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Intergenerational Knowledge Transfer and Technical Workforce Development in The Net-Zero Transition

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Abstract- The confluence of demographic attrition, sustainable industrial transformation, and generational cognitive differences presents an unprecedented challenge to engineering workforces. As senior technical professionals retire, they carry with them decades of tacit operational knowledge essential for energy-efficient production. Simultaneously, the material and technological foundations of engineering practice are shifting toward net-zero systems, demanding fundamentally new competencies. This review synthesizes evidence from human resource management, knowledge management theory, engineering education, and organizational behavior to examine the intersection of these forces. We identify three compounding challenges: the erosion of tacit knowledge through demographic attrition, the emergence of new competency requirements driven by sustainable material transitions, and the cognitive friction between analog expertise and digital-native learning modalities. Analysis of recent empirical studies on intergenerational knowledge transfer among engineers reveals that generational differences significantly influence knowledge-sharing effectiveness, with organizational culture and structured transfer mechanisms moderating these effects. The review proposes an integrated framework emphasizing systematic identification of critical expertise, structured mentorship architecture, pedagogical adaptation to generational learning differences, and organizational infrastructure supporting technical career development. We conclude that organizations failing to bridge the intergenerational knowledge chasm risk not only competitive disadvantage, but the systematic erosion of the operational intelligence required for sustainable industrial transformation.

Keywords: technical succession planning; tacit knowledge; knowledge transfer; sustainable engineering; workforce transition; intergenerational learning.

I. INTRODUCTION

The engineering profession stands at a pivotal juncture. Three transformative forces are converging: a demographic exodus of experienced technical professionals, a fundamental restructuring of industrial processes toward net-zero emissions, and the rapid digitization of engineering practice through artificial intelligence and cyber-physical systems. Each force alone would constitute a significant human resource challenge; their convergence represents an organizational challenge of unprecedented scope. The demographic dimension is stark. Workforce aging, retention of tacit knowledge, and the competitive imperative of knowledge transfer constitute the business rationale for technical succession planning (Lorman Education Services, 2025; Rothwell, 2011; Nwokoro, E. C., et al, 2024). When senior engineers retire, they depart with what Polanyi (1966) characterized as "tacit knowledge", the intuitive, context-dependent understanding that resists complete codification in manuals or standard operating procedures. Rothwell (2011) emphasizes that identifying knowledge-holders whose expertise is essential to organizational success, and implementing systematic processes for transferring their knowledge to successors, constitutes the core of technical talent management. This knowledge, accumulated through decades of direct engagement with physical systems, constitutes the operational intelligence upon which industrial efficiency and safety depend.

Research conducted within large research infrastructure projects such as CERN and ITER confirms that knowledge retention across a multigenerational workforce, insufficient capture and transfer of tacit expertise, and motivation gaps represent recurrent challenges that require structured governance mechanisms (Carrano, 2026). These findings, presented at the International Conference on Nuclear Knowledge Management and Human Resources Development, demonstrate that human-factor mitigation and knowledge management implementation strategies must function as structural components of project governance rather than support functions (Carrano, 2026).

Simultaneously, the engineering knowledge base itself is undergoing transformation. The transition to sustainable industrial systems demands competency in alternative materials, renewable energy systems, circular economy principles, and digital technologies (Baillie & Kadetz, 2024). Engineering education must increasingly integrate interdisciplinary knowledge spanning climate sciences, engineering, economics, and environmental regulation. The University of Sydney's Sustainable Infrastructure Research Hub has developed a competency framework for engineers transitioning to sustainable infrastructure, identifying critical areas including systems thinking, digital information in infrastructure projects, digitalization to ensure sustainability, and design for the circular economy (TSI Competency Framework, 2023). Engineering education must increasingly integrate interdisciplinary knowledge spanning climate sciences, engineering, economics, and environmental regulation. The engineering workforce must therefore not only replace retiring expertise but also acquire fundamentally new competencies. The mechanisms for transferring technical knowledge across generational boundaries remain inadequately understood and resourced. Traditional succession planning models, designed primarily for leadership roles, offer limited guidance for managing the horizontal career paths typical of technical specialists (Lorman Education Services, 2025) (Rothwell, 2011). Rothwell (2011) distinguishes technical succession planning from managerial succession planning, noting that the former emphasizes isolating, distilling, and transmitting the "right information" to people at the "right times" to ensure continuity of operations and provide a foundation for future improvements. The emphasis is on what, exclusively, the implicit and explicit experiences of running a process or operation, rather than on identifying future leaders. Moreover, cognitive and pedagogical differences between generations compound the challenge of knowledge transmission. Moreover, cognitive and pedagogical differences between generations compound the challenge of knowledge transmission.

This review addresses these intersecting challenges through systematic synthesis of scholarship from human resource management, knowledge management, engineering education, and organizational theory. We examine mechanisms for preserving and transferring technical knowledge across generational transitions, evaluate how workforce development strategies must adapt to the dual pressures of demographic attrition and sustainable technological change, and propose frameworks for building resilient technical talent systems for the net-zero era.

II. THEORETICAL FOUNDATIONS

2.1 Tacit Knowledge and Its Epistemological Significance

The distinction between tacit and explicit knowledge originates with Polanyi (1966), who observed that "we can know more than we can tell." Explicit knowledge is codifiable, articulated, documented, and transmitted through formal channels such as manuals and training materials. Tacit knowledge, by contrast, is personal, context-dependent, and acquired through experience. It encompasses intuitive grasp of complex systems, diagnostic ability, and embodied understanding of material behavior that distinguishes the master practitioner from the novice. Song et al. (2023) extend this understanding through the SECI model, Socialization, Externalization, Combination, and Internalization, developed by Nonaka. Socialization represents the transfer of tacit knowledge between individuals through imitation and practice. Externalization converts tacit knowledge to explicit knowledge through language and symbols. Combination systematizes explicit knowledge.

Internalization transforms explicit knowledge back into tacit knowledge through practice and application. This dynamic, iterative process is essential for understanding how engineering expertise is created, transferred, and institutionalized.

In engineering contexts, tacit knowledge is not supplementary to explicit procedures; it enables effective application of explicit knowledge in the variable, imperfect conditions of real-world practice. The case of storm surge barrier engineering in the Netherlands illustrates this principle. Research on intergenerational transfer of engineering expertise in this context demonstrates that knowledge continuity management requires systematic approaches to develop new engineering talent, document redesigns systematically, reduce the knowledge-use gap, design and buy for maintainability, and learn from redesign projects (de Boer et al., 2024). When a senior engineer departs, the organization loses not merely their individual output but their professional networks, heuristic shortcuts, and capacity to solve novel problems.

2.2 Codification and Its Limits

The impulse to codify tacit knowledge is understandable and partially achievable. Knowledge codification- articulating, standardizing, and documenting information, can render aspects of technical expertise transmissible across time and space. However, codification has limits. Song et al. (2023) note that while the SECI model provides a framework for knowledge transformation, it presents challenges when applied to education contexts because the knowledge cycle process and knowledge innovation pathway differ from corporate settings.

Over-reliance on codification, assuming tacit knowledge can be fully captured in digital systems, may accelerate erosion of the expertise required to operate, maintain, and improve complex industrial systems. The capacity to exercise judgment in non-routine situations, to innovate in response to novel challenges, and to integrate diverse forms of knowledge cannot be reduced to documented procedures. Research from the European ECRH (Electron Cyclotron Resonance Heating) community demonstrates that structured knowledge exchange mechanisms, including communities of practice, mobility and experiential learning, and intergenerational knowledge transfer, are essential for preserving critical expertise from retiring experts to early career professionals (Belonohy & Sanchez Arcos, 2026). This epistemological limitation is central to understanding why knowledge transfer between retiring and incoming engineers requires more than documentation.

2.3 Technical Talent Management as Distinct from Leadership Succession

Technical succession planning requires departure from conventional leadership-focused models (Lorman Education Services, 2025). Traditional succession planning focuses on vertical career progression, identifying and developing candidates for leadership roles. This orientation assumes organizational success depends primarily on management quality. However, in knowledge-intensive engineering organizations, technical specialists' contributions are equally critical.

Rothwell (2011) identifies several key distinctions: technical succession planning addresses the special case of knowledge workers including engineers, scientists, and IT professionals; it requires attention to horizontal as well as vertical career paths; and it emphasizes capturing both tacit and explicit technical knowledge. Rothwell (2011) outlines a seven-step model for technical succession planning: (1) making the commitment to identify and capture specialized knowledge; (2) clarifying work processes key to the organization's mission; (3) clarifying who possesses specialized knowledge about those work processes; (4) assessing the risk of losing key people; (5) capturing and distilling essential knowledge; (6) developing practical ways to transfer knowledge; and (7) evaluating results and making continuous improvements.

For technical workforces, extended time horizons required to develop deep expertise make strategic approaches essential. Yet organizations continue to invest disproportionately in leadership development while neglecting technical talent pipelines. De Long (2004) documented the threat of an aging workforce to organizational knowledge continuity, emphasizing that lost knowledge represents a significant risk to operational performance and innovation capacity.

III. COMPOUNDING CHALLENGES

3.1 The Demographic Imperative

The aging of the engineering workforce represents a structural transition with cascading consequences. Lužar et al. (2023) investigated intergenerational differences and their impact on knowledge transfer among engineers in large Slovenian production organizations using a Delphi method followed by questionnaire administration to engineers across all age groups. Their findings indicate that generational differences significantly influence knowledge transfer effectiveness, with experts reaching consensus on the importance of structured transfer mechanisms. Statistical analysis revealed statistically significant intergenerational differences in knowledge transfer among engineers in large production organizations ($p < 0.001$) (Lužar et al., 2023).

Siewert and Louderback (2019) emphasize that departure of colleagues with long tenure, whether planned or unplanned, can be devastating. Organizations must plan for effective knowledge transfer early, ensuring explicit knowledge is maintained in accessible forms and tacit knowledge is transferred through methods including phased retirement, cross-training, and storytelling. The "bus proof" concept, ensuring organizational continuity in the event of sudden loss of key personnel, underscores the imperative of proactive knowledge transfer planning (Siewert & Louderback, 2019).

Public sector organizations face particularly acute demographic pressures. Rothwell (2011) notes that perhaps as much as half of the federal, state, county, and city government workforce may be nearing retirement, posing a very real threat to national security at all levels. The loss of experienced personnel who know how to run schools and universities, fix roads and bridges, repair sewer lines, protect the public from diseases, and perform other essential functions represents a governance challenge requiring systematic technical succession planning.

Denmark (2025) examined intergenerational knowledge transfer from Generation X to Millennials among software engineers employed by the United States government. Using a qualitative descriptive phenomenological approach, the study found that both generations understand the knowledge transfer problem well and have the desire to work through technology-induced barriers to develop common practices and tool usage. The findings suggest that investment decisions for future knowledge transfer require understanding the shared experiences and insights across generational cohorts (Denmark, 2025).

3.2 The Sustainable Transition Imperative

The transition to net-zero industrial systems introduces a second challenge: emergence of new competency requirements. A competency framework developed for the sustainable infrastructure transition identifies critical competencies including systems thinking, implementation effectiveness, digital information in infrastructure projects, digitalization to ensure sustainability, and design for the circular economy (TSI Competency Framework, 2023). The framework provides a structured approach for industry to consistently integrate sustainability into all projects by building it into workforce development, operations, and decision-making.

Industry demand for sustainable solutions are driving engineering job markets. Experts highlight industry and consumer demands for sustainable solutions as the key factor driving engineering job markets (University of Sydney, 2026). Demand for engineering skills is increasing due to the expansion of infrastructure projects and the reliance on the engineering profession for national priorities, such as the transition to clean energy and achieving net-zero emissions objectives. Environmental, Social, and Governance (ESG) credentials have become essential to future industry opportunities (University of Sydney, 2026).

The Singapore energy sector illustrates the scale and nature of this transition. The Energy Market Authority (2024) projects clean energy workforce growth of approximately 60 percent (roughly 1,000 additional workers) over the next decade, driven by solar deployment, energy storage systems, and low-carbon electricity imports. The traditional power and gas sector is also forecast to grow by 13 percent, adding

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about 800 workers by 2034. EMA (2024) identifies evolving skill requirements: engineers trained in solar photovoltaic system design and optimization; specialists capable of evaluating cross-border electricity import projects; and competencies in future technologies including carbon capture and storage, hydrogen, and ammonia systems. Between 2022 and 2024, engineers increased by 13 percent and technical officers by nearly 7 percent, reflecting robust demand for specialized energy skills.

Industry demonstrates commitment to workforce transformation. In Singapore, Keppel expanded its integrated power operations workforce by 30 percent and delivered over 3,650 training hours focused on next-generation energy systems and AI-driven operations. Sembcorp Solar Singapore, designated as the first SkillsFuture Queen Bee for the Energy and Power Sector, is partnering with educational institutions to train up to 100 professionals by 2027 in digital system design and data-driven solar performance analytics (EMA, 2024).

The UK's green skills development demonstrates similar patterns. The Local Enterprise Partnership (2023) identifies that existing jobs will be fundamentally changed by low-carbon demands, while new jobs will emerge due to new low-carbon industries and businesses. The bulk of jobs affected will be in existing sectors and services, including transport, manufacturing, energy, construction, and agriculture. Highly specialist skills required include food science and agritech, carbon capture, hydrogen, and battery technology. Significantly, many low-carbon sector jobs will use skills that workers already have, even though the focus or purpose may be directed toward a low-carbon outcome (Local Enterprise Partnership, 2023).

3.3 The Cognitive Friction Between Generational Learning Modalities

A third challenge compounds the first two: cognitive and pedagogical differences between generations. Lužar et al. (2023) demonstrate that intergenerational differences among engineers significantly affect knowledge-sharing patterns. The retiring generation, baby boomers and early Generation X, learned linearly through extended apprenticeships and sustained physical engagement. The incoming generation, Generation Z and younger millennials, exhibit non-linear learning, searching for specific information rather than reading systematically, preferring short-form content, and processing information through digital interfaces.

Denmark (2025) provides detailed characterization of generational learning differences. Generation X are characterized as strong-willed with creative and critical thinking skills developed through deep knowledge of their work environment. They are "thinking-oriented," preferring traditional lecture methods and processing information via contemplation. They remain comfortable with one-on-one mentoring and learning styles that facilitate knowledge transfer (Denmark, 2025). Millennials, by contrast, are typically considered confident and demanding, accustomed to receiving frequent praise and immediate feedback. Their hyper-familiarity with technology has created a generation accustomed to getting immediate answers from the Internet, and they have lost some patience for the training methods of their parents (Denmark, 2025).

Research on the learning methods of Millennials found that 98 percent of respondents went to Google first and over 87 percent went to government, educational, or professional websites as a primary source of information (Nicholas, 2008, cited in Denmark, 2025). Millennials excel at multitasking and are especially skilled at sorting through large amounts of information on the Web. They prefer working in teams but prefer working with members of their own generation. While Millennials applaud diversity, they possess high expectations for team performance particularly in terms of speed and flexibility (Denmark, 2025).

This cognitive friction has profound implications for knowledge transfer. Traditional corporate training programs, designed by and for linear learners, attempt to transmit complex technical knowledge through extended documentation and structured courses. For non-linear learners, these formats appear inefficient. Song et al. (2023) observe that knowledge transfer in educational contexts must account for how learners process and internalize information, a finding equally applicable to corporate training.

The challenge extends beyond format to epistemology. Tacit knowledge, the feel of a machine, intuitive diagnosis of system behavior, is acquired through direct engagement with physical systems over time. It is precisely the kind of knowledge that cannot be readily digitized or transmitted through short-form content. As retiring engineers depart, they carry with them not only knowledge of specific processes but also capacity to generate that knowledge through embodied practice. Intergenerational learning (IGL) represents a combination of interactions between groups representing different generations (Ropes & Ypsilanti, 2016, cited in Denmark, 2025), but these interactions require deliberate structuring to overcome cognitive and pedagogical barriers.

IV. APPROACHES TO TECHNICAL KNOWLEDGE TRANSFER

4.1 Succession Planning for Technical Roles

Technical succession planning requires systematic approaches. Rothwell (2011) outlines a model emphasizing: identifying knowledge-holders whose expertise is essential; creating conditions for technical experts to thrive; implementing systematic knowledge transfer processes. Rothwell (2011) identifies barriers to overcome in knowledge transfer, including organizational culture, lack of incentives, and the inherent difficulty of capturing tacit knowledge. The model emphasizes practical approaches to knowledge transfer, pilot-testing transfer methods, and continuous evaluation and improvement.

Lorman Education Services (2025) emphasizes that distinctive challenges include understanding workers' expectations about co-workers, managers, assignments, and technology, factors influencing knowledge-sharing receptivity. Effective technical succession planning must integrate knowledge transfer into regular work processes rather than treating it as an additional activity.

Carrano (2026) demonstrates how large research infrastructure projects embed knowledge management and people management directly into project management cycles through a project-integrated framework including: risk-based tacit knowledge capture through mentoring, shadowing, and structured technical walkthroughs prioritizing high-criticality know-how; people-factor diagnostics assessing workload, communication, and motivation to reduce knowledge-flow bottlenecks; structured onboarding with controlled documentation ensuring configuration consistency; and governance alignment mechanisms linking knowledge management to risk registers and reporting cycles. Preliminary outcomes include increased reporting stability, reduced rework due to undocumented know-how, and improved consistency in cross-functional technical decision-making (Carrano, 2026).

4.2 Knowledge Transfer Mechanisms

Siewert and Louderback (2019) identify key mechanisms for tacit knowledge transfer: phased retirement enables gradual transfer while maintaining institutional knowledge; cross-training distributes expertise across multiple individuals; storytelling captures contextual understanding that eludes documentation.

Mentoring has received substantial attention as a vehicle for tacit knowledge transmission. When structured effectively, mentoring enables sustained, context-rich interaction through which tacit knowledge is acquired. However, mentoring requires careful design: alignment of mentor and mentee expertise, dedicated time, and organizational support. Lužar et al. (2023) found that effective employee engagement, including exemplary leadership, a system of mentoring and reverse mentoring, and a supportive organizational culture, enhances the flow of knowledge transfer. Reverse mentoring, where younger employees share digital skills with senior colleagues, addresses the bilateral nature of intergenerational learning.

The European ECRH community demonstrates how structured knowledge exchange mechanisms can be implemented at scale. The European Operations Network on ECRH (EUROfusion-F4E ECRH network), established in September 2023, functions as a formal Community of Practice implementing strategic principles including communities of practice as knowledge hubs, structured knowledge exchange mechanisms (seminars, workshops, curated learning pathways), mobility and experiential learning to transfer tacit operational know-how, intergenerational knowledge transfer ensuring critical expertise is preserved from retiring experts to early career professionals, and integration of research, operations,

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and industry (Belonohy & Sanchez Arcos, 2026). The network currently brings together more than 100 collaborators from over 15 European institutions, with special participation from ITER Organization, QST (Japan), and DIII-D (USA). Activities include bimonthly online technical seminars, an annual ECRH operator school organized by EPFL on gyrotron physics and technologies, and mobility actions enabling young scientists to visit laboratories with ECRH installations for hands-on exposure to system integration, commissioning, troubleshooting, and operation (Belonohy & Sanchez Arcos, 2026).

Digital approaches to knowledge capture present opportunities and limitations. Digital twin technology can capture operational data and enable simulation-based learning. However, the distinction between tacit and explicit knowledge (Polanyi, 1966) suggests that not all knowledge can be digitized. The "hum of the turbine" and intuitive diagnosis resist capture in data and algorithms. Rothwell (2011) notes that people will not necessarily go to a computer-based knowledge-management system as their first step when seeking information, emphasizing the importance of practical, usable knowledge transfer methods.

4.3 Reskilling and Upskilling for Sustainable Transitions

The sustainable transition demands both knowledge preservation and new competency development. The TSI Competency Framework provides a structured approach for industry to build sustainability into workforce development. The framework can be used to assess individual, team, or organizational learning needs and to design learning curricula. When combined with Engineers Australia's Engineering Skills Framework, it can target specific role requirements or the capabilities of an individual (TSI Competency Framework, 2023).

EMA (2024) documents educational initiatives in Singapore: the Institute of Technical Education launched a Technical Engineer Diploma in Electrical Engineering (Clean Energy) in April 2025, recognized for licensing applications; Singapore Polytechnic and Singapore Institute of Technology offer continuing education courses focused on renewable energy integration and smart grid technologies; Ngee Ann Polytechnic requires students to complete key power engineering modules within their first two years and added a one-year Industry Immersion Internship.

Baillie and Kadetz (2024) advocate for transdisciplinary learning and integration of sustainability across engineering curricula. They argue that engineers must think beyond disciplinary silos to design innovative solutions to complex global challenges, requiring reexamination of traditional professional education.

UNSW Sydney (2024) research from the Student Energy Transition Skills Project reveals that 75 percent of respondents are interested in or want to work in roles supporting energy transition; however, 58 percent cite lack of awareness about existing job opportunities, and 68 percent believe they need a STEM background. This indicates both opportunity and challenge for employers seeking to attract talent for sustainable engineering roles.

The UK Local Enterprise Partnership (2023) identifies multiple pathways for green skills development including Skills Bootcamps (Level 2-5), Apprenticeships (Level 2-7), T Levels, Free Level 3 Qualifications, Institutes of Technology, and Higher Technical Qualifications. Over 100 apprenticeship standards support green skills, with engineering and manufacturing standards being reviewed by employers for suitability. Current or planned provision includes Skills Bootcamps delivering skills to support sustainability and the green industrial revolution, such as retrofit construction, electric vehicles, and woodland management.

V. FRAMEWORK FOR TECHNICAL WORKFORCE RESILIENCE

Building on this analysis, we propose an integrated framework addressing three dimensions: knowledge preservation, competency development, and organizational infrastructure.

5.1 Knowledge Preservation: Institutionalizing Tacit Expertise

First, systematic identification of critical knowledge-holders. Rothwell (2011) emphasizes identifying what makes individuals the in-house experts: what special knowledge they possess and why it is important. This includes information about when the individual joined the organization, how long they have been in that position, major work accomplishments, and other information relevant to decision makers. Rothwell (2011) recommends that HR practitioners be the keepers of the list, working with MIS departments to secure appropriate software for tracking this information. Organizations must identify individuals whose departure would create irreplaceable knowledge gaps, assessing both formal expertise and informal networks through which knowledge is shared.

Second, structured knowledge transfer processes. Rothwell (2011) outlines practical methods to transfer knowledge: surveys, interviews, focus groups, observation, brainstorming distilled by a panel of experts, and mapping to flowcharts, especially electronic flowcharts with mouseover links to coaching tips tied to specific steps in work processes. Methods include phased retirement, cross-training, mentoring, and storytelling. The European ECRH network demonstrates that communities of practice, mobility actions, and structured seminars provide effective mechanisms for intergenerational knowledge transfer (Belonohy & Sanchez Arcos, 2026). Rothwell (2011) emphasizes pilot-testing transfer methods to ensure they work, noting that corporate and national cultures differ, and what works at one place may not work in another.

Third, capturing tacit knowledge in appropriate forms. While complete codification is impossible, externalization through narrative, demonstration, and guided practice can render aspects of expertise accessible. Carrano (2026) demonstrates that risk-based tacit knowledge capture through mentoring, shadowing, and structured technical walkthroughs prioritizing high-criticality know-how is effective in large research infrastructure projects. Lužar et al. (2023) found that intergenerational differences influence transfer effectiveness, suggesting transfer mechanisms must accommodate diverse learning modalities.

5.2 Competency Development: Bridging to the Sustainable Future

Competency development must address foundational knowledge for sustainable engineering and specific skills demanded by emerging technologies:

First, curriculum adaptation in partnership with educational institutions. Baillie and Kadetz (2024) advocate transdisciplinary approaches integrating sustainability across engineering education. The TSI Competency Framework provides a common language for clients and suppliers to specify required areas of competency for the delivery of specific projects and enable comparison of responses from potential suppliers (TSI Competency Framework, 2023). EMA (2024) demonstrates how policy can coordinate industry-education partnerships through curriculum development, internships, and mentorship programs.

Second, pedagogical innovation for generational alignment. Song et al. (2023) demonstrate that educational knowledge transfer requires models suited to learner characteristics. Denmark (2025) found that both Generation X and Millennials understand the knowledge transfer problem well and have the desire to work through technology-induced barriers. Training programs must adapt to learning preferences while maintaining rigor and depth, integrating digital tools and experiential learning while preserving time for reflection and practice. The European ECRH network's annual operator school and mobility actions exemplify pedagogical approaches combining structured learning with hands-on experience (Belonohy & Sanchez Arcos, 2026).

Third, continuous learning infrastructure. The pace of technological and material change demands continuous rather than episodic learning. Keppel's investment in 3,650 training hours on next-generation energy systems exemplifies organizational commitment to ongoing skill development (EMA, 2024). The TSI Competency Framework provides a foundation that can be fine-tuned for different levels of competence for different roles and individuals, depending on organizational requirements (TSI Competency Framework, 2023).

5.3 Organizational Infrastructure: Supporting Knowledge Continuity

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Organizational infrastructure encompasses policies, practices, and cultural norms enabling knowledge preservation and development:

First, career pathways for technical specialists. Rothwell (2011) emphasizes that organizations must provide compelling opportunities for engineers to deepen technical expertise rather than move into management, requiring parallel career tracks, recognition for technical achievement, and development opportunities that extend rather than dilute competence. Dual-career ladders, where technical specialists can advance without moving into management, represent an established approach to retaining technical talent (Rothwell, 2011).

Second, incentives for knowledge sharing. Knowledge transfer requires time, effort, and willingness, all requiring recognition and reward. Performance evaluation, promotion criteria, and compensation should incorporate knowledge-sharing contributions. Rothwell (2011) recommends evaluating knowledge transfer capability using tools measuring how often organizations adhere to characteristics of effective knowledge transfer, including clarified goals, roles, and accountabilities of the knowledge-transfer program; identification of work processes key to the organization's mission; and assessment of the risk of losing key people. Lužar et al. (2023) found that organizational culture significantly influences knowledge transfer, suggesting incentives must be embedded in cultural norms.

Third, risk management integration. Loss of technical expertise represents enterprise risk requiring proactive management. Rothwell (2011) emphasizes assessing the risk of losing key people: how likely are these high-probability knowledge-holders to leave, what special knowledge do they possess, what will be the likely consequences if they leave, and what risks will their loss pose to the organization. Workforce planning, succession planning, and knowledge management must integrate with enterprise risk management processes. Siewert and Louderback (2019) emphasize that proactive planning is essential for continuity. De Long (2004) documented that confronting the threat of an aging workforce requires systematic knowledge preservation strategies.

VI. RESEARCH GAPS AND FUTURE AGENDA

6.1 Empirical Evidence on Knowledge Transfer Effectiveness

The most pressing gap is the scarcity of systematic evidence on knowledge transfer intervention effectiveness. While numerous approaches are advocated- mentoring, documentation, digital capture- few have been rigorously evaluated. Lužar et al. (2023) provide valuable empirical evidence but focused on Slovenian manufacturing; studies across diverse contexts and sectors are needed. Denmark (2025) provides qualitative insights from U.S. government software engineers, but quantitative evidence across engineering disciplines remains limited.

6.2 Measurement of Tacit Knowledge

Measurement of tacit knowledge presents methodological challenges limiting empirical research. Polanyi (1966) argued tacit knowing resists complete formalization. Song et al. (2023) illustrate knowledge transformation processes, but measurement remains challenging. Developing valid measures, whether through performance assessment, cognitive task analysis, or other approaches, would enable rigorous evaluation. Rothwell (2011) provides tools for measuring the extent of knowledge transfer, but these rely on perceptual assessments rather than objective measures.

6.3 The Sustainability Transition Competency Gap

Research on competency requirements of sustainable engineering remains fragmented. EMA (2024) provides sector-level workforce projections, and the TSI Competency Framework (2023) offers a structured approach, but systematic analysis of knowledge, skills, and abilities required for net-zero industrial systems, and the gap between current and required competencies, would inform workforce development. Baillie and Kadetz (2024) advocate transdisciplinary approaches but empirical evidence on specific competency development is limited.

6.4 Intergenerational Learning Dynamics

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Cognitive and pedagogical differences between generations merit deeper investigation. Lužar et al. (2023) found generational differences significantly influence knowledge transfer among Slovenian engineers. Denmark (2025) identified themes and shared experiences across generations of software engineers. Research on how tacit knowledge is acquired across generational cohorts would inform transfer intervention design. The European ECRH network (Belonohy & Sanchez Arcos, 2026) offers a model, but systematic evaluation of outcomes across different contexts is needed.

6.5 Organizational Resilience and Knowledge Loss

Organizational consequences of knowledge loss require further study. Mechanisms through which resilient organizations withstand demographic transitions, comparative case research examining successful and unsuccessful transitions, would yield actionable insights. De Long (2004) documented the threat of an aging workforce, and Siewert and Louderback (2019) provide initial frameworks, but longitudinal studies tracking knowledge transfer outcomes across organizational settings are needed to identify best practices and contextual contingencies. Carrano (2026) demonstrates implementation in large research infrastructure contexts, but applicability to diverse organizational settings requires investigation.

VII. CONCLUSION

The convergence of demographic attrition, sustainable technological transition, and generational cognitive difference presents an unprecedented challenge to engineering workforces. Organizations face not only loss of skilled personnel but erosion of tacit knowledge underpinning operational excellence, innovation, and competitive advantage.

This review argued that conventional workforce planning, focused primarily on leadership succession and reactive recruitment, is inadequate for this challenge. Rothwell (2011) distinguishes technical succession planning from managerial succession planning, emphasizing that technical knowledge requires distinctive strategies: systematic identification of critical expertise, structured mechanisms for tacit knowledge transfer, pedagogical adaptation to generational learning differences, and organizational infrastructure supporting technical career development and knowledge sharing.

The implications extend beyond organizational competitiveness to the broader project of sustainable industrial transformation. The net-zero transition depends fundamentally on the capacity of engineering workforces to design, operate, and improve complex systems. Erosion of technical expertise threatens not only individual organizations but collective capacity to address environmental challenges. The TSI Competency Framework (2023) and initiatives documented by EMA (2024) demonstrate that systematic approaches to workforce development for sustainability are feasible.

Recent evidence from energy sector workforce development demonstrates that proactive approaches can succeed. Coordinated efforts between government agencies, educational institutions, and industry partners (EMA, 2024) create pathways for workforce transformation. Interdisciplinary engineering education models (Baillie & Kadetz, 2024; Song et al., 2023) provide frameworks for competency development. Structured knowledge transfer mechanisms demonstrated in large research infrastructure projects (Carrano, 2026) and communities of practice (Belonohy & Sanchez Arcos, 2026) offer approaches to preserving and transmitting expertise.

Future research should examine the conditions under which knowledge transfer interventions succeed, develop measures for tacit knowledge, analyze competency requirements of sustainable engineering, and investigate organizational resilience mechanisms. The future of sustainable engineering depends not only on technological innovation but on the human infrastructure through which technical knowledge is preserved, transmitted, and advanced across ge nerations.

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