Sustainability through Education: A Competency Development Framework

1st Alexander Berndt
ENGINEERING IT
CUAS
Villach, Austria
https://orcid.org/0000-0001-5912-345X

2nd Wolfgang Werth
ENGINEERING IT
CUAS
Villach, Austria
w.werth@cuas.at

3rd Christian Madritsch
ENGINEERING IT
CUAS
Villach, Austria
c.madritsch@cuas.at

4th Hannes Oberlercher
ENGINEERING IT
CUAS
Villach, Austria
h.oberlercher@cuas.at

***Abstract*—This paper presents an educational framework developed by the Interreg SIAT H2GreenFuture and Interreg ITAT EDU-CIRC projects to promote sustainable technologies and address competency gaps. The Competence Development Framework (CDF) focuses on sustainability, decarbonization, hydrogen, and fuel cell technology across basic, intermediate, and advanced levels. Utilizing the ADDIE model, the training emphasizes remote and problem-based learning with practical applications in learning factories and laboratories. Innovative teaching methods like experiential learning and simulations enhance engagement. Pilot modules at the bachelor's level highlight education's critical role in the energy transition.**

***Index Terms*—education, sustainability, hydrogen, decarbonization, framework,**

I. Introduction

Hydrogen technology is increasingly recognized as a cornerstone for achieving sustainable energy solutions and meeting global climate goals. The European Union's initiatives, including the Hydrogen Strategy [1] and European Green Deal [2], highlight hydrogen's role in reducing fossil fuel dependency and supporting a green economy. As Europe seeks to achieve climate neutrality by 2050, the demand for hydrogen technology professionals has increased, presenting an urgent need for competency-based education aligned with industry and sustainability requirements.

However, existing engineering curricula often lack specific training in hydrogen technologies and sustainability, leaving graduates underprepared for the sector's specialized needs. The challenge of building this workforce extends to educators, who need structured frameworks that address both theoretical foundations and practical applications in hydrogen technology. This gap in competencies is a barrier to advancing hydrogen-driven sustainable practices, underscoring the need for an educational framework that prepares students for real-world challenges in this emerging industry.

A. Research Goals and Framework

To address this gap, this paper proposes a competency-based framework that integrates sustainability and hydrogen technology into engineering education. The framework, grounded in the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) [3] is structured to provide a systematic, scalable approach to curriculum design. By organizing competencies into basic, intermediate, and advanced levels, the framework enables a stepwise progression that combines theoretical knowledge with hands-on skills relevant to hydrogen technology.

- **Analysis:** This phase identifies specific skill gaps and competency needs in hydrogen technology, informed by industry insights and sustainability goals.
- **Design:** This phase establishes the instructional strategy and competency modules, aligning them with desired outcomes in hydrogen technology and sustainability.
- **Development:** Educational materials are created, integrating both theoretical and practical learning elements to support competency acquisition.
- **Implementation:** The framework is piloted in engineering programs, with an emphasis on practical applications that mirror industry environments.
- **Evaluation:** The framework is refined based on feedback, ensuring it meets evolving industry standards and educational effectiveness.

Through this structure, the framework equips educators to deliver targeted training that addresses the technical and interdisciplinary skills necessary for sustainable hydrogen technology.

B. Relevance for Industry and Academia

This framework has significant implications for both industry and academia. For industry, it addresses the demand for professionals trained in hydrogen and sustainable energy, facilitating innovation and supporting the transition toward decarbonized energy systems. By integrating competencies in fuel cell technology, decarbonization strategies, and environmental impact assessment, graduates can contribute to hydrogen's growing role in energy transitions. The framework's alignment with industry needs ensures that graduates are not only knowledgeable but also ready to apply their skills in real-world scenarios.

For academia, this framework aligns engineering programs with current industry standards and sustainability targets. Integrating hydrogen technology competencies into engineering curricula enhances students' employability. The framework encourages industry-academia partnerships by incorporating

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real-world industry insights, fostering collaborative development, and addressing immediate workforce needs in hydrogen technology.

II. Literature Review

Competency-Based Education (CBE) has emerged as an important framework for bridging the gap between traditional educational systems and the evolving needs of industry, particularly in fast-developing technical fields such as sustainability and hydrogen technology. This section reviews the current literature on CBE models, best practices, and challenges, emphasizing its unique applications and benefits. The relevant literature [4], [5], [6] outlines the key features of CBE, which can be summarized as follows:

- **Clearly Defined Learning Outcomes** CBE emphasizes mastery of specific skills and competencies. Each learning unit is carefully designed to develop measurable, concrete abilities, ensuring that students acquire the essential knowledge required to meet industry standards.
- **Modular Learning Path or Curriculum:** The curriculum is divided into smaller, manageable modules and units, each focused on specific competencies. This modular structure facilitates a more targeted and efficient learning process.
- **Individual Learning Pace:** Students are able to progress at their own pace, working on each competency until they achieve mastery before moving on to the next. This flexibility allows learners to spend more time on challenging topics and progress more quickly through areas they already understand.
- **Continuous Assessment and Feedback:** Assessment in CBE is ongoing, designed to monitor learner progress and provide regular feedback. Rather than a final exam, learners receive feedback throughout their education, helping them improve their skills incrementally.
- **Practical, Hands-On Learning, Lab Exercises:** Assessment in CBE is ongoing, with regular feedback designed to monitor student progress. Rather than relying on a single final exam, learners receive continuous feedback throughout their education, helping them refine their skills incrementally.
- **Personalized Learning Paths:** Since students advance at their own pace, learning paths can be individualized. This makes the CBE model more flexible and student-centered, catering to the unique needs, goals, and interests of each learner.

As global demand for sustainable energy solutions grows, educational models in sustainability and hydrogen technology must equip students with highly specialized and continually evolving skill sets. Additionally, it is important to raise awareness of these technologies among younger students, ensuring that they are introduced to these fields early on. Key competencies in sustainability include systems thinking, environmental policy knowledge, and technical engineering skills. In hydrogen technology, competencies extend to understanding fuel cells, energy storage and production solutions, and regulatory frameworks for hydrogen use. Given this context, CBE is particularly well-suited for technical fields such as hydrogen technology, where specialized knowledge and precise skills are essential. As [4] points out, CBE is especially effective in engineering education, where skills must be specific, measurable, and demonstrable. For example, mastering the operation of fuel cells or understanding the hydrogen production process requires breaking down these complex skills into smaller, more manageable units that can be adapted to the learner's level. Furthermore, each competency can be measured against industry standards, ensuring that the education provided aligns with real-world practices. Despite its benefits, implementing CBE in fields like hydrogen technology presents several challenges. One major issue is the resource-intensive nature of CBE, which often requires specialized equipment, laboratories, and extensive instructor training. As noted by [6], limited resources can hinder the ability to provide the hands-on learning experiences crucial for mastering competencies in technical fields. Another challenge, highlighted by [7], is the rapid pace of technological advancements, which necessitates frequent updates to the curriculum and modules. In sectors like hydrogen technology and sustainability, competencies must be adaptable to new regulations, tools, and practices. Therefore, successful CBE programs in these fields require flexible structures and active collaboration with industry partners to ensure they remain relevant. Industry and project collaborations allow for timely updates to learning modules, which is particularly important in emerging sectors like hydrogen technology, where rapid developments require continuously updated competencies. The literature consistently underscores CBE as a powerful model for addressing the educational needs of the sustainability and hydrogen technology sectors. It offers a flexible, modular framework for building industry-relevant skills, ensuring that students are well-prepared to meet the demands of these dynamic fields.

III. Competency Development Framework

As the demand for sustainability professionals grows, educational institutions and training programs face the challenge of providing a structured yet adaptable learning framework. The development of the Competency Development Framework (CDF) presented here addresses this challenge by offering a modular system that not only covers technical knowledge but also emphasizes sustainable practices. The CDF is organized into core competency categories designed to equip learners with both technical and interdisciplinary skills. The total number of modules, courses and units is not limited to a specific number. This means that in the future, this framework can be adapted to new objectives. At the top category, modules represent broad blocks of learning, covering primary topics within hydrogen technology, such as sustainability, technical fundamentals and interdisciplinary applications. These modules are designed to provide comprehensive knowledge and enable learners to focus on specific areas. Each module is associated with ECTS credits, ensuring compatibility with academic systems and formal recognition of learning achievements. (Fig. 1) gives an overview of CDF structure. Within each module, course units provide a more focused insight into particular topics, such as hydrogen production methods, system integration or environmental impacts. Courses are structured to build specific competencies within the overarching module theme, and are broken into manageable components that allow learners to progress in stages. This structure is particularly beneficial for people with limited time, such as professionals in SMEs who may only need knowledge in a specific area and can complete a single course rather than an entire module.

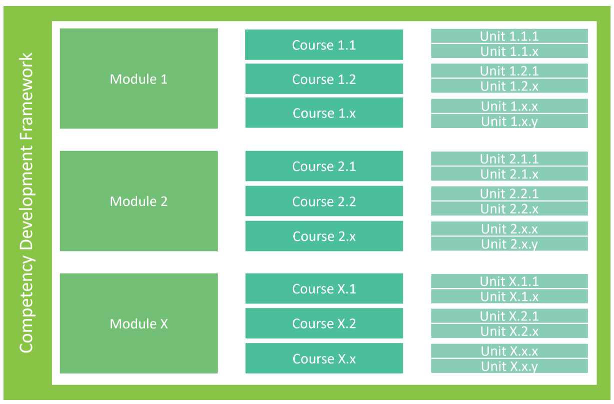

Fig. 1. Example of the Competency Development Framework. Modules include different courses and within are several units implemented.

At the basic level, units address individual skills or concepts within a course. These are the smallest, most targeted components and provide significant flexibility. Learners can select units that are relevant to their goals or areas of interest, creating a personalized learning path. For example, students can follow a structured path from introductory to advanced modules, while researchers can mix units across modules for a cross-disciplinary approach. This flexibility at the module level is also beneficial for young learners and high school students, as it allows them to start with basic concepts and build their understanding incrementally. The adaptable design of the modular framework means that it can meet diverse learning needs, including continuous professional development for SMEs, structured academic learning for students, and accessible introductory content for younger audiences. By offering customizable, skills-based learning pathways, the CDF equips diverse learners with the skills they need to succeed in the evolving hydrogen and sustainable technologies sectors, ensuring that training remains relevant and aligned with industry standards and sustainability goals.

A. Overview of the ADDIE Model in Framework Development

The ADDIE model offers a structured approach to curriculum development, guiding the CDF's creation from initial needs assessment through implementation and iterative refinement. Each phase contributes uniquely to a flexible, modular framework that meets the evolving requirements of hydrogen technology education.

The **Analysis** phase showed specific gaps and needs within sustainability education. Based on feedback from industry partners, academic institutions, and target learners (students, SMEs, researchers), critical competencies were identified in four areas: technical knowledge, sustainability, interdisciplinary skills, and soft skills.

- **Industry Consultation:** Engagement with hydrogen and energy industry experts highlighted essential skills like electrolysis technology, fuel cell operation, and environmental impact assessments. Industry demand for cross-disciplinary competencies such as policy knowledge and systems thinking also emerged as significant.
- **Educational Needs Assessment:** Surveys and focus groups within academic circles identified gaps in existing engineering curricula, particularly the absence of hands-on, sustainability-focused modules in hydrogen technology.
- **Targeted Learner Needs:** Insights from students, researchers, and SMEs indicated diverse needs, from foundational knowledge in hydrogen processes to advanced interdisciplinary applications.

This analysis shaped the framework's structure, establishing the necessity for a modular approach that can accommodate both comprehensive foundational education and targeted skill development. Based on the understanding of competence needs, the **Design** phase structured the CDF into modules, courses, and units. Each component is tailored to provide both depth and flexibility, allowing for customized learning pathways based on individual or organizational needs.

- **Modules:** The modular structure consists of large educational blocks covering broad topics in hydrogen technology. For instance, a module titled "Fundamentals of Hydrogen Technology" may encompass key areas such as hydrogen production, storage, and application. Each module is assigned a specific European Credit Transfer and Accumulation System (ECTS) value, typically 5 ECTS, representing approximately 125-150 hours of study. This modular approach allows flexibility and ensures that learners can focus on foundational knowledge before advancing to more specialized topics.
- **Courses:** Within each module, courses are designed to provide more in-depth knowledge on specific subjects. For instance, in a module on hydrogen production, courses may include topics such as steam methane reforming, water electrolysis, and renewable energy integration. Each course has an assigned ECTS value proportional to its content and required learning time, enabling learners to accumulate credits incrementally and tailor their study focus.
- **Units:** are the smallest, most targeted elements within each course. Each unit focuses on a single concept or skill, making it easy for learners to engage with specific information without requiring full module completion. Units enable mixing and matching across courses, creating custom learning paths.

In the **Development** phase, educational materials were created to support both theoretical and practical learning, aligned with the structure designed in the previous phase. The CDF incorporates various instructional methods to foster an engaging, competency-based learning environment:

- Theoretical Content: Lectures, readings, and online resources cover fundamental knowledge in hydrogen technology and sustainability, laying a strong academic foundation.
- Hands-On Workshops and Simulations: To reinforce technical competencies, hands-on workshops and simulation-based learning are integrated into courses. For instance, virtual training environments allow learners to simulate hydrogen production and storage scenarios, which are especially valuable for distance learners or SMEs with limited access to laboratory facilities.
- Interactive Learning Activities: Problem-based learning and experiential activities promote active engagement, helping learners apply theoretical knowledge to real-world challenges. Such activities support the practical skills necessary in hydrogen applications, reinforcing industry alignment.
- Assessment Tools: To ensure mastery, each unit incorporates formative assessments, allowing learners to evaluate their understanding continuously. These assessments enable educators to provide feedback and adjust in real time, ensuring that students meet competency milestones as they progress.

The Implementation phase focuses on deploying the framework across different learning environments, adapting delivery methods to fit various educational and professional contexts. Implementation strategies include:

- Blended Learning: Combining online modules with in-person workshops where possible, the blended learning approach provides flexibility, accommodating both remote learners and those in traditional classroom settings.
- Self-Paced Learning for SMEs: For SMEs, the self-paced online component allows employees to access training on their schedules, addressing the time constraints often faced by professionals in the industry.
- Instructor-Led Sessions for Structured Learning: In academic settings, structured, instructor-led modules guide students through foundational to advanced topics, supporting those who benefit from a more directed educational experience. Implementation also includes pilot programs, where select courses or units are trialed in bachelor's or vocational programs, providing initial feedback on the framework's effectiveness in building industry-relevant competencies

The last phase, **Evaluation**, ensures that the framework remains responsive to learner needs and industry standards. Evaluation methods include:

- Learner Feedback and Performance Data: Surveys and assessments provide insights into learner satisfaction, engagement, and competency acquisition, informing adjustments to improve educational outcomes.
- Industry Feedback: Periodic consultations with industry stakeholders ensure that the curriculum remains aligned with evolving standards and technologies in hydrogen and sustainability sectors.
- Iterative Refinement: Based on feedback, modules, courses, and units are periodically updated. For instance, new competencies may be added as hydrogen technologies advance, and course content may be adjusted to reflect updated environmental regulations.

B. *Implemented Unit for Hydrogen Fuel Cell Technology*

Two units from the CDF were implemented in a bachelor's degree program. The first unit provides theoretical background for engaging with hydrogen technology exercises, covering hydrogen fundamentals, electrochemical principles, storage methods, and safety protocols. Students began with an overview of hydrogen as a clean energy carrier, exploring its properties, environmental benefits, and roles in various sectors. This foundation helped learners understand hydrogen's significance in energy transition efforts. Next, the unit covered the electrochemical principles behind proton exchange membrane (PEM) fuel cells, detailing the chemical reactions that convert hydrogen into electricity, produce water, and generate usable power.

Fig. 2. Required equipment for lab exercises. left: H2-Engineering Kit with proton exchange membrane; right: HydroFill Pro with inserted Hydrostik [11]

The second unit was focused on hands-on, practical engagement with hydrogen fuel cell technology and hydrogen storage systems, primarily using the H2-Engineering Kit and HydroFill Pro (Fig. 2). These tools provide a comprehensive, experimental environment for learning and practicing the fundamentals of hydrogen energy, from production and storage to operating behavior and efficiency measurement. The learning objectives for the students were:

- To understand the operation and basic principles of a hydrogen fuel cell system.
- To measure and analyze the voltage-current (U/I) characteristics of a PEM fuel cell.

- To calculate hydrogen consumption and efficiency under various loads.

After conducting both units, students gained a basic understanding of fuel cell technology, focusing on practical operation, efficiency, and safety. Through hands-on interaction with the H2-Engineering Kit and HydroFill-Pro, they learned essential principles and technical skills related to hydrogen fuel cells, an increasingly important technology in sustainable energy.

IV. Discussion and Conclusion

The presented Competency Development Framework (CDF) effectively addresses the growing demand for specialized education in hydrogen technology and sustainability. Developed within the scope of the Interreg SIAT H2GreenFuture and Interreg ITAT EDU-CIRC projects, this framework leverages insights from these initiatives to ensure industry relevance and sustainability alignment. Key takeaways include:

Relevance to Industry and Academia: By integrating outcomes from H2GreenFuture and EDU-CIRC, the CDF aligns with industry standards, addressing critical workforce gaps in hydrogen technologies and sustainability. It supports academia in preparing students for emerging roles in the energy transition.

Flexible and Modular Structure: Building on EDU-CIRC's focus on circular economy principles and H2GreenFuture's emphasis on hydrogen innovation, the framework provides personalized learning paths to meet diverse educational and professional needs while adapting to technological and regulatory changes.

Innovative Learning Approaches: The inclusion of hands-on workshops, simulations, and problem-based learning, inspired by pilot activities from H2GreenFuture, ensures that learners develop practical competencies for real-world challenges in hydrogen technology.

Pilot Success: The implementation of hydrogen fuel cell technology units in a bachelor's program, supported by H2GreenFuture's resources and experimental setups, highlighted the framework's capacity to combine theoretical knowledge with practical engagement.

Sustainability and Scalability: Based on the circular economy principles from EDU-CIRC and the sustainability focus of H2GreenFuture, the CDF ensures applicability across diverse educational contexts and scalability for future advancements.

By integrating the innovative methodologies and sustainability-focused goals of H2GreenFuture and EDU-CIRC, the CDF will become a key tool for bridging skills gaps in hydrogen and sustainable technologies. Future efforts should expand the framework, encourage greater collaborations with industry and academic stakeholders, and refine curriculum elements to adapt to the fast-evolving energy landscape.

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