model. Softw. **39**(1), 39 (2013)
51. D.A. Kolb, *Experiential Learning: Experience as the Source of Learning and Development* (Prentice Hall Inc., Englewood Cliffs, 1984)
52. R. Fox, Constructivism examined. Oxford Rev. Educ. **27**(1), 23–35 (2001)
53. C.T. Fosnot, R.S. Perry, *Constructivism: A Psychological Theory of Learning* (Columbia University, New York, 1996)
54. M. Csikszentmihalyi, Flow: The psychology of optimal experience: Steps toward enhancing the quality of life. Des. Issues **8**(1), 80 (1991)
55. D.H. Choi, J. Kim, S.H. Kim, ERP training with a web-based electronic learning system: The flow theory perspective. Int. J. Hum. Comput. Stud. **65**(3), 223 (2007)
56. J. Liu et al., On knowledge generation and use for sustainability. Nat. Sustain. **2**(2), 80–82 (2019)
57. UK National Commission for UNESCO, Good practice in Education for Sustainable Development (ESD) in the UK: Case Studies (2017)
58. E. Knol, P. De Vries, EnerCities, a serious game to stimulate sustainability and energy conservation: Preliminary results. eLearning Pap. **25**(13) (2011
59. K.A. Whalen, C. Berlin, J. Ekberg, I. Barletta, P. Hammersberg, 'All they do is win': Lessons learned from use of a serious game for Circular Economy education. Resour. Conserv. Recycl. **135**, 335 (2018)
60. M. Ashby, T. Vakhitova, Teaching package: Active-learning toolKit - sustainable development. Ansys (former Granta Design), Cambridge, pp. 1–13 (2017)
61. M. Ashby, Materials and sustainable development (2015)
62. S. Alberty, B.J. Mihalik, The use of importance-performance analysis as an evaluative technique in adult education. Eval. Rev. **13**(1), 33 (1989)
63. A. Redman, A. Wiek, M. Barth, Current practice of assessing students' sustainability competencies: A review of tools. Sustain. Sci. **16**, 117 (2020)
64. C. Bullock, G. Hitzhusen, Participatory development of key sustainability concepts for dialogue and curricula at The Ohio State University. Sustain **7**, 14063 (2015)
65. M. Singer-Brodowski, K. Grossmann, S. Bartke, S. Huning, T. Weinsziehr, N. Hagemann, Competency-oriented education for sustainable development: Lessons from five courses on energy poverty. Int. J. Sustain. High. Educ. **19**(7), 1299–1316 (2018)
66. K. Brundiers et al., Key competencies in sustainability in higher education—toward an agreed-upon reference framework. Sustain. Sci. **16**, 13 (2020)
67. M. Rieckmann, Future-oriented higher education: Which key competencies should be fostered through university teaching and learning? Futures **44**(2), 127–135 (2012)
68. V. Kioupi, N. Voulvoulis, Education for sustainable development: A systemic framework for connecting the SDGs to educational outcomes. Sustain **11**(21), 6104 (2019)
69. UNICEF, T. W. Bank, UNFPA, UNDP, U. Women, and UNHCR, "Education 2030 - Incheon Declaration and Framework for Action - Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all," Unesco, p. 83 (2016)
70. L. Ilomäki, A. Kantosalo, M. Lakkala, What is digital competence? 2. Digital competence is an evolving concept (2011)
71. M.T. Fuertes-Camacho, M. Graell-Martín, M. Fuentes-Loss, M.C. Balaguer-Fàbregas, Integrating sustainability into higher education curricula through the project method, a global learning strategy. Sustain **11**(3), 767 (2019)
72. F. Dean, B. Karen, N. Sandra, W. Frances, Core implementation components. Res. Soc. Work Pract. **19**(5), 531–540 (2009)
73. A. Zaffiro, D. Tablado, R. Le Failler, F. van der Ploeg, The role of self-awareness for sustainability practitioners. Blekinge Institute of Technology (2020)

74. L.K. Withycombe, Anticipatory competence as a key competence in sustainability education. Arizona State University, vol. MA Thesis, no. August, p. 37 (2010)
75. P.M. Senge, The fifth discipline, the art and practice of the learning organization. Perform. + Instr. (1991)
76. V. Kioupi, Using Elements of the Impact of Materials on Society (IMOS) Course to demonstrate the potential of a systems approach in Sustainability Education in Greek Secondary Schools. MRS Adv. **3**(12), 609 (2018)