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# AN INTERNATIONAL VIEW OF STEM EDUCATION

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## ABSTRACT

Science, technology, engineering and mathematics (STEM) education and research are increasingly recognized globally as fundamental to national development and productivity, economic competitiveness and societal wellbeing. There has been a global turn to STEM that is clearly evident in government efforts worldwide to elaborate STEM policy governing school science and mathematics, and tertiary level education and research in the STEM disciplines. This shift is also reflected in emerging research priorities that are most frequently conceived in STEM terms, underpinned by commitments to internationalization and multidisciplinarity. This chapter explores STEM policies and programs from an international perspective extending from the Anglosphere, East Asia, Western Europe and Latin America to the Middle East. We identify discernible trends and parallels regarding government STEM policy and structural responses, school and tertiary level STEM education participation, comparative performance measured by international assessments such as PISA and TIMMS, STEM research and innovation, and issues concerning gender and under-represented groups. The chapter examines various programs and solutions including school-level curriculum and pedagogy reform to enhance science and mathematics participation and performance, teaching-related initiatives, and strategies at the tertiary-level to redress current systemic disparities.

## PREVIOUS LITERATURE:

Science, technology, engineering and mathematics (STEM) education and research are increasingly recognized globally as fundamental to national development and productivity, economic competitiveness and societal wellbeing (Marginson et al., 2013). There has been a global turn to STEM (Freeman, Marginson & Tytler, 2015) that is clearly evident in government efforts worldwide to elaborate STEM policy governing school science and mathematics, and tertiary level education and research in the STEM disciplines. In recent years awareness of the ubiquity and impact of technology has grown as the influence of artificial intelligence, automation and big data on the world of work is imagined, and increasingly realized.

## CONTEXT OF THE STUDY:

This chapter discusses the findings of the STEM: Country Comparisons project initiated by Australia's Chief Scientist, and funded by the Australian Council of Learned Academies (ACOLA). The project commissioned 23 reports that investigated attitudes towards STEM, the perceived relevance of STEM to economic growth and wellbeing, patterns of STEM provision in school and tertiary education, student uptake of STEM programs, factors affecting student performance and motivation, and strategies, policies and programs to enhance STEM. Country and regional reports spanned the Anglosphere (United States, Canada, New Zealand, United Kingdom, Australia), Europe (Western Europe, Finland, France, Portugal, Russia), Asia (China, Taiwan, Japan, Singapore, South Korea), Latin America (Argentina, Brazil), the Middle East (Israel), and South Africa. The project also commissioned a small number of special interest

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reports focused on Indigenous peoples and STEM, the Australian labour market, gender and 'identity' and international agencies involved in international assessments and reporting. The project was overseen by an expert working group comprising fellows of Australia's learned academies.

RESEARCH FINDINGS:

*Secondary school science and mathematics education participation*

Participation in school level biology, chemistry, physics and mathematics reflects students' attitudes, especially interest and self-efficacy, and ability, with gender playing an important role (Palmer, Burke & Aubusson, 2017). Other factors, such as socioeconomic status and geographic location, also impact on school student participation and learning. Exploring secondary school participation in science and mathematics programs is problematic as there are no international, standardized datasets for school level fields of study. In addition, there are fundamental systemic differences regarding curriculum and schooling structures, including streaming practices. The number of years of schooling, and level of compulsion also add complexity. For example, in a small number of instances, such as China, Taiwan, Finland, Israel and Brazil participation in mathematics is compulsory in one or both of the final years of schooling (see Marginson et al., 2013). Despite these constraints, some examples from high performing school systems and Anglosphere systems are illustrative.

School students in both Singapore and Japan perform very well in international science and mathematics assessments. While performance is not necessarily simply a function of participation, in Singapore it is notable that participation in school level mathematics and sciences is high. Singapore's secondary school students enrolled in the academic express course participate in mathematics and sciences, while those enrolled in the normal (academic) and normal (technical) course undertake mathematics (Ministry of Education Singapore, 2017). In Japan, government curriculum reforms dating from the 1990s impacted total school hours dedicated to mathematics and science, and course content. The government's 'relaxed education' policy, which aimed to alleviate unnecessary student pressure while simultaneously enhancing student motivation, was reversed after Japan's 'PISA-shock' in 2003. More recent reforms have emphasized reading literacy and increased school hours for mathematics and science (Ishikawa, Moehle & Fujii, 2015).

In the United States, consistently over the period 1990-2009 more high school graduates completed early mathematics courses (algebra I, algebra II/trigonometry and geometry I) than advanced mathematics courses (algebra/pre-calculus, statistics/probability and calculus). However, the proportion of high school graduates completing all of these courses increased over this period. In relation to school science, more high school graduates completed biology than chemistry, while fewer again completed physics. During the same period, the proportion of high school graduates completing biology, chemistry and physics courses progressively increased (National Center for Education Statistics, n.d.; Maltese et al., 2015). By contrast, in Australia participation in both senior secondary school science and mathematics experienced long term decline (Ainley, Kos, & Nicholas, 2008; Kennedy, Lyons & Quinn, 2014; Lyons & Quinn, 2015); however, the preference of Year 12 students for elementary mathematics rather than either intermediate or advanced level mathematics (Barrington & Evans, 2017) was consistent with the trend observed in the United States.

Concerns regarding participation in and motivation for school science and advanced mathematics have impacted school curriculum, pedagogy and resourcing, and post-school options. With curriculum, systems have sought to balance a focus on lifting all students' STEM capabilities, and a focus on nurturing an elite STEM workforce. This is also related to the tension between tightly scripted curricula and testing and a desire to nurture critical and creative STEM capabilities. The impact at the post-school level is most evident in relation to tertiary education program pre-requisites and admissions systems, and the necessity for foundational or preparatory programs, particularly for STEM disciplines.

*Tertiary education STEM participation*

At the tertiary education level, countries have focused attention on their population's preparedness for a rapidly changing, globally interconnected world requiring increased scientific literacy, and high-level STEM research skills. Accordingly, participation in tertiary education STEM disciplines has been closely monitored, as have efforts to increase graduates' transferable skills and to develop curricula responsive to industry needs. Science and technology advances have encouraged a reimagination of the future world of work, and the place of disciplinary knowledge in preparing for this.

Participation in broadly defined STEM disciplines, including engineering, sciences, information technology, health and agriculture, varies by country/territory and region, over time. For the period 2011 to 2015, participation was highest in some Western European (Finland, Germany, Sweden, United Kingdom) and East Asian (South Korea, China) economies, as well as Singapore. Comparatively, the United States and Australia lagged behind (UNESCO Institute of Statistics [UNESCO], 2018; Ministry of Education of the People's Republic of China, 2015). Large numbers of tertiary education students enrolled in these STEM programs are located in the three largest higher education systems, that is, China, India and the United States (UNESCO, 2018; Ministry of Education of the People's Republic of China, 2015).

Over the period 2011 to 2015, participation remained relatively static in most countries across the STEM disciplines (Table 1); however, there were some exceptions. Enrolments in natural sciences, mathematics and statistics tertiary education programs increased in the United Kingdom, India and France. At the same time, enrolments in information communication technologies increased in Brazil and Israel, and enrolments in agriculture, forestry, fisheries and veterinary increased in Brazil. Greater volatility was recorded in engineering, manufacturing and construction, where enrolments dropped marginally in Brazil and Finland, and considerably in India, while increasing in Norway (UNESCO, 2018).

Table 1: Percentage of Students in Tertiary Education Enrolled in STEM Tertiary Education Programs (both sexes) (2011-2015)

| Country | 2011 (%) | 2012 (%) | 2013 (%) | 2014 (%) | 2015 (%) |
|---|---|---|---|---|---|
| Finland | 53 | 53 | 52 | 53 | 54 |
| South Korea | 47 | 47 | 48 | 48 | 47 |
| Singapore | 49 | 47 | .. | .. | .. |
| Germany | .. | .. | 46 | 46 | 46 |
| Sweden | 44 | 45 | 46 | 46 | 44 |
| United Kingdom | 41 | 41 | 45 | 46 | 44 |
| Denmark | 41 | 41 | 42 | 43 | 43 |
| Switzerland | 39 | 40 | 40 | 40 | 42 |
| France | | 42 | 38 | 38 | 42 |
| Norway | 37 | 38 | 35 | 35 | 40 |

| | | | | | |
|---|---|---|---|---|---|
| New Zealand | 37 | 38 | 39 | 39 | 39 |
| Israel | 35 | 36 | 37 | 38 | 39 |
| Brazil | .. | 34 | .. | 38 | 39 |
| India | .. | 43 | 37 | 38 | 38 |
| Australia | .. | .. | .. | .. | 37 |
| Japan* | .. | .. | .. | .. | 37 |
| United States | 32 | 32 | 36 | 36 | 36 |

Source: UNESCO, 2018; OECD, 2017.
* The OECD data for Japan excludes agriculture, forestry, fisheries and veterinary.

In these selected countries, typically a larger proportion of women than men enrolled in health and welfare tertiary education programs. For many countries, a marginally higher proportion of women than men enrolled in agriculture, forestry, fisheries and veterinary programs, with notable exceptions including India, the United States and Israel. In other STEM disciplines, a larger proportion of men enrolled. Gender disparity is most evident in engineering, manufacturing and construction programs, and information and communication technologies programs (UNESCO, 2018). Typically a larger proportion of students enrolled in engineering, manufacturing and construction, and health and welfare programs than other STEM disciplines (Table 2).

Table 2: Percentage of Students in STEM Tertiary Education Programs (both sexes), by Discipline (2015)

| Country | Engineering, manufacturing and construction (%) | Health and welfare (%) | Natural sciences, mathematics and statistics (%) | Information and communication technologies (%) | Agriculture, forestry, fisheries and veterinary (%) |
|---|---|---|---|---|---|
| South Korea | 25 | 12 | 6 | 3 | 1 |
| Germany | 21 | 7 | 10 | 6 | 2 |
| Finland | 19 | 18 | 6 | 9 | 2 |
| Israel | 19 | 8 | 6 | 5 | 0 |
| Sweden | 18 | 18 | 5 | 2 | 1 |
| Japan | 16 | 16 | 3 | 2 | .. |
| Switzerland | 15 | 15 | 8 | 3 | 1 |
| India | 14 | 3 | 15 | 5 | 1 |
| France | 13 | 16 | 10 | 3 | 1 |
| Norway | 12 | 18 | 5 | 4 | 1 |
| Brazil | 12 | 5 | 2 | 8 | 12 |
| Denmark | 10 | 22 | 5 | 4 | 1 |
| United Kingdom | 9 | 14 | 15 | 4 | 1 |
| Australia | 9 | 18 | 5 | 4 | 1 |
| New Zealand | 8 | 14 | 9 | 6 | 2 |
| United States | 7 | 18 | 6 | 4 | 1 |

Source: UNESCO, 2018; OECD, 2017.
Note: Any discrepancies in totals between Table 1 and Table 2 result from rounding.

Germany, Finland and Switzerland, which each had a high percentage of students enrolled in STEM tertiary education programs, also had the highest percentage of students enrolled in doctoral level programs (UNESCO, 2018).

*Issues concerning gender and under-represented groups*

There is also considerable variability within countries and territories in terms of demographics (gender, ethnicity, socio-economic status, religion) and distribution (metropolitan/non-metropolitan). Gender disparities persist in STEM education (Marginson et al., 2013), and women typically remain under-represented in the STEM workforce, including the United States (Beede et al., 2011) and Australia (Office of the Chief Scientist, 2016). Similarly, while there is a growing body of literature regarding cross-cultural science and technology (Aikenhead & Jegede, 1999) and indigenous ways of knowing (see Borden & Wiseman, 2016), disparities persist in indigenous participation in STEM education and the STEM workforce (Marginson et al., 2013). Redressing systemic inequities would go some considerable way to meeting STEM-focused human capital targets, and broader social agendas. Accounts of the challenges, and encouraging policy and practice approaches to indigenous participation in STEM, can be found in the commissioned reports by Aikenhead, Nelson-Barber, and in the New Zealand report (https://acola.org.au/wp/stem-consultants-reports/)

*Comparative performance in school level science and mathematics*

International assessment and reporting regimes, while contested in terms of the impact on student learning and government and institutional intervention, provide some indication of the variation between countries and territories with respect to student performance in school level science and mathematics. In some instances, the results from the international assessments generated renewed government policy and societal attention on students' learning generally, and school-based science and mathematics specifically. The most notable example of this was the experience of 'PISA-shock' in Germany (Bank, 2012) and Japan (Ishikawa, Moehle & Fujii, 2015) in response to decreasing comparative and absolute performance.

The 2015 Programme for International Student Assessment (PISA) exercise undertaken by the Organisation for Economic Co-operation and Development (OECD) illustrates the dominance of East Asia, Singapore, Western Europe and Canada in 15 year old school student proficiency in science, reading, mathematics and collaborative problem solving. In relation to science, Singapore, Japan, Estonia and Finland are the highest-performing OECD countries, while school students from Taiwan and Macao (China) perform very well. In relation to mathematics, Singapore, Hong Kong (China), Macao (China), Taiwan, Japan and Beijing-Shanghai-Jiangsu-Guandgdong (China) dominated. Equity in education outcomes is most readily observed in relation to the science and mathematics performance of school students in Canada, Denmark, Estonia, Hong Kong (China) and Macao (China) (OECD, 2018).

Similarly, the 2015 International Association for the Evaluation of Educational Achievement Trends in International Mathematics and Science Study (TIMSS) also reveals the strength of East Asia in fourth and eighth grade school student science and mathematics performance. Particularly strong performance was reported for Singapore, South Korea, Japan, Hong Kong (China) and Chinese Taipei. Russia ranked well in relation to performance by grade four science students (Martin et al., 2016; Mullis et al., 2016).

*Government STEM policy*

Recognition of the growing imperative for foundational scientific literacy, STEM skills and research and development (R&D) capacity has seen the establishment of legislation and policy governing STEM, science and technology, industry innovation and commercialization. These policies typically focus on areas most receptive to government intervention, including education and R&D. Variations in terms of policy responses have been observed between high performing Anglosphere countries and a number of Western European countries, dynamic East and South

East Asian countries with a Post-Confucian heritage, and emerging economies and education systems (Freeman, Marginson & Tytler, 2015).

High performing Anglosphere countries such as the United Kingdom, Canada, Australia and New Zealand, and a number of Western European countries have national STEM policies aimed at addressing unmet labour market demand for STEM skills, and securing international competitiveness within an increasingly globalized economy. Several of these policies have emerged within a narrative of 'STEM crisis' and declining relative performance in international science and mathematics assessments, along with growing emphasis on industry human resource requirements and innovation. Notable examples include the United Kingdom's *Science & Innovation Investment Framework 2004-2014* and 2017 paper, *Industrial Strategy: Building a Britain fit for the Future.* In Australia, STEM education, R&D and industry innovation-related policy includes the *National STEM School Education Strategy* released in 2015, and 2018 plan, *Australia 2030: Prosperity Through Innovation*. New Zealand's *National Statement on Science Investment 2015-2025* aims to establish a coherent vision for the country's science system. In the United States, leading reports such as *Rising Above the Gathering Storm* and *Revisiting the STEM Workforce* have generated interest in the development of a national STEM workforce strategy (see National Academies of Sciences, Engineering, and Medicine, 2016). In Western Europe, STEM or science policies have been adopted in Germany, France, Ireland, the Netherlands and Spain. They typically address public perceptions and knowledge of science, school-based mathematics and science teaching, participation and performance, and tertiary-level participation in STEM disciplines.

In contrast, East and South East Asian countries with very high performing education systems, including Japan, South Korea, China and Taiwan, typically have national science and technology policies and plans. Examples include the Japanese *Science and Technology Basic Law* (S&T Law) and attendant five year *Science and Technology Basic Plan*, and China's *Science and Technology Development Goal (2006-2020)* and *National Mid and Long-term Education Reform and Development Framework* (2010-2020). These policies emphasize university science and technology, industry-driven R&D and innovation.

Finally, emerging economies and education systems, including Brazil, Argentina, and arguably South Africa, have established national policies focused on quality education and emerging industry development. For example, Brazil's *Education Development Plan 2011-2020* emphasizes school education, teaching quality and teacher career pathways; and Argentina's *National Plan of Science, Technology and Innovation: Argentina Innovadora 2020* prioritizes research and innovation, general scientific capacity, and development of biotechnology and health. South Africa *National Development Plan 2030* of the National Planning Commission aims to redress injustices of the past, facilitate economic growth, and improve education, health and social protection.

As these examples illustrate, there is a great deal of variability with respect to STEM policy objectives, and these variations in part reflect different economic, cultural and social contexts. Some policies seek to promote a positive image of science while others aim to increase public engagement with and knowledge of science, through increasing scientific literacy and understanding of the scientific method. Policy aimed at the education sectors frequently focus on strategies to enhance student engagement and ultimately, consolidate the STEM pipeline. Policy may focus on some or all aspects of increasing participation and performance in school-based mathematics and science, tertiary level STEM-disciplines and high-end STEM R&D, including doctoral training and post-doctoral research. Policy may be aimed specifically at encouraging transition into the STEM labor-market. In many instances STEM policy seeks to redress disparities based on gender, ethnicity or race for minority groups including Indigenous peoples, and geographical location. STEM policy may establish mechanisms for co-ordination across STEM-related ministries, agencies and organizations (including scientific agencies, and R&D funding agencies). Policies may articulate annual and long-term objectives, common metrics or performance indicators to monitor progress, and establish an evaluation strategy.

Government STEM policy increasingly complements national research priorities that aim to focus public investment in global science. These priorities are typically framed in STEM terms as wicked problems or grand challenges, such as energy, water, resources, agriculture, climate change, and security. Concurrently, governments have acknowledged the emerging importance of internationalization and interdisciplinarity, including collaborations involving scholars from the humanities, arts and social sciences disciplines. For developing economies, governments have also prioritized the shift from the adoption of foreign technologies to indigenous technological innovation.

*Structural responses*

The STEM agenda is diverse, spanning different education and training sectors, global science and the labour market. In the school education sector, there are a range of structures that have responsibility for supporting science and mathematics teaching, student learning and engagement, and scientific literacy more broadly. Structures may be at regional level, for example connecting education ministries across Europe through the European Schoolnet. Numerous other regional structures, such as the STEM Alliance (which superseded inGenious) co-ordinate STEM education initiatives. At the national and local level, there are structures that disseminate science and mathematics curriculum and teaching resources, and promote innovative science and mathematics pedagogy such as the United Kingdom's Science Learning Centres. In many countries, including Russia, Japan and Singapore, specialist or selective schools focus on science learning. There are numerous examples or organizations that conduct complementary or after-class STEM initiatives including competitions (Science, Mathematics and Engineering Olympiads), enrichment activities (museums, festivals, planetaria) and science centres, such as San Francisco's Exploratorium. Structures have also been established to communicate science and creativity more broadly to the population such as the Korea Institute for the Advancement of Science and Creativity (KOFAC). These examples illustrate the concerted and multilayered efforts at regional, national and local levels to engage young people in science and mathematics education and experiences. These structures are shaped by histories, traditions, geopolitics, priorities and public perceptions.

*Programs and solutions*

The STEM: Country Comparisons project highlighted the need to broaden and deepen school students' STEM learning. This involves providing some STEM education for all school students, improving the engagement and performance of students from under-represented groups, and increasing participation in, and improving achievement through, intensive STEM education. The project report suggests consideration be given to mandating mathematics and/or at least one science subject for the final one or two years of senior secondary education. In relation to school curriculum and pedagogy, the international comparative analysis illustrated the importance of inquiry, reasoning, and creativity and design in school science and mathematics curriculum. The project highlighted the importance of career pathways for STEM teachers, discipline-specific professional development, and the negative impact of 'out of field' teaching, particularly in science and mathematics. In relation to early childhood and primary education, the project recommended increasing the confidence and competence of primary teachers in science and mathematics. Finally, the project discussed strategies to increase the engagement and participation of girls and indigenous students (Marginson et al., 2013).

LIMITATIONS:

The research explored sectors and solutions where national government intervention was most prevalent, including school and higher education. Less emphasis was given to the important vocational education and training (VET) sectors, and the STEM labour market.

IMPLICATIONS FOR K-12 EDUCATION:

The STEM: Country Comparisons project suggests that engaging K-12 school students in science and mathematics will involve reforms to curriculum, pedagogy and the learning environment to ensure a strong focus on disciplinary knowledge, as well as creativity, reasoning and innovation. It will involve resourcing schools with teachers who have science and mathematics disciplinary training, and progressive professional development opportunities.

FUTURE RESEARCH:

The STEM: Country Comparisons study arose from a desire to identify successful strategies that could be implemented to enhance participation in STEM at a range of levels. One needs to be mindful of the dangers of any simplistic 'policy borrowing' that may be tempting, looking at the STEM policies and practices of the more dynamic economies. The STEM focus in these different countries is shaped by cultural, historical and economic factors. Nevertheless there are lessons to be learned from these policy/practice drivers, and patterns have emerged, as described in this chapter, that help clarify the choices that are available in relation to STEM. Much of the focus on international comparative tests such as PISA is driven by the correlation between results on these tests and the degree of dynamism of a country's economy, but the direction of the causal connection is not clear. Further clarification is needed on the nature of relations between different aspects of education policy (age of focus, relative focus on elite students compared to disadvantaged populations, subject focus), R&D policy, and industry drivers. As workplaces change in response to technological advances, and internationalization, and economic drivers shift, there is an increasing focus in education on core competences such as critical and creative thinking or collaborative reasoning, transferable across professions, that are associated with both disciplinary and interdisciplinary thinking. There is a need for research that examines the nature of these competences and how to address them in pursuing an engaging and rigorous education in STEM.

The countries represented in the STEM: Country Comparisons study are in the main successful in STEM education, research, and industry. They are mostly developed economies. There is a need for a similar study that represents a range of developing economies, to identify the policies and practices and their attendant conditions that lead to a STEM educated citizenry and to an expanding economy.

Last, the report focused mainly on the education pathways leading from school to tertiary STEM studies. There is a need to more closely examine the relative roles of mainstream and vocational education in supporting STEM and the relationship between the variety of work in STEM in different economies, and the training needs that this implies.

PROPOSE FUTURE RESEARCH QUESTIONS:

1. What is the nature of the relationship between particular types of focus in STEM education, on traditional disciplinary knowledge compared to higher order reasoning competences, or of the relative emphasis on inclusivity in STEM education policy, and growth factors in a STEM based economy?
2. What is the nature of the causal links between the quality of STEM education and the dynamism of economies at different stages of growth?
3. What policy and practice settings in STEM lead to successful economic outcomes for emerging economies?
4. What is the role of the training sector in supporting STEM education, research and industry development?

CONCLUSION:

STEM is an increasing focus for governments around the world, with concerns driven mainly by the links made between STEM education and research, and wealth creation. The STEM country comparison study identified strong commonalities across countries in their focus on STEM participation and quality, but differences in policy and practice that could be broadly grouped according to economic regions. Major groupings in this study were the emerging East Asian economies, Anglophone countries, and Western Europe. Concerns about STEM participation differed in intensity, but the focus followed broadly similar patterns, including quality of education participation and outcomes in STEM, public perceptions of and engagement with STEM, recruitment into targeted STEM professions, supporting disadvantaged as well as elite groupings, and developing coherent policy that coordinated STEM effort. The particular focus and strategies depended on historical, cultural and economic factors, with developing economies having distinctive foci for policy framing.

There is a need to extend the comparative analytic work of this study to pursue research that identifies the particular links between STEM education foci, education more generally, and the nature and needs of emerging work futures. We also need to understand better the links between STEM education, research, and the economic wealth of a country and wellbeing of its citizens.

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