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Transforming engineering-focused STEM education to aligning current teaching practices with the “Industry 5.0” paradigm

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Abstract

In the context of the rapidly intensifying challenges facing the global economy, engineering-focused STEM education is increasingly recognized as a structural factor of strategic, state-level significance, - one capable of exerting a decisive influence on the formation of a nation's industrial dynamics, productivity trajectories, and pathways of technological development. Within the revolutionary paradigm of Industry 5.0, whose defining feature is the imperative of complementarity between humans and machines (the digital domain), the modernization and strategic alignment of engineering education with contemporary industrial realities emerge as a fundamental prerequisite for ensuring national competitiveness. Accordingly, this study presents a comparative analysis of the effectiveness of educational and human-capital policies in leading industrial economies that underpin industrial advancement, alignment with global market demands, and the capacity for adaptive governance. In particular, paper examines the current challenges of engineering-focused STEM workforce preparation within Technical and Vocational Education and Training (TVET) systems, and substantiates the necessity of elevating cooperation between educational institutions and industrial enterprises to a new, more productive institutional level. Particular emphasis is placed on the transformation of university-level engineering education, - specifically, on the rationale for its evolution from a neutral, academically autonomous subsystem into an instrument that actively supports national industrial and strategic development. To this end, the study recommends the integration of several key components into the educational process: the expansion of inclusive and diversified STEM pathways; the development of human capital equipped with digital and green technology competencies; the transformation of existing academic and laboratory infrastructures into applied R&D and innovation hubs; and the establishment and institutionalization of forward-looking methodologies for anticipating shifts in engineering competency demands. Based on the foregoing, it has been concluded that the proposed modernized model of engineering-focused STEM education can serve as a crucial mechanism for virtually any country, acting not only as a guarantor of technological sovereignty and industrial autonomy, but also as a source of adaptive capabilities necessary for full integration into the emerging industrial landscape of "Industry 5.0."

Keywords

Engineering TVET and Higher Education, Industry-relevant competencies, Early Identification, University–Industry Linkages, Industrial and Educational Policy.

I. Introduction

National industrial trajectories, technological competitiveness, and long-term economic sustainability depend on engineering education as the cornerstone. Within the operational reality of Industry 5.0, where human-technology synergies and environmental imperatives dictate market survival, STEM (science, technology, engineering, mathematics) competencies have moved beyond their role as mere assets to become mandatory structural prerequisites for sovereign technological development (Breque et al., 2021).

It is well known that engineering education functions as a key mechanism for the development of intellectual human capital, allowing societies to accelerate technological progress, modernize production systems and build adaptive industrial ecosystems focused on innovation. This role is constantly emphasized in international assessments, which note that engineering and technical skills, along with a wide range of competencies in the field of STEM, are among the most demanded, but structurally deficient skills in the global labor market (Hagenreiner et al., 2015; Oeij et al., 2024).

Over the past decade, the global economy has undergone a profound transformation driven by digital technology, automation, artificial intelligence and a shift to low-carbon production models. These changes have increased the demand for engineering talent in virtually every sector - from advanced manufacturing and renewable energy to microelectronics, robotics and critical infrastructure. The presence of engineers increasingly determines not only the operational stability of industries, but also their ability to innovate, increase productivity and technological renewal (Rampasso et al., 2020; Garcés et al., 2025). In this context, engineering education systems face unprecedented pressure to expand, diversify and modernize their curricula, pedagogical approaches and institutional structures (Matsaberidze et al., 2022).

The global expansion of higher education has simultaneously reached historic proportions. Between 2000 and 2025, the number of students worldwide more than doubled, rising from about 100 million to more than 260 million. STEM fields have been a major driver of this growth, reflecting the growing demand for science and technology competencies in both developed and developing countries. However, quantitative expansion alone did not result in proportional industrial benefits.

Three interrelated issues, which include the continued shortage of engineering staff, non-compliance of education results with production needs, and uneven distribution of engineering talent across regions and sectors, are consistently addressed by international reports (OECD, 2025*a*; UNESCO, 2021; World Bank, 2019; Council of the European Union, 2026; World Economic Forum, 2025; UNESCO-UNEVOC, 2020; International Energy Agency, 2023; UNIDO, 2025). Together, these challenges limit investment, slow innovation cycles, and reduce the effectiveness of industrial modernization strategies.

Despite the growing body of research in engineering education, several critical gaps remain. First, existing research often considers national systems in isolation, lacking a comprehensive global view of how engineering education interacts with broader technological and industrial transformation. Second, the mechanisms by which engineering competencies are translated into industrial productivity, such as innovation capacity, productivity growth, and technology uptake, remain insufficiently conceptualized. Thirdly, literature rarely integrates demographic, spatial and sectoral dynamics, such as regional imbalances in skills, migration flows and the growth of new high-tech industries, into a single analytical structure. As a result, the relationship between engineering education and industrial development is often described in general terms, without a systematic assessment of how specific educational structures, pedagogical models, and institutional arrangements determine production outcomes.

These research gaps are particularly significant in the context of Industry 5.0, which places new demands on engineering competencies. Engineers are now expected not only to master technical knowledge, but also to work in complex socio-technical systems, integrate digital and physical technologies and contribute to sustainable, human-centered industrial solutions. This shift requires educational systems to move beyond traditional lecture-based teaching to adopt more practice-oriented, interdisciplinary, and industry-specific pedagogies. Project-based learning (PBL) and problem-based learning (PrBL) have become leading approaches in this regard, enabling students to develop systems thinking, collaboration skills, and practical problem-solving abilities (Lavado-Anguera et al., 2024). Nevertheless, the global spread of these pedagogical methods remains uneven and their impact on production performance has yet to be fully assessed.

Another important aspect is the spatial and industry distribution of engineering personnel. While some regions, such as East and South Asia, have dramatically increased tech graduation, others continue to face chronic shortages. Even in industrialized countries, significant differences remain between major technology centers and minor industrial cities. Rapidly growing sectors such as renewable energy, microelectronics and robotics attract disproportionate proportions of engineering graduates, leaving core but less prestigious sectors such as water management, recycling, and traditional light and heavy industries experiencing acute skills shortages. These imbalances are further exacerbated by global migration flows, including both physical mobility and the emerging phenomenon of "virtual brain drain," where engineers from lower-income countries work remotely for foreign companies, reducing the availability of talent for domestic industries.

Collectively, these dynamics underscore the need for a comprehensive, data-driven assessment of how engineering education systems contribute to industrial development in a rapidly changing global environment. Such an assessment should combine quantitative indicators (graduation, enrollment trends, labor market data) with qualitative indicators (curriculum relevance, pedagogical innovation, links between universities and industry). It must also address the broader socioeconomic and technological context, including demographic shifts, digital transformation and green transition.

Against this background, the present study has two interrelated goals. First, it aims to systematize international data on the current state of STEM engineering education, focusing on global trends in STEM expansion, regional and industry skills imbalances, and the dissemination of practical pedagogical models. Second, it seeks to analyze how engineering education systems affect industrial development, technological modernization and innovation potential, as well as identify key areas, in which these systems must evolve in response to the demands of industry 5.0. by integrating different sources of empirical data and adopting a global comparative perspective, the study will contribute to a deeper understanding of the strategic role of engineering education in shaping the future of the industrial economy.

II. Material and methods

The research methodology includes global aggregate analysis using official datasets from the following sources: OECD Education at a Glance (OECD, 2025*a*), UNESCO Institute for Statistics (2021), World Bank World Development Indicators (World Bank, 2019; World Economic Forum Future of Jobs (2025), and UNIDO Industrial Competitiveness Index (UNIDO, 2025). These datasets provide comparable, validated measures of engineering education outcomes, R&D intensity, industrial competitiveness, and skilled labor shortage.

Conceptually, the study defines engineering-focused STEM education as a subsystem of industrial-economic development opportunities. In particular, engineering education is viewed as part of the national intellectual capacity system for inclusive development, alongside industrial policy and sectoral strategies, research and innovation systems, vocational education and training (VET), and infrastructure and energy systems.

From this perspective, given its paramount practical role, engineering education is regarded as a key factor in building the human resource capacity (intellectual capital) required for the design of targeted processes or technological schemes that take into account the capabilities of artificial intelligence, for the operational management and maintenance of complex industrial systems, for testing and implementing new technologies and production approaches in the industrial sector, and for developing enterprises' capacity to master and fully adapt imported, modernized, and cutting-edge technologies.

Based on the above, a two-way model that represents the relationship between engineering education and industry is used to analyze the relationship between supply and demand. This relationship is considered as a comprising system of "Supply side" - universities, technical institutes, polytechnic colleges, and other vocational training institutions that provide training for engineers, technicians, and technologists; and "Demand side" - sectors of light and heavy industry, energy, construction, transport, infrastructure and logistics systems, as well as other high-tech services requiring professional engineering competencies.

Subsequent analysis uses an analytical framework based on the premise that engineering education is a strategic tool for accumulating the human resources (intellectual capital) needed to ensure technological sovereignty and sustainable industrial development. This structure allows you to structure the analysis according to the following parameters: *a*) development of competencies that ensure the design of technological processes and production schemes regardless of the prevalence and maturity of artificial intelligence systems; *b*) maintaining operational stability in the industrial sector through skilled operation and maintenance of complex technical systems; *c*) acceleration technology refresh by testing, adapting, and implementing innovative solutions in the production environment; and *d*) increasing the ability of enterprises to assimilate, integrate and institutionally adapt imported high-tech solutions.

Based on the above, it can be emphasized that the analytical prerequisites used form the methodological basis for assessing the mutual, bilateral impact between engineering education and production dynamics: on the one hand, the quality of training, which determines the technological advantages of countries, and on the other, industrial transformations, which, in turn, impose new requirements for the content, structure and mechanisms for updating engineering-focused STEM education.

III. Findings and discussion

A. Current state of engineering education within the STEM framework

A significant body of contemporary research highlights that engineering education is central to the broader STEM paradigm. Within this paradigm, STEM functions as a foundational cognitive and methodological platform that provides core scientific, technological, and mathematical competencies. Building on this foundation, engineering education constitutes the applied dimension of STEM - an integrated set of professional practices, design methodologies, and technology solutions that translate STEM knowledge into specific products, processes, and innovations. These engineering transformations shape industrial productivity and economic development at local, national and global levels.

Data from UNESCO (2021) and the World Bank (2019) over the past two decades indicate a significant expansion of STEM and engineering programs, especially in East and South Asia (China, India, the Republic of Korea), a number of European countries, and a growing number of developing economies. Key trends in this expansion include rapid growth in the absolute number of engineering graduates in China and India, stabilization or moderate growth in many OECD countries, and - relatively low but gradually increasing enrollment and graduation rates in sub-Saharan Africa and selected Latin American states.

Taken together, these data indicate that the development of engineering education cannot be considered in isolation. It is embedded in the broader global dynamics of STEM learning and depends on how effectively countries build a continuous pipeline linking STEM competencies → engineering skills → technological development. This pipeline ultimately determines the national potential for industrial modernization, innovation and long-term economic growth. However, the global expansion of STEM and engineering programs shows an important pattern: quantitative growth alone does not lead to strengthening industrial capacity unless it is accompanied by improvements in the quality of education, regular modernization of curricula, and deeper links between educational institutions and industrial sectors. Analysis of the period 2000-2025 confirms this dependence. As noted earlier, the number of students in higher education has increased on an unprecedented scale, with the number of students worldwide more than double over the past two decades. STEM fields have been the primary driver of this expansion, although growth rates and geographic distribution vary significantly across regions. Evidence (UNESCO, 2021; World Bank, 2019; Council of the European Union, 2026) shows that expanding STEM education provides a necessary foundation for engineering education but translating that foundation into tangible industrial outcomes depends on the quality of national education systems and the degree to which they integrate with real industrial needs. In other words, the effectiveness of engineering education is determined not by the number of graduates, but by the degree to which educational systems can align STEM competencies with industry engineering skills and translate them into technological development.

The observed expansion of STEM and engineering programs in different regions of the world reflects not only the growing demand for technical competencies, but also deeper structural shifts in the global economy. In East and South Asia, the rapid growth of engineering graduates is closely related to accelerated industrialization, large-scale investments in high-tech industries, and strategic government planning aimed at strengthening national technological sovereignty. In OECD countries, modest growth or stabilization in enrollment reflects the transition to a knowledge-based economy, where the emphasis is less on graduation rates than on educational quality, interdisciplinarity, and innovative capacity. In sub-Saharan Africa and parts of Latin America, the gradual increase in STEM graduation rates shows a commitment to catching up with global technological trends, yet progress remains constrained by institutional and infrastructural constraints.

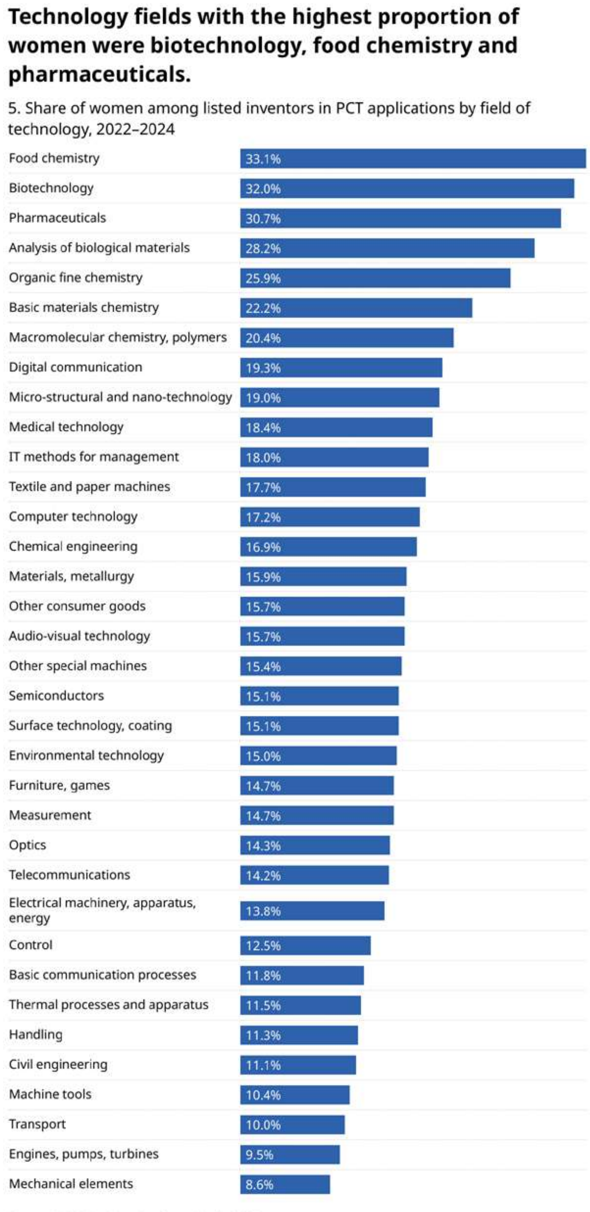
International evidence consistently indicates that quantitative growth alone does not guarantee an increase in industrial potential. Without improving the quality of education, modernizing curricula, developing research ecosystems, and strong links between universities and industry, the growth of STEM programs remains a statistical indicator rather than a genuine driver of industrial development. The transformational potential of STEM expansion is only realized when educational systems can translate increasing enrollment into industry competencies, applied engineering skills, and support technological advancement.

Analysis of data from 2000-2025 shows that much of the global growth in STEM and engineering education is driven by regional dynamics. The most significant expansion occurred in China and East Asian countries. During that period, China became the world leader in STEM graduates, awarding nearly two million bachelor's degrees in science and engineering each year by 2020, compared with less than one million in the United States. Today, more than 40% of all Chinese graduates hold STEM degrees. India ranks second in the world in engineering talent production, graduating about 2.6 million STEM professionals annually, with about 34% of all Indian students opting for STEM disciplines.

Within the European Union and OECD, Germany stands out as a clear leader in STEM participation, with more than 30% of graduates pursuing degrees in these fields. In the 2024/25 academic year, 43% of all foreign students in Germany studied engineering and science. At the same time, some countries, such as France, recorded small declines and STEM enrollment fell to 23.7% in 2023. The European Union has set a strategic goal to increase the share of STEM students in higher education to at least 32% by 2030 (European Commission, 2025).

In North America, and especially in the United States, the proportion of STEM degrees remains relatively modest at around 20% (Oliss et al., 2023), despite overall growth in graduation rates. However, the number of STEM degrees awarded exceeded the targets set in 2012 by more than 16%. In Latin America, countries such as Brazil and Chile show a growing interest in STEM as a tool to strengthen national competitiveness, although expansion is constrained by socio-economic inequalities and unequal access to education (Oliss et al., 2023).

An analysis of demographic factors based on OECD data shows that mechanical engineering remains the most attractive area within STEM, reflecting the ongoing global demand for engineering competencies and their central role in technological development. The example of Germany in the academic year 2024/25 illustrates this trend: engineering programs continue to dominate the preferences of both domestic and foreign students, emphasizing the high international competitiveness of German engineering education and its strong compliance with the country's industrial base (Kercher et al., 2025).



Source: WIPO Statistics Database, March 2025.

Fig. 1. Share of women among listed inventors in PCT applications by field of technology, 2022–2024

While women's participation in STEM is gradually increasing, the gender balance remains uneven. The highest proportion of female inventors is found in fields such as biotechnology, food chemistry and pharmaceuticals (Figure: 1). On average, women account for just 32–34% of STEM students in the European Union, with the highest proportions observed in Romania (42.5%) and Poland (41.5%) (UNESCO, 2024). These differences are a reflection of the impact of cultural norms, national education strategies, and targeted initiatives aimed at increasing women's participation in technical fields.

Global mobility is another important determinant of the STEM landscape. The number of international students studying abroad, predominantly in STEM disciplines, tripled, rising from 2.1 million in 2000 to 6.9 million in 2023. This trend indicates the emergence of a global market for engineering competencies (ICEF Monitor, 2025a). While this dynamic is generally positive, it requires careful planning, strengthening education infrastructure, adapting to industrial needs, and targeted support for underrepresented groups. Only under these conditions can demographic growth lead to a steady expansion of industrial and technological potential.

From the point of view of human capital theory, the growth in the number of registered engineers reflects the willingness of both states and individuals to invest in competencies that bring the greatest return in technologically intensive economies. Engineering remains the most popular field in STEM precisely because it provides the most direct link between education investment and economic productivity at both the individual and national levels. The example of Germany, where engineering programs dominated the preferences of both domestic and international students in 2024/25, illustrates how advanced industrial economies continue to view engineering education as a strategic asset to maintain competitiveness.

In terms of global talent flow theory, the threefold increase in international students, most of whom are studying STEM disciplines, signals the emergence of a global market for engineering competencies. Students are increasingly moving to countries where educational systems have a high reputation and where industry has shown a steady demand for engineering skills. This increases competition between countries for attracting and retaining talent and fosters new models of cerebrovascular accident, in which graduates return to their home countries with globally relevant competencies. Germany, Canada, the United States, South Korea and the Netherlands have emerged as major destinations for these flows, strengthening their innovative ecosystems and strengthening their long-term technological capabilities.

Within the national and industry theory of innovation systems, demographic trends in STEM are directly related to how many countries manage to integrate education, industry and research infrastructure. Increasing enrollment alone does not strengthen innovation capacity unless educational programs are embedded in national knowledge and technology chains. The persistent gender imbalance, with women accounting for just 32-34% of STEM students in the EU, is also affecting innovative systems, limiting the diversity of engineering perspectives and reducing the overall pool of available human capital. The relatively high level of participation of women in Romania and Poland indicates that targeted national policies can significantly expand the talent base of innovative systems.

Collectively, the trends identified indicate that demographic growth in STEM - rising student numbers, increasing international mobility, and gradually increasing female participation - is creating a favorable foundation for the development of engineering education. However, with the quantitative expansion of programs, these processes are not automatically translated into production or technological advantages. Their impact depends on how effectively countries integrate STEM dynamics into their national innovation systems: through strategic workforce planning, curriculum modernization, strengthening university-industry linkages, and institutional settings that allow global talent flows and gender diversity to function not only as statistical indicators but also as genuine drivers of industrial development. In this sense, demographic shifts in STEM education represent a necessary but insufficient condition; their transformation into industrial capacity requires concerted policy action and coordinated modernization of educational and industrial institutions.

B. Key deficiencies in engineering education and strategies for their improvement

International assessments and surveys of employers in many countries consistently highlight several critical shortcomings in engineering graduates: insufficient practical skills, limited influence of real industrial environments, inadequate training in digital tools, data analysis and system integration, as well as gaps in interpersonal competencies, such as project management, communication and interdisciplinary cooperation (World Economic Forum, 2025).

The combined analysis of these issues indicates the need for a systematic transformation of engineering education in the period 2026-2030 in the following areas:

1. lagging and non-compliance of curricula with technological cycles: The main problem is the constant lag of curricula caused by the fact that technological cycles in industry, especially in artificial intelligence, robotics and materials science, are now average 2-3 years, while university curricula are usually updated every 5-7 years. As a result, graduates enter the labor market with skills that already require retraining. Such structural misalignment reduces the relevance of engineering programs and weakens the responsiveness of education systems to industrial needs.

2. Lack of T-shaped competencies: Employers are increasingly looking for T-shaped professional engineers capable of deep expertise in one area (vertical strip "T"), with broad competencies in related areas (horizontal strip). The dearth of such profiles is compounded by insufficient training in hard digital skills, including big data, simulation environments, and digital twins, even among traditional mechanical engineers. Modern engineering is inherently collaborative, and deficiencies in project management and communication have become critical obstacles to both individual career growth and the efficient functioning of industrial production systems.

3. The introduction of cutting-edge educational models (trends for 2024–2025) and the addressing of existing gaps through the implementation of advanced educational approaches such as dual education systems, project-based learning, and micro-credentials: Under the dual education system (Germany, China), students can spend almost 50% of their study time in an industrial setting (Wehnert et al., 2021). This model directly addresses employers' concerns regarding a lack of practical skills; Within project-based learning (widely implemented in the US and Singapore), the focus shifts from abstract theoretical lectures to solving real-world industrial problems provided by corporate partners; Meanwhile, the micro-credentialing (certification) approach, which offers short, targeted modules on new tools such as AI-assisted design, helps to fill gaps in core engineering skills and qualifications. This approach has been successfully implemented in EU countries, and regions such as Latin America and the Caribbean are preparing to adopt it with the support of UNESCO (Gutovic, 2025).

Together, these models represent a shift towards more flexible, industry-oriented, and competency-based engineering education systems capable of responding to rapid technological changes and changing labor market demands.

The analysis shows that in the future, a global increase in STEM students will no longer serve as a guarantee of economic success. The central challenge of the 2026-2030 period will not be competition for more engineers, but the ability to close the gap between university classes and the sexes of industrial production or IT/AI laboratories. Countries that succeed in aligning engineering education with real technological conditions through hands-on training, industry-specific learning models, and ongoing curriculum modernization will be able to turn STEM expansion into tangible industrial and technological benefits. Only under these conditions can engineering education fulfill its strategic function of supporting sustainable industrial and technological progress and strengthening national innovation systems.

C. The role of technical and vocational education in industrial systems

Technical and Vocational Education and Training (TVET) plays a key role in providing the industry with qualified technicians, operators, and mid-level professionals. Joint analytical reviews by UNESCO (2021), World Economic Forum (2025), the World Bank (2019) and Council of the European Union (2026) emphasize that countries with well-developed and institutionally sustainable TVET systems, such as Germany, Switzerland, Austria, and the Republic of Korea, demonstrate higher levels of industrial productivity and competitiveness. These countries also have low youth unemployment, a smoother transition from school to work, and strong potential to introduce and spread new technologies.

Under these conditions, TVET systems function as an important link between education and industry, providing a continuous flow of personnel able to operate modern equipment, comply with quality and safety standards and quickly adapt to technological changes. Due to the close integration between educational institutions and enterprises, TVET is becoming not only a mechanism for training the workforce, but also an important component of national innovation systems. It accelerates the adoption of advanced technologies and supports the sustainable development of industrial sectors. In such systems, engineers do not work in isolation but are built into a dense structure of the workforce, consisting of highly qualified technicians and technologists.

Based on the accumulated international experience by 2026, we can confidently state that the key to the success of countries such as Germany and the Republic of Korea lies not in a strict hierarchy between engineers and technical personnel, but in a symbiotic relationship between engineering and technical intelligence. Their engineering ecosystems are built on the principle of functional complementarity: each design engineer is supported by a whole community of highly qualified technicians and mid-level specialists. Without their participation, even the most complex engineering projects remain "on paper," since there is no workforce capable of ensuring their physical implementation, scaling and maintenance.

A typical example is the introduction of new production technologies, such as metal 3D printing. Engineers can design technology by adapting it to production requirements and integrating it into broader engineering workflows. Nevertheless, it is the TVET level personnel who ensure its practical implementation: operation and calibration of equipment, quality control, troubleshooting, and scaling of technology on production lines. With this separation of functions, technology evolves from an experimental prototype to a fully operational industry standard.

Another major benefit of advanced TVET systems is the substantial reduction of the gap between education and employment in transition. In countries with strong vocational training, the transition from school to stable employment occurs with minimal friction. This is essential not only for industrial productivity, but also for youth integration, sustainable employment and prevention of structural unemployment. As a result, TVET is becoming more than a mechanism for training the workforce; it acts as a fundamental component of socio-economic stability and industrial development.

The key conclusion is that effective educational and industrial policies in the 2020s require the simultaneous development of both pillars of the workforce system, engineering and technical levels. The widening gap between "over-qualified theorists" and "under-qualified workers" creates a structural imbalance that can slow down techno-economic and environmental progress. When engineering expertise is not supported by enough skilled technicians, innovation remains at a conceptual stage; conversely, when technical staff lack modern training, industry loses the ability to adopt, adopt and scale new technologies. Therefore, overcoming this gap becomes a strategic prerequisite for sustainable industrial development and the formation of fully functional production ecosystems.

D. Dual systems and work-based learning

The need to balance both engineering and technical levels of the workforce makes dual systems and work-based learning models one of the most effective mechanisms for bridging the structural gap between education and industry. Dual systems are learning models in which students divide their time between classroom learning and hands-on learning directly in enterprises. International evidence shows that such systems are particularly effective in aligning educational outcomes with actual industrial needs (Martínez-Izquierdo et al., 2022). Their main features include the participation of employers in the development of curricula, formalized apprenticeship programs and the joint responsibility of the state, employers and educational institutions. These models significantly reduce the mismatch between supply and demand for skilled personnel by closely linking engineering education with industrial development.

Dual learning is widely recognized as one of the most effective mechanisms for overcoming curriculum lag because it integrates learning processes with real-time business practices. Under this model, employers are not just consumers of labor, but co-authors of curricula, sharing risks and costs with governments and educational organizations. This approach ensures a smooth transition of students into the corporate environment, speeds up recruitment processes and supports the formation of a stable professional identity. By 2025, dual systems are increasingly seen as a critical component of STEM development as they make engineering ecosystems more flexible, adaptive, and able to respond quickly to technological change (Quirós-Alpera et al., 2025).

Despite their clear advantages and proven effectiveness, dual systems also face several structural challenges that need to be addressed when scaling or adapting to new environments. Of particular importance there are two issues:

1. Coordination difficulty: Effective cooperation between educational institutions and enterprises remains organizationally demanding. This requires flexible public policies, stable partnership mechanisms, and professional management by both education and industry. Without clear procedures, clearly defined responsibilities, and long-term commitments, the dual model loses much of its effectiveness.

2. Limited attractiveness of TVET pathways: Efforts are ongoing in many countries to elevate the prestige and social value of TVET and dual study programs to levels comparable to academic higher education. This is particularly important as industries face a growing shortage of qualified technicians and mid-level professionals (Alexandrova & Krasteva, 2026). Without enhancing the appeal of a tech career, even well-designed dual systems can struggle to attract enough talent.

Taken together, these factors indicate that the further development of dual systems requires not only institutional support, but also a change in the public perception of technical professions, as well as stronger mechanisms for cooperation between governments, enterprises, and educational organizations.

E. Skill shortages as a constraint on industrial and technological progress

Studies by the World Bank and OECD on industrial competitiveness show that firms in manufacturing and heavy industry consistently identify a shortage of sufficiently qualified engineers and technicians as the main constraint for sustained production expansion, technological modernization, and compliance with increasingly stringent quality and environmental standards (OECD, 2025*b*). Therefore, in many middle-income countries, industrial policy is shifting from low-value assembly operations to higher-value activities such as advanced design, engineering, and R&D. Such a transition is impossible without a corresponding deepening of engineering education and expansion of national research potential.

Modernization of the industry is being held back by the lack of appropriate engineering skills. Countries with low STEM participation are increasingly losing momentum in industrial growth because their education systems cannot keep up with technological innovation cycles. This skills deficit has become a major obstacle to sustainable integration into industry 4.0 and preparation for the transition to industry 5.0. Modern equipment, robotic production lines, and predictive analytics systems can be purchased by industrial firms, but these investments are not profitable without engineers who can program, adapt, and support them flexibly. As a result, entire economies face technological stagnation, despite the formal availability of new capacities and technologies (Senna et al., 2023; Brückner et al., 2025).

The second major obstacle in industrial and technological advancement is the difficulty, sometimes impossible, of meeting ESG, ISO, and environmental standards. This problem arises not only due to additional financial burdens associated with compliance (Reis et al., 2025), but also due to the lack of engineers who are able to conduct timely analyzes and make optimal production decisions in response to regulatory requirements (Grüner, 2024; Smirnov, 2025). The global value chains of today require strict compliance with environmental regulations and quality standards. Meeting these demands requires more than just operators of new technologies; it requires environmental engineers and systems integrators who can adapt technology solutions to regulatory frameworks and industrial processes.

This segment of the labor force is either very scarce or completely absent in many developing countries (Smirnov, 2025; Aiginger, 2024). As a result, firms are struggling to meet the standards required to participate in EU and US markets, effectively limiting their integration into high-value global supply chains. Thus, failure to comply with ESG and ISO requirements becomes not only a regulatory problem, but also a structural obstacle to industrial modernization, export diversification, and long-term technological competitiveness.

Systematic analysis of ways to accelerate industrial development emphasizes the importance of engineering sovereignty as a critical factor associated with the accumulation of advanced engineering skills (Blind, 2025). Engineering sovereignty refers to the ability of engineers to go beyond simple reproduction and targeted adaptation, where they must strictly and without deviation follow instructions, to genuine creation, including design, innovation, and research and development. Achieving this level of capability requires a fundamentally different type of education: engineers must be able to solve open problems through design thinking, use existing research infrastructures and, if necessary, initiate cooperation with relevant research institutions (Zhao et al., 2025).

This leads to the conclusion that meaningful industrial modernization is impossible without strong, institutionalized links between the manufacturing sector and universities. Higher education institutions, instead of functioning as isolated academic entities, should assume the role of fully integrated research centers within industrial ecosystems.

Empirical evidence supports this argument. Studies conducted in 2024-2025 (Angerott et al., 2024; Reshoring Initiative, 2025) show that the shortage of STEM specialists has become a bottleneck even for developed countries, such as the United States and Germany, in their attempts to reorient production from Asia. According to the MINT Autumn Report (Angerott et al., 2024) and the Reshoring Initiative (2025), Germany faces a shortfall of more than 200,000 STEM professionals, threatening its innovative capabilities, while the United States could face a manufacturing labor shortage of up to 3 million by 2030. Such shortages could block large-scale reorganization efforts and undermine the competitiveness of the industry.

The scale of these gaps makes it unlikely that internal learning alone can address them in the near term. A key strategic response is international certification of engineers. In modern practice, this includes recognition through the EUR ING title or accreditation under the Washington Agreement, both of which serve as mechanisms for verifying engineering sovereignty (National Society of Professional Engineers, 2025; U.S. Green Building Council, 2024). These structures enable engineers to move from local performers to internationally recognized design professionals capable of enforcing stringent safety and sustainability standards such as ASME and ISO.

F. The role of digitalization and industry 4.0/5.0 in advancing engineering education

Digitalization and Industry 4.0 by 2025 ceased to be merely "topics to be explored" and instead became a technological environment that fundamentally changes the structure of engineering education. The transition to industry 5.0, where the focus shifts to human-AI cooperation, further increases the qualification requirements for both human experience and the complexity of artificial intelligence systems (Jandieri et al., 2023; Deloitte Insights, 2025; Kavlashvili, 2026).

The emergence of automation, robotics, the Internet of Things (IoT), and cyber-physical systems has radically transformed the profile of competencies that are in demand in modern production. According to the World Economic Forum's 2023–25 Jobs Future Report, the global labor market is undergoing a structural shift. Demand for traditional, highly specialized engineering roles is giving way to hybrid profiles, such as mechatronics specialists, data engineers and industrial artificial intelligence professionals. Under these conditions, continuous professional development and retraining have become the only viable means of maintaining professional significance.

Engineering education systems that do not integrate digital competencies into the core of their curricula inevitably create skill deficits, producing graduates who are structurally and technologically unsuited to the needs of the modernized industrial sector. Skill hybridization helps bridge the gap between technical execution and compliance. For example, an engineer with expertise in data analytics and environmental management can embed ISO standards and ESG criteria into the product DNA itself during the design phase. This transforms international standards from an administrative burden to a natural competitive advantage in global markets.

The latest reports, including WEF Future of Jobs 2025 (World Economic Forum, 2025) and Stemgenic Global: Future of Jobs Report 2025 (Stemgenic Global, 2025), indicate that three competency levels will be the most important for employers in 2026-2030. These three levels are as follows:

1. *Technology Literacy and Hybridization*: Demand for AI-enabled manufacturing professionals is projected to grow 117%. This includes expanding the competencies of the digital twin, where the creation of virtual replicas of factories becomes a basic requirement for mechanical engineers and technologists.

2. *Cognitive flexibility*: Emphasis on analytical thinking and integrated problem solving in complex socio-technical ecosystems.

3. Adaptability: Lifelong learning ability and ability to work under high levels of uncertainty.

Studies (Khan et al, 2025; Naseer et al., 2025) have shown that universities which successfully integrate digital competencies have achieved a 35% higher level of employer satisfaction. This correlation suggests that, by 2026, the value of an engineering degree will be determined by the graduate's immediate operational readiness. Consequently, leading educational institutions have adopted the “Learning by Doing 2.0” model, characterized by high-fidelity immersive simulations and mixed reality (deploying 'virtual factories' and digital twins enables risk-free learning and optimisation of complex processes, significantly reducing the learning curve), as well as industry-integrated project-based learning (PBL), which uses applied industrial tasks such as IoT-based precision agriculture or intelligent network management to develop systems thinking and interdisciplinary flexibility. These events represent a fundamental paradigm shift. Digital immersion and experiential learning are no longer optional; they are fundamental elements of next-generation engineering curricula. Institutions using these hybrid models effectively protect their graduates from the future, allowing them to navigate and lead in the AI ecosystems of Industry 5.0.

G. The impact of the green transition and the role of the green economy in advancing engineering education

Climate change and decarbonization policies are reshaping key industrial sectors, including energy, transport, construction and heavy industry, creating a new demand for energy systems, environmental and sustainability engineers, as well as technological design that can reduce emissions and consumption of non-renewable resources (Jandieri, 2022; Abdelali at al., 2025; Ghazal et al., 2026). International reports on energy and climate (IEA, 2024; IRENA, 2024) emphasize that the green transition is essentially an engineering problem that requires large-scale application of technical knowledge in renewable energy, power grids, energy storage, efficiency and redesign of industrial processes.

According to the latest data from the International Energy Agency (IEA, 2024) and the International Renewable Energy Agency (IRENA, 2024) for 2024-2026, a new hierarchy of high-demand engineering professions has emerged, such as power system and network engineers, engineers of industrial decarbonization, and circular economic engineers. At the same time, energy system engineers need to integrate renewable energy variables (solar, wind) into existing power systems and develop long-term energy storage technologies; industrial decarbonization engineers must build understanding of how energy-intensive industries, such as steel and cement, shift from coal to hydrogen or renewable electricity? Circulary economic engineers must design products with full recyclability in mind, minimizing waste and maximizing resource efficiency throughout the product lifecycle.

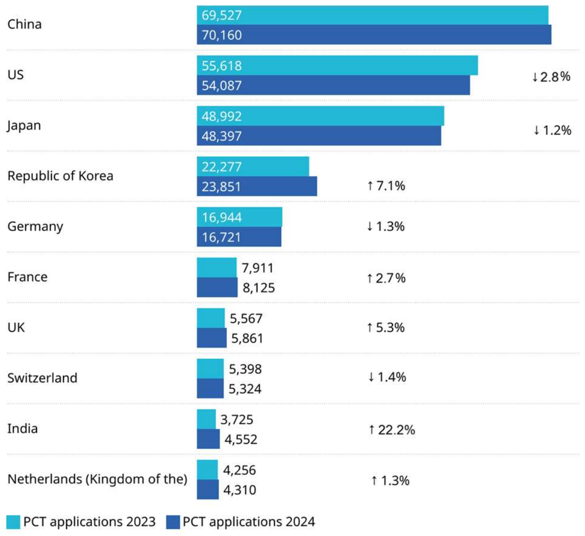
According to the latest research (Bashmakov et al., 2022; Wojtaszek, 2025; Hoving, 2025), the key competencies of Green Engineer in 2026 include several mandatory modules that did not exist ten years ago. These new competencies reflect the structural transformation of industrial systems under the pressure of decarbonization, resource efficiency, and ESG-based management. The most important profiles include:

- Life Cycle Assessment Engineers (LCAs) who are skilled in assessing the environmental impact of a product at all stages of the material cycle - from raw material extraction to end-of-life disposal. Their expertise allows companies to quantify emissions, resource use and waste generation, and to redesign products according to cyclical economic principles.

- Energy efficiency engineers capable of implementing intelligent metering systems and optimizing energy consumption through AI-based analytics These professionals play a central role in reducing operating costs, improving energy efficiency and enforcing increasingly stringent energy efficiency regulations.

- ESG compliance engineers who understand how technical solutions affect a company's non-financial reporting and how to align production processes with environmental, social and governance standards. Their role is becoming indispensable as global supply chains demand transparent sustainability metrics and verifiable compliance with international norms.

Estimates for 2025 suggest that the global economy faces a shortfall of approximately 7 million skilled technicians needed to meet Net Zero's current commitments. At the same time, more than 40% of all R&D budgets in the global automotive and energy sectors are projected to focus on environmental and sustainability-oriented innovations by 2026. The acuity of this problem is illustrated by a comparative regional analysis (Figure 2) showing China’s leadership in patent numbers, which highlights the importance of not having a staff shortage and indicates a high level of activity among engineers engaged in innovation, mainly "green" activity. Most Chinese developments focus on solar and other forms of renewable energy, while the European Union prioritizes high-tech solutions in hydrogen energy and carbon capture, use, and storage (CCUS) (World Economic Forum, 2025; IEA, 2024; International Energy Agency, 2025). The development of the latter is hampered precisely because of the aging and passivation of the engineering potential. Meanwhile, encouraging progress in engineering education is showing in India, with a 22% jump in activity.



Source: WIPO Statistics Database, March 2025.

Fig. 2. A comparative regional analysis of patent activity across the world

The scale of the global skills gap indicates that the green transition is not just a political issue, but a deep engineering bottleneck. A shortage of specialists capable of developing, integrating and supporting low-carbon technologies is slowing the deployment of renewable energy systems, electrification pathways and industrial decarbonization strategies. As a result, even countries with ambitious climate goals risk falling behind because of insufficient human capital.

H. Challenges associated with engineering skill mismatches

A well-documented illustration of the problem of skills mismatch in engineering is the phenomenon commonly known as the "paradox of unemployed engineers" (Tilak et al., 2021; New York Academy of Sciences, 2024). Several countries, including India, Egypt, Latin American states and CIS countries, have a glut of graduates from traditional engineering disciplines such as civil engineering and general mechanics who are struggling to find work. At the same time, industries in these countries report an acute shortage of engineering talents.

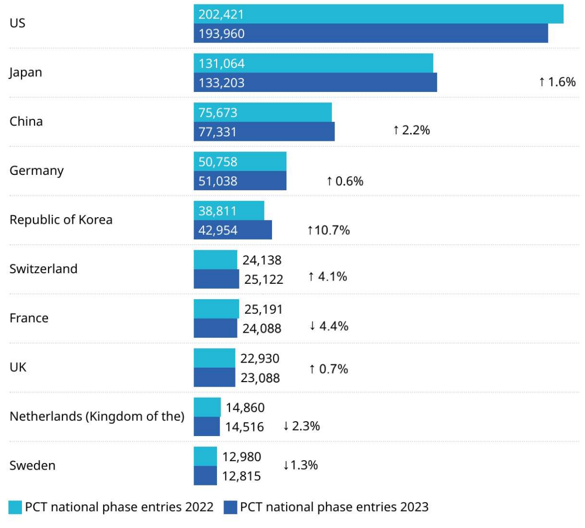
The main reason for this imbalance is the inability of universities to keep up with the real dynamics of the global labor market. Higher education institutions in these regions continue to produce so-called "universal theorists" in state-approved curricula, while the labor market increasingly requires "narrow specialists" in emerging non-traditional niches. This structural lag results in a workforce that is formally educated but not technologically suited to industrial needs.

Recent studies (Li et al., 2021; Rikala et al., 2024) show that the most serious skills mismatches occur in the following sectors: *a*) Advanced manufacturing, a critical shortage of specialists in industrial-scale additive manufacturing (3D printing) and smart production planning; *b*) Automation and control,- a growing demand for engineers capable of integrating robotics into legacy production lines; *c*) Energy systems are experiencing a constant shortage of engineers who understand the physics of distributed networks and modern energy storage systems; d) software and Data Engineering,- mechanical engineers trained in classical programs but lacking coding skills to collect and analyze data from industrial sensors and drives are becoming increasingly uncompetitive.

These mismatches create systemic constraints to industrial development: firms cannot adopt advanced technologies, graduates face unemployment despite having engineering degrees, and economies lose competitiveness in global value chains. Thus, the paradox of unemployed engineers reflects not an excess of talent, but a structural mismatch between educational outcomes and technological demand.

According to the OECD analysis (2025*b*), the main drivers of engineering skills mismatch are institutional inertia, weak signal from industry, and prestige-driven bias, which often contradicts actual labor market needs. Institutional inertia arises because traditional universities with outdated curricula face significant financial and organizational barriers to modernizing laboratories, upgrading equipment, and retraining conservative academic workforces. The weak signal from industry comes as many companies as possible struggle to articulate what skills they will need in the next five years; they often lack the foresight and analytical capacity to predict technological change. Prestige bias occurs when students choose "trendy" fields such as general computer science, artificial intelligence, robotics or data engineering, while ignoring areas of high demand such as industrial IT, mechanized systems automation and systems engineering, where salaries are often higher and competition is lower.

The combined effect results in a chronic lack of automation, a glut in traditional areas and reduced national capacity to adopt Industry 5.0. This slows down industrial modernization and weakens integration into the global economy.



Source: WIPO Statistics Database, March 2025.

Fig. 3. Number of PCT applications entering the national phase across the top ten countries of origin, 2023-2024.

By the beginning of 2026, it is obvious that an increase in the number of students without updating content leads to a decrease in profits. Countries that have successfully reoriented their engineering education to double-crossing (digital + green), such as South Korea and Singapore, exhibit GDP and productivity growth rates 2 to 3 percentage points higher than those still trapped in traditional educational models. This emphasizes that bringing education in line with technological demand is no longer just a social goal, but a strategic imperative for national survival.

To confirm the above, we can cite PCT data (Figure 3), reflecting the progress of countries in the amount of growth in patent activity. In this case, the United States is already leading in terms of the number of applications (≈ 200 000), followed by Japan (≈ 130 000), followed by China and Germany (≈ 75 000 - 50 000, respectively), but the Republic of Korea became the only country from the top twenty where there was a double-digit increase in PCT applications (+ 10.7%), which switched to the national phase.

I. Regional and sectoral imbalances in engineering skills

Despite the global surge in STEM enrollment and the expansion of engineering programs, regional and sectoral imbalances in engineering competencies remain among the most persistent structural challenges to industrial development. The shortage of engineering and technical personnel manifests unevenly, creating spatial and sectoral gaps that directly impede the competitiveness of regions, specific industries, and national economies. These imbalances demonstrate that a quantitative expansion of the STEM base does not guarantee an equitable distribution of expertise, nor does it eliminate the structural constraints inherent in diverse industrial systems.

First, the engineering talent gap is most acute in industrial clusters and secondary cities, where production facilities are concentrated but major universities or research centers are absent. These territories face chronic shortages, which constrain production expansion, hinder the adoption of new technologies, and deter investment. Consequently, a spatial divide emerges between "talent magnets" and "competency deserts."

Second, labor shortages are concentrated in high-growth sectors, such as renewable energy, advanced manufacturing, microelectronics, robotics, and ICT (Information and Communication Technologies). The pace of development in these industries significantly outstrips the capacity of educational systems to supply qualified specialists, resulting in a persistent mismatch between supply and demand. Simultaneously, foundational sectors, including traditional mechanical engineering, water resource management, waste processing, and urban infrastructure, face a "workforce graying" effect and an insufficient influx of young professionals, despite their critical role in economic stability.

Third, global migration flows exacerbate these imbalances. Skilled engineers continue to migrate to high-income countries offering advanced research infrastructure and superior working conditions. Parallel to this, the phenomenon of "virtual brain drain" has accelerated: specialists from low-income countries work remotely for foreign corporations, bypassing the development needs of local industry. This creates a double-tier gap, where countries lose both physical mobility and the participation of their best talents in local value chains.

By early 2026, these regional and sectoral imbalances will emerge as a primary structural bottleneck in the global economy. Despite record numbers of engineering graduates, their distribution remains highly skewed.

Analysis of development trends shows that the modern landscape of engineering human capital is formed by the following three interrelated factors:

1. Spatial imbalance: "Magnets" versus "Deserts": Even in industrialized countries, there is a sharp contrast associated with the formation of so-called attractive industrial clusters and secondary, less attractive cities. For example, industrial clusters and hubs such as Shenzhen (China), Munich (Germany), or Monterrey (Mexico) have begun to "absorb" global talent, creating the localized overheating of wages and associated industrial boom (König & Brenner, 2025; Mi et al., 2025; Jordaan et al., 2024). At the same time, secondary cities, i.e., "second-tier" industrial centers, began to face production stagnation due to the gradual decline in the number of skilled technicians and engineers at the higher and middle levels. To make matters worse, local university graduates have increasingly migrated to administrative capitals or technology hubs immediately after completing their degrees (Turgel et al., 2023; Demirović Bajrami t al., 2025).

2. Sectoral bias, i.e., the tendency to "noise". Engineering talent is increasingly distributed disproportionately among sectors with quick returns on investment, leaving fundamental industries relatively in short supply. Among these "neglected" sectors are traditional manufacturing, water management and waste treatment. These industries are most likely to suffer from chronic aging of the labor force (in many OECD countries, the average age of a construction engineer is over 50). Meanwhile, the "magnet" sectors are becoming ICT, renewable energy and autonomous systems. They attract much of the young talent through perceived prestige and higher pay at the primary level.

3. The global engineering migration known as "Brain Drain 2.0," which took on new forms in 2025-2026, such as physical and virtual outflow of personnel. For example, developing countries (India, Nigeria, Eastern Europe, etc.) continue to physically miss out on leading STEM specialists in favor of Germany, Canada, or the US through simplified, highly qualified visa programs (Hoppe & Fujishiro, 2025). But, in parallel also occurs so-called virtual outflow, the reason for which becomes the format of remote online work. This employment format allows engineers in emerging economies (for example, Vietnam and Kazakhstan) to service Western corporations without moving. While this is financially beneficial for an individual, it deprives local industries of the expertise needed to make domestic technological breakthroughs. The negative effects of the noted have been exhaustively reported in a study (Walsh et al., 2023).

Hence, the primary challenge in 2026 and beyond is not only generating engineers but also retaining them and strategically distributing them across regions and sectors. Nations that fail to develop localized ecosystems, including housing, infrastructure, social mobility, and quality of urban life, will lose the competition for talent, regardless of the strength of their universities.

A comprehensive policy mix is necessary to address these imbalances, which includes strategic regional planning of vocational training, stimulation of industrial clusters, strengthening of universities in Tier-2 cities, and the creation of robust incentives for talent retention. To ensure sustainable distribution of engineering competencies and support long-term industrial resilience, educational reform and spatial-economic policy must be integrated.

J. Research universities as industrial partners

High-performance engineering education systems are typically embedded within resilient, institutionalized forms of cooperation between academia and industry. In advanced innovation ecosystems, research universities are no longer viewed as autonomous educational institutions but as integral participants in industrial development, functioning as technology generators, talent incubators, and knowledge transfer platforms (Jonbekova et al.,2020).

In line with the noted Triple Helix II models, key formats for collaboration are to establish joint research centers, conduct contract research and consulting, develop new doctoral programs in industry, and create common laboratories and test sites. In this context, joint research centers could also be associations where universities and corporations address common technological challenges; Contract research and consulting should include enterprises with easy access to specialized academic expertise; Industrial PhD programs should encompass doctoral research conducted directly within a corporate environment to address applied problems, whilst shared laboratories and test facilities should refer to jointly managed infrastructure for high-precision experiments and prototyping.

These mechanisms catalyze the transition to a modern "University 3.0" model (Álvarez Torres et al., 2025), characterized by accelerated transfer of technology from laboratory to production, accelerated familiarization of students with genuine industrial problems rather than abstract academic cases, and - to align research programs with market needs, enhancing their commercial potential. There is no doubt that by 2026, this integration had moved from a strategic choice to a fundamental survival mechanism for technical universities.

In this regard, it should be emphasized that recent reports (OECD, 2025c; Lutchen, 2024; Li et al., 2023; BMWK, 2025; Cunningham et al., 2025; Compagnucci et al., 2025; Compagnucci & Spigarelli, 2025) have revealed the following three transformative trends:

1. *Joint laboratories and innovation testbeds*: Rather than procuring equipment in isolation, universities establish alliances with industrial giants, e.g., Siemens-TU Munich, Apple-

MIT (Elia et al., 2021; Fraunhofer, 2024). This provides universities with access to cutting-edge instrumentation they could not otherwise afford, while businesses gain access to "fresh intellectual capital" and the ability to test prototypes without disrupting primary production lines. Representatives from those participating companies serve on ongoing advisory boards charged with providing real-time input on the critical technological skills students will need in their careers. They also help educators make sure curricula evolve as technologies evolve (Lutchen, 2024).

2. The rise of the industrial PhD: This format emerged as a highly effective instrument during 2024-2025: doctoral candidates develop their dissertations while simultaneously solving specific applied tasks for industrial partners (Compagnucci et al., 2025; Compagnucci & Spigarelli, 2025).

In the early 2000s, the first author of this study was among the pioneers of the Industrial PhD model in Georgia, conducting applied research under the auspices of Kutaisi State Technical University and implementing findings directly at the production sites of the Zestafoni Ferroalloy Plant (Dzhandieri, 2005; Dzhandieri et al., 2007; Dzhandieri et al., 2009).

International evidence suggests that Industrial PhD programs significantly enhance the integration of early-career researchers into production processes (Boman et al., 2026). Notably, approximately 85% of participants remain with the partner company post-completion, directly mitigating the high-level skill shortage and cultivating a sustainable pool of R&D leaders.

3. Technology transfer and SME consulting: Universities are increasingly serving as R&D departments for Small and Medium Enterprises (SMEs) that lack internal research capabilities (Sarpong et al., 2025). By 2025, the share of extra budgetary income for leading engineering schools derived from industrial contracts reached 30-40% (CESAER, 2025). This dual-benefit model ensures financial sustainability for the university while driving long-term technological progress for the industrial sector (Jin et al., 2026).

All the aforementioned processes, - the surge in technology transfer, the expansion of contract research, and the proliferation of industrial PhDs and joint laboratories, converge into a defining trend for the 2026-2030 period: the emergence of "Regional Innovation Hubs.

Governments in leading economies (EU, China, USA) are shifting from supporting isolated academic institutions toward funding integrated consortia that unite universities, major industrial enterprises, and networks of technology startups. This model fosters a "dense" innovation environment where scientific inquiry, engineering development, and production competencies coexist within a single functional space. Consequently, the trajectory from fundamental research to industrial implementation is compressed from the traditional 3-7 years to a matter of months.

Regional innovation hubs are becoming more than just infrastructure; they are a new type of industrial organization that facilitates faster technology transfer, fosters technological entrepreneurship, and enhances national industrial competitiveness. It follows that a university operating in isolation by 2026 and beyond will be increasingly categorized as obsolete. The success of modern engineering education will be no longer measured primarily by publication volume, but by the quantity of implemented patents and the viability of technological spin-offs (startups emerging from the academic environment).

K. Features of project-based learning and real-world problem solving

Pedagogical approaches also play a pivotal role in shaping the engineering competencies required for the modern industry. Leading global universities and engineering schools are transitioning from traditional lecture-based formats to Project-Based Learning (PBL) and Problem-Based Learning (PrBL). These methods achieve maximum efficacy when implemented in close synchronization with corporate and industrial partners (Lavado-Anguera et al., 2024).

Such formats enable students to develop not only the systems thinking required to understand and manage complex industrial and technological ecosystems, but also skills in interdisciplinary collaboration (for example, integrating knowledge from fields such as mechanics, electronics, programming, materials science, ecology, and economics) and practical skills for solving engineering problems, including diagnostics, optimization, prototyping and the seamless implementation of technologies.

By shifting the focus from passive content absorption to active inquiry, PBL and PrBL foster a "Learning-by-Doing" environment. This environment is critical for the Industry 5.0 era, where engineers must not only possess technical mastery but also the cognitive agility to address unstructured industrial challenges. It is therefore logical that, according to source (O'Connor et al., 2026), by early 2026, PBL had moved beyond the realm of a pedagogical experiment to become the “gold standard” of engineering education, based on the following three transformative changes in the approach to developing engineering competencies:

a) From "Formula" to "System" (System Thinking): In classical education, students typically solve problems with a single correct answer. In contrast, real-world projects are perpetually constrained by budgets, timelines, environmental regulations, and material properties. The primary outcome of PBL is a graduate who understands how a change in a single component affects the entire ecosystem. For instance, reducing a vehicle's chassis weight is analyzed not just as a mechanical task, but through its impact on handling, energy efficiency, maintenance costs, and market viability.

b) Interdisciplinarity as the Norm: Modern engineering challenges, such as the development of industrial drones, require the simultaneous input of mechanical engineers, software developers, industrial designers, and economists. By forming project groups that simulate actual corporate departments, universities create the only viable environment for developing "soft skills", i.e., high-level communication and the ability to integrate insights from diverse technical fields.

c) Industry-Driven PBL (Corporate Collaboration): The most successful cases of 2024-2025 involve companies bringing "raw" industrial problems to the university, - challenges that the company itself could not solve rapidly.

This collaboration offers a twofold benefit. Firstly, students gain genuine practical experience by grappling with real-world production constraints, technical uncertainties and professional responsibilities. This enables them to transition from the role of passive learners to that of junior engineering consultants. Secondly, there are benefits for industry partners, who gain a “fresh perspective” on intractable technical problems and gain direct access to a pre-vetted talent pool. This integration effectively eliminates the traditional six-month retraining and adaptation period, as graduates are already aligned with the company’s specific technology stack and corporate workflow from the outset.

Project-based learning (PBL) ultimately contributes to the development of high-level professional resilience and cognitive strategies, which include: *a*) resilience to setbacks when a project encounters technical or systemic obstacles (in such cases, students learn to change their approach and seek alternative solutions rather than getting bogged down in the problem, which is a crucial trait for the R&D sector); *b*) information literacy and rapid data synthesis (in the digital landscape of 2026, the aim is not to memorise reference books, but to master the art of “smart searching”, that is, to effectively locate, filter and verify complex data for engineering calculations); and *c*) professional conviction (technical communication), where an engineer must possess sufficient presentation skills to effectively and intelligently “sell” a technical solution to management or clients, bridging the gap between engineering complexity and business value.

Based on this comprehensive analysis, it can be argued that by 2026 and in the medium term, a successful engineering environment will be shaped by three complementary elements: *a*) quantitative and qualitative indicators of workforce training, i.e. the number and level of training of graduates; *b*) the relevance of knowledge, i.e. the relevance and alignment of study programs with the requirements of digital and 'green' transformation; and *c*) education integrated with the needs of industry, with strong practical links through PBL models, dual education formats, and partnerships with industry.

The collapse or absence of any single corner of this triangle can transform engineering education into an expensive but low-efficiency process. Without this balance, the system becomes incapable of generating either innovative technological solutions or sustainable industrial advantages for the nation.

IV. Effective pathways for modernizing engineering-focused stem education

A. Integrating engineering skills into industrial policy

The experiences of nations that have successfully modernized their industrial bases, such as the Republic of Korea, Singapore, Taiwan, and Finland, demonstrate that engineering education must not be treated as an autonomous academic sphere, but as an indispensable element of national industrial strategy (OECD, 2023; Shin, 2025). In these states, the training of engineering and technical personnel is embedded within long-term industrial development plans. Consequently, educational policy is formulated in tight synchronization with the priorities of technological and digital transformation, the advancement of high-tech sectors, and the strengthening of the national innovation ecosystem.

Key elements of such comprehensive strategies include: a) the targeted expansion of engineering programmes in strategic sectors, which involve concentrating resources on critical areas such as semiconductors, advanced energy technologies, precision engineering, robotics, biotechnology, and digital manufacturing; b) linking government scholarships and grants to specific sectors, which involve providing financial incentives tied to priority sectors to ensure a steady influx of high-calibre specialists into high value-added sectors; c) joint funding of research centres bringing together universities and industry, ensuring the establishment of collaboration centres where students, engineers, and researchers tackle real-world industrial challenges, blurring the boundaries between academia and industry; and d) long-term strategic planning of human resources, aligning the supply of engineering personnel with technological forecasts and sectoral roadmaps to prevent a future structural shortage of qualified specialists.

To ensure that the set objectives are achieved, according to sources (OECD, 2023; Shin, 2025; Center for Strategic and International Studies, 2025; Ministry of Digital Development and Information, 2024; ICEF Monitor, 2025*b*; Ministry of Education Singapore, 2026), by early 2026 the leading industrialized nations had established four clearly defined strategic priorities: *a*) Targeted expansion of priority sectors; *b*) Strategic scholarship models for talent retention; *c*) Co-financing R&D and the "green-digital twin transition"; and *d*) Long-term planning and the "t-shaped" professional modern.

As part of a targeted approach to developing priority sectors, the government is moving away from a general increase in student intake towards a system of “strictly linking” university quotas to projected industrial needs for the period 2025–2030. Real-time labor monitoring systems now adjust training quotas in strategic fields such as next-generation semiconductors and biopharmaceuticals. Under the 2024–2028 Master Plans, these nations are directing multi-billion-dollar investments into the "cultivation" of engineers specialized in Smart Manufacturing, AI Infrastructure, and Next-Gen Intelligent Chips (OECD, 2023; Shin, 2025).

As part of the development of strategic scholarship models designed to retain talent, financial support for students must become a long-term geopolitical tool. For instance, South

Korea's "Study Korea 300K" initiative aims to attract and critically retain 300,000 international STEM students by 2027 through simplified residency pathways for high-tech graduates (Center for Strategic and International Studies, 2025). The 47% growth in international student enrollment over the past two years demonstrates the efficacy of this retention-led strategy. Similarly, Singapore's 2025 expansion of WSQ (Workforce Skills Qualifications) supports technical institute graduates with direct training subsidies aligned with national competency standards (Ministry of Digital Development and Information., 2024).

As part of the initiative for co-funding R&D and the "transition to environmentally friendly digital twins", industrial subsidies are now to be allocated on a "hand-in-hand" basis, i.e. support for industry must be accompanied by investment in education. For example, in 2025, Finland launched a €400 million decarbonization scheme where grant eligibility requires the development of new staff competencies and collaboration with research centers. Finland leads in integrating micro-credentials into Vocational Education and Training (VET), allowing "green" and digital skills to be rapidly injected into classic engineering profiles (Ministry of Digital Development and Information, 2024; ICEF Monitor, 2025*b*).

In turn, as part of a long-term planning approach and the concept of the "T-shaped" professional, STEM policy is gradually shifting its focus from training narrowly specialised technical professionals to developing "T-shaped" competencies (ICEF Monitor, 2025b; Ministry of Education Singapore, 2026). This approach emphasizes deep technical expertise (e.g., AI, Cybersecurity) combined with broad cross-functional skills (e.g., systems thinking, technology ethics, and professional communication). Furthermore, this model incorporates Continuous Skill Recalibration. In the 2026 landscape, an engineer's education does not end with a diploma; rather, the T-shaped profile is maintained through lifelong learning pathways. Professionals are encouraged to return to Regional Innovation Hubs every 3–5 years to update their skills in response to new technological disruptions, ensuring that human capital remains as dynamic as the industry itself.

The trends outlined above clearly indicate that future economic success belongs to nations where the Ministry of Industry and the Ministry of Education operate as a unified talent management body. This integration ensures that every dollar invested in education is converted into patents, technological spin-offs, and high-value jobs in strategic sectors. By 2026, the benchmark of a successful educational system is its ability to function as a seamless R&D arm of the national industrial strategy.

B. The early forecasting model for industry-relevant competencies (EFM-IC): A conceptual framework

Effective alignment of engineering education with industrial demands is impossible without systemic and regular skills forecasting. In an era of rapid technological progress and accelerating innovation cycles, traditional planning methods based on historical statistics or static expert opinions have become insufficient. By 2026, leading economies are transitioning to data-driven forecasting models rooted in Big Data analytics, intelligent labor market monitoring, and the active participation of industrial stakeholders (OECD, 2025*d*; Ministry of Economic Affairs and Employment, 2025).

Recent studies and international reports (Ministry of Education Singapore, 2026; OECD, 2025*d*; Ministry of Economic Affairs and Employment, 2025; Chikasha et al., 2020; European Education Area, 2024; World Economic Forum, 2025; Udemy Business, 2026; Cedefop, 2025*a*; Cedefop, 2025*b*; Hyndman et al., 2021) indicate that this transition requires the following instruments:

- Dynamic labor market research, - utilizing employer surveys and real-time data to identify immediate and emerging deficits in engineering and technical competencies.

- Sectoral skills councils - institutional platforms uniting employers, universities, TVET providers, and government agencies to co-define workforce development priorities.

- Medium- and long-term predictive modelling, - forecasting demand based on industrial trajectories, patent trends, and global socio-economic data.

These instruments empower governments and educational institutions to calibrate student enrollment in accordance with future sectoral needs, update curricula to reflect actual technological shifts, direct strategic investments toward high-growth competency domains, and preemptively mitigate structural skill shortages and regional imbalances.

It is evident that from 2026 onward, data-driven forecasting will become the standard approach for synchronizing engineering education with industrial development. This shift is characterized by the deployment of intelligent monitoring systems that leverage Big Data analytics of job vacancies and Artificial Intelligence to provide real-time, actionable insights into the global engineering talent landscape.

With the aim of bridging the structural gap between research outcomes and the growing demands of Industry 5.0, the authors of this study propose a multi-layered graphical model for the early forecasting of competencies required in industry (EFM-IC). The model is presented as a conceptual circular structural diagram and is illustrated in Figure 4.

The presented EFM-IC model is more than just another employer survey; it creates a Hybrid Predictive Loop that aligns educational recalibration with technological maturation cycles.

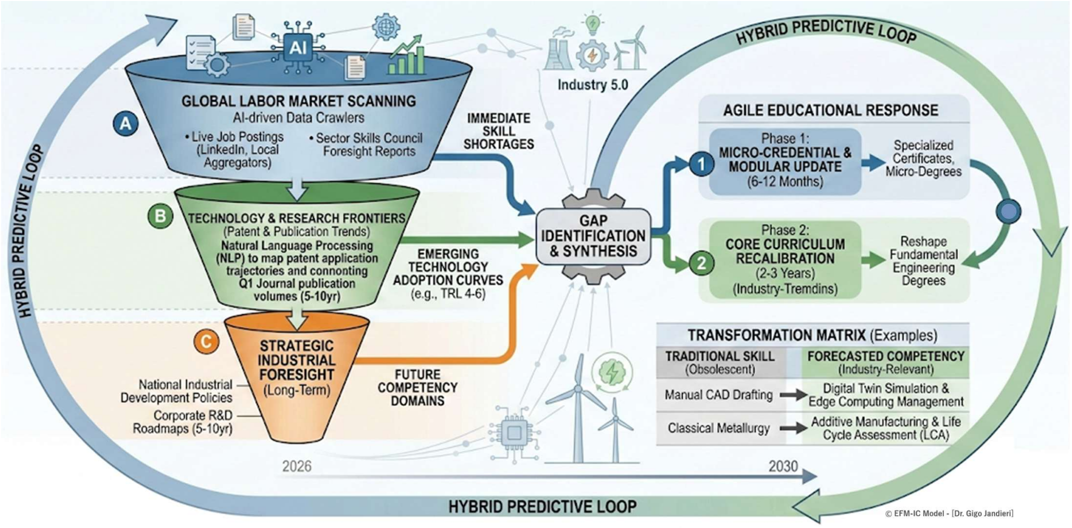
The model’s architecture is predicated on the integration of three distinct temporal data streams:

Layer A: Real-time labor market intelligence. Utilizing AI-driven natural language processing (NLP) and data crawlers, this layer scans global and local job aggregates (e.g., LinkedIn, Glassdoor) and Sector Skills Council reports. This provides high-velocity data on immediate skill shortages and shifting job descriptions.

Layer B: Technology and research frontiers. This layer monitors "Leading Indicators" of industrial change by analyzing patent application trajectories and publication volumes in Q1 scientific journals. By identifying surges in specific domains (e.g., solid-state electrolytes or neuromorphic computing) at Technology Readiness Levels (TRL) 4-6, the model anticipates mass-market competency demands 3–5 years before they materialize.

Layer C: Strategic industrial foresight. This top-down layer integrates long-term national industrial policies and corporate R&D roadmaps, defining the future competency domains required for sovereign technological development and the Green-Digital "Twin Transition."

At the core of the EFM-IC is a synthesis engine (Gap Identification and Synthesis Engine) that correlates the aforementioned data streams to identify "Competency Deviations." This engine utilizes a Transformation Matrix to map the obsolescence of traditional skills against forecasted high-value competencies. For example, the transition from Manual CAD Drafting to Digital Twin Simulation and Edge Computing Management is flagged as a critical curriculum update trigger.



TRANSFORMATION MATRIX (Examples)

TRADITIONAL SKILL (Obsolescent)	FORECASTED COMPETENCY (Industry-Relevant)
Manual CAD Drafting →	Digital Twin Simulation & Edge Computing Management
Classical Metallurgy →	Additive Manufacturing & Life Cycle Assessment (LCA)

Fig. 4. Early forecasting model for industry-relevant competencies

The model on Figure 4 operationalizes its findings through a bifurcated implementation strategy:

Phase 1: Rapid modular integration (6-12 months). Upon detection of a high-growth competency, the system triggers the development of Micro-credentials and modular certificates. This allows for an immediate infusion of relevant skills into the workforce without waiting for full degree re-accreditation.

Phase 2: Core curriculum recalibration (2-3 years). Sustained trends identified by the funnel are used to fundamentally reshape core engineering degrees, ensuring that foundational STEM education remains aligned with the long-term industrial trajectory.

Based on the conceptual forecasting approach described above, it is evident that the proposed EFM-IC model possesses the potential to fundamentally transform the paradigm of engineering education, shifting it from a state of "institutional inertia" toward "anticipatory governance." By establishing this continuous, data-driven feedback loop, higher education institutions can transcend their traditional roles and evolve into proactive R&D hubs. Consequently, such centers will acquire the strategic capabilities necessary to sustain national industrial competitiveness amidst the structural volatility and rapid technological transitions anticipated throughout the 2026-2030 period.

C. Strengthening synergy between TVET and higher education

Recent research (Farran & Nunez, 2025) confirms that strengthening the linkages between Technical and Vocational Education and Training (TVET) and Higher Engineering Education is becoming a fundamental prerequisite for cultivating a holistic and resilient industrial skills ecosystem. In nations aiming to accelerate industrial modernization, these synergies are viewed as a strategic instrument to bridge the gap between technical and conceptual competencies, ensuring maximum flexibility in career trajectories.

The development of integrated TVET-university pathways will contribute both to the creation of flexible pathways enabling qualified technical specialists to transition to professional engineering roles without devaluation or loss of accumulated practical experience, and to the provision of a continuous infrastructure for upskilling, enabling the workforce to rapidly master new technologies as they are introduced into production. Furthermore, such a development scenario will also contribute to the formation of industrial environments in which technical and engineering levels will no longer be isolated "silos» but will constitute complementary components capable of preventing the fragmentation of national competencies.

The traditional, rigid dichotomy between the "vocational diploma holder" and the "university-educated engineer" has emerged as a primary bottleneck for industrial innovation. Leading global systems in 2025–2026 have addressed this by implementing the following strategic mechanisms:

1. Vertical mobility and the career "Upgrade". Advanced educational frameworks have institutionalized the transition from technician to engineer without temporal loss. This is operationalized through Recognition of Prior Learning (RPL), where industrial shop-floor experience and TVET competencies are converted into ECTS (European Credit Transfer and Accumulation System) credits. This reduces university residency by 1-2 years. Implementation of "2+2" or "3+1" articulation agreements, where students obtain practical certifications at the college level before seamlessly transitioning to a Bachelor of Engineering (B.Eng.) program.

2. Lifelong learning: dynamic upskilling and reskilling. With technical skillsets currently facing a 5-year half-life in Industry 4.0 environments, the fluidity between TVET and universities facilitates continuous workforce recalibration (Upskilling): Practicing engineers return to technical colleges to master specific high-tech tools (e.g., programming collaborative industrial robots). Mid-level technicians can pursue modular university education in Industrial Data Management or Digital Twins without exiting the workforce (Reskilling).

3. The "Full-Stack" talent ecosystem. Open pathways generate a "full-stack" of specialists who share a common technical language, yielding two critical advantages:

3.1. Elimination of Professional Elitism: Engineers with TVET backgrounds possess a superior grasp of real-world manufacturing constraints, leading to a significant reduction in design-to-production errors.

3.2. Technological Coherence: Synchronizing curricula ensures that the software and hardware utilized in colleges and universities are identical. This establishes a national technological standard, drastically lowering the total cost of system maintenance and industrial integration.

Comprehensive data, from enrolment surges to integration policies, underscores that the success of future industrial policy will be measured by the quality and agility of human capital, rather than mere headcount.

In light of the above, it can be confidently stated that, at the current stage of global development, engineering is no longer a static profession. It is evolving into a dynamic ecosystem based on the following four pillars: 1. Digitalization (the integration of artificial intelligence, big data and robotics); 2. Green transformation (a focus on environmental sustainability and energy efficiency); 3. Structural flexibility (a seamless link between vocational and technical education and training and higher education); and 4. Practical orientation: the widespread adoption of project-based learning (PBL) and dual education models.

D. Implementation of Continuous Engineering Education Systems

Given the current velocity of technological change, the traditional model of "one-time education for life" has ceased to align with industrial reality. An engineering career spanning 30-40 years can no longer rely solely on initial university training. As technological cycles now renew every 2-3 years, key competencies face rapid obsolescence. Consequently, modern advanced engineering training systems should be designed to provide continuous professional development (CPD), closely integrated with the professional career, modular upgrading programs, enabling rapid adoption of new technologies without long-term absence from the workplace and a flexible system of micro-certification, specializing in high-demand areas such as artificial intelligence, digital duplicates, robotics, ESG engineering, and cybersecurity.

The peculiarities and advantages of implementing the noted approaches to the system of continuous education have been thoroughly described in research (Soeiro, 2022; de Boer, 2025; Sanchez Barrioluengo, 2025). The studies noted show that expanding continuous learning opportunities can develop skills to master such flexible mechanisms of accumulation and retention of relevant knowledge, as a custodial finding of effective channels of communication with the possibility of harmonizing strategies for crisis management, timely development of plans to respond to all types of disruptions in the production process, Adequate digital infrastructure with at least basic digital literacy, etc. With a CPD system, the economic resilience of institutions is increased, which in turn, as a feedback note, demonstrates a strong sense of community among staff and students, providing further support for the professional development of their staff, increasing their motivation and conditions of work.

Nations that fail to establish institutional mechanisms for lifelong learning (LLL) will inevitably face chronic deficits in engineering competencies and a stagnation of industrial modernization. The absence of systemic LLL solutions will lead to a workforce unprepared for the integration of digital, automated, and green technologies, thereby capping productivity and eroding national industrial competitiveness.

Conversely, countries that successfully build Lifelong Learning Ecosystems, integrating the TVET sector, universities, industrial competency centers, micro-credentials, and corporate academies, will secure a strategic advantage. Such ecosystems will foster the development of a broader and more dynamic talent pool, accelerate the spread of innovation, and ensure industrial resilience in the midst of upcoming technological disruption.

Thus, the LLL approach is evolving from a mere educational STEM paradigm into a fundamental element of national industrial policy. It is the primary determinant of a country's capacity to adapt to the twin challenges of digital and green transformation. Looking ahead to 2026-2030, the ability of engineers to "retrain" will undoubtedly become one of the most important building blocks in the chain of ensuring and maintaining successful and sustainable industrial sovereignty.

E. Integrating equity and inclusivity into engineering-focused STEM education

Global data (UNESCO, 2024; OECD, 2025*b*; Royal Academy of Engineering; 2022) consistently indicate a significant underrepresentation of women and specific social groups within engineering disciplines. This disparity is not merely a matter of social justice, it is a critical factor limiting the available talent pool necessary for robust industrial development.

Accumulated practical experience, as reflected in the noted sources, shows that such a lack of inclusivity can lead to a diminished total workforce, a loss of the cognitive diversity essential for innovation, exacerbated regional and sectoral imbalances, and reduced efficiency of state investments in education.

Addressing these challenges requires a comprehensive set of measures to address systemic barriers and increase participation by both women and young people, who are also a vulnerable group in STEM education. Of these measures, three can be distinguished for their importance and practical value: *a*) Promotion of initial vocational guidance through the development of programs specifically aimed at young women and adolescents from lower socioeconomic backgrounds. These programs should promote early interest in engineering, break existing gender stereotypes and boldly demonstrate viable career paths in STEM; *b*) Create targeted financial incentives for scholarships and grants, target underrepresented groups; and *c*) Develop inclusive educational environments that ensure appropriate adaptation of curricula in universities and TVET institutions to include mentorship programs, Educating teachers on diversity and a culture of mutual respect. There is no doubt that such measures are vital to reducing dropout rates among minority students.

The implementation of the above measures could help to remove hidden barriers, which are a source of unconscious bias in teaching practice, and overcome the outdated dichotomy between "male" and "female" professions. This also involves promoting diverse role models and collaborating with employers to create inclusive career pathways.

Such inclusion strategies will enable companies and educational institutions to significantly expand their talent pool, alleviate chronic labor shortages, and enhance the adaptability of teams by drawing on a wide range of previously untapped life experiences and cognitive approaches to stimulate the emergence of the breakthrough ideas needed to solve complex problems.

The proposed transformative shift in the organizational culture of engineering education will directly strengthen the macroeconomic stability of the interconnected and, consequently, interdependent education-industry complex.

In its quest to ensure equality, the engineering sector must undoubtedly go beyond mere compliance with social norms in order to secure the long-term sustainability, enhanced innovation capacity and structural growth necessary for prosperity in the period 2026–2030. In this context, workforce diversity must cease to be an optional or "non-essential" value, it must become the primary driving force behind national technological sovereignty.

Here, we must not forget that measures to protect against global competition for engineering talent must become an integral part of national industrial policy. As noted above, it is no longer enough simply to train engineers – the state must create a "talent retention ecosystem" comprising lifelong learning opportunities, attractive career paths, competitive working conditions, a well-developed research infrastructure, and incentives for domestic high-tech enterprises. Such measures are necessary not only to mitigate the effects of the "brain drain", but also to strengthen national human capital in the face of growing international demand.

In the era of global talent volatility, countries that fail to invest in the holistic retention and development of their engineer's risk being relegated to the technological periphery, becoming mere consumers of innovations created elsewhere (Center for China and Globalization, 2025; World Bank, 2023).

V. A multidimensional framework for engineering education transformation

The cumulative evidence of this study indicates that the modernization of engineering education cannot be achieved through isolated curricular updates. Instead, it requires a fundamental shift toward engineering- focused STEM Education. This approach positions engineering as the primary integrative discipline that translates scientific discovery into industrial innovation. As synthesized in the framework below (see Table 1), this transition is a multilevel institutional process. It necessitates the convergence of national strategic planning (Macro-level), university–industry operational synergy (Meso-level), and the dynamic integration of emerging competencies into the pedagogical process (Micro-level). By aligning these dimensions, engineering education transcends its traditional role, becoming a foundational pillar of national technological sovereignty.

Table I: Systemic conditions for engineering-focused stem education transformation

Systemic Condition	Key Transformation Mechanism	Level of Implementation	Strategic Objective
Strategic Alignment	Synchronizing enrolment quotas with industrial priorities.	National / Macro	Elimination of labour market structural imbalances.
University–R&D Hubs	Deployment of Industrial PhD programs and Shared Labs.	Institutional / Meso	Closing the theory-practice gap via applied innovation.
Twin Transition Skills	Integration of Digital (AI) and Green (ESG) competencies	Curricular / Micro	Ensuring workforce readiness for the dual transition
Seamless Continuum	Integration of TVET and Higher Ed via micro-credentials	Systemic / National	Enabling lifelong professional mobility and agility
STEM Pipeline Expansion	Inclusive talent attraction and regional life ecosystems	Regional / Social	Securing a sustainable and diversified talent pool
Predictive Forecasting	Institutionalizing Data-Driven foresight and Big Data	State / Regulatory	Proactive and agile curriculum recalibration

According to the multi-level framework presented in Table 1, the transition to the “Industry 5.0” landscape requires a move away from traditional, passive models of education. The research confirms that engineering-focused STEM Education serves as the vital link between theoretical knowledge and industrial application, forming the backbone of national technological autonomy. In this context, the engineering component of STEM acts as the catalytic force that transforms scientific inquiry into resilient industrial solutions.

By institutionalizing the five systemic conditions identified in this study (sections 4.1–4.5), by focusing on the particularly important stages of data-driven skills forecasting and the integration of seamless pathways from traditional vocational and technical education to continuous, inclusively expanded higher STEM education, countries can move beyond simply producing graduates and transition to the development of high-quality human capital capable of responding in a timely manner to the challenges of Industry 5.0. Ultimately, such a strategic reorientation ensures that the engineering ecosystem will function not merely as a passive academic subsystem, but as a key structural mechanism that ensures technological sovereignty and creates the conditions for sustainable competitiveness in an increasingly volatile global economy.

Conclusions

The transition from Industry 4.0 to 5.0 requires a decisive shift away from traditional, isolated academic models towards an integrated and adaptive, industry-relevant ecosystem capable of evolving in step with current and future technological and industrial changes.

In a paradigm defined by human-machine complementarity and the strategic coupling of digital and human capabilities, expanding university enrollment alone can no longer serve as a meaningful driver of industrial development. Without sustained alignment with industry needs and continuous curricular recalibration, engineering education risks devolving into a credential-producing system detached from economic reality.

Engineering-focused STEM education, in response to the challenges of the modern world, is becoming a key link between scientific knowledge and industrial application. Within this interface, the engineering component functions as the catalytic mechanism that transforms research into resilient, scalable, and context-specific industrial solutions. As global competition for talent intensifies, processes such as inclusivity expansion, lifelong learning, micro-credentialing, and vertical mobility must be understood not as peripheral trends but as structural imperatives for sustainable industrial transformation. Likewise, modular and flexible programs that cultivate T-shaped STEM competencies will become essential for building a workforce capable of navigating the complexity of Industry 5.0.

To bridge the widening digital and environmental divide, a systemic approach is required rather than a fragmented one. The following three interdependent conditions therefore need to be met:

1. Strategic realignment at the macro level to ensure that engineering talent pipelines are synchronized with national industrial priorities.

2) Institutional integration at the meso level, where universities evolve into applied R&D hubs supported by industrial PhD programs and shared laboratories.

3) Pedagogical evolution at the micro level, eliminating the digital–green skills gap and establishing seamless TVET–higher education pathways that support lifelong professional adaptability.

A further shift from reactive planning to proactive, evidence-based forecasting is essential. Integrating big data analytics of labor markets, real-time monitoring of job vacancies and continuous tracking of innovation and patent activity will allow education systems to predict rather than simply react to industrial change.

Once early forecasting mechanisms and deep industrial integration become embedded within the educational environment, the alignment of human capital with Industry 5.0 will transcend conventional workforce development and emerge as a matter of national strategic security. In this context, the cumulative effect of targeted reforms will not only strengthen technological sovereignty but also convert academic achievements into durable industrial capital, laying the foundation for long-term economic resilience.

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ინჟინერიაზე ფოკუსირებული STEM განათლების ტრანსფორმაცია სწავლებისადმი არსებული მიდგომის „Industry 5.0“ პარადიგმასთან შესაბამისობის უზრუნველსაყოფად

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ანოტაცია

მსოფლიო ეკონომიკის წინაშე მდგარი მუდმივად მზარდი გამოწვევების პირობებში ინჟინერიაზე ფოკუსირებული STEM განათლება სულ უფრო ხშირად განიხილება სახელმწიფოებრივი რანგის გადამწყვეტი მნიშვნელობის მქონე სტრუქტურული ფაქტორის რანგში, რომელსაც რეალურად ძალუძს არსებითი გავლენა იქონიოს სახელმწიფოს ინდუსტრიული დინამიკის, პროდუქტიულობისა და ტექნოლოგიური განვითარების ტრაექტორიების მართებულ ჩამოყალიბებაზე. თანამედროვე ინდუსტრიის ახალი რევოლუციური პარადიგმის „Industry 5.0“ პირობებში, რომლის ერთ-ერთ საკვანძო მახასითებელს ადამიანსა და მანქანას (ციფრულ სამყაროს) შორის კომპლემენტარობის მოთხოვნა წარმოადგენს, სახელმწიფოს კონკურენტრუნარიანობის უზრუნველყოფის ერთ-ერთ მთავარ წინაპირობად სწორედ, რომ საინჟინრო განათლების გათანამედროვებისა და არსებულ რეალიებთან სტრატეგიული შეთანხმებულობის ამოცანის გადაჭრა გვესახება. ამდენად, წინამდებარე კვლევაში წარმოდგენილია მოწინავე სახელმწიფოთა ინდუსტრიული განვითარების, მსოფლიო ბაზრის მოთხოვნებთან შეთანხმებულობისა და მართვის შესაბამისი ფუნდამენტის უზრუნველმყოფი საგანმანათლებლო-საკადრო პოლიტიკის პროდუქტიულობათა შედარებითი ანალიზი, განიხილება ინჟინერიაზე ფოკუსირებული STEM კადრების პროფესიულ-ტექნიკური განათლება-გადამზადების (TVET) აქტუალური საკითხები. არგუმენტირებულად საბუთდება საგანმანათლებლო სასწავლებლებსა და მრეწველობის ობიექტებს შორის თანამშრომლობის ახალ, უფრო პროდუქტიულ ინსტიტუციონალურ რანგში აყვანის აუცილებლობა. გამოკვეთილია საუნივერსიტეტო საინჟინრო განათლების ტრანსფორმაციის, კერძოდ კი - ნეიტრალური, სრულებით დამოუკიდებელი აკადემიური სისტემიდან, ქვეყნის სამრეწველო-სტრატეგიული განვითარებისათვის ხელშემწყობ ინსტრუმენტად გარდაქმნის მიზანშეწონილობა, რისთვისაც შემოთავაზებულია სწავლების პროცესში ისეთი ახალი კომპონენტების გათვალისწინება, როგორებიცაა ინკლუზიური და დივერსიფიცირებული STEM განათლების დანერგვა, ციფრული და მწვანე ტექნოლოგიების განვითარების უნარების მქონე, ადამიანური კაპიტალის დივერსიფიცირებული განვითარება, არსებული

სასწავლო-სამეცნიერო და/ან ლაბორატორიული ბაზების გამოყენებითი კვლევების R&D ინოვაციების ჰაბებად გარდაქმნა, საინჟინრო კომპეტენციებზე ფაქტობრივი მოთხოვნების, ცვალებადობის წინმსწრები პროგნოზირების მეთოდოლოგიების დამუშავება და ინსტიტუციონალიზაცია. ყოველივე აღნიშნულის საფუძველზე გამოტანილია დასკვნა, რომ ინჟინერიაზე ფოკუსირებული STEM განათლების შემოთავაზებული მოდერნიზებული მოდელი, პრაქტიკულად ნებისმიერი სახელმწიფოსათვის შეიძლება გახდეს არა მხოლოდ ტექნოლოგიური სუვერენიტეტის ან ინდუსტრიული ავტონომიის უზრუნველყოფის ერთგვარი გარანტი, არამედ შესძინოს მათ ადაპტაციური შესაძლებლობები „Industry 5.0“ ახალ ინდუსტრიულ ლანდშაფტში სრულფასოვანი გაწევრიანებისათვის.