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Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach

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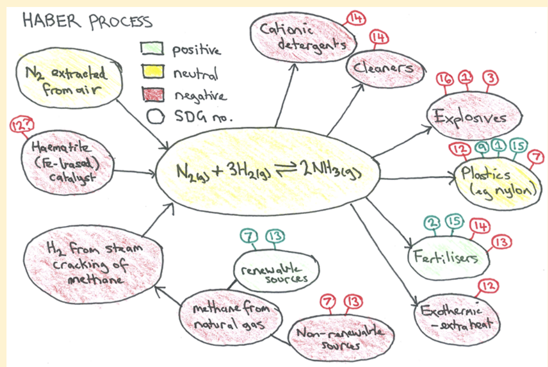
Supporting Information

ABSTRACT: We report here a teacher action research project in which a Systems Thinking approach was implemented into a 15 h Depth Study for students in their final year of secondary chemistry. Students were introduced to the concept of Systems Thinking and the use of systems maps, along with the United Nations Global Goals for Sustainable Development (SDGs). Integrating these ideas, students created their own systems maps for specific chemical processes. Specifically, they represented their chemistry curriculum content knowledge in the context of the SDGs, by considering whether the impact of each aspect of the chemical process is positive, negative, or neutral for each SDG. The purpose of the approach was to give students the opportunity to situate their knowledge of sustainability in the context of the sourcing, uses, and other intended and unintended consequences of a variety of chemical processes, and how these processes impact the wider global community. The teacher action research was conducted through the development and testing of the teaching materials as part of an iterative cycle of improvement. The teaching and assessment approach was evaluated utilizing reflections of the teacher in an action research cycle. The project is described in the context of how Systems Thinking influenced the inclusion of sustainability as a cross-curriculum priority in Australia. This report gives secondary teachers tools to implement Systems Thinking in their own classrooms in a way that integrates it within the chemistry curriculum without requiring additional time or resources.



KEYWORDS: *High School/Introductory Chemistry, Industrial Chemistry, Interdisciplinary/Multidisciplinary, Problem Solving/Decision Making, Green Chemistry, Sustainability, Systems Thinking*

INTRODUCTION

The meaningful incorporation of sustainability learning contexts into science discipline teaching and learning has been an objective of many curriculum change proposals.[1−8] Situating sustainability within chemistry curriculum content has posed challenges, with evidence to suggest that students consider societal issues such as sustainable development as everyday knowledge, and struggle to link them with their learning of chemistry content.[9,10] Eminent researchers in the field of chemistry education have challenged chemistry teachers to make the material basis of society[11] more prominent and explicit, for instance by meaningfully embedding the United Nations Global Goals for Sustainable Development (SDGs) into chemistry curriculum learning contexts at all education levels.[12] Systems Thinking has been suggested as an integrated way to work toward sustainability, rather than separating the SDGs into isolated and potentially mutually dissonant targets.[13] Linking to the SDGs is expected to influence learners to regard their chemistry knowledge as central to understanding how materials and processes impact sustainable development in the global community.[14] As a means to do this, three recent reports have presented a powerful argument for the adoption of a Systems Thinking approach in chemistry education.[11,15,16]

Systems Thinking is an approach to addressing problems that incorporates the complexity of a whole system in a holistic manner. It has been defined somewhat differently in different contexts, and in particular the nature of what constitutes a system for this purpose can vary from a small, discrete system such as a cell to an ecosystem.[17,18] Systems Thinking is growing in applications such as sustainability and international aid, because it is uniquely adapted to solving complex problems.[15,16,19] In education, Systems Thinking has been used extensively within the field of biology to encompass

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several different theories with the common feature of understanding, interpreting, and explaining complex and dynamic systems.[20] Verhoeff and colleagues have argued that Systems Thinking is a cognitive skill, and that students should be introduced to the theoretical basis being applied.[20] Thus, we suggest that Systems Thinking should feature prominently in a skills-based curriculum.

In Australia, state and national education bodies list Sustainability as one of three "cross-curriculum priorities" for K−10.[21] Although the term cross-curriculum priority echoes the terminology of the *Next Generation Science Standards* (NGSS) "cross-cutting concepts",[22] it has a somewhat different meaning in Australia. In the case of NGSS, these cross-cutting concepts act to bridge *science* discipline boundaries,[2] whereas the three cross-curriculum priorities are intended to be addressed in *all learning areas* (science, the arts, humanities, languages, etc.).[1] Unlike within the NGSS, Systems Thinking is not explicitly mentioned within the sustainability cross-curriculum priority, but it did feature prominently in its development. The *Sustainability Curriculum Framework* policy document, published in 2010 by the Australian government,[23] sought to establish the importance of *Education for Sustainability* (EfS) in Australian schools. The framework described three repertoires of practice ("world viewing", "Systems Thinking", and "futures and design thinking"), and following further curriculum development these practices became in essence the organizing key concepts of the sustainability cross-curriculum priority ("world view", "systems", and "futures").[1,24]

In 2014, a report commissioned by the Australian government and produced by the Australian Education Sustainability Alliance to establish the state of play of the sustainability cross-curriculum priority in schools that were early adopters of the new curriculum found a raft of disappointing evidence. The report found that less than 1 in 10 (9%) teachers adequately incorporated sustainability into their teaching, and most teachers (80%) did not understand or had not even heard of *Education for Sustainability (EfS)*.[1] Despite this, the majority of the same teachers (85%) saw it as important to personally integrate sustainability into their own teaching practice, suggesting that should effective means of incorporating the teaching and learning of sustainability into content areas develop, engaged teachers could drive its implementation.

A recent change in the State of New South Wales (NSW) across all senior secondary science (years 11 and 12) discipline curricula (chemistry, physics, biology, earth and environmental science) provided an opportunity for teachers to incorporate sustainability into content knowledge within a traditional high school chemistry curriculum. The key feature of the change is the addition of a "Depth Study" to the years 11 and 12 curricula for each subject.[25] A Depth Study is intended to provide "opportunities for students to pursue their interests in their particular discipline, acquire a depth of understanding, and take responsibility for their own learning".[26] The topic and scope for the Depth Study is open for each school and teacher to set. This flexibility provides a practical means for a school or teacher to embed relevant local contexts. Assessment and reporting specifications for the Depth Study are described in the Supporting Information.

At the 2018 International Conference on Chemistry Education in Sydney, the Systems Thinking theme included an introduction to Systems Thinking from Peter Mahaffy and Stephen Matlin[27] and a presentation by Tom Holme on the use of Systemigrams in chemistry education.[28] The teacher in this project attended those sessions and was inspired to integrate Systems Thinking into his grade 12 classes immediately. The requirement for schools to implement the new Depth Study in 2018 became the natural place to implement this teaching approach. Linking to the chemistry curriculum content, the context of the Depth Study was to develop an in-depth understanding of industrial chemical processes, including the Haber process, the Solvay process, the production of biofuels and ethanol, and alkene polymerization. In order to meet the requirement to have "Working Scientifically" skills-based outcomes in the Depth Study, the implemented task also situated Systems Thinking as an approach to question, analyze, and process information, and importantly for the students to communicate their understanding of how each of the chemical processes impacts the SDGs. Thus, the Depth Study was designed as a means to situate students' chemistry content knowledge within their growing knowledge of how society has an impact on sustainable development, or, as a group of eminent researchers in this field has described it, to refocus their education on the *molecular basis* of sustainability.[11]

The development and evaluation of the materials in this study involved reflective practice on the part of the teacher and formed a teacher action research study. Teacher action research is a broad paradigm that has been successfully used to improve practice and achieve change in educational environments.[29] As described in that work, the teacher is the agent and source of the reform and is empowered as the owner and initiator of changes in their practice. Action research is one of the fundamental theoretical frameworks for educational research[30] and involves recognizing a problem and forming a plan, followed by a cycle of acting, monitoring, and evaluating.[31] Thus, it is the ideal methodology for an individual teacher to adopt when initiating change. However, to interpret the findings of teacher action research, one must have some basis to evaluate the weight of the teacher's reflection, and so the teacher, their background and professional experience must also be also described.

The research question addressed by this study is "How can systems maps allow a teacher to situate the learning of sustainability within the learning of chemistry content?"

THE SYSTEMS THINKING IN CHEMISTRY DEPTH STUDY

Context

The Systems Thinking in Chemistry Depth Study was developed by a single teacher, teaching senior chemistry at Wollondilly Anglican College, a small, private high school located within a rural area in NSW, Australia. This teacher has extensive experience not only teaching senior chemistry for over 20 years, but also as a writer and assessor for national tests. In addition, he is engaged with chemistry education research, attending conferences regularly to keep abreast of developments. He is extensively involved with outreach activities from which his students benefit. His skills and commitment to teaching were recognized in the award of the Royal Australian Chemical Institute's Centenary of Federation Teaching Award in 2015. Thus, his reflections on student outcomes from this project have significant weight.

The students involved were final year (year 12) chemistry students. In NSW, the senior chemistry curriculum is spread

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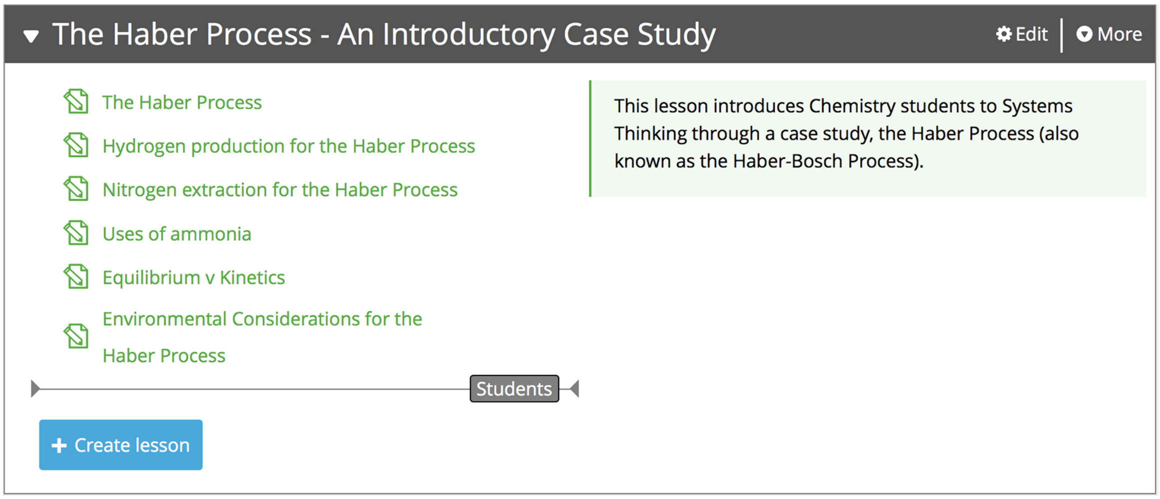

Figure 1. Screenshot of the online interface used by students for the Haber process.

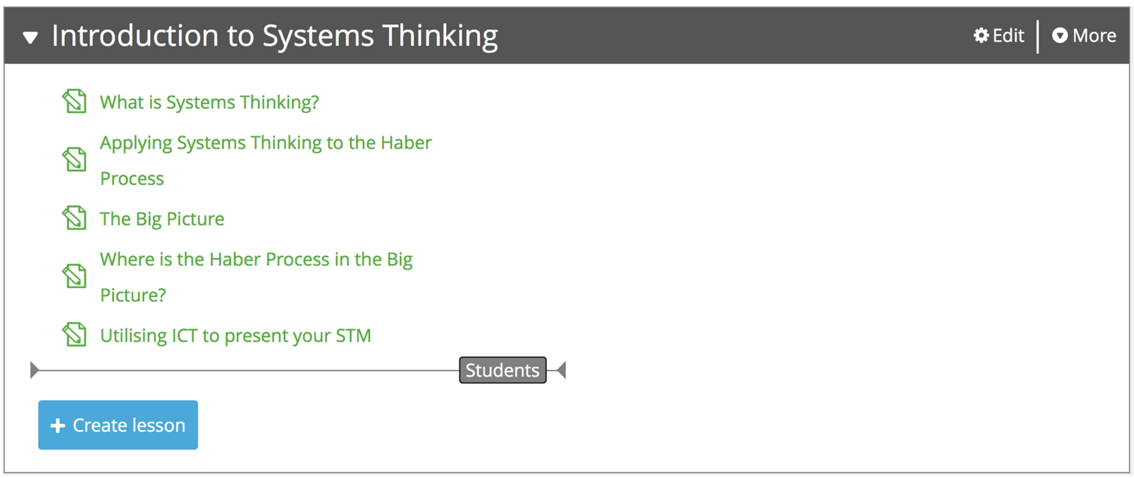

Figure 2. Screenshot of student interface introducing Systems Thinking and situating it within their learning about the Haber process. The Big Picture submodule includes information about the SDGs and planetary boundaries.

across 8 modules in four semesters.[24] The 2018 curriculum prescribes completing two Depth Studies, one in year 11 relating to content in modules 1−4, and one in year 12 relating to content in modules 5−8.[25] Teachers are free to implement the Depth Study at any time of year and it can target one or more of the content modules. In this instance, the Depth Study was run at the beginning of the year 12 course. Because of this timing, each of the chemical processes included in the Depth Study required some introductory material so the students would have enough understanding of the process to be able to apply Systems Thinking. This was achieved by breaking the Depth Study down into a series of self-paced modules that students accessed through an online platform. The full contents of each submodule, along with information regarding the digital platforms utilized, are provided in the Supporting Information.

Introducing the Systems Maps Evaluation Process

The Haber process, which has been highlighted as a useful context to embed Systems Thinking into the learning of chemistry curriculum content,[3] was used as the initial case study for students to investigate (Figure 1).

Each submodule included a sequence of multimedia content, including an introductory video, links to useful information, and some reflective questions for students to document their learning and knowledge. The teacher in this project developed this material on the basis of textbooks and literature searches.

The main innovation in this content was the inclusion of information about the production of the starting materials and the uses of the product directly after introducing the reaction itself. Traditionally, the Haber process is taught in a reductionist way,[13] often as an example of equilibrium, sometimes with the inclusion of some historical background. Therefore, students are not challenged to consider how a process that is used on such a large scale globally impacts the planet in terms of starting material production, product consumption, and intended and unintended consequences of these. The goal of the materials developed in this project was to prime the students to start thinking more broadly and to make connections beyond the boundaries of the reaction itself.

Having considered the Haber process from a number of perspectives, students were introduced to Systems Thinking, again through a self-paced module (Figure 2). Within this module, students were asked to consider how Systems Thinking could be applied to the Haber process. This included guiding students to consider the Haber process through two lenses:

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- the concept of planetary boundaries[32] and
- the United Nations' 17 Global Goals for Sustainable Development (SDGs).[13,33]

As part of this module, students were given an example of a systems map constructed by the teacher (shown in Figure 3).

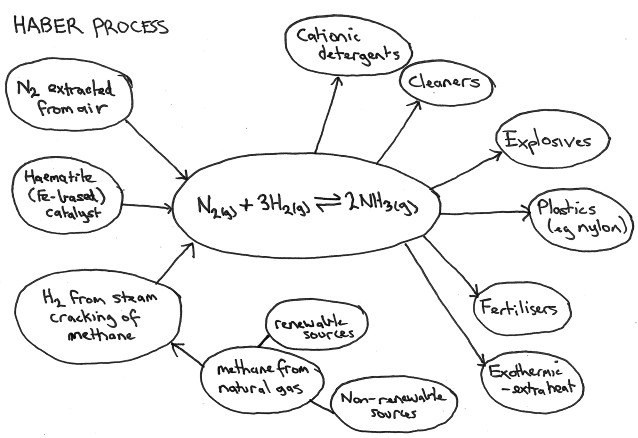

Figure 3. Preliminary systems map developed by teacher for the Haber process to illustrate the expectations of a systems map and possible elements.

Systems maps have been recommended for use in secondary science teaching, and a methodology for their analysis has been reported.[34,35] Having been introduced to the use of systems maps and having been shown an example, the students in this study were then encouraged to construct their own systems map based on what they had learned.

Focusing now on *situating the learning* of issues of sustainable development related to this chemical process, the Depth Study next required students to consider whether each of the elements in their systems map had an impact on any of the SDGs. The number of the corresponding SDG was written next to each element of their systems map where they found an impact. Importantly, students were also told to consider whether this impact was positive, negative, or neutral, and then to color code that element of their systems map to reflect its overall impact on all relevant SDGs. Again, an example was provided by the teacher (see Figure 4), to help students

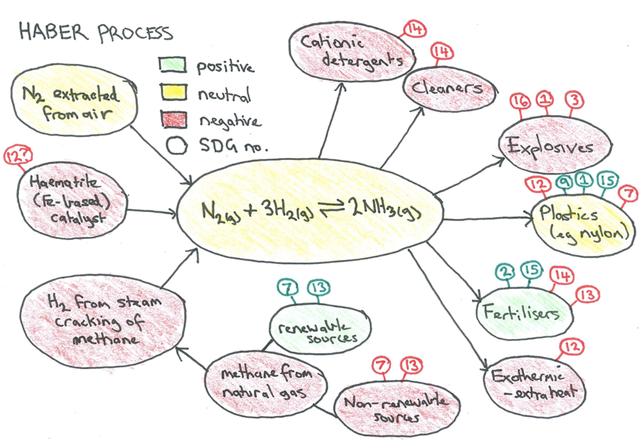

Figure 4. Color-coded systems map from teacher illustrating a possible perception of positive, neutral, and negative impacts related to the SDGs for elements of the Haber process.

construct their own. Through interactive questions in the module, they were also required to justify their evaluation of the impact based on what they had previously learned about planetary boundaries, the SDGs, and the Haber process. This evaluation by students was not rigorously assessed; instead, the questions being asked and topics raised by students when considering the SDGs were taken as evidence for their engagement with Systems Thinking.

Students continued with the Depth Study over several more hours by repeating this self-paced investigative process with other chemical processes (alkene polymerization; biofuels; Solvay process). Again, the relevant materials for their study were developed by the teacher and integrated into the online platform. For the systems maps completed on these processes, the teacher did not provide a sample and students were required to develop their own.

Student Assessment within the Depth Study

The Depth Study assessment involved students completing an analogous evaluation investigating the syntheses of ethylene and ethanol as interrelated chemical processes. The students had 2 h to construct a systems map (hand-drawn, then digitally) and a further hour to evaluate their systems map with reference to the SDGs.

Students were assessed on the following criteria:

- identifying the sources and uses of ethylene;
- identifying the sources and uses of ethanol;
- constructing a systems map, based on the ethylene/ethanol system;
- evaluating the elements of their systems map based on the SDGs; and
- creating a digital representation of their systems map.

The full marking rubric is provided in the Supporting Information.

■ TEACHER REFLECTIONS AND PERCEPTIONS OF STUDENT LEARNING

The purpose of incorporating Systems Thinking into a Depth Study was 5-fold:

(1) to introduce year 12 topics on equilibrium and organic chemistry;
(2) to explore the connections between chemical processes;
(3) to situate the learning of sustainability into the learning of chemical processes (i.e., learning the impact of individual chemical processes on sustainable development);
(4) to encourage the use of digital technology, both through self-paced multimedia learning resources and as a means to present their results; and
(5) to employ a rigorous assessment of the students including assessment of "working scientifically".

These five objectives were then used by the teacher as a basis of the reflection step of the teacher action research cycle.[29] His reflection was evaluated and reframed below to address the research question, namely, how the teacher perceived the Depth Study (specifically the use of systems maps) to situate the learning of sustainability into the learning of chemistry content.

Systems Thinking as a Vehicle for Introducing Topics

The chemistry content was first introduced to the students using the online resources that the teacher had collated and generated. The teacher observed that students were able to gain the traditional content knowledge for these topics within this format comparably to his experience from prior years. In discussions with students after the assessment task, he was told that after being introduced to Systems Thinking through evaluating the Haber process, the students found it was easy to replicate the approach with some topics (biofuels), but less so with others (alkene polymerization). The teacher's overall perception, however, was that it did require more time and explicit teaching than expected, reducing the time students had to explore and develop mastery in Systems Thinking.

Systems Thinking for Exploring the Connection between Chemical Processes

Despite the limited time, the teacher did observe that students were enthusiastic about exploring the connections between various chemical processes. Collaboration was encouraged, and the teacher noted in his reflection that the students did take advantage of these opportunities to collaborate and also reflect on their own learning. This was evident in the wide variety of systems maps that were generated. As would be expected, he observed that common elements appeared in students' systems maps. However, the spatial structure of the systems maps (both those created by hand, and the digital representations) was predominantly determined by the artistic skills of individual students. The broad range of level of interconnectivity in the chemical processes in students' systems maps suggested to the teacher that the students exhibited a range of ability and engagement in learning chemistry through the systems mapping approach.

Evaluating the Impact of Chemical Processes on Sustainability

Evaluation is a higher order critical thinking skill, and from reading the student responses, it was the teacher's perception that the students embraced the opportunity to evaluate the different chemical processes. He noted that different students sometimes evaluated a particular product or process at polar opposites, with individuals providing different justifications. This aspect of the Depth Study was particularly encouraging to the teacher because it indicated that students had embraced the opportunity to provide an informed justification for their evaluation of the impact of an individual chemical process on SDGs. However, the breadth of justifications indicated that the systems mapping approach did not lead all students to the "correct" conclusion (a negative or positive impact on sustainable development caused by a stage of the life cycle of a chemical), and as stated above, the justifications were not rigorously assessed. Evaluating this aspect of student introspection on the SDGs was beyond the scope of this teacher action research project, and a content analysis of student responses will be a focus of future research. However, it was the teacher's perception that this structured approach to Systems Thinking via a systems mapping approach provided a possible way for students to apply the SDGs (and thus knowledge of sustainable development) to fundamental chemistry content.

Incorporation of Digital Technology as a Learning Tool and Presentation Mode for Systems Thinking

The online platform allowed the teacher to evaluate student progress regularly and ensured students maintained a satisfactory pace. He was able to give ongoing feedback on work they completed, as well as their overall progress, without the process becoming onerous. By monitoring student access to the online modules, the teacher was able to note that most students worked only during class time, but some did work through modules in their own time. Requiring students to also present a digital representation of their systems map did not seem to impact learning, but upon reflection it did not seem to benefit learning either, as most students simply replicated their hand-drawn systems maps.

Systems Thinking as a Form of Assessment

Reflecting on the assessment aspect, the teacher concluded that the systems map rubric (provided in the Supporting Information) worked well as a discriminating tool and largely reflected his expectation based on viewing student work and the students' previous work. While the assessment served its purpose in this iteration, he has decided for the next iteration that students will be given 2 weeks to research a chemical process that has not been discussed in class, such as the contact process, esterification, or saponification, and prepare a handwritten A4 page (double-sided) with information about the process. They will then be allowed one double teaching hour to complete a systems map including its evaluation with respect to the SDGs.

Summary of Teacher Reflections and Utility of the Approach

Overall, the teacher action research described here supports the assertion that incorporating Systems Thinking into a Depth Study had a range of positive outcomes for student learning and fit well within the spirit of the curriculum's objectives for the Depth Study, in particular in incorporating the sustainability cross-curriculum priority into the chemistry discipline. With respect to the research question, it was the teacher's overall perception that the Systems Thinking Depth Study, and systems mapping in particular, did situate student learning of sustainability within the learning of chemistry content. Specifically, the online platform worked well for self-paced learning of both chemistry and sustainability concepts, and the teacher observed positive attitudes and motivation in students when drawing their systems maps and linking them to the SDGs, suggesting a broadening understanding and appreciation of how particular aspects of chemical processes can be linked to sustainable development in the global community. Future research will seek to better encapsulate and document changes in student perspectives and conceptual understanding through undertaking the Systems Thinking Depth Study.

■ CONCLUSIONS AND IMPLICATIONS FOR PRACTICE

The principles of Systems Thinking were successfully incorporated into a 15 h Depth Study for year 12 chemistry students, and similar curriculum opportunities are likely to exist within other regulatory frameworks. A shortened version would be possible in contexts where 15 h are not available, either by introducing systems maps later so that less time is spent on content delivery, or using systems mapping for only one or two examples. The findings in this teacher action research project indicated that the systems mapping approach provided a means for the students not only to learn about chemistry and about sustainable development, but also to interconnect their understanding of these two topics in a meaningful way. Through the Depth Study, the teacher was able to provide students with an appreciation of the wider sustainable development contexts surrounding a number of

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chemical processes in parallel with learning the chemistry principles. As part of their learning and for assessment, students were able to draw systems maps and evaluate the positive and negative impacts of elements in these systems maps based on the SDGs. This is a powerful and relatively easy way to meet what is not only a national priority in Australia but also a global imperative to prepare citizens of the 21st century to meet challenges through science practice.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00266.

> Information about the Australian assessment and reporting requirements for the Depth Study, the choice of online platforms, the assignment instructions and rubric used for the Depth Study task, a screenshot of one of the online modules for students, as well as the full set of resources from the online modules (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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