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Knowledge, skills, and attributes needed for developing a hydrogen engineering workforce: A systematic review of literature on hydrogen engineering education

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ABSTRACT

Growth in Australia's demand for engineers is fast outpacing supply. A significant challenge for Australia to achieve high projected low emissions hydrogen export targets by 2030 will be finding engineers with suitable knowledge, skills, and attributes to deliver hydrogen engineering projects safely and sustainably. This systematic review investigates educational outcomes needed to develop a hydrogen engineering workforce. Sixteen relevant studies published between 2003 and 2023 were identified to explore "What key knowledge, skills and attributes support the development of a hydrogen engineering workforce?". While these studies advocated the need for training and prescribed areas of required knowledge for the low-emissions hydrogen sector, there was limited empirical evidence that informed what knowledge, skills and attributes are relevant for entry to practice. This finding represents a significant opportunity for researchers to engage with employers and engineering practitioners within emerging low-emissions hydrogen sector, capture empirical evidence and inform the design of educational programs.

1. Introduction

The low-emissions hydrogen economy is experiencing significant growth and investment, as societies globally progress towards a net zero energy sector by mid-century [1]. Australia is projected to produce up to half of global low-emissions hydrogen exports by 2030 representing up to $300 billion (AUD) in potential investment [1,2]. According to Net Zero Australia modelling [3], the clean energy transition will create between 0.5 and 1 million new jobs in Australia by 2050, with approximately 75 000–100 000 of those roles situated in hydrogen related sectors. Electricians, engineering professionals, project managers, associated trades and construction labourers are considered the occupations that will see the greatest increase in absolute job growth in these sectors [3].

Growth in the national demand for engineers across all disciplines is outpacing supply at three times the rate in Australia [4]. Australia is also not abundant with skilled engineers in the low-emissions hydrogen sector. Acceptance of hydrogen technologies is potentially very low due to low levels of public knowledge, awareness, and concerns with safety [5–9]. Developing and delivering high quality training is critical to Australia's ability to deliver hydrogen related projects safely and affordably to gain public trust and transition towards a net-zero future [9].

Efforts to address hydrogen engineering training needs in Australia are led by not-for-profit organisations, private industry leaders and expert practitioner communities [10,11]. Examples include Engineers Australia's [12] efforts to establish a Hydrogen Engineering Area of Practice and competency framework, and support of the highly successful National Hydrogen Industry Technical Series pilot program run by industry leaders in 2023 [13]. Another example is the CSIRO's development of an online Hydrogen Knowledge Sharing Centre (https://research.csiro.au/hydrogenknowledge/) that shares reliable and relevant information on hydrogen research and project activities online [11]. As is the emergence of private training providers such as 'H2H advantage Pty. Ltd.' (2024) who deliver hydrogen fundamentals training programs that have evolved out of their experience delivering hydrogen engineering related projects.

However, there are not enough hydrogen engineering experts nationally with sufficient time to continually educate and credential newcomers while delivering a growing number of projects that require

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their expertise [10]. Together, a general lack of availability of mentors and insufficient training programs are both specific challenges faced by Australia's hydrogen sector. These challenges provide an opportunity for higher education institutions to collaborate with industry experts to develop engineering education programs that align accurately with regional needs and occupational competency expectations [14].

Training programs co-designed and developed between higher education providers and industry practitioners can help ensure that there is a skilled and knowledgeable workforce available to safely design, build, and operate hydrogen systems across all levels of delivery to support uptake of the technology and improve social license [15–17]. As recently outlined in the European Hydrogen Skills Strategy [18] such training programs could be delivered by augmenting existing undergraduate and postgraduate degrees to include hydrogen engineering focus [19] or providing micro-credential style learning programs that supplement traditional degree programs and target the specialised professional development of currently practicing engineers [20,21].

The aim of this research was to identify key educational outcomes, curriculum, teaching and learning strategies that support the training and development of career starters or mid-career changers entering the Australian low-emissions hydrogen sector. A systematic review of research literature on educational outcomes needed for developing a hydrogen engineering workforce was planned to utilise and draw upon current work in the field. The research question guiding this systematic review was: What key knowledge, skills and attributes are required to support the development of a hydrogen engineering workforce? The focus of this study was on how authors describe training and development of engineers needed for entry to practice to the Australian low-emissions hydrogen sector, what curriculum, teaching and learning strategies they suggested are critical and what evidence they provided to substantiate their claims. This review drew upon critical theory to question more positivist approaches that are used to describe the knowledge, skills, and attributes required for entry to practice.

2. Theoretical framework

Engineering practice involves engagement in all phases of the lifecycle of products, processes and systems that have one feature in common: they meet the changing needs of society [22]. Consequently, engineers are expected not only to find solutions to technical problem but address economic and societal needs. The knowledge, skills and attributes required of engineers are expected to extend their broader leadership role. Yet, engineers commonly do not reflect critically on social issues; nor are they asked to consider these issues during their engineering training [23]. To assist engineering graduates to develop deeper understanding of the sociotechnical nature of engineering practice, engineering curriculum design requires educators to identify and develop more than just relevant technical knowledge [23–27]. Identifying skills and attributes that help develop an engineer's ability to apply their technical knowledge within relevant practice contexts is important to support employability skills development [28–31].

Integrating theory and practice, influenced by a demand-driven skilled labour, has been a long-standing problem in higher education contexts [32]. Addressing this problem requires integration of practical and personal skill development to enable graduates to be immediately effective in the workplace. To develop employability skills alongside engineering discipline knowledge, a socially critical approach to curriculum design is recognised within the literature. In this approach to curriculum design, knowledge is constructed by and within historical and cultural frameworks; learning is envisaged from a socially critical perspective to foster conceptual change; learning outcomes measure student ability to critique, defend decisions; assessment allows negotiation and collaboration between students and teachers; and learning activities are often resource intensive and requires small group work, community-based projects, and investigations.

This research utilises critical theory [33] to evaluate the characteristics of training and development described within research literature for developing the knowledge, skills and attributes of engineers considering entry to practice within the Australian low-emission hydrogen sector. As many of the research literature reviewed as part of this study utilised an advocacy pitch to promote training and development, critical theory proved particularly valuable to question such positivist approaches that can inaccurately assume scientific neutrality. Many educational studies in higher education, including that of Ramsden [34] and Biggs and Tang [35], draw on social constructivist theory to highlight the importance of active learner engagement in the learning process. Emphasis placed on students and the nature of learning has often resulted in undervaluing the complexity of the concepts and topics to be learned in engineering disciplines [31]. Critical theory is rooted in critiquing and exposing such dominations and subordinations, as well as the contradictions in which humankind is entrenched. We found applying this liberatory philosophy to this systematic review a sensible approach for deconstructing what knowledge, skills and attributes are valued for work within the Australian low-emission hydrogen sector. Our intent was to look at, continuously question and depict the world, rather than embracing a world without question. We were able to reflexively engage with the research literature in this systematic review to question biases and identify educational outcomes that support the development of engineers entering the hydrogen sector, either as career starters or mid-career changers.

3. Methodology of the systematic review

This section outlines our approach to the systematic review of research literature on engineering education relevant to the hydrogen sector. The study was designed based on the typical procedure for conducting systematic literature search, selection, data collection, synthesis methods, bias assessment and management outlined within the PRISMA 2020 guideline for systematic literature reviews [36]. The PRISMA 2020 guideline for reporting systematic reviews was utilised for presenting the outcomes of this review [36].

A search of the literature published between 2003 and 2023 within journals in the Scopus and Engineering Village databases was conducted. A title search approach was used, and as an example of the search criteria used in the Scopus database is provided below. This criteria can be used in Scopus to reproduce the search results obtained in this study.

TITLE ((hydrogen AND education) OR (hydrogen AND training) OR (hydrogen AND curriculum) OR (hydrogen AND skill*) OR (hydrogen AND knowledge) OR (hydrogen AND attitude*) OR (hydrogen AND attribute*) OR (hydrogen AND pedagog*)) AND PUBYEAR >2002 AND PUBYEAR <2024 AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "d")) AND (LIMIT-TO (LANGUAGE, "English"))

Ninety-eight publications were retrieved from searching the Scopus and Engineering Village databases. Publication titles that indicated a narrow focus on technological or scientific advancement research in their title were excluded. The remaining 46 publications underwent an abstract review applying an inclusion criterion that was guided by the research question, 'What key knowledge, skills and attributes are required to support the development of a hydrogen engineering workforce?' Therefore, abstracts needed to satisfy one or multiple of the following criteria to be included in this study.

- Have full-text available, not abstract only.
- Have a clear focus on the development of education or training experiences or products within a hydrogen knowledge, skill, or attribute context.
- Have a clear focus on either reporting or evaluating the delivery of an education or training product or program within a hydrogen knowledge, skill, or attribute context.
- Have a clear focus on evidencing and reporting the education or training needs of the hydrogen sector in terms of either knowledge, skills, or attributes from any source data.

- Not have a sole focus on social license, public acceptance, or policy and legislation related to hydrogen as a material or hydrogen related technologies.
- Not have a sole focus on a hydrogen related technological or scientific advancement.

Papers that did not meet the inclusion criteria were excluded. The abstract review resulted in the identification of 16 relevant publications provided in Table 1. Of those excluded, fifteen studies focused primarily on the social licence or public acceptance of hydrogen technologies with many advocating the need for greater public education and awareness (E.g., Ref. [7,37]) rather than outlining specific training needs for practitioners. The remaining excluded papers investigated the creation of technical or project knowledge sharing networks (E.g., Ref. [11,38,39]), discussed policy or legal implications related to the adoption of hydrogen (E.g., Ref. [40,41]), revealed a narrow technical focus upon further review, or the full-text publication with abstract was not available.

4. Findings

Four high-level themes emerged from the synthesis of these studies. These themes are.

1. Advocacy for hydrogen related training,
2. Hydrogen engineering related curriculum definitions and development,
3. Scholarship of teaching and learning (SoTL) studies in hydrogen contexts, and
4. Empirical studies including practitioners or industry informants.

The articles that represented these themes are briefly identified within Table 1. The emerging themes form the focus of the discussion presented in this section.

4.1. Advocacy for hydrogen related training – cross sector collaboration is key

The first emergent theme within the included literature reviewed was around advocating the need for more availability of high-quality hydrogen technology related engineering education. Callouts from authors were associated with mitigating risk and enabling the safe uptake of these new technologies. Authors emphasised the need for a skilled and knowledgeable workforce to safely design, build, and operate hydrogen systems across all levels of delivery to ensure safe uptake of the technology and improve social license [15–17]. More than half of the shortlisted studies had an explicit focus on safety within their work, be it from the point of view of training and upskilling first responders [17,45,46,51], vocational trades people [10,46,48], or engineers and researchers [15,44,49].

Reijalt [50] highlighted that an immediate, intense and coordinated approach is required to introduce hydrogen and fuel cell related education systems at all levels to support sector growth. Cross-sector collaboration between education institutions and industry appeared to be central to sustainably meeting these needs [10,14]. The first responder training community has spearheaded this cause [45,48,51] by establishing training programs and generating publicly available training and knowledge databases such as https://h2tools.org/ in the US and https://hyresponder.eu/ in Europe with great success. At an engineering level, the European Network of Excellence "Safety of Hydrogen as an Energy Carrier" (HySafe) community has established a Hydrogen Safety Engineering discipline [15] with the support of numerous partners from public research institutions, authorities, universities, standard developing organisations, and industry across Europe [52].

Zheng et al. [14] asserted from their analysis of survey data collected from hydrogen sector related enterprises that it is important for universities to develop education programs that align accurately with the regional industrial economy. Within Australia, Beasy et al. [10] observed a low volume of local expertise in hydrogen technologies when consulting the industry, and identified a lack of available and accessible high quality training options as a significant barrier to supporting the hydrogen industry's success.

Table 1
List of included publications and aligned themes identified from systematic literature review for hydrogen education, skills, knowledge, and attitudes related studies.

Publication	Theme/s
Alzahrani [42]	Curriculum definition, SoTL
Beasy et al. [10]	Training advocacy, Empirical study
Zheng et al. [14]	Training advocacy, Empirical study
Kurniawan et al. [43]	SoTL
Alanne [44]	Training advocacy, SoTL
Upham et al. [16]	Training advocacy, Empirical study
Barilo et al. [45]	Training advocacy, Curriculum definition, SoTL
Tretsiakova-McNally et al. [46]	Training advocacy, Curriculum definition, SoTL
Nowotny et al. [47]	Curriculum definition
Weiner [17]	Training advocacy
Weiner et al. [48]	Training advocacy
Aceves et al. [49]	Training advocacy, Curriculum definition
Reijalt [50]	Training advocacy
Dahoe and Molkov [19]	Curriculum definition
Dahoe and Molkov [15]	Training advocacy, Curriculum definition, Empirical study
Fassbender et al. [51]	Training advocacy

4.2. Hydrogen engineering related curriculum definitions and development

A substantial body of work to document the technical knowledge base that underpins learning relevant to engineers who intend to work with or around hydrogen systems is observed within the literature reviewed. The International Curriculum for Hydrogen Safety Engineering [15] outlined detailed curriculum and provided a comprehensive overview of relevant scientific knowledge. Dahoe and Molkov [15] proposed constructive alignment of hydrogen safety engineering technical knowledge to scaffold the development of appropriate integration of hydrogen safety engineering at undergraduate and post-graduate degrees such as that offered at the University of Ulster and others within Europe. Table 2 presents a summary form of this comprehensive curriculum and shows the modules that have been structured to identify basic, fundamental, and applied levels of knowledge development and learning.

According to Dahoe and Molkov [15] the basic modules are intended to provide a broad basis of well-established scientific knowledge that can be introduced at an undergraduate level or provided to post-graduate students to support later learning in the fundamental and

Table 2
Structure of the HySafe International Curriculum on Hydrogen Safety Engineering adapted from Dahoe & Molkov, (2007, p1118).

Basic Modules	Fundamental Modules	Applied Modules
• Thermodynamics • Chemical kinetics • Fluid dynamics • Heat and mass transfer • Solid Mechanics	• Introduction to hydrogen as an energy carrier • Fundamentals of hydrogen safety • Release, mixing and distribution • Hydrogen ignition • Hydrogen fires • Explosions: deflagrations and detonations	• Fire and explosion effects on people, structures, and the environment • Accident prevention and mitigation • Computational hydrogen safety engineering • Risk assessment

applied modules. The fundamental modules cover transient topics that require regular revision relative to the ever-evolving nature of the hydrogen technology sector. The fundamentals then scaffold into the applied modules that specifically focus on hydrogen safety problems to develop learner specialisation in hydrogen safety engineering. Each of these fundamental and applied modules are connected to specific activities within the hydrogen economy such as production, distribution, storage, and utility to provide context and meaning to learning. While recognising the multidisciplinary nature of the sector, Nowotny et al. [47] similarly asserted that a hydrogen energy curriculum should cover hydrogen generation, storage, transportation, delivery and distribution, and safety.

Other narrower studies that reported on curriculum related content [42,45–47,49] are summarised in Table 3. The knowledge and skill areas identified within these studies are listed with an indication of the target audience, as described within the source publication. The focus on safety is evident when reviewing this list, as is the importance for learners to understand the fundamentals of hydrogen, the technologies they are likely to interface with, and the appropriate codes and regulations for their region and area of practice. From a skills perspective the focus appears to be on supporting the application of informed approaches to critical thinking and decision-making.

4.3. Scholarship of teaching and learning (SoTL) studies in hydrogen contexts

Five of the shortlisted studies provided some discussion related to the scholarship of teaching and learning within Hydrogen industry related contexts. This included some who discussed their scholarly pedagogical approach [43,44,46] and others who provided some commentary on suitable learning formats and environments for different aspects of learning [45,46].

Three of the five curriculum outlines presented within the reviewed literature listed in Table 3 described an intention to engage students in practical or experiential learning activities to enhance student engagement [42,45,46]. While not explicitly described or explained, the ‘applied modules’ within the HySafe International Curriculum (Table 2) [15] implied that learners need to engage in practical activities to develop and demonstrate competence in those areas.

Tretsiakova-McNally et al. [46] emphasised their application of a pedagogy aligned to their first-responder adult learner audience. Key to their ‘andragogy’ approach adopted from Knowles [53] was to provide learners with experiences that allow for mistakes as the basis for learning and ensure learning is problem-centred in the context of their practice, and not content-oriented. Their learning design utilised Virtual Reality (VR) exercises to engage learners within individual and team-based scenarios to allow for failure in a safe manner and foster thorough competency development through repetition [46]. The learning scenarios they applied were context specific to their first responder audience. Unfortunately, their study did not report on any learning evaluation, however the value of applying active learning pedagogies is well documented in education literature [54,55] and supported by the work of Alanne [44] within a hydrogen engineering context.

Alanne [44] quantitatively evaluated the change in 93 student perceptions of hydrogen technology and safety before and after completing an extensive team based technical hydrogen systems project. He also provided a detailed description of the project scenario and expectations of students within his paper. Key to his project design was its contextual and partially open-ended nature, and the systems level approach he applied to curriculum development. Learners engaged in peer evaluation to explicitly support development and assessment of knowledge and professional identity competencies appropriate to the field. His comparative analysis between pre and post assignment survey data revealed significant improvement in student knowledge of relevant chemical reactions, hydrogen production and storage methods, fuel cell operation, and hydrogen safety. His data also showed a notable increase in student willingness to take home a hydrogen system, indicating that high quality education can change people’s perspectives and levels of acceptance for the technology.

The work of both Tretsiakova-McNally et al. [46] and Alanne [44]

Table 3
Summary of knowledge and skill area topics identified from existing hydrogen education related literature excluding the HySafe International Curriculum presented in Table 2.

Source	Target audience	Curriculum topics identified
Aceves et al. [49]	Researchers using hydrogen in labs	Hydrogen properties Pressure safety Cryogenic safety Emergency response Codes and standards
Alzahrani [42]	Electrical engineering students	Fuel cell fundamentals
Barilo et al. [45]	First responders	Background (context) Hydrogen and Fuel Cell basics Hydrogen-fuelled vehicles Stationary facilities Managing hydrogen-related emergencies Practical exercises
Nowotny et al. [47]	Front line technical staff, students (disciplines not specified), and managers	Life cycle analysis Industrial ecology Multi-criteria decision analysis Risk assessment Economics Energy policy Hydrogen energy fundamentals Energy systems fundamentals Electrochemical energy fundamentals Alternative energies
Tretsiakova-McNally et al. [46]	First responders	Hydrogen production (overview) Hydrogen storage (overview) Hydrogen transportation and delivery (overview) Hydrogen applications (overview) Fuel cell and hydrogen systems Fuel cell and hydrogen infrastructure Safety features of fuel cell and hydrogen application Basic hydrogen properties Hydrogen storage options Compatibility of hydrogen with different materials Hazards and events that may lead to fires, loss of life and cause damage to structures, equipment and environment Typical incidents/accidents scenarios Ignited and unignited hydrogen releases Possible ignition sources and prevention of ignition Combustion of flammable hydrogen-air mixtures Separation from hydrogen flames and firefighting Hydrogen deflagrations and detonations European guidelines for inherently safer use of fuel cell and hydrogen systems indoors Identification and mitigation measures Regulations, codes, and standards Intervention strategies and tactics

advocates the use of problem-based learning pedagogies [54] in hydrogen related education programs. Tretsiakova-McNally et al. [46] utilised Virtual Reality (VR) exercises to engage first responder learners within individual and team-based scenarios to allow for failure in a safe manner and foster thorough competency development through repetition. While Alanne's [44] findings underlined the significance of applying a systems level approach to hydrogen technology curriculum development, and advocated the need to ensure topics related to hydrogen are treated as part of a larger system rather than just focusing on the chemical reactions or single components in isolation.

Recommendations for creating different learning environments and modes for different levels of learning was also worth noting in the literature reviewed. The use of online learning environments including self-paced learning modules and knowledge sharing databases appeared to be well suited to awareness level knowledge development [15,45,48]. Whereas, a classroom environment seemed to be better suited to facilitation of social learning to share ideas and explore contextual scenarios or case studies [15,44–46]. Nevertheless, the need to engage students in practical experiences, which often requires learners to be on site at a suitable facility was obvious [42,45,46]. The scope for Virtual Reality experience to support distance learning with use of dynamic 3D representations of immersive virtual environments converted to an accessible HTML format was explored [46]. In any case, a notable challenge for education providers will be to resource deeper learning. The relationship between the format of educational delivery (online, in-person, practical experience) and depth of learner engagement must be considered when designing learning experiences [10].

4.4. Empirical studies including practitioners or industry informants

None of the reviewed studies collected or reported on the analysis of empirical evidence from practice to inform curriculum design or define educational outcomes. Beasy et al. [10] provided the closest alignment to this intention, drawing on hydrogen industry stakeholder perspectives about the skills and training landscape. However, Beasy et al. [10] did not explicitly explore the knowledge, skills, and attributes relevant to engineering practice in the low-emissions hydrogen sector. Similarly, Upham et al. [16] reported on a qualitative study with hydrogen technology related stakeholders and presented challenges faced by society when adopting new technologies that connect elements necessary to fulfil societal functions such as the adoption of hydrogen as a clean energy carrier. This study also stopped short of utilising stakeholder perspectives to define educational outcomes for entry to practice.

Dahoe and Molkov [15] included contributions from many relevant hydrogen sector stakeholders for the development of the International Curriculum for Hydrogen Safety Engineers. However, the process they used to draw empirical evidence to inform educational outcomes, curriculum design and development was not clear. While acknowledging the significance of this comprehensive and well accepted curriculum, we highlight our observation, and to some extent our reservation, in relation to the application of a positivist research paradigm within which this study is situated. As evidence in the form of direct quotations or insights from participants is neither used nor provided to justify claims and validate findings, it was challenging to differentiate opinion and bias, isolate distortions and draw value.

Zheng et al. [14] comprehensively engaged enterprises within the hydrogen technology sector, however their work was focused mostly on identifying enablers for university-industry collaboration to ensure appropriate and timely development of suitable education programs. Key to their findings was their advocacy for the need to collect empirical evidence from and collaborate with local industry practitioners to inform regionally appropriate education programs, rather than just rely on the existing evidence from other regions.

5. Discussion

5.1. Lack of empirical evidence

The first observation from this systematic review is that information reported in a significant proportion of the selected papers is claimed out of experience, with limited presentation of empirical evidence gathered from practice. This observation is consistent with that of Mazzurco et al. [56] that there is a lack of empirical research that focuses on gaining a deeper understanding of engineering 'fundamentals' from practice to inform engineering education design. The application of a positivist research paradigm in most of the articles selected for review was in stark contrast to a social constructivist paradigm that we pursued to develop our research question. However, a critical theory perspective was necessary to seek and use evidence to generate value positive information to support engineering educators.

An example is the work of Dahoe and Molkov [15]. While they presented a comprehensive knowledge base and scaffold for Hydrogen Safety Engineers that has global relevance, they did not clearly describe the methodology used for collecting and applying empirical evidence to develop curriculum. Similar can be said for the collective work of Aceves et al. [49], Alzahrani [42], Barilo et al. [45], Nowotny et al. [47], and Tretsiakova-McNally et al. [46] presented in Table 2. These studies contributed to our understanding of relevant knowledge, and in some cases implied skills. However, they stopped short of describing empirical data collection and analysis methods to explain the inclusion or exclusion of key concepts that are useful for developing the capacity of engineers transitioning to work in the hydrogen sector.

5.2. A focus on knowledge

The second observation made in the context of the research question is that the reported information mostly focuses on knowledge, with some discussions of skills, and offers no focus on the development of desired attributes with the exception of Alanne [44]. This represents a technicist view of engineering practice and education that places greater value on the more technical and hands-on aspects of engineering than the equally critical social attributes required for effective engineering practice [24,25]. The evidence that engineering is sociotechnical in nature [23–27] asserts that engineering practiced within low-emissions hydrogen contexts would be no exception, and potentially of even greater importance given the socio-political drivers for hydrogen technology uptake, and the reported low levels of public awareness and perceptions of hydrogen technologies (E.g., Ref. [7,37]). Creating learning experiences that capture the knowledge, skills, and attributes in the context of practice, which is both technical and social in nature, is critical for developing employable engineers entering the sector [31].

5.3. A focus on skills

The third observation made in the context of the research question is identification of key skills for capability development of engineers transitioning to work within an Australian low-emissions hydrogen context. The review found that there was limited discussion on hydrogen specific skills outside of those already applied in other fields such as lifecycle analysis, multi-criteria decision analysis, and risk assessment [47]. The focus on knowledge implies that these skills are likely to be transferable, so long as engineers are suitably aware and capable of applying the appropriate hydrogen related knowledge to their given area of practice. However, this is not clearly evidenced empirically in the reviewed literature.

Zheng et al. [14] strongly advocated the need to collaborate with local industry practitioners and collect empirical evidence to inform regionally appropriate education programs, rather than relying on evidence from other countries and regions with significantly different regulations and operating environments. They highlighted that such

collaboration is a key enabler for strengthening university-industry relationships and for ensuring appropriate and timely development of relevant educational programs. With exception of the work conducted by Beasy et al. [10] that focused on vocational training needs, there were no other studies that explicitly captured evidence from industry to inform engineering curriculum or skill development within Australia. Notably, there is an absence of empirical studies globally, which addresses the need for regionally relevant educational programs advocated by Zheng et al. [14].

5.4. A focus on attributes

A final observation is that Alanne [44] was the only reviewed study that explicitly discussed or considered developing social attitudes or attributes of learners in conjunction with technical knowledge and skills. While many authors advocate for collaboration to support knowledge sharing [14,17,48] and to develop industry relevant education programs [10,45,50] it was surprising that only one study focused on professional identity in the context of what is required to succeed within the hydrogen technology sector. Alanne [44] advocated for the development of teamwork capabilities and professional identity as key educational outcomes. Nevertheless, this assertion was drawn from personal experience rather than from contemporary practice. Generally, the attributes required for practice were scattered throughout the literature with limited discussion. For example, individual capacity for decision-making and critical thinking underpinned by a sound understanding of the fundamentals were highlighted by Alanne [44], Dahoe and Molkov [15], and Nowotny et al. [47] but the purpose was not discussed.

5.5. Limitations

The original aim of this study was to support engineering educators by identifying educational outcomes for the development of engineers entering the hydrogen sector through a systematic review of published studies. This included bringing to the fore the curriculum, content, teaching, learning and assessment approaches that support the development of career starters or mid-career changers entering the Australian low-emission hydrogen sector. However, this study found that there was limited evidence-based guidance available to support the development of educational programs. There was little to no mention of the depth or the level of competency we should be aiming as educational outcomes [35] for engineers entering practice in the hydrogen sector, particularly in relation to diverse contexts or roles. Dahoe and Molkov [15] identified what is important for a Hydrogen Safety Engineer, but the depth of ability is unclear. Similarly, Alanne [44] described 'knowledge' and 'identity' based learning outcomes with use of Blooms Taxonomy [57] but with a narrower focus on a specific sub-set of knowledge and skills at undergraduate level. The only other explicit descriptions of learning outcomes identified that give an indication of depth of intended learning are within the first-responder contexts [45,46,48].

While a systematic approach has been applied using the PRISMA method [36], there are limitations to this review that could impact the comprehensive nature of our search and the outcomes to arise from the review. For example, the search and inclusion criteria applied to this study excluded our ability to explore educational innovations and emerging trends arising from other high-tech industries, the effects of government policy on driving innovation in hydrogen workforce development, or the specific challenges faced when industry, academia, and government attempt to collaborate. However, further ad-hoc searches were attempted and revealed minimal additional studies relevant to our aims and inclusion criteria. This indicated that the observations made from the reviewed literature, while possibly incomplete, are a fair representation of the landscape of hydrogen engineering specific education literature that can inform the required knowledge, skills and attributes for development at the time of writing. Clearly, there is not enough evidence to establish key learning outcomes for entry to practice within the hydrogen sector. There is an urgent need to define levels of learning and competencies based on evidence from practice, and standards for training that delivers to different levels of competencies.

6. Conclusions and recommendations

This paper presents a systematic review of research literature in the exploration of educational outcomes needed for developing a hydrogen engineering workforce. The research question guiding this review was: What key knowledge, skills and attributes are required to support the development of a hydrogen engineering workforce? The particular focus of this study was on how authors describe training and development of engineers needed for entry to practice to the Australian low-emission hydrogen sector, what curriculum, teaching, and learning strategies they suggested are critical and what evidence they provided to substantiate their claims.

Four high-level themes emerged from the 16 relevant publications identified within the inclusion criteria of the review (Table 1) were discussed. These themes related to.

- advocacy for hydrogen related training that employs cross sector collaboration,
- definitions of hydrogen engineering related curricula that predominantly focused on technical knowledge and some skills, with limited emphasis on attributes or sociotechnical competencies important to practice,
- reports on a limited number of studies that explore the scholarship of teaching and learning in hydrogen contexts that highlighted the value of applying active learning pedagogies, and
- a notable absence of empirical studies that capture the perspectives of practitioners in the field working within the region to inform curriculum design.

These themes from literature did not fully address the proposed research question. There was limited evidence that informed relevant skills and attributes and expected depths of technical knowledge or competency for entry to practice in the low-emissions hydrogen sector. This presents an opportunity for researchers to engage engineering practitioners and employers within emerging low-emissions hydrogen sectors globally to capture evidence to inform the design and development of educational programs that focuses on both the technical and social aspects of engineering work to prepare engineers for entry to practice within their region. Key to this body of work would be to identify both 'what' knowledge, skills, and attributes are important for entry to practice, and to what level of competency do employers expect they can demonstrate upon entry. Identifying educational outcomes and entry to practice competencies will be important to provide practical guidance to educators responsible for the development, delivery, and assessment of learning experiences in the hydrogen engineering related fields. Future investigation including studies on workforce demographics, comparative analyses of training programs, or evaluations of workforce development policies and interventions could be useful for monitoring workforce development trends.

CRediT authorship contribution statement

Robert McHenry: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Siva Krishnan:** Writing – review & editing, Methodology. **Loren Tuck:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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