Engineering Education for the Future

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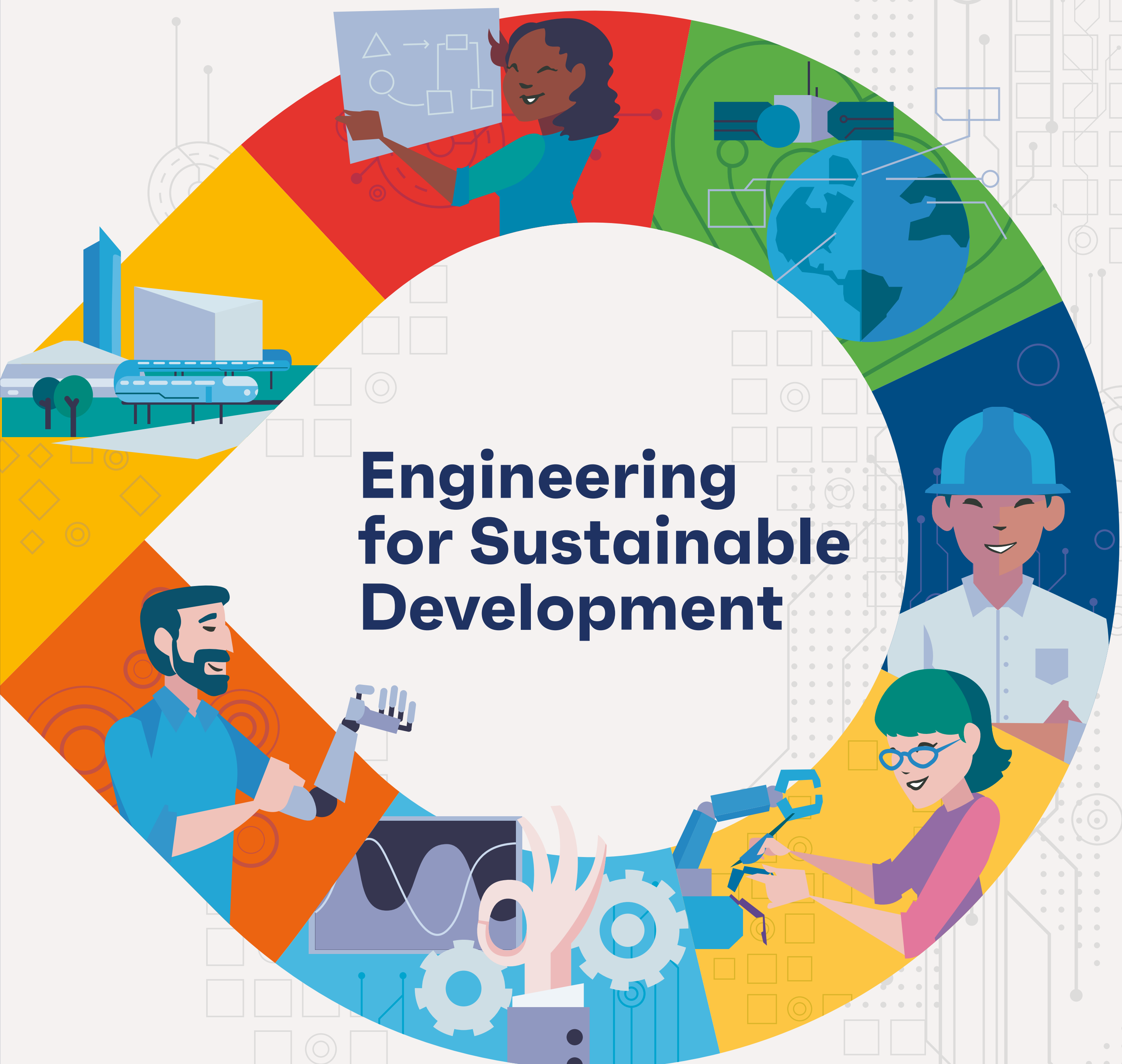

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Engineering for Sustainable Development

Delivering on the Sustainable Development Goals

SHORT SUMMARY

Engineering the SDGs

The report highlights the crucial role of engineering in achieving each of the 17 SDGs. It shows how equal opportunities for all is key to ensuring an inclusive and gender balanced profession that can better respond to the shortage of engineers for implementing the SDGs. It provides a snapshot of the engineering innovations that are shaping our world, especially emerging technologies such as big data and AI, which are crucial for addressing the pressing challenges facing humankind and the planet. It analyses the transformation of engineering education and capacity-building at the dawn of the Fourth Industrial Revolution that will enable engineers to tackle the challenges ahead. It highlights the global effort needed to address the specific regional disparities, while summarizing the trends of engineering across the different regions of the world.

By presenting case studies and approaches, as well as possible solutions, the report reveals why engineering is crucial for sustainable development and why the role of engineers is vital in addressing basic human needs such as alleviating poverty, supplying clean water and energy, responding to natural disasters, constructing resilient infrastructure, and bridging the development divide, among many other actions, leaving no one behind.

It is hoped that the report will serve as a reference for governments, engineering organizations, academia and educational institutions, and industry to forge global partnerships and catalyse collaboration in engineering so as to deliver on the SDGs.

It is essential that more young people, especially **girls**, consider **engineering** as a career

UNESCO

'Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed'

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Foreword
Director-General of UNESCO

Engineering plays a vital role in addressing basic human needs by improving our quality of life and creating opportunities for sustainable growth on a local, national, regional and global level. Crucially, it also contributes to UNESCO's two Global Priorities: Africa and Gender Equality.

Engineering has major potential, but we need to make even better use of it, especially by including girls and women. Governments around the world have a responsibility to provide opportunities for all and to attract young people to consider engineering as a vocation and a profession. These career choices depend on access to quality curricula in STEM subjects, guidance and mentorship, access to valuable information and communication, and government support and scholarships.

Addressing sustainable development within the challenges of climate change, population growth and urbanization will require innovative engineering and technology-based solutions. Engineering capacity and competence-building activities are critical to ensuring that there is an adequate number of engineers capable and ready to work on these global challenges. This is particularly important in Africa where the per capita number of engineering professionals is lower than in other regions of the world. In Swaziland for example, there is one engineering graduate for more than 170,000 people, compared to the United Kingdom where there is one engineering graduate for 1,100 people. Addressing this knowledge gap is vital and one of the key challenges facing engineering.

The 17 Sustainable Development Goals were conceived to raise awareness of the different aspects of sustainability, outlining specific targets that comprise a plan of action across a broad range of social, environmental and technological issues from poverty reduction, health for all, infrastructure development, education, gender equality, to the sustainable use of oceans, energy, and water and sanitation. All 17 Goals can be related to engineering and every one requires engineering to achieve its goal.

This report, *Engineering for Sustainable Development: Delivering on the Sustainable Development Goals,* presents the different fields of engineering where engineers can contribute towards realizing the 2030 Agenda and the SDGs. In providing examples of innovations and actions, as well as recommendations, this report shows the relevance of the engineering profession in responding to the sustainability challenge, and how inclusive and equitable education can bring about new perspectives and thus respond to the shortage of engineers – one of the principal impediments to economic growth.

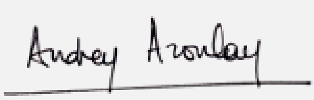
At the dawn of the Fourth Industrial Revolution, this report highlights the current technological advances in Artificial Intelligence, big data and the Internet of Things that are changing the way we live and interact with our physical, biological and digital space. These transformations can be seen in every field of engineering, profoundly affecting industrial systems, production and governance.

This report was finalized and published during the global COVID-19 pandemic. Far from diminishing the relevance of global engineering, this crisis has amplified the need for global cooperation to create solutions that address the root causes of chronic and emerging environmental issues. The global community has responded to the pandemic with urgency and efficiency, but it risks in the process to take resources away from efforts to address other pressing issues, such as climate change, environmental degradation, and access to clean water and energy.

In addition, the current pandemic has placed further strain on engineering education. To train our best engineers to tackle these global challenges, we need young people to study mathematics and science from an early age. However, the global pandemic has led to the closure of educational institutions for 1.5 billion learners worldwide – more than 90% of the world's school population – with dire consequences for their education. In the face of this educational catastrophe, UNESCO has, together with the Global Education Coalition, worked towards ensuring the continuity of learning, particularly in science.

Engineering has always been part of UNESCO. It was the intention of the founders in November 1945 that the 'S' in UNESCO refers to science and technology. Indeed, UNESCO was established at the Institution of Civil Engineers in London, one of the oldest engineering institutions in the world. Over the years, UNESCO's engineering programme has been developing engineering education through its human and institutional capacity-building projects, particularly in Africa, and it has fought against the under-representation of women in engineering to bridge the knowledge gap and promote intercultural cooperation through its support to international engineering organizations and NGOs. In 1968, UNESCO participated in the creation of the World Federation of Engineering Organizations (WFEO) that has a voice at the highest levels of government and international policy. In recent years, important initiatives such as World Engineering Day and UNESCO Africa Engineering Week have been established to celebrate the achievements of engineers and their contributions to sustainability and a better quality of life for all.

Engineering for Sustainable Development: Delivering on the Sustainable Development Goals is an important milestone in the standard-setting work of UNESCO and I wish to extend my gratitude to the UNESCO team behind this report and to our partners, the World Federation of Engineering Organizations, the Chinese Academy of Engineering (CAE), Tsinghua University, and the International Centre of Engineering Education (ICEE) for realizing this important publication, which perfectly embodies the spirit of cooperation in our shared vision for a sustainable world.



Ms Audrey Azoulay
Director-General of UNESCO

Foreword
Chinese Academy of Engineering and Tsinghua University

Engineering, science and technology function as the engine of economic development, and provide an inexhaustible source for the progress of human civilization.

Engineering has a central role in the UN 2030 Agenda for Sustainable Development adopted by the United Nations in 2015, which set forth 17 Sustainable Development Goals (SDGs) that constitute a global action plan for addressing development problems. Engineering underpins all the 17 SDGs and plays an instrumental role in sustainable development. We believe that the publication of the 2020 UNESCO Engineering Report, *Engineering for Sustainable Development: Delivering on the Sustainable Development Goals,* will contribute to sustainable development and the global development of engineering for the future.

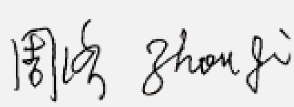
Engineering is experiencing a moment of profound transformation and is facing immense challenges. As a discipline, it is expanding rapidly beyond the creation of artefact-based solutions to permeate economic, ecological and social systems. This evolution is taking place within a broader context in which the timeframe for new discoveries, new technologies, new materials and new products is becoming increasingly short. Meanwhile, the challenges facing engineering, including those encapsulated in the SDGs, are becoming ever more complex and often require multi-disciplinary, cross-country and inter-cultural solutions. Such transboundary solutions have played an invaluable role in the prevention and control of the COVID-19 pandemic.

The realization of the SDGs depends on innovation in engineering education. Fostering a large contingent of engineering talent with a creativity mindset will necessitate the development of sustainability and creativity-oriented engineering education. Every branch of engineering education must shoulder the responsibility to make sustainability a core competency in order to cultivate a generation of future engineers focused on innovation and creativity with an ethical mindset. We must develop engineering professions and activities in line with sustainability and innovation. Our shared goal must be to weave the idea of sustainability into each and every aspect of engineering activity, and to make responsible engineering a common faith among engineering enterprises and engineering professionals.

The realization of the SDGs depends on strengthening global partnerships in engineering. At present however, resources for engineering, science and technology and engineering education are not equitably distributed. Developing countries and regions in particular, are lacking qualified engineers and engineering resources. We therefore urge the global engineering community to work to establish a more equitable, inclusive, developmental and mutually beneficial world for all by working closely with government, industry and academia; by empowering engineering capacity-building in disadvantaged regions; and by tackling global challenges through joint efforts.

The International Centre for Engineering Education (ICEE) was co-founded by the Chinese Academy of Engineering and Tsinghua University in 2016 under the auspices of UNESCO. The mission of the ICEE is to support the realization of the UN SDGs through coordinated efforts in engineering, especially engineering education, across the world. This mission is encapsulated in the preparation, organization and compilation of this report. The ICEE expects to work closely and in joint cooperation with its international counterparts in the international engineering community and engineering education to fulfil its contribution to the realization of the UN Sustainable Development Goals.

We hope that this 2020 UNESCO Engineering Report will help stakeholders from government, industry and academia articulate the value of engineering, inspire ideas to improve and innovate engineering, and help achieve the full potential of engineering to benefit the sustainable development of humankind and planet Earth.



Zhou Ji
Honorary Chairman of the Governing Board
Chinese Academy of Engineering
Co-chair, Advisory Board of ICEE

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Ten years after its landmark publication and the first Engineering Report of its kind, the engineering community came together once more to shed light on the pioneering work of engineers who are defining a new vision for engineering at a time when a global pandemic has further brought to the fore the fault lines of inequalities around the world, chief among them, the glaring scientific, technological and digital divide between countries, which is particularly detrimental to youth. This second Engineering Report is thus a timely reminder of the crucial role played by engineers and the engineering profession in responding decisively to the pressing challenges and new requirements raised by the 2030 Agenda for Sustainable Development.

Thanks to UNESCO's close partnership with the Chinese Academy of Engineering (CAE), Tsinghua University and World Federation of Engineering Organizations (WFEO), this second Engineering Report will become a reference on how engineering can deliver on the Sustainable Development Goals. UNESCO greatly acknowledges their enthusiastic patronage and valuable support in the realization of this important publication, without which this report would not have been possible. Special thanks go to the International Centre for Engineering Education (ICEE) and their team of experts, Zhu Gaofeng, Zhou Ji, Qiu Yong, Wu Qidi, Gong Ke, Yuan Si, Wu Guokai, Wang Sunyu, Kang Jincheng, Qiao Weifeng, Xu Lihui, Fan Xinyan, Tian Qi, Liu Wei, Ji Xue, Li Manli, Zhong Zhou, Xie Zheping, Wu Fan for their work on this report from its inception. UNESCO also acknowledges with gratitude XuetangX for its sponsorship of this report, as well as the institutions, researchers, professionals and individual experts representing every region of the world for their expertise and valuable contributions.

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Finally, UNESCO wishes to acknowledge the many thousands of engineers and the engineering community for their work every day in advancing scientific and engineering expertise, and for their commitment and sense of duty in responding to the 2030 Agenda for Sustainable Development, which is reflected in this report.

Gong Ke[1]

Introduction
Engineering to accelerate delivery of the Sustainable Development Goals

KeepWatch/Shutterstock.com

1 President, World Federation of Engineering Organizations.

A new engineering report

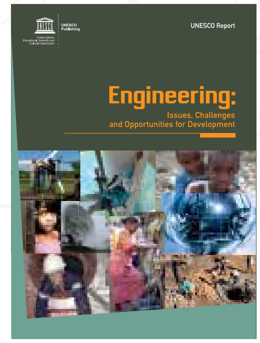
Engineering is about the knowledge and practice of solving problems. For thousands of years, engineering as both a profession and a discipline, has evolved with the development of humanity. Engineering has helped solve our daily problems and our production needs by applying scientific knowledge, technical methods, design and management principles. Indeed, engineering, with its range of sub-disciplines, has been a prime contributor to the survival of humankind on Earth and to improving our quality of life. It has contributed to our ability to survive disasters and public health challenges, to secure food and water, to communicate and transport, and to innovate and create new products and services. Wherever there is a problem, there is a need for engineering solutions. The foremost problem facing the world today is sustaining human development and preserving the planet. In this context, engineering has a central role to play.

Published in 2010, the first engineering report, *Engineering: Issues, Challenges and Opportunities for Development* (UNESCO, 2010), emphasized the importance of science, technology and engineering to address the economic, social and environmental dimensions of human development around the world in the context of the Millennium Development Goals[2] – a United Nations framework and road map for sustainable development for the period 2000–2015.

The first engineering report emphasized the wide impact of engineering and the need for its promotion as 'a human and social as well as a scientific, technological and innovative activity, in social, economic and cultural contexts'. The report stressed the need to:

- develop public and policy awareness and understanding of engineering, affirming the role of engineering as the driver of innovation, social and economic development;
- develop information on engineering, highlighting the urgent need for better statistics and indicators on engineering;
- transform engineering education, curricula and teaching methods to emphasize the relevance and a problem-solving approach to engineering; and
- more effectively innovate and apply engineering and technology to global issues and challenges such as poverty reduction, sustainable development and climate change, and urgently develop greener engineering and lower carbon technology.

The first UNESCO Engineering Report 2010



Since the publication of the first engineering report, significant advances have been made in engineering worldwide and major contributions by engineers have moved towards sustainable development. At the same time, there are ever-pressing challenges that threaten the sustainability of humankind and the planet. Recognizing the social, economic and environmental dimensions of these challenges, world leaders gathered together on the occasion of the 70th anniversary of the United Nations in 2015 to formulate a new plan of actions for sustainable development in a declaration of intent in the historic document, *Transforming our world: the 2030 Agenda for Sustainable Development* (UN, 2015).

This new agenda represents an ambitious blueprint for building a future of peace and prosperity, and a healthy planet for all people. It comprises 17 goals and 169 targets built on the Millennium Development Goals and seeks to mobilize actions over the next 15 years in areas of critical importance for humanity and the planet. Achieving the SDGs involves mitigation and adaptation to climate change, building resilient infrastructures, ensuring food supply and nutrition, providing clean and affordable energy and water, conserving and restoring biodiversity on land and underwater, and much more. Innovative engineering solutions will be vitally important, and engineers are expected to shoulder more responsibility than ever before.

A decade later, this second engineering report published by UNESCO reiterates the importance of engineering as it seeks to respond to the new challenges and expectations raised by the UN 2030 Agenda for Sustainable Development. This report brings together the voices of engineers who have joined the call to create and implement solutions to address the issues of sustainability that affect every aspect of our lives, thus positioning engineering as crucial to achieving a more sustainable world.

2 For more information on the Millennium Development Goals: www.un.org/milleniumgoals

The COVID-19 pandemic has accelerated the call for urgent action to deliver on the SDGs, while affirming the relevance of engineering to sustainable development

Engineering for Sustainable Development: Delivering on the Sustainable Development Goals was finalized and published in the midst of the COVID-19 pandemic. This deadly crisis revealed the urgency and importance of science, technology and engineering innovation for the emerging challenges ahead, as engineers look to create solutions to deliver on the SDGs, in order to transform our world into one that is more resilient, inclusive and sustainable.

COVID-19 unleashed an unprecedented health, economic and social crisis, which threatens the lives and livelihoods of all humankind irrespective of nationality, race, gender, or social and economic status. The collective response around the world illustrates the potential of solidarity to help one another. However, the impact on public health and the economic effects of this pandemic are not equally experienced in different countries and among different groups of people as a result of historical inequalities in their economic, social and environmental conditions. The *Sustainable Development Goals Report 2020* found that the pandemic 'has exposed and exacerbated existing inequalities and injustices' (UN, 2020). It goes on to say, that '[I]n advanced economies, fatality rates have been highest among marginalized groups. In developing countries, the most vulnerable – including those employed in the informal economy, older people, children, persons with disabilities, indigenous people, migrants and refugees – risk being hit even harder' (UNDESA, 2020).

The Sustainable Development Goals Report 2020 analysed the impact of COVID-19 on every SDG and revealed that (as of June 2020) the livelihoods of half the global workforce have been severely affected and tens of millions of people are being pushed back into extreme poverty and hunger, erasing the modest progress made in recent years. At the time of writing (4 February 2021), more than 105 million people around the world have been infected, with the death toll approaching 2.5 million, and continuing to climb with almost no country spared. This crisis testifies to the urgent need to achieve the SDGs, as highlighted by UN Secretary-General, António Guterres, in his foreword to the UN progress report, 'far from undermining the case for the SDGs, the root causes and uneven impacts of COVID-19 demonstrate precisely why we need the 2030 Agenda for Sustainable Development, the Paris Agreement on climate change and the Addis Ababa Action Agenda, and underscore the urgency of their implementation. I have therefore consistently called for a coordinated and comprehensive international response and recovery effort, based on sound data and science and guided by the Sustainable Development Goals'.

Engineering should play a more proactive role in the fight against COVID-19 in pursuit of a truly transformative recovery to build back better. Together, engineers can work alongside other professionals in countries and communities to identify and dismantle the underlying causes of persistent global poverty, thereby elevating all people and their environment, and implementing the recommendations of this report to accelerate actions in engineering practice to deliver on the SDGs.

Understanding the role of engineering in achieving SDGs

Science, technology and engineering lie at the heart of sustainable development. As the Secretary-General of the United Nations, António Guterres, pointed out in his congratulatory letter to the Global Engineering Congress celebrating the 50th anniversary of the World Federation of Engineering Organizations (WFEO) in 2018, 'we strive to achieve the 17 Sustainable Development Goals – the world's blueprint for building a future of peace and prosperity for all, on a healthy planet. Every one of the Goals requires solutions rooted in science, technology and engineering' (Guterres, 2018). In 2019, driven by WFEO along with other UNESCO engineering partners and more than 75 institutions, UNESCO's 40th General Conference unanimously proclaimed 4 March as the World Engineering Day for Sustainable Development[3]. This is a global acknowledgement of the important role of engineering for the SDGs and it represents a unique opportunity to highlight the role of engineers and engineering, and to foster solutions to advance the SDGs.

It is important to recognize the role of science, technology and engineering for the SDGs, for it is science, technology and engineering that establish the factual basis, anticipate future consequences, and contribute to finding innovative pathways to sustainability transformations; they are the lever to advance the SDGs in an integrated manner. In parallel, it is essential to increase public awareness of the role of engineering for the SDGs through the World Engineering Day for Sustainable Development, for it is engineering that applies scientific knowledge, technical methods and design principles to the practice of solving the problems that hamper sustainable development, and which ensures well-being for all people and the health of the planet.

Chapter 1 of this report 'Engineering a More Sustainable World', explains the key role that engineering plays in transforming the world, and gives a brief historical review to show how engineering

3 For more information on World Engineering Day for Sustainable Development: https://en.unesco.org/commemorations/engineering

and its practitioners – engineer – have been changing the world for millennia, from the invention of the first stone tools and simple devices, such as the pulley and lever in ancient times, to the application of the most advanced Artificial Intelligence (AI) techniques and biomedical engineering technology to improve people's lives and production. A thorough analysis of the potential functions of engineering associated with each of the 17 SDGs demonstrates the indispensable role that engineering and engineers play in achieving every SDG by 2030. The chapter also indicates the gaps between current engineering capacity and the requirements for achieving the SDGs, and calls for a close synergy between government, industry, education and research institutes, civil society and the engineering community to deliver strong investment in support of engineering development.

In the same vein, the engineering community and individual engineers, inspired and guided by the 2030 Agenda for Sustainable Development, must acquire a clearer understanding of their roles and responsibilities for delivering the SDGs. Engineering communities worldwide need to embrace the ultimate mission of engineering and engineers today in the advancement of the SDGs to help shape a sustainable future for humanity and the planet, and to carry out engineering practices in a more sustainable, innovative, inclusive, eco-friendly and safer way, while achieving net zero carbon emissions.

Engineering itself needs a transformation to be more innovative, inclusive, cooperative and responsible

To achieve the SDGs, engineering itself needs to undergo transformative developments worldwide to address the multifaceted challenges facing humanity. The 2030 Agenda declares that '[w]e are determined to mobilize the means required to implement this Agenda through a revitalized Global Partnership for Sustainable Development, based on a spirit of strengthened global solidarity, focused in particular on the needs of the poorest and most vulnerable and with the participation of all countries, all stakeholders and all people' (UN, 2015). This is also true for engineering partnerships within the engineering community across the world and with all stakeholders such as governments and policy-makers, academia and educators, industry and foundations, and civil societies. The report stresses the crucial importance of global partnerships among the engineering communities, and highlights the essential need to enhance capacity-building in developing countries.

Chapter 2 of this report, 'Equal Opportunities for All', outlines how diversity and inclusiveness in engineering are vital to ensuring that sufficient numbers of engineers, representing different viewpoints and backgrounds, are attracted to the engineering profession. A diverse engineering workforce can address the SDGs more effectively by providing creative solutions that are relevant to all, and ensuring that future engineering solutions avoid bias and discrimination, while at the same time tackling social injustice. The chapter gives a wide-ranging view of this issue with emphasis placed on women and young engineers. Although significant progress has been achieved – thanks to the joint efforts of engineering organizations, governments and educational institutions, among others – the process is imbalanced. Much more needs to be done to further improve diversity and inclusiveness in the engineering profession, and a more interdisciplinary approach – with a more inclusive mindset – is vitally important to achieving this ambition. The engineering community needs to further strengthen its collaborations with multiple sectors of society to address the SDG challenges in a more balanced and holistic way, while ensuring that progress made against one goal is simultaneously balanced with respect to the other goals.

To solve the problems of unsustainability and to transform our world, innovative engineering solutions are needed. While the range of engineering applications is vast, Chapter 3, 'Engineering Innovations and the Sustainable Development Goals', provides some selected areas of work that show how engineering innovation with emerging technologies can help achieve the SDGs. The role of engineering for the SDGs is demonstrated more concretely, and the gaps between current engineering capability and that needed to achieve the SDGs are also acknowledged. Investment and collaboration on engineering research and development in the context of the Fourth Industrial Revolution (Schwab, 2017) is the way forward to meet the ever-pressing challenges to deliver on human well-being and health, clean water and food security (for a fast-growing population), climate emergency, energy decarbonization, disaster risk management, biodiversity, urban development and other vital challenges.

Engineering education and capacity-building is the key to enabling engineering for the SDGs

Engineering education and capacity-building are addressed in Chapter 4 of this report, 'Engineering Education and Capacity-building for Sustainable Development'. It explains how engineering education is fundamental to building engineering capacity and to meeting the demand for engineers worldwide, both in terms of quantity and quality. It is important to note that engineering capacity-building is a continuous process, starting in school, proceeding through higher learning with formal programmes, and then continuing through the entire professional career of an engineer, technologist or technician through an optic of ongoing professional development so as to meet the rapid growth in knowledge and attendant skills.

Training engineers for the implementation of the SDGs not only requires new competencies of creative learning and thinking, complex problem-solving, interdisciplinary and international cooperation and an ethical attitude, it also requires a change in engineering education itself, shifting from an academic technical knowledge-focused path to a much broader interdisciplinary approach to learning, and from a teacher-centric focus to one that is more student-centred and problem-based. It will require building a structured approach, with related quality assurance and accreditation, to promote lifelong learning and professional development. Periodic reviews of graduates' attributes and professional competencies involving multiple stakeholders will help guide engineering education to meet the changing demands of sustainable development, while a global system of accreditation is needed to help ensure the quality of engineers in carrying out engineering practices to implement the SDGs – and to help engineers work across national boundaries.

Fostering engineering development by the joint efforts of governments, academia, industry, engineering organizations and civil society

Guided by the 2030 Agenda for Sustainable Development, engineers worldwide have made great strides in promoting the SDGs and in enhancing engineering capacity for the SDGs. Chapter 5 of this report 'Regional Trends in Engineering' presents an overview showing how interregional cooperation has facilitated the progress of every region towards achieving the SDGs. It demonstrates that engineering is indeed an enabler for regional development and inter-regional partnership to 'enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation', to 'enhance knowledge sharing on mutually agreed terms, including through improved coordination among existing mechanisms', and to 'enhance international support for implementing effective and targeted capacity building in developing countries to support national plans to implement all sustainable development goals, including through North-South, South-South and triangular cooperation' (UN, 2015). The UNESCO-WFEO project of African Engineering Week[4] carried out by the Federation of African Engineering Organisations (FAEO), and project Africa Catalyst (Africa Catalyst, 2014) supported by the Royal Academy of Engineering (RAEng) and WFEO, provide good examples of the implementation of SDG 17: Partnerships for the goals.

However, significant gaps still exist between the progress achieved and the targets set by the 2030 Agenda to which Member States of the United Nations have committed. Looking at the gaps, it is evident that one prominent factor is the lack of engineering capacity, international interdisciplinarity and inter-sectoral cooperation for engineering development, among many other causes.

The world must overcome a large number of challenges if it is to meet the SDGs by 2030, among which the imbalance in development between different regions is the most serious. This further emphasizes the need for global partnership in building engineering capacity, especially in developing countries. This report recognizes the challenges faced for engineering development worldwide and in different regions, and it proposes a set of recommendations to governments, industry, academia, education institutions, and civil society as the way forward. In summary, the report calls on all stakeholders to realize the critical role of engineering for the SDGs, to recognize the urgent demands for engineering, and to join hands to foster engineering development through investment and cooperation in every country, in every region and worldwide, so as to make engineering a true enabler, equalizer and accelerator to deliver on the SDGs.

4 For more information on African Engineering Week: http://www.wfeo.org/wfeo-in-africa/

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1. ENGINEERING A MORE SUSTAINABLE WORLD

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Abstract. Engineers have played a key role in transforming the world through invention and the development of new technologies, which has had a significant impact on economic growth and quality of life. The United Nations Sustainable Development Goals (SDGs) seeks an integrated approach to development that addresses the needs of all people by calling for equitable opportunities and economic prosperity for all, while mitigating its deleterious effects on the planet. Engineering is crucial for the advancement of each of the 17 goals, as shown in Table 1. Demand for engineers around the world is high, both in developed countries in the fields of high technology, software, Artificial Intelligence and communications, and in developing countries for basic city infrastructure, transport systems, and energy and water supply networks. It is also vital that engineering education meets the current and future needs of employers. Government, engineering educators and professional engineering institutions need to work together to ensure that the standards of engineering education address the SDGs and that more young people, especially girls, consider engineering as a career.

Engineering our world

Engineers have been innovating and changing the world for centuries., from the invention of the first stone tools to such simple devices as the pulley and lever that enabled people to lift and move heavy objects which are beyond the capacity of a single person. The word 'engineer' comes from the Latin *Ingenium*, which is also the root of 'ingenuity' and refers to innate qualities, especially mental agility. For millennia, engineers have been recognized as individuals with the ability to find solutions to everyday problems by employing science, mathematics and ingenuity to do what has never been done, to go where no one has been before and to achieve what had previously been thought impossible.

Engineering is truly a remarkable and extraordinary profession that encompasses many disciplines, ranging from the oldest, military and civil feats of engineering, to mechanical, electrical, electronic and chemical engineering, and more recent emerging disciplines such as environmental engineering, mechatronics (combining mechanical and electronics), bio-medical, bio-chemical and others yet to be named. The emergence of these new disciplines is a key characteristic of engineering, which constantly pushes the boundaries of what can be achieved through ingenuity and smart thinking.[2]

Evidence of the remarkable impact of engineering can be found in sites dating back to ancient times. The Acropolis and the Parthenon in Greece, the Roman Colosseum, the pyramids in Egypt, and the cities and pyramids of the Mayan, Inca and Aztec Empires are testaments to the ingenuity of engineers. Civil and military engineers constructed the Roman aqueducts and roads such as the Via Appia, as well as the Great Wall of China which served the political and military ambitions of the country's rulers. For ordinary populations, engineers built cities in the Indus Valley around 2600 BCE and the Nile Delta (3300 BCE to 2600 BCE) with rectangular street grids, grand buildings and public baths. Engineering underpinned political, military and economic power.

The First Industrial Revolution took place in the eighteenth century in Great Britain and elsewhere in Europe, and was driven by inventions such as the steam engine, which reshaped the world by yielding massive improvements in productivity for those who had the means and the determination to implement them. The technological advancements of the Second Industrial Revolution in the nineteenth and twentieth centuries were led by developments in electricity generation and civil engineering works, such as water supply and sewage networks, and the construction of roads and bridges, marking the dawn of engineering as a profession. These innovations transformed countries from agricultural to manufacturing economies, resulting in increased incomes and prosperity, especially in Europe and North America. The Third Industrial Revolution followed in the second half of the twentieth century and was driven by advancements in computing and information technology – the age of information.

The creativity of engineers has changed the world, impacting the quality of human life in almost every part of the globe. The world now finds itself on the threshold of the Fourth Industrial Revolution where data and the interconnectedness of machinery and the Internet of Things (IoT) will drive new efficiencies and innovation. Engineering remains at the heart of this revolution, with emerging innovations and scientific

2 The first UNESCO Engineering Report defined engineering as 'the field or discipline, practice, profession and art that relates to the development, acquisition and application of technical, scientific and mathematical knowledge about the understanding, design, development, invention, innovation and use of materials, machines, structures, systems and processes for specific purposes'. The report explored the major established engineering disciplines that were prevalent 10 years ago, as well as the pressing needs of the engineering profession. Not much has changed since, except that the needs have become more pressing, new disciplines in engineering have emerged, and society is demanding more from engineers in the context of sustainable development to meet the basic needs of everyone while also protecting the planet and ensuring prosperity for all (UNESCO, 2010).

breakthroughs transforming new ideas into inventions and products. Engineers continue to do what they have always done; use science and mathematics and highly trained intellectual skills to transform the world. The key difference today is that the pace of change is accelerating such that the cumulative technological breakthroughs of the last 100 years have exceeded those of the last few thousand years.

The work of engineers is not only one of shaping cities and industries, it is transforming social and political interactions through breakthroughs in information and communications technologies (ICTs). The last 30 years alone have seen rapid growth in the use of computers and new communication technologies, with the invention of the smartphone in 2007 altering social behaviour. Today, young people can simply not imagine life without a smartphone. Technology has also driven social and political change. For example, the Arab Spring protests in the Middle East in 2012 (Beaumont, 2011) and the political upheaval in Malaysia in 2017 (Abdullah and Anuar, 2018) were triggered by social media. In many countries, social media plays a key role in elections, engaging young people like never before – a development that would not have been possible without the extraordinary accessibility enabled by mobile telecommunications (Newkirk, 2017).

The significant positive effects of engineering are visible in terms of output, productivity and growth, as well as the innovative capacity of economies (Maloney and Caicedo, 2016). Engineers play a key role in supporting the growth and development of essential infrastructure such as roads, railways bridges, dams, communications, waste management, water supply and sanitation, and energy and digital infrastructure. They enable a country's economy to grow and develop, which in turn can lead to better economic and social outcomes, including improved life expectancy, higher literacy rates and a better quality of life.

Countries around the world now realize that engineering, science and technology are the route to economic growth, and that it is not possible to have a modern economy without engineering. Six major trends are impacting the world today: rapid urbanization and the development of large cities, shifts in global economic power, climate change, changing demographics with ageing populations in the developed world, technological innovations and the rise of a culture of entrepreneurship. These trends are driving recognition of the important link between a country's engineering capacity (i.e. the number and 'quality' of its engineers) and its economic development.

Engineers and engineering innovation have been at the forefront of actions to manage the impacts and spread of the COVID-19 virus, as well as the use of innovative technologies to detect, monitor and prevent the spread of the coronavirus. Sensors and Artificial Intelligence are being used to check people's temperatures when they enter important facilities, as fever is an important indicator of the virus. Sensors are also monitoring sewage to trace the spread of the virus in urban areas. Artificial Intelligence is being applied for rapid analysis of the performance of possible new vaccines and therapeutic approaches, and 3-D manufacturing is being used to produce face shields and other personal protective equipment as well as ventilators and medical equipment in high demand. Mobile communications are being used to track and trace people who could be carrying the virus. Importantly, communications have also facilitated online learning for millions of young people around the world and for those working from home following the implementation of lockdowns (WFEO, 2020*a*).

Consequently, in the post COVID-19 world, engineers and engineering will be recognized more than ever as the key driving force for countries to develop their economies in every area including education, health, transport, housing, smart cities and industries that provide jobs for all.

Population growth and urbanization are key areas driving the demand for engineers. More than 50 per cent of the world's population now lives in cities, a proportion that will grow by 2.5 billion by 2050 (UNDESA, 2014). In India, for example, according to the McKinsey Global Institute, the pace of urbanization is akin to a revolution amounting to 3,000 times that of the Industrial Revolution of the nineteenth century (Paul, 2016). Rapid urbanization requires engineering solutions for transport, air quality, food security, water supply and sanitation, energy and telecommunications. For cities exposed to natural disasters and rising sea levels, engineers must develop sustainable approaches to mitigate these risks and build resilience. These are just a few examples of the enormous economic and social benefits of engineering.

The United Nations *Global Sustainable Development Report* (UN, 2019) recognized the importance of science and technology in advancing sustainable development, especially in cities, as one of four levers to achieve the 2030 Agenda. New technologies are rapidly evolving and being deployed to make cites smarter, safer and more sustainable. For instance, the implementation of ICTs, Internet of Things (IoT) devices, video and other sensors monitor and provide data to manage cities (WFEO, 2020*b*). Advanced technologies like integrated geospatial and Building Information Modelling (BIM) for city planning, including the use of digital twins, enable the protection of heritage structures, the monitoring of climate change impacts and the mitigation of natural disaster impacts, and are now becoming essential for sustainable development (WFEO, 2020*c*). This is recognized by the International Telecommunication Union (ITU)-UNESCO proposed 'digital moonshot' to implement broadband in Africa to accelerate economic growth and sustainable development (Broadband Commission, 2019). Similarly, the UN Committee of Experts on Global Geospatial Information Management has recommended addressing the 'geo-spatial digital divide' for sustainable infrastructure and city development (UN-GGIM, 2018).

Moreover, engineers are in increasing demand not only for their skills with advanced technologies but also to deliver engineering for infrastructure in Africa, Asia and Latin America. For example, the Belt and Road Initiative (BRI) led by China[3] and which covers more than 65 countries, will facilitate the development of roads, railways and ports across Africa, Central Asia and Europe, and will increase the demand for engineers (Wijeratne, Rathbone and Lyn, 2017). Engineers are expected to develop innovations for green infrastructure for new smart cities and to develop renewable energy sources. Engineers are also essential to mitigating the risks of natural disasters and implementing integrated water management solutions for water usage in urban environments (UNDESA, 2019).

Technological breakthroughs and the rise of a new breed of entrepreneurs has led to an explosion in new companies and start-ups led or supported by engineers. China's largest new companies, Baidu, Alibaba and Tencent, and India's largest, Flipkart, Ola and others, are driving a revolution that is now spreading to other parts of Asia and Africa (ETtech, 2018). These companies are creating new industries and jobs that have spillover effects for the rest of the economy.

Countries that have a sufficient number of engineers experience a significant positive impact in terms of GDP growth (CEBR, 2015). However, quality as well as quantity affects the outcomes of engineering projects and their contributions to the economy. Engineers not only need to be technically competent, they also need to incorporate the imperatives and values of the twenty-first century: the responsible use of resources, an awareness of the possible negative impact of their work on society and the environment, the need to mitigate these to the extent possible, and the importance of inclusive development that supports both urban and rural populations, leaving no one behind. It is essential for a country to have its own pool of engineers which draws on its best intellects, male and female, who are able to design, build and maintain engineering works that meet national objectives and comply with recognized international standards to deliver maximum benefit to the economy.

The role of engineering in sustainable development

In September 2015, the 193 Members of the United Nations General Assembly came together to declare their commitment to the SDGs. These 17 goals represent an integrated approach to addressing the imperatives of poverty alleviation, the urgent need for basic amenities for many (including education, health and sanitation), gender equality, the impacts of climate change and the rapid depletion of the world's resources. In December 2015, at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in Paris[4], the world agreed on global emission targets and to commit to limiting the warming of the climate to below 2ºC (UNFCCC, 2015).

Every nation has commitments to keep that will be met through the work of engineers, and achieving each of the 17 SDGs will require engineering (see Table 1). These global challenges demand almost unprecedented ingenuity on the part of engineers to develop and implement the solutions needed to advance these goals. Engineers are now needed to change the world again to help create a smarter world, one that is committed to sustainable development for all. This requires new kinds of engineering and engineers to incorporate the values and objectives of sustainable development into their work. Government, policy-makers and the community need to understand the key role of engineering for sustainable development, and initiatives such as 'World Engineering Day for Sustainable Development' have a key role in promoting this awareness (Box 1)

For example, it is estimated that approximately 12 per cent of the world's population did not have electricity in their homes in 2016 (Our World in Data[5]). In 2015, three out of ten (or 2.1 billion) people did not have access to safe drinking water, and six out of ten (or 4.5 billion) people lacked safely managed sanitation facilities (WWAP, 2019). Addressing these challenges requires adopting a more thoughtful approach that encompasses the social, human, economic and environmental impacts of engineering. Moreover, such values-based engineering has yet to be incorporated into the engineering curriculum of most educational institutions.

3 China's Belt and Road initiative (BRI) refers to the Silk Road Economic Belt and the 21st Century Maritime Silk Road. The network connects Africa, Central Asia and Europe, and passes through more than 65 countries and regions encompassing a population of about 4.4 billion and a third of the global economy. It will involve significant engineering works for the development of roads, railways, ports, airports and other infrastructure, as well as manufacturing capabilities, involving significant investment, financing and trade.
4 Known as the Paris Agreement.
5 See number of people with and without electricity access at https://ourworldindata.org/grapher/number-of-people-with-and-without-electricity-access

Box 1. World Engineering Day for Sustainable Development

World Engineering Day for Sustainable Development on 4th March is an annual UNESCO day of celebration of engineers and engineering.

The proposal for World Engineering Day for Sustainable Development was led by WFEO, which recognized the important role of engineering in achieving the UN Sustainable Development Goals. World Engineering Day for Sustainable Development is an opportunity to celebrate engineers and engineering around the globe and to engage with the community, government and policy-makers in the important role of engineering in modern life.

Eighty letters of support were received from international and national institutions, academies and National Commissions for UNESCO, representing 23 million engineers around the world with an estimated impact on 2 billion people. This resolution was backed by Member States of UNESCO and was supported by more than 40 nations from every continent including: Bangladesh, China, Comoros Islands, Côte d'Ivoire, Dominican Republic, Egypt, Equatorial Guinea, Ethiopia, France, Gabon, Gambia, Guatemala, Iran, Iraq, Jordan, Kenya, Liberia, Madagascar, Mali, Mozambique, Namibia, Nicaragua, Nigeria, Oman, the Islamic Republic of Pakistan, Palestine, Philippines, Poland, the Russian Federation, Senegal, Tanzania, Tunisia, Turkey, Saudi Arabia, Serbia, the United Kingdom, Uruguay, Zimbabwe and others. This widespread support by governments demonstrates their recognition of the important role of engineering in sustainable development.

The logo for World Engineering Day conveys the role of engineering and sustainable development around the world. Coordinated celebrations for World Engineering Day worldwide are an opportunity to garner media coverage for key events, thereby increasing the profile of engineering. Social media channels engage with young people in particular, and institutions that celebrate the event are asked to register their events through a dedicated website to build momentum for the celebrations. Ninety events in 50 nations were celebrated in 2020 and these are expected to grow each year and increase in importance as each nation celebrates engineering[6] and makes World Engineering Day their own.

United Nations Educational, Scientific and Cultural Organization

World Engineering Day

World Engineering Day for Sustainable Development is an opportunity to engage with government and industry to address the role and impact of engineering on the economy and society, to recognize the need for engineering capacity and quality engineers around the world, and to develop strategic frameworks and best practices for the implementation of engineering solutions for sustainable development. It is also an opportunity to encourage young women to consider the opportunities of engineering as a career.

Importantly, World Engineering Day for Sustainable Development can be used to engage with young people everywhere, to say: *'If you want to make change for a better world – become an engineer'*.

Getting the numbers right: The demand and supply of engineers

Although engineers are crucial to advancing the SDGs and to meeting the aspirations of developing nations, the world is currently experiencing a shortage in both the number of engineers and in the calibre of engineering skills available.

The growing demand for engineers is evident from global – albeit limited – statistical data, with technology transformation increasing demand in developing and developed countries. The fields in highest demand in Africa are agricultural engineering and civil engineering to support the development of agriculture, which currently accounts for 15% of GDP, as well as infrastructure development (Gachanja, 2019). In South Africa, the shortage is approaching a crisis point (Nyatsumba, 2017).

In developed countries, data from the U.S. Bureau of Labor Statistics show that occupations involving computer technology and engineering are set to grow at 12.5 per cent p.a. until 2024, and that these occupations will also have higher than average salaries (Fayer, Lacey and Watson, 2017). Data from the Organisation for Economic Co-operation and Development (OECD) also show that growth in jobs is highest for engineering and ICTs in response to the digital transformation of economies worldwide (OECD, 2017*a*). The *Future of Jobs Report 2016* conducted by the World Economic Forum also shows that these fields are expected to demonstrate the greatest demand up to 2020 (World Economic Forum, 2016). Software engineers and civil, mechanical and electrical engineers are in demand in many countries around the world with critical shortages being reported in some regions (OECD, 2017*b*).

The participation of women in engineering also represents a significant gap and one that needs to be addressed urgently, not only to increase the numbers of available engineers worldwide but also to ensure that the best intellects are able to resolve the challenges posed by sustainable development (UNESCO, 2018).[7] Issues related to increasing diversity and inclusion in engineering are addressed in Chapter 2.

It is clear that government policy needs to be directed towards providing the number of engineers necessary for the economy to grow and prosper. Governments need to enhance the attraction of engineering as a career for both young men and women, and to ensure the necessary financial and institutional support to help more engineers graduate. A good example of successful government policy can be found in Malaysia where a strategic approach to science, technology, engineering and mathematics (STEM) education has resulted in a significant increase in the number of male and female engineers over the

6 Read more about the World Engineering Day for Sustainable Development at https://worldengineeringday.net/

7 Global data on the participation of women in engineering are not available; however, evidence from various countries such as Australia, Canada, New Zealand and the United States, as well as anecdotal evidence, indicate the low levels of participation of women in engineering. The UNESCO STEM and Gender Advancement (SAGA) project is intended to address the lack of data in this area.

last 10 years (MOHE, 2010). There is also a need to highlight the contributions of engineering to the community, as well as contributions made by engineers and engineering in the past, and their ability to contribute to a better world for the future.

Getting the skills right: The quality of engineers beyond technical capabilities

A key issue for many countries is to ensure not only that engineers graduate in sufficient numbers to meet the demands of the economy, but also the quality of those graduates (see Chapter 4). Many countries produce large numbers of graduates that lack the necessary basic skills to work as competent engineers. The imperatives of sustainable development also necessitate an urgent review of the engineering curricula to incorporate the new skills demanded by employers and society to address the associated challenges, in other words, to mitigate the impacts of climate change and to ensure that engineering works meet societal aspirations and needs.

The ecosystem for the development of human capital for engineering is mainly a national affair. It comprises the educational institutions and organizational bodies of engineering that ensure the quality of education through accreditation processes and the regulation of practising engineers through registration systems.

The quality of engineering graduates is usually ensured through the accreditation of institutions mandated either by government departments in education or professional engineering institutions. The continuing professional development and competency of engineers is guaranteed mainly through training provided by professional engineering institutions that award professional credentials such as 'Chartered' engineer. The registration of engineers may be performed by registration bodies operating under government legislation or under the auspices of professional engineering institutions. The system is complex and varies between countries, as well as with engineering disciplines within a country. Generally, engineering disciplines involving construction (civil, structural, mechanical and electrical) are regulated by the government due to the safety implications of buildings and other structures. New disciplines in engineering, such as nano-engineering and bio-medical engineering, have low or no levels of formal regulation.

International multilateral and bilateral agreements facilitate the mutual recognition of engineering education systems that have achieved agreed standards (Hanrahan, 2013). These are important to ensure that national systems attain an appropriate standard relative to international benchmarks. However, a plethora of systems exist that are regional and international, and cover single or multiple disciplines[8]. The two largest multilateral agreements are the European Network for Accreditation of Engineering Education (ENAEE[9]), which authorizes accreditation, and quality assurance agencies that award the EUR-ACE® label to accredited engineering degree programmes, mainly in Europe with 22 signatories. The International Education Alliance (IEA) manages seven multilateral agreements related to engineering education and professional competencies for engineers, technologists and technicians in 30 countries (IEAgreements.org[10]). In Latin America, the Lima Accord[11], signed in December 2016, provides mutual recognition and currently has seven signatories whose rules and procedures, as well as its website, are under development.

Emerging engineering disciplines such as software engineering are covered by other agreements including the Seoul Accord[12], which currently provides mutual recognition for computing and information technology programmes and has eight signatories. In addition, single discipline global institutions provide accreditation for engineering education programmes relevant to their fields, for example the Institute of Electrical and Electronics Engineers (IEEE)[13] for electrical and electronics professionals. Courses in chemical engineering are often accredited by the Institution of Chemical Engineers in the United Kingdom (IChemE.org)[14]. Some national accreditation bodies, such as the US-based Accreditation Board for Engineering and Technology (ABET)[15], provide international accreditation services to the various systems. Institutions in many countries achieve international benchmarks via this route, although it comes at a high cost.

Clearly, the systems of mutual recognition of engineering education and accreditation of engineering education programmes – both national and international – are complex. This means that to build capacity for engineering (increasing the number and quality of engineers), the whole ecosystem must be supported to grow. Significant effort is required to build the capacity of the engineering education ecosystem in order for institutions to raise their standards, to meet employer requirements for competent engineers and to meet the need for countries to develop sustainably.

8 For example, see: https://www.abet.org/global-presence/mutual-recognition-agreements/
9 European Network for Accreditation of Engineering Education official website: www.enaee.eu
10 IEAgreements.org official website: www.ieagreements.org
11 Lima Accord official website: https://limaaccord.org/
12 Seoul Accord official website: https://www.seoulaccord.org
13 IEEE Accreditation Committee: www.ieee.org/education/accreditation/accred-committees/ceaa.html
14 IChemE.org. Universities: Accredit your degree, see www.icheme.org/education/universities-accredit-your-degree
15 Accreditation Board for Engineering and Technology official website: www.abet.org

Most of the signatories to the mutual recognition agreements are high- and middle-income countries. The small number of signatories to the various mutual recognition agreements means that much of Africa, Asia and Latin America is lagging behind in terms of achieving the global standards of engineering education. In many countries, the organizations that are needed, such as accreditation bodies or professional engineering institutions, simply do not exist.

There is a significant gap in the capacity of many nations to produce engineers with the requisite skills which are now in urgent need. For example, engineering academics may require training and mentoring on how to achieve the desired graduate outcomes, and accreditation systems may need to be established to ensure that educational institutions are genuine establishments with the appropriate resources and systems to provide ongoing professional training to maintain competency. In most countries, efforts to build capacity tend to focus on one part of the ecosystem at a time (often engineering universities). At the international level, a lack of funding means that the development of these systems, and the support that is needed, are dependent on the work of a small number of volunteers, and progress is therefore very slow.

Urgent action is required to provide mentoring and support in countries that are not signatories to multilateral agreements, so as to ensure the development of strong institutions as part of national engineering education systems able to produce engineering graduates of the required standards. This will not only ensure the efficient and effective use of education resources in these countries, but also expedite the training of a new generation of engineers with the requisite skills to make an effective contribution to their country.

Ideally, coordinated action is needed at an international level. Led by UNESCO, organizations such as the World Federation of Engineering Organizations (WFEO), and funding bodies including the World Bank, can ensure that a single global engineering standard is recognized and that the fragmentation of systems is avoided. Fragmentation only results in multiple systems and standards with potentially adverse impacts that could hinder the objectives of sustainable development.

Given the vast pent-up demand, it is not surprising that multiple systems have already been developed over the past five years, which may lead to further fragmentation of an already complex system. For example, the Federation of Engineering Institutions of Asia and the Pacific (FEIAP) has established a mentoring and support programme for institutions in Asia and Africa. Recognition of institutions is provided via the FEIAP Engineering Education Guidelines (FEEG), leading to recognition of the registration of engineers as 'APEC Engineers'. Although initially established to support countries in Asia and the Pacific in the face of huge demand, mentoring and support has been extended to Nigeria through the Council for the Regulation of Engineering in Nigeria (COREN) and to Rwanda (Chuah, 2013; Liu, Liang and Than, 2016).

The Digital @ B&R Double Hundred Universities Cooperation Program (DHUCP) is a collaborative project between the Sugon Ruiyi Education Cooperation Center in China and the Academy of Engineering and Technology of the Developing World (AETDEW), headquartered in Malaysia, to support training and skills development in the 68 countries of the Belt and Road Initiative (BRI) (AETDEW, 2019). The current focus of this programme is new information technologies, including Artificial Intelligence and big data, but it could also expand to include other engineering disciplines and function as a potential new benchmark for engineering education.

The Federal Government of Germany has increased the budget for collaboration on engineering education, especially with sub-Saharan countries. German universities are seeking to transfer engineering knowledge from Germany to Africa and to collaborate on research and education to European standards (Sawahel, 2018).

The Africa Catalyst project of the Royal Academy of Engineering (RAEng) Global Challenges Research Fund (GCRF) has received significant funding from the UK Department for International Development (DfID)[16] to support capacity-building in Africa and the development of professional engineering institutions, and to attract more girls to engineering[17]. Further funding from the Lloyds Foundation has enabled the publication of the *Global Engineering Capability Review* (RAEng, 2020), which recommends 'producing high-quality engineers who are able to conduct the work required of them', as well as more accurate global data on engineering, which is consistent with the recommendations made in this chapter.

Other institutions, including the International Federation of Engineering Education Societies (IFEES)[18] and the Global Engineering Deans Council (GEDC), are committed to improving the standards of engineering education through training and mentoring of engineering academics in developing countries. The World Council of Civil Engineers (WCCE) is also reviewing current education standards in civil engineering to ensure that they meet the current and future needs of industry[19] .

The WFEO, as the peak body for engineering representing nearly 100 nations and 30 million engineers, is leading action to build capacity in engineering education. Based on its global reach and its broad remit covering all engineering

16 The Department for International Development has since been replaced by the Foreign, Commonwealth & Development Office (FCDO).
17 For more information: https://www.raeng.org.uk/global/sustainable-development/africa-grants/africa-catalyst
18 For more information: www.ifees.net/iidea
19 For more information: https://wcce.biz/index.php/issues/education/268-effed

disciplines, it is playing a key role in leading and coordinating projects to develop a recognized international benchmark for engineering graduate attributes and professional competencies, and to develop the engineering capacity necessary to achieve the SDGs in the long term.

The WFEO has mobilized the engineering ecosystem of academics and universities, government, industry, and business and professional engineering institutions as stakeholders in an interrelated partnership that optimizes engineering output to produce the best outcomes for all. The national and international members of the WFEO, which represent leading professional engineering institutions, have a key role to play in this endeavour and in developing country and region-specific responses.

As an example of how the SDGs can be advanced through partnerships (SDG 17), the WFEO has established collaborations with the following key international engineering organizations to undertake coordinated action in engineering education and business:

- The International Education Alliance (IEA) hosts the international Accords and Agreements for mutual recognition of engineering qualifications.
- The International Federation of Engineering Education Societies (IFEES) and the Global Engineering Deans Council (GEDC) consists of members who are engineering education institutions and academics at the forefront of engineering education.
- The International Federation of Consulting Engineers (FIDIC), the peak body of consulting engineering associations around the world, represents organizations in the engineering consulting sector that employ approximately 40 per cent of the world's engineers.
- The International Network of Women Engineers and Scientists (INWES), the peak body for associations of women engineers and scientists around the world, represents the voice of women and girls in STEM internationally.
- Major UNESCO Category 2 Centres include the International Science, Technology and Innovation Centre (ISTIC) in Malaysia with a focus on South-South Cooperation for capacity-building in engineering, and the International Centre for Engineering Education (ICEE) at Tsinghua University with a focus on capacity-building for engineering education in developing countries.

This growing network of organizations brings together key stakeholders in the engineering ecosystem to produce consistent outcomes that support engineering education standards internationally and ensure the mutual recognition and global mobility of engineers. The network enables engineers with the required education, training and experience to be deployed globally where they are most needed to develop solutions for sustainable development.

The specific requirements for engineering education are the subject of Chapter 4 and are not covered here. The details of projects being led by the WFEO are given in Box 2 (WFEO, 2018).

A great deal of progress has been made by UNESCO, the WFEO and the IEA in reviewing the benchmarks for graduate attributes for professional engineers, technologists and technicians and for their professional competencies once they enter the workforce. These changes include a focus on the use of information technologies, data and analytics, and the ability to learn and adapt to new and emerging technologies, along with a greater responsibility to society and the environment incorporating the need to address the objectives of the SDGs through an integrated approach to engineering solutions that takes account of people, planet and prosperity. Another achievement is the embedding of cultures, behaviours and values for a more diverse and inclusive profession, and a broad ethical approach and responsibility regarding the development of engineering solutions. The COVID-19 lockdown has accelerated online communication and consultations within the engineering profession and global acceptance has been remarkably fast, demonstrating that engineers recognize the need for urgent change to maintain the social license for relevant, contemporary engineering solutions.

Governments and funding organizations such as UNESCO and the World Bank play a key role in supporting these activities. Their work plans have been defined and scheduled, and address the multiplicity of systems, the needs for engineering education standards that meet current and future needs, and the requirements for supporting national engineering education systems in developing countries. Funding will determine how quickly change will occur, but the potential impact of such initiatives is immense and will benefit millions around the world.

Box 2. WFEO Engineering 2030 Plan

The World Federation of Engineering Organizations has established a Plan to address the need for quality engineers to achieve progress towards the SDGs. The projects that form part of this Plan were established in early 2018 and will continue until 2030, reporting annually on progress.

Ongoing and future projects developed by the WFEO and its international partners include the following:

- Review current international engineering education benchmarks for graduate attributes and professional competencies to ensure that they meet the requirements of current and future employers, and incorporate the values and principles of sustainable development, diversity and inclusion, and ethical engineering practice. The recommendations in this report are an important input to this project, which is progressing well as a partnership between UNESCO, the WFEO and the International Engineering Alliance (IEA).
- Improve the standards of engineering education within national engineering systems including by the training of engineering educators, and thereby extend the multilateral recognition of engineering education and the professional development of engineers through mentoring and the support initiatives of institutions that have already achieved international standards. These institutions are national members of WFEO and are supported in Africa, Asia and Latin America.
- Facilitate professional lifelong training to support engineers throughout their careers in partnership with the key employers of engineers, such as the International Federation of the Consulting Engineers (FIDIC), for which national members of WFEO provide the delivery mechanism.
- Increase the participation of women and girls in engineering through programmes that attract girls to science and mathematics and encourages them to consider careers in engineering, and promote changes to curricula and professional development requirements that will support the retention of women in engineering. The recommendations in this report address diversity and inclusion in engineering and constitute an important input to this project.
- Support the activities of UNESCO Category 2 Centres such as the International Centre for Engineering Education (ICEE) based in Tsinghua University in China and the International Science, Technology and Innovation Centre (ISTIC) based in Malaysia, as well as other centres in Africa and the Americas.
- Support approaches for regional and international recognition of engineering qualifications and professional credentials in partnership with IEA and UNESCO.

Conclusion

Engineers have been changing the world for millennia. Advancements in science, engineering and technology have led to engineering solutions underpinning successive industrial revolutions that have powered economic growth. In the midst of the COVID-19 lockdowns and at the threshold of the Fourth Industrial Revolution, engineers are needed more than ever. Engineers and engineering skills are recognized as being crucial for economic growth and for advancing the goals of sustainable development.

However, there is a lack of understanding among governments, policy-makers and the broader community of the role of engineers and engineering in modern society and in advancing sustainable development. There is also a global shortage of engineers, especially those with the skills needed to address the challenges of sustainable development. It is also essential to address the shortfall in the participation of women and girls in engineering. Their participation is essential to increase the number of engineers and to ensure the diversity of thought and innovation crucial to developing the solutions necessary to achieve the SDGs.

Urgent action is required by governments, industry, academia and the engineering profession to collaborate to increase the number of engineers, and to fund and support an internationally harmonized approach for graduate attributes in engineering and for ongoing professional competencies needed to meet the goals for sustainable development. These standards need to be recognized across the world and form the basis of national engineering education systems for engineers with the right skills, especially in Asia, Africa and Latin America. There is no time to lose as this action is essential to advance the 2030 Agenda for Sustainable Development.

Recommendations

1. Government, engineering educators, industry and professional engineering institutions need to promote greater understanding of the crucial role played by engineers and engineering in creating a more sustainable world.
2. Government, engineering educators, industry and professional engineering institutions need to collaborate to fund and support strategies to increase the number of engineers, to introduce an internationally harmonized approach for graduate attributes in engineering, and to promote ongoing professional competencies to ensure the high quality of engineers so as to achieve the Sustainable Development Goals. These benchmarks need to be recognized across the world and form the basis of national engineering education systems to train engineers with the right skills, especially in Asia, Africa and Latin America.
3. Governments and policy-makers should take urgent action to encourage more young people, especially girls, to consider engineering as a career in order to address the shortfall in the number of engineers, and to ensure the diversity of thought and inclusive participation that is essential to achieving the Sustainable Development Goals.

1

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Table 1. Engineering and the UN Sustainable Development Goals

SDG 1


Engineering can address extreme urban poverty. © Marlene Kanga

How engineering can make it happen

Engineering drives economic growth and alleviates poverty. The development of basic infrastructure such as roads, railways, telecommunications and other infrastructure underpins modern economies. However, much engineering work remains to be done to develop technologies that improve access to basic services such as clean water and sanitation, reliable energy and clean cooking fuels (SDG Tracker[20]). As traditional approaches to developing this infrastructure come with a high cost, engineers are developing innovative approaches and new technologies to address these challenges (see SDG 6: Clean water and sanitation, and SDG 7: Affordable and clean energy).

In addition to basic services, large populations in low-income countries are demanding access to the latest technologies. Frugal innovation enables the development of affordable and reliable technologies that can be accessed by low-income users (Chabba and Raikundalia, 2018). In India, for example, more than 100 million low-income users, mainly in rural areas, have access to mobile phones that cost less than US$25. These devices greatly enhance communication, enabling users to better manage their work, farm production and finances (LiveMint, 2019).

Engineers in India have also enabled access to low-cost personal and family transport, which is critical to increasing productivity. The Tata 'Nano' car represents a breakthrough in low-cost transport with numerous innovations and a light weight of just 600 kg. Engineers are continuing to innovate in this field with the development of electric and solar-powered vehicles. Such low-cost innovations have major spillover effects, encouraging entrepreneurship and the development of small businesses that create employment.

SDG 2


Engineered mechanization of farming for food production in India. © Marlene Kanga

How engineering can make it happen

Engineering has already mechanized agriculture and food production, and increased productivity through the use of fertilizers and pesticides. These advances are the work of agricultural, mechanical and chemical engineers.

Future technological innovations by electronics and agricultural engineers for sustainable development include automated sensors for soil moisture and condition monitoring to optimize the delivery of scarce water and fertilizers, robotics for the application of pesticides and fertilizers and for weeding and planting, and communications technology for weather monitoring, forecasting and natural disaster warnings, as well as providing farmers with accurate, up-to-date information on harvest potential, which is crucial to achieving global food security (GEO, 2020).

An example of a global-scale approach to improving food security with technology is the Famine Early Warning Systems Network, a network of satellite and Earth-based monitoring and remote-sensing technologies that provide early warning and analysis on food security. Funded by the US Agency for International Development (USAID), it links the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the US Department of Agriculture (USDA) and the US Geological Survey (USGS).

Satellite and ground-based monitoring and advanced data management are used to monitor the climate and therefore food security in 34 countries in Africa and Asia, enabling relief agencies to plan for and respond to humanitarian crises (FEWS[21]).

Technologies are also being deployed by engineers to assist farmers at a local level. For example, one initiative is *FarmerLink,* an innovative mobile-based farmer advisory service that links poor coconut farmers to an early warning system and market buyers in the Philippines, providing access to vital agricultural training and financial services (Gatti, 2018).

20 Search the SDG Tracker for 'No poverty' at https://sdg-tracker.org/no-poverty
21 Famine Early Warning Systems Network official website: https://fews.net/sobre-n%C3%B3s

SDG 3

Artificial Intelligence camera vision for COVID-19 fever detection in crowds.
© Marlene Kanga

How engineering can make it happen

Engineering has improved global health by eradicating numerous diseases, such as typhoid and cholera, through improved water and sanitation. Advances in biomedical engineering continue to improve quality of life with medical devices for limbs, and improvements in hearing, heart health and brain functioning. Robotics, computer vision and Artificial Intelligence will all continue to drive advances in health.

For example, computer vision technologies are being used in various types of scans for the purpose of diagnosis and detection, which are themselves the result of advanced technologies. Artificial Intelligence and big data are being applied to analyse trends in health data, producing new insights into the causes and management of diseases. Advanced technologies such as 3D-printing are being used to produce prosthetics and other body parts to closely match an individual's physical dimensions, thereby enhancing comfort. Meanwhile, laser, robotics and miniature camera technologies have revolutionized surgical procedures.

Universal and inclusive access to health technologies is a key goal for sustainable development. The development of low-cost medical devices including electrocardiograph machines, ultrasound machines, low-cost prosthetics and medical devices that facilitate low-cost operations, such as cataract eye surgery, are improving the health outcomes of millions of people in low-income countries.

Engineers at General Electric have developed a low-cost portable electrocardiograph machine that can be carried to remote villages. It requires only battery power, has a simple dual-button interface (reducing the need for training), and costs less than 10 per cent of conventional machines used in the developed world, thereby enabling access to health diagnostics in rural areas in developing countries (GEHealthcare, 2011; NESTA, 2019).

Another low-cost innovation is the 'Jaipur Foot'[22], a rubber-based prosthetic for people who have undergone a below-knee amputation. The invention is enabling thousands of people with disabilities to become more mobile.

Healthcubed is a start-up that provides access to low-cost medical diagnostics for chronic health conditions in developing countries, particularly in remote areas. It uses low-cost mobile phones, data analytics, and cloud-based data storage and access to assist clinicians in diagnosing conditions including heart disease, diabetes and other chronic ailments (Healthcubed[23]).

Engineering responses during the COVID-19 lockdowns have accelerated the uptake of tele-health technologies, bringing medical services to remote and rural communities (Keshvardoost, Bahaadinbeigy and Fatehi, 2020). Biomedical engineers are accelerating methods for detecting and treating the virus (Washington University, 2020), engineers are developing 3D-printed and advanced manufacturing solutions for personal protective equipment for medical staff (Zhang, 2020), and Artificial Intelligence is being used to fast-track vaccine development (Ross, 2020).

SDG 4

Young engineers learning about engineering and sustainable development.
© WFEO

How engineering can make it happen

Education at every level – primary, secondary and tertiary – is a key enabler of development (Roser and Ortiz-Ospina, 2019). Engineers are facilitating the delivery of education through the creation of new technologies, such as online learning tools and technologies that rely on fast communication. These advances improve accessibility and reduce costs for students. Wi-Fi is one such technology that was invented in 1977 by an Australian engineer, John O'Sullivan, and is now implemented in more than 40 billion devices worldwide, underpinning advances in education and making millions of other applications possible[24].

Software and telecommunication engineers are fast expanding access to the internet and a world of connectivity through the rapid development of low-cost satellites and other aerial devices to deliver information and services to remote and low-income communities. Access to low-cost technologies such as the 'Aakash' or 'Ubislate' tablets, available for US$35, is enabling the Government of India to link 25,000 colleges and 400 universities to e-learning programmes. E-learning is currently delivering a wide range of education programmes from the world's top universities to the poorest countries (Datawind[25]).

Artificial Intelligence (AI) is being used to develop 'chatbots' that will answer routine student questions, thereby promoting faster learning. Engineers are developing learning systems that use AI to enable significant advances in conventional teaching methods, providing

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22 For more information on Jaipur Foot: https://www.jaipurfoot.org/how-we-do/technology.html
23 Healthcubed official website: www.healthcubed.com
24 For more information: https://www.csiro.au/en/Research/Technology/Telecommunications/Wireless-LAN
25 For more information on Datawind, manufacturer of Ubislate tablets: www.datawind.com/about-datawind.html

personalized content and instruction that is locally relevant, gender- and ethnically inclusive, and dynamic and interactive. Such technologies can enable real-time tracking of progress, anticipate future performance and take corrective actions, and support experienced teachers, resulting in superior learning outcomes at low cost (Marr, 2018).

With over a billion students impacted globally by lockdown measures and unable to attend school, telecommunications networks have been crucial in sustaining inclusive learning opportunities for all; a significant paradigm shift which will have impacts beyond 2020[26] (UNESCO, 2020).

SDG 5

Women engineers working on high voltage electrical systems. © Chinese Society for Electrical Engineering

How engineering can make it happen

Ensuring women's access to technology and engineering will close many gender gaps and ensure that women can benefit from and participate in the technology revolution, as well as take up leadership positions (SDG Tracker[27]).

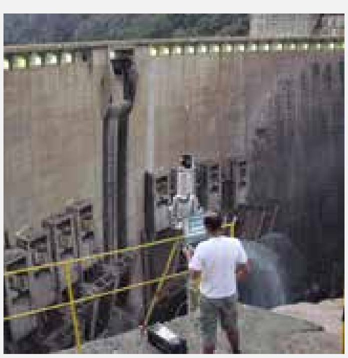
A statement by the United Nations Economic and Social Council (ECOSOC, 2017) at the Commission on the Status of Women (CSW) recognized the transformative potential of new technologies, such as advanced automation, telecommunications, robotics and 3D-printing for the world of work and the participation of women in a digitally connected workforce.

The participation of women in the development of advanced technologies, especially engineering, is critical to achieving the SDGs. Diversity of thought is vital for innovation and the development of solutions that reflect community standards, values and aspirations.

In recognition of this imperative, professional engineering institutions have been developing strategic approaches to increase the participation of women in engineering (Diversity Agenda[28]; Engineers Canada, 2019; RAEng[29]). Breakthrough programmes such as WomEng[30] are set to attract one million girls into science, technology, engineering and mathematics (STEM) by 2027, and are having a particularly significant impact in Africa. Others have showcased the achievement of women engineers as leaders, as well as strategies to change the work culture for a more inclusive profession (IFEES, 2019; Kanga, 2014)

New technologies developed by engineers are increasingly empowering female users. For instance, mobile communications and the internet have facilitated access to banking, financial and information services by different sectors and at various income levels. In many countries, these new technologies and communication systems have supported the development of entrepreneurship among women, especially small business enterprises. Providing women with access to the internet will facilitate the flow of information in areas such as health, education and childcare, resulting in better outcomes. Other new technologies, such as biometric systems, ensure the personal safety of women, empower them to own land and assets, enable them to access accurate personal educational and medical histories, and help them become active in financial systems.

SDG 6



Advanced engineering technologies using laser scanning for monitoring the Cahora Bassa Dam, Mozambique, one of the largest dams in the world. © Antonio Berberan, Eliane Portela and João Boavida

How engineering can make it happen

Civil and environmental engineers have saved billions of lives through technologies designed to provide clean water and sewage treatment. Such advances have already eradicated many waterborne diseases in the developed world, such as cholera and typhoid. Electrical and mechanical engineers continue to ensure that these systems operate reliably around the world. More recent innovations in water treatment and recycling ensure clean water for all, even in arid zones. However, more than one billion people still lack access to clean water and two billion lack access to basic sanitation (SDG Tracker[31]). Urgent action, including by engineers, is required to address this challenge.

New systems are replacing traditional project-based approaches for water and sanitation services. For example, Agenda for Change (A4C) is providing water and sanitation services by establishing partnerships between a number of non-government agencies (see SDG 17: Partnerships), thereby driving a national and local systems approach for cost-effective, sustainable delivery (WASH Agenda for Change[32]).

Engineers are also developing new technologies that use smart sensors to assess groundwater availability, and are making advances in the use of metal organic frameworks for low-energy water purification systems. At a small scale, the

26 Read more about UNESCO's Global Education Coalition for COVID-19 Response at https://iite.unesco.org/news/global-education-coalition-for-covid-19-response
27 Search the SDG Tracker for 'Gender' at https://sdg-tracker.org/gender-equality
28 Diversity Agenda official website: www.diversityagenda.org, Engineering New Zealand
29 See the Royal Academy of Engineering website on diversity and inclusion at www.raeng.org.uk/policy/diversity-in-engineering
30 WomEng official website: www.womeng.org
31 Search the SDG Tracker for 'Water' at https://sdg-tracker.org/water-and-sanitation
32 WASH Agenda for Change official website: www.washagendaforchange.net

women-led company Banka BioLoo[33] has developed a sustainable small-scale approach to eliminating open defecation and managing solid bio-waste.

Climate change impacts will make integrated water management systems incorporating engineering solutions an imperative in both developed and developing countries, especially in arid areas. Spain's water governance model is designed to adapt to the environment using a system based on planning, public-private participation, and technological development and innovation by engineers (MAPAMA, 2014).

The WFEO works with engineers around the world on approaches for the integrated management of water resources and river basins, the development and adaptation of sustainable infrastructure, hydrological modelling for planning purposes and adaptation to the impacts of climate change (WFEO, 2018*a*).

SDG 7

Engineers are essential for designing, building and maintaining power infrastructure.
© Chinese Society for Electrical Engineering

How engineering can make it happen

Electricity is essential for economic growth and improved living standards, yet nearly one billion people, mainly in sub-Saharan Africa and South Asia, still lack access to a reliable source of electricity (Ritchie and Roser, 2019).

Electrical, mechanical and environmental engineers have been central to the development of low-cost renewable energy solutions, including wind, solar, wave and geothermal energy, all of which provide access to electricity in remote regions while mitigating the impacts of climate change. For example, the development of photovoltaic cells that convert the sun's light energy into electricity has enabled the development of solar panels: a safe, reliable and affordable energy source. Today, 20 per cent of the world has access to solar power, with a consequent reduction in greenhouse gas emissions. This solution is increasingly a key source of energy in developed and developing economies (Amelang, 2018; UNDP[34]).

Household energy generation and distribution, mini-grids and smart grids are all innovations developed by electrical, electronics, mechanical and telecommunications engineers that are transforming access to energy while reducing environmental impacts. Advances in energy storage are making sources of reliable energy accessible and affordable. For example, the World Bank is facilitating the delivery of solar technologies in Africa through consumer education, quality assurance on products and financing for consumers (Lighting Africa[35]).

Access to clean renewable energy is also supporting agriculture through the operation of irrigation pumps, enabling refrigeration for food and medicine, and providing power for household appliances such as televisions and refrigerators. The successful implementation of low-cost, accessible, solar technology in developing countries, especially in remote rural areas, is having a significant impact on the social fabric and economies of these nations.

SDG 8

Transport engineering is essential for economic growth and for sustainable cities.
© Marlene Kanga

How engineering can make it happen

Approximately half the world's population lives on less than US$2 per day with access to regular work uncertain (SDG Tracker[36]).

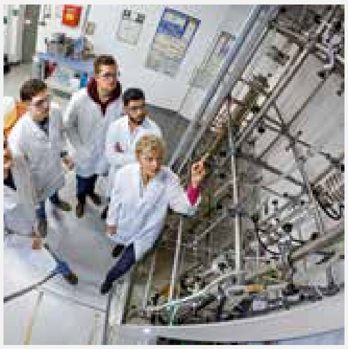
Developed countries have benefited from significant advancements in economic prosperity that were made possible by the engineering innovations of the Industrial Revolution. Engineering is now recognized as an essential enabler of economic growth. In addition, a recent report by the Centre for Economics and Business Research for the Royal Academy of Engineering demonstrated the positive relationship between economic growth and the number of engineers in a country on a global basis (CEBR, 2016).

Roads, railways, airports, water supply, electricity and telecommunications are considered essential infrastructure underpinning all economies. All are designed, developed and maintained by civil, mechanical, electrical and environmental engineers. Clean water, energy and housing are basic amenities – also developed by engineers – that enable citizens to maintain healthy and therefore productive lives and to engage in decent work. A recent report by the World Bank estimates that approximately 4.5% of GDP is needed by middle and low-income countries to bridge the infrastructure gap. This gap refers not only to new infrastructure, but also to existing infrastructure that needs to be maintained for sustainable development. This is the essential work of engineers and technicians (Rozenberg and Fay, 2019).

33 For more information on Banka BioLoo: www.bankabio.com
34 For UNDP facts and figures on Goal 7: Affordable and clean energy: www.undp.org/content/undp/en/home/sustainable-development-goals/goal-7-affordable-and-clean-energy.html
35 Lighting Africa official website: www.lightingafrica.org
36 Search the SDG Tracker for 'Economic growth' at https://sdg-tracker.org/economic-growth

Engineers also have a role to play in diversifying national economies and creating new job opportunities (SDG 8.2), as well as in developing new technologies and innovations that create jobs in new industrial sectors while managing resource consumption – a key goal for sustainable development (SDG 8.4). The need to build and maintain infrastructure is a source of employment in many developing countries. For example, renewable energy projects have created expanded employment opportunities in Africa and Asia (IRENA, 2018).

SDG 9



Students developing innovations in chemical process engineering. © Technische Hochschule Georg Agricola (THGA)

How engineering can make it happen

A modern economy cannot exist without engineering. The United Nations recognizes that growth in productivity and incomes, and improvements in health and education outcomes, require investment in infrastructure (UN, 2019).

Engineers are responsible for the design, construction and maintenance of infrastructure. Roads, transport, communication, water supply and energy are all the result of the work of civil, mechanical and electrical engineers. The challenge for engineers is to develop sustainable, resilient and inclusive infrastructure, especially in countries that are exposed to the adverse impacts of climate change (see SDG 13: Climate action).

Infrastructure enables industry to develop and thrive. Industry also needs engineers of every description in areas such as mining, petroleum, chemical and food processing. Every type of manufacturing is underpinned by engineers: mechanical, electrical, chemical and environmental. Industrial developments in these sectors result in increased employment and the production of goods for domestic and export markets. Infrastructure built by engineers also facilitates trade through the development of transborder roads and railways, ports and airports.

There is a positive correlation between the number of engineers in a nation and its innovative and productive capacity (Maloney and Caicedo, 2014).

Engineering is also the source of innovation. The development of new industries and investments in research and development is an important goal (see SDG 9.5). Innovations in AI, robotics, cloud computing and big data are emerging rapidly and will drive future economic growth and employment. For example, AI is transforming healthcare by providing insights into the management of chronic diseases such as asthma. It also provides insights into: i) finance to monitor fraudulent activities; ii) shipping and transport to drive logistics and autonomous vehicles; and iii) education to develop student-specific programmes. Robotics are being used in a wide range of industries to replace repetitive or dangerous tasks, or where high precision is required, as in surgical procedures. New technologies will create new industries and new jobs, and they are also enabling millions more people to become entrepreneurial and creative at work.

SDG 10

Engineering generates work and incomes. © Ingénieurs et Scientifiques de France

How engineering can make it happen

Global inequality in terms of incomes, health, education and asset ownership continues to be an important goal of sustainable development, ensuring that no one is left behind (SDG Tracker[37]). The work of engineers and engineering is crucial to reducing inequalities through the development of infrastructure (see SDG 8: Decent work and economic growth) and new technologies and innovations (see SDG 9: Industry, innovation and infrastructure) that create jobs and provide opportunities for everyone. Such outcomes enable access to housing, food, health and a decent living for all.

Ensuring that the latest innovations are accessible, especially in low-income countries, is essential to reducing inequalities around the world. This includes access to: i) low-cost communications and mobile phones; ii) information and education through low-cost mobile devices; iii) low-cost medical diagnostics and treatment[38] (see SDG 3: Good health and well-being); and iv) national data and identity systems that enable the protection of assets (*The Economist*, 2017).

Technologies that empower women to increase their participation in the workforce and that address chronic gender-based economic inequality include solar-powered household appliances and low-cost refrigeration systems. Examples include the 'Chotukool' fridge, which costs US$69 and keeps food cool, enabling women to spend more time on economic activities (WIPO, 2013).

Other technologies developed by engineers include mobile payment systems. For example in Africa, the mobile-based 'M-Pesa' money transfer system enables financial transactions, including for individuals without a bank account (Safaricom[39]).

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37 Search the SDG Tracker for 'Inequalities' at https://sdg-tracker.org/inequality
38 See NESTA UK (National Endowment for Science Technology and Arts), for examples of frugal innovations such as the low cost GE Electro Cardiograph (ECG) machine at https://www.nesta.org.uk/feature/frugal-innovations/ge-ecg-machine/
39 Read more about 'M-Pesa Tips' at www.safaricom.co.ke/personal/m-pesa/getting-started/m-pesa-tips

SDG 11

Engineering infrastructure, such as this underground metro tunnel, is essential for sustainable development. © Mr Pung Chun Nok, Hong Kong Institution of Engineers

How engineering can make it happen

More than two-thirds of the word will live in cities by 2050. The development of safe, inclusive and resilient cities is therefore a key SDG (SDG Tracker[40]).

Access to affordable housing and public transport is a priority in developed and developing nations. Other imperatives for cities are clean air, water and energy, the protection of natural and cultural heritage assets, and resilience against natural disasters (SmartCitiesWorld, 2018).

Civil, structural, electrical, mechanical, environmental, software and telecommunications engineers have an important role to play in engaging with policy-makers and planners to design and develop liveable, sustainable and resilient cities. Engineers and engineering are essential for sustainable smart cities that incorporate energy efficiency into buildings, smart lighting, efficient transportation systems, renewable sources of energy, and effective water resource management. For example, India is building 100 smart cities[41] by 2022, all of which will require engineering for sustainable solutions. Cities are also collaborating to share best practices, for example though the Resilient Cities Network.[42]

Advanced technologies are being used by engineers to achieve many of the goals necessary to developing sustainable cities. For instance, geospatial engineering, Building Information Modelling and data analytics can be used in smart cities to make transportation systems more efficient and sustainable (Massoumi, 2018; WFEO, 2020*a*).

The blue LED light bulb invented by engineers and scientists is an example of an invention that has significantly reduced greenhouse gas emissions. These energy-efficient devices are now installed in cities around the world, including the city of Bhubaneshwar, India, as a low-cost, low-energy, sustainable solution that improves safety and security for citizens (Ramanath, 2017).

SDG 12

Biogas from treated sewage used to generate electricity at North Head Wastewater Treatment Plant, Sydney, Australia. © Marlene Kanga

How engineering can make it happen

Mining, civil, mechanical, electrical and environmental engineers play critical roles in efficiently managing resources from mining, processing essential minerals, generating energy from renewable resources, ensuring the effective use of water resources, agricultural production and the management of biodiversity.

Engineers are developing solutions for resource management and responsible consumption through the concept of the circular economy where outputs and products can become inputs into other processes and products, thereby conserving the Earth's resources (TNO[43]).

Technology innovations have been developed to recycle or reuse waste materials. For example, the Kenya-based company EcoPost recycles urban plastic waste into plastic lumber with applications such as fencing, road signage and outdoor furniture. This innovation creates jobs, reduces deforestation and helps address climate change. Chemical engineers are also developing technological solutions to increase plastic recyclability by addressing the molecular structure of the component chemicals, enabling reuse into new products (Lozkowski, 2018).

In the water industry, technologies are already being used to manage and treat wastewater streams for reuse in irrigation and for drinking water.

Today, billions of mobile phones, personal computers and tablets are in use. Managing e-waste is therefore critical to managing resources. Engineers have developed processes to extract metals from e-waste, which can then be recycled into other products (Strom, 2016). Another company has developed a 3D-printing machine from discarded components found in e-waste dumps (Ungerleider, 2013).

Technologies to extract energy from biomass, and thus also reduce greenhouse gas emissions, are increasingly becoming mainstream (Scallan, 2020).

40 Search the SDG Tracker for 'Cities' at https://sdg-tracker.org/cities
41 For more information on Smart Cities Mission: www.smartcities.gov.in
42 Resilient Cities Network official website: https://resilientcitiesnetwork.org/
43 Read more from the Netherlands Organization for Applied Scientific Research (TNO) on the circular economy: the basis for a sustainable society at https://www.tno.nl/en/focus-areas/circulaCr-economy-environment/roadmaps/circular-economy/

SDG 13

The impacts of climate change caused intense bush fires and smoke haze over Sydney, January 2020. © Marlene Kanga

How engineering can make it happen

Engineers are at the forefront of tackling climate change through the development of a wide range of technologies to reduce greenhouse gas emissions especially from energy generation, to remove greenhouse gases from the atmosphere, and to mitigate the impacts of climate change through the development of resilient infrastructure.

Engineers have developed new technologies for alternative sources of energy that have zero carbon emissions. These include energy from hydroelectric power stations, green hydrogen, solar, wind and wave power. Nuclear fission is also a well-established technology. Engineers are now working to access the huge amounts of solar energy available in space that is already being used to power space stations.[44]

Engineers employ a range of strategies and technologies to remove greenhouse gases. Carbon capture can be increased through forestation and habitat restoration, and by changing agricultural practices such as tillage and crop rotation to increase the carbon content in soils, as well as adding biochar to soils. Carbon capture and sequestration underground or the transformation of bio-solids into gas energy is now in use worldwide. Methods used to absorb carbon from the atmosphere include ocean fertilization (to increase the rate of photosynthesis in oceans) and building with timber from rapid growth forestation projects. The use of low-carbon concrete for construction is another example of technology that is available today (RAEng, 2018).

Future technologies use new materials to absorb carbon dioxide. For example, metal organic frameworks enable storage in significantly smaller volumes than conventional sequestration (Zhao *et al.*, 2016).

One new technology being developed by chemical engineers is the use of chemical processing to remove carbon from air for use as chemical feedstock by industry. Engineers are also leading collaborative research on low carbon living in cities with a focus on building and construction materials, energy and water use, and smart transportation technologies (Low Carbon Living CRC[45]).

Engineers are responsible for the design, construction and maintenance of essential infrastructure for cities such as transport, water and energy, and communications systems. Incorporating principles for resilience against climate change impacts can have huge economic and social benefits, and enable faster recovery from natural disasters such as cyclones and floods whose frequency is increasing (OECD, 2018).

In 2015, the Committee on Engineering and the Environment (CEE) of the World Federation of Engineering Organizations (WFEO) developed a guide for engineers, the *Model Code of Practice: Principles of Climate Change Adaptation for Engineers*, on key principles in developing infrastructure that is resilient to natural disasters and mitigates the impacts of climate change (WFEO, 2015). In the midst of the COVID-19 pandemic, the WFEO has echoed the call of the UN Secretary General to 'build back better' to accelerate the mitigation of climate change impacts with engineering solutions (WFEO, 2020*b*).

SDG 14

Engineering is needed to protect against rising sea levels and increasing beach erosion in coastal communities.
© Marlene Kanga

How engineering can make it happen

Oceans are a vital resource for the planet. They supply water and marine-based foods and provide modes of transport, while also regulating the climate. Preserving and protecting the oceans and seas, and the life within them, is a vital task for engineers.

Marine engineers are working with scientists and other engineering disciplines to implement solutions to address the degradation of fisheries, the pollution of oceans and the use of resources, including wave energy and oil and gas exploration.

For example, engineers are working on a clean-up solution for the Great Pacific Garbage Patch[46], which comprises approximately 80,000 tonnes of plastic waste. This waste is not only slow to biodegrade, it breaks down into micro-plastics that are harmful to marine life starving them of food and causing entanglement, eventually affecting the human food chain. The work of engineers in analysing these plastic materials and developing a viable solution is crucial to undertaking a successful clean-up of the oceans.

The Reef 2050 Long-Term Sustainability Plan for the Great Barrier Reef[47] provides clear actions and outcomes for its management and addresses cumulative impacts including threats such as climate change.

44 See, for example, National Space Society UK (NSS) on space solar power at https://space.nss.org/space-solar-power
45 Learn more about the Low Carbon Living Co-operative Research Centre (CRC), Australia at http://www.lowcarbonlivingcrc.com.au/
46 For more information on the work of The Ocean CleanUp 2019 and the Great Pacific Garbage Patch: www.theoceancleanup.com/great-pacific-garbage-patch
47 Read more about the Reef 2050 Long-Term Sustainability Plan at www.environment.gov.au/marine/gbr/publications/reef-2050-long-term-sustainability-plan-2018

The Australian Institute of Marine Science (AIMS[48]) is innovating engineering solutions, including shading for the reef and aerial and underwater robots, to improve monitoring and protection.

SDG 15

15 LIFE ON LAND

Geo-engineering innovation is essential for discovering and protecting the Earth's resources. © Technische Hochschule Georg Agricola (THGA)

How engineering can make it happen

The protection of forests, which cover 30 per cent of the Earth's surface, is vital to combating climate change and protecting biodiversity in terms of both flora and fauna, as well as preventing desertification and ensuring food supplies (SDG Tracker[49]).

Engineers have an important role to play in managing biodiversity through the responsible use of forestry resources and the preservation of habitats to mitigate the impacts of hazardous industries. Engineers have also developed innovative technologies to map the Earth's surface. These provide valuable geospatial information that can be used in agricultural monitoring, the design of infrastructure and predicting natural disasters such as earthquakes.

One example is the development of participatory geographic information systems and 3D-modelling by the Technical Centre for Agricultural and Rural Cooperation ACP-EU (CTA). This tool is an effective means for disadvantaged groups, including indigenous communities, to enhance their capacity to map, analyse and negotiate for the appropriate and sustainable development of their resources, while protecting natural forests. These tools have been used effectively in Africa, the Caribbean and the South Pacific Islands (CTA, 2016).

Sensor and drone technologies are being used to map populations of endangered animals. DNA sequencing is also being used to track animals from water samples in known habitats. One example includes platypus monitoring in Australia (CESAR[50]).

The International Meridian Circle Project is an example of collaboration between engineers in China, Poland and the Russian Federation. It uses satellite information to monitor the Earth and provides early warning of earthquakes (NSSC, 2017).

SDG 16

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

Engineers from around the world discuss strong institutions for engineering education at the International Engineering Alliance Meeting, Hong Kong, June 2019. © Marlene Kanga

How engineering can make it happen

The promotion of peace, justice and inclusive societies through good governance and strong institutions is a priority for everyone in society, including engineers.

Engineering practice involves embracing the values of diversity and inclusion, sustainable practices and ethical engineering, all of which are essential for delivering safe, sustainable engineering solutions. Engineers are also partnering to develop strong institutions for engineering education, accreditation and regulation, which are essential to ensuring the competency of engineers everywhere. For example, the WFEO is partnering with the International Engineering Alliance (IEA) and its peers in international engineering to ensure that engineering education standards for the graduates of tomorrow reflect the values of sustainable, ethical and inclusive engineering. These organizations are also working in partnership to develop strong accreditation institutions to regulate university education systems and professional engineering institutions to support the professional development of engineers in the workforce (WFEO, 2018*b*).

The WFEO has developed a Model Code of Ethics for engineers (WFEO, 2010) that has been used as a basis for codes of ethics by other professional engineering institutions such as Engineers Australia (Engineers Australia, 2019).

The Committee on Anti-Corruption of the WFEO[51] has partnered with other international organizations such as the OECD and the World Justice Project to promote frameworks to address corruption in engineering with a view to maximizing the benefit of infrastructure investments that support sustainable development. It is a member of the International Standards Organization Technical Committee TC-309 that developed the ISO 37001 Anti-bribery Standard and the ISO 37000 Guidance for the Governance of Organizations, to be released in early 2021 (ISO 37001, 2016; WFEO 2020*c*).

The Global Infrastructure Anti-Corruption Centre (GIACC)[52] in the United Kingdom is an independent not-for-profit organization that provides resources to assist in understanding, identifying and preventing corruption in the infrastructure, construction and engineering sectors.

48 Australian Institute of Marine Science official website: www.aims.gov.au
49 Search the SDG Tracker for 'Biodiversity' at https://sdg-tracker.org/biodiversity
50 Read more about the work of the Centre for Environmental Stress and Adaptation Research (CESAR) at http://cesaraustralia.com/biodiversity-conservation/environmental-dna-edna
51 For more information of WFEO Committee on Anti-Corruption: www.wfeo.org/committee-anti-corruption
52 Global Infrastructure Anti-Corruption Centre official website: https://giaccentre.org

SDG 17

17 PARTNERSHIPS FOR THE GOALS

UNESCO Member States discuss the declaration of 4th March as World Engineering Day for Sustainable Development. © Marlene Kanga

How engineering can make it happen

Partnerships in engineering are essential to advancing the goals of sustainable development, whether within engineering disciplines or across national and international engineering institutions involving government, industry and universities. These partnerships are developing innovative solutions to address the issues of today and the future, and providing roadmaps for the implementation of technologies for sustainable development to build capacity and knowledge transfer mechanisms for inclusive approaches to sustainable development.

For example, the WFEO has established partnerships with peer international engineering organizations including the International Engineering Alliance (IEA), the International Federation of Consulting Engineers (FIDIC), the International Network of Women Engineers and Scientists (INWES) and the International Federation of Engineering Education Societies (IFEES). These partnerships encompass global engineering organizations which aim to develop international standards for engineering education for graduate attributes and professional competencies, and to support capacity development in engineering in Africa, Asia and Latin America (WFEO, 2018*b*).

In March 2018 these organizations signed the Paris Declaration as a statement of commitment to advance the SDGs through engineering (WFEO, 2018*c*). INWES and WFEO then collaborated at the United Nations Climate Change Conference (COP 24) in Katowice, Poland, in December 2018, to showcase good engineering practices that mitigate the impact of climate change, with a focus on innovation by women engineers (INWES, 2018).

Partnerships to develop solutions to advance the other 16 SDGs are being implemented effectively around the world. For example, the Resilient Cities Network[53] is a collaborative network that shares best practices to achieve SDG 11 on sustainable cities and communities.

The WASH Agenda for Change[54] is a partnership between a number of non-governmental agencies that is driving national and local system approaches for cost-effective and sustainable delivery of water, sanitation and hygiene (WASH) services in Africa and Asia, which are essential for the advancement of SDG 6 on clean water and sanitation.

53 Resilient Cities Network official website: https://resilientcitiesnetwork.org/
54 WASH Agenda for Change official website: www.washagendaforchange.net

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2.
EQUAL OPPORTUNITIES FOR ALL

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Abstract. The two most recent United Nations Sustainable Development Goals reports (UN, 2019; 2020) shed light on the progress the world is making to achieve the Sustainable Development Goals (SDGs) and highlight the areas that need urgent attention. Both reports show that despite advances in a number of areas over the past four years on some of the SDGs, progress has been slow or even reversed[1]. The most vulnerable people and countries continue to suffer the most and the global response has not been sufficiently ambitious. Engineers play a pivotal role in addressing challenges for the planet and people, and the COVID-19 pandemic has created new challenges and opened up new opportunities for engineering professionals. Engineers are problem solvers, providing solutions to societal challenges as they build a sustainable world. However, more engineers need to be trained and enter the workforce. The world today is home to the largest generation of young people in history, 1.8 billion. Close to 90 per cent of which live in developing countries where they constitute a significant proportion of the population. At the same time, women engineers are grossly under represented. Ensuring equal opportunities for all and reducing inequalities (SDG 10), providing decent work and economic growth (SDG 8) and ensuring gender equality (SDG 5) will enable a more representative cross-section of people to join the engineering workforce and thus contribute to a fairer, more resilient and more sustainable world, which is at one with nature.

1 As noted in the 2020 progress report, p.2: '[t]hrough the end of 2019, progress continued to be made in some areas: global poverty continued to decline, albeit at a slower pace; maternal and child mortality rates were reduced; more people gained access to electricity; and countries were developing national policies to support sustainable development and signing international environmental protection agreements. In other areas, however, progress had either stalled or been reversed: the number of persons suffering from hunger was on the rise, climate change was occurring much more quickly than anticipated and inequality continued to increase within and among countries'.

Dawn Bonfield[2]

2.1 DIVERSITY AND INCLUSION IN ENGINEERING

Robert Kneschke/Shutterstock.com

2 Royal Academy of Engineering, Visiting Professor of Inclusive Engineering, Aston University; Director, Towards Vision.

Drivers for change

Over the past decade, diversity and inclusion in engineering has become a mainstream topic for many engineering organizations around the world. This has been driven largely by a number of overarching factors including: i) increasing recognition of the current and historic lack of equality in opportunities for all; ii) a skills shortage driven by an increasingly technical world, coupled with an ageing demographic (RAEng, 2019); iii) acknowledgement of the reality that innovation, profit and high-quality engineering is improved with a more diverse team of engineers (Hunt, Layton and Prince, 2015); and iv) an increasing focus on the SDGs and what this means within the engineering sector. It is now recognized that a more interdisciplinary approach and inclusive mindset will enable global challenges to be addressed in a more balanced and holistic way, ensuring that progress made against one goal is simultaneously considered against other goals. A diverse and inclusive workforce is vital for the successful implementation of solutions to address these multiple and diverse goals, and this workforce must ensure that their engineering and technological outputs (products, services, solutions) are equally accessible and inclusive of all. Indeed, none of the SDGs will be achieved without considering solutions through a 'diversity' lens and without the full participation of under-represented and marginalized groups, as well as their effective participation in decision-making roles in political, economic and public life.

Moreover, it is understood that the effects of climate change, such as droughts, floods and other extreme weather events, will have a disproportionate effect on women and marginalized people globally (WHO, 2011). In many occupations, women's lower socio-economic and managerial status results in them having a limited voice where key decisions are being taken, and their status and experience as gatekeepers of family, food, health and home mean that these perspectives are poorly represented in solution outcomes. Women's restricted access in some parts of the world to education, land ownership and independence often means that their needs are poorly served by engineering and technology solutions. Encouraging more diverse representation in engineering and ensuring the progress of these groups towards senior decision-making positions is seen as crucial to enabling these views, so that they are equally represented and ultimately successful in addressing all of the SDGs (Huyer, 2015; UNESCO, 2017).

A factor that is growing in importance and recognition is the need to ensure that bias and discrimination are not embedded in future engineering solutions. Huge changes are taking place with a shift towards a more digitized world driven by big data, machine learning, autonomous systems and Artificial Intelligence. Without vigilance, there is a risk that historical biases and discriminations will be built into new systems, inadvertently resulting in the proliferation of discrimination and the reinforcement of bias. Many examples have already come to light where largely unseen algorithmic decision-making succeeds in further discriminating against certain groups of the population (Angwin *et al.,* 2016; Criado-Perez, 2019). By ensuring a diverse workforce that represents all perspectives, these biases are more likely to be recognized and prevented.

Changing culture

In order to successfully achieve diversity and inclusion, the culture of engineering must ensure that *all* people feel comfortable and included, and that they are able to bring their own identity and their own differences to the sector. Care must be taken to change the culture rather than changing people to fit the existing culture. Failure to do this prevents the 'diversity premium' from being achieved, and the rewards of less biased and more socially just engineering solutions will not be maximized (RAEng, 2017) such that the retention of diverse talent will falter. Employee resource or affinity groups play an effective role in supporting and empowering under-represented groups. There is also growing evidence that the non-inclusive culture in the construction sector is leading to mental health issues and an increased risk of suicide among male workers (Burki, 2018).

Some progress can be achieved through changes to structures and processes, such as: i) adopting inclusive recruitment mechanisms and leadership styles (Moss-Racusin *et al.*, 2012); ii) embedding bias eliminators into systems such as pay and remuneration; and iii) implementing mentoring and reverse mentoring to ensure the progression of under-represented groups and the elimination of inequalities (Yin-Che, 2013). Targets, action plans, metrics and accountability are crucial for driving culture change (RAEng, 2016).

Finally, it should be noted that the inherent skills required from engineers are distinctly changing as technology evolves. As Artificial Intelligence, machine learning and the use of robotics distance humans from the 'hands-on' skills that were synonymous with engineering in the past, the need for people with competencies that were previously described as 'soft skills' are increasingly being seen as the 'critical skills' of the future. Competencies such as resilience, agility, the ability to acquire new knowledge, team working and communication will all become as important, if not more important, than the detailed technical knowledge that has previously been valued in engineering (Jackson and Mellors-Bourne, 2018). This in turn will call for a different type of engineer, one where diverse characteristics are valued at a premium. This shift in the perception of engineering will over time bring with it a change in employees, as people see engineering less as a dirty, mainly masculine occupation, and more as a profession that requires a wide range of skills to ensure success (World Economic Forum, 2016).

Recommendations

The following recommendations aim to address existing barriers that prevent the engineering sector from being more diverse and inclusive.

1. Educational institutions should provide barrier-free pathways and access to engineering education for all students and at every career stage, so as to enable a diverse educational environment where inclusive teaching and learning – with a consistent focus on the role of engineering to address the SDGs – will develop an inclusive mindset among future engineers.
2. Workplaces should foster a culture of change by assigning clear responsibility and accountability for success, as well as a business strategy with targets and metrics for achieving equality, diversity and inclusion.
3. Professional engineering institutions and registration bodies must provide leadership in order to embed the values of diversity and inclusion into training courses, accreditation and professional registration, and to develop benchmarking data, gathered in compliance with the Inclusive Data Charter (IDC) (GPSDD, 2018) to standardize monitoring and international comparisons.
4. Governments should increase funding for key priorities in conjunction with: i) levers such as the integration of equality, diversity and inclusion (EDI) metrics and targets into public procurement contracts; ii) structural enablers such as shared parental leave, flexible working policies and mandatory pay gap reporting; and iii) the use of Diversity Impact Assessment (DIA) audits for all policy decisions.
5. Organizations should identify and address systemic and structural discrimination, intolerance and inequalities that prevent certain sectors of society from obtaining equal access to opportunities.
6. The engineering sector as a whole should embrace the ‘leave no one behind’ ethos of the SDGs and ensure that technological solutions address current inequalities.

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2.2 WOMEN IN ENGINEERING


Global Engineering London Congress 2018

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Abstract. Data are not consistently and widely reported on the number of women qualifying as engineers, working in the engineering sector or gaining professional status as registered engineers on a global level. While gender disaggregated national data are available in some countries, these have not been collected against any international standards and are often difficult to compare from country to country. This lack of reliable data limits the possibility to clearly assess and justify the need for action and thus ensure evidence-based planning and policy-making.

Introduction

Based on data from the UNESCO Institute of Statistics, the Engineering Index 2019 shows the number of women who graduate from tertiary education in engineering, manufacturing and construction programmes worldwide by country in ranking order (RAEng, 2019). Gender disaggregated percentages for tertiary engineering education are reported on a country-by-country basis in the *UNESCO Science Report: Towards 2030* (Huyer, 2015). Data from 2015 showed a world average of 27% graduates from tertiary education in engineering, manufacturing and construction, representing 8% of the global female population compared to 22% of the global male population (UNESCO, 2017). Data for women progressing to engineering careers and becoming professionally registered are not available at a global level.

The report, *Engineering and economic growth: A global view* (RAEng, 2016), found that developing economies, including Myanmar, Tunisia and Honduras, lead the world in gender parity in engineering, with the highest proportion of female engineering graduates at 65%, 42% and 41%, respectively. The majority of OECD countries increased the number of female engineering graduates over the period 2008–12, with the most notable increases seen in the emerging economies of Mexico, Hungary and Turkey (by over 150%). However, in developed countries, the increase was often less marked, with countries such as the United Kingdom and the United States increasing the number of female engineering graduates, from an already low starting point, by 31% and 24%, respectively.

Professional engineering institutions have provided some comparable statistics for female membership, representing women engineers working in the engineering profession. Female membership of the International Council on Systems Engineering (INCOSE) was 17% in 2018, female membership of the Institute of Electrical and Electronic Engineers (US) was 12.2% in 2019, and female membership of the Institute of Engineering and Technology (UK) was 9% in 2019.

Education and progression barriers

Making engineering education, professional development opportunities, pay equity and career-life integration initiatives available to women are key to their engagement, retention, leadership growth and desire to stay in the workforce and make contributions to the profession (Montgomery, 2017; O'Meara and Campbell, 2011; Tull *et al.*, 2017). Many existing barriers prevent women and girls accessing STEM subjects. In some countries, restrictions still exist that prevent girls from taking certain subjects at school including science (Agberagba, 2017). In addition, other non-policy restrictions, such as gender stereotyping and parental expectations, continue to prevent girls from accessing science and engineering careers. Many interventions address these barriers, but evidence of their impact and rates of success are often unavailable (OECD, 2019). The need to increase the participation of girls and women in engineering at every level was highlighted at the 61st session of the Commission on the Status of Women (CSW) at the United Nations in New York in 2017 and at its 62nd session in 2018. The Commission recommended that the career pipeline be strengthened by exposing more girls to global challenges, such as those embodied by the SDGs.

The OECD Programme for International Student Assessment (PISA) revealed that there is very little difference between the abilities of girls and boys in STEM subjects at the age of 15, with the difference occurring in 'relative strength'. This means that girls, although as good at STEM subjects as boys, are relatively stronger in reading, whereas boys are relatively stronger in science and mathematics, when all subjects are considered. It is suggested that students choose their field of study based on their *comparative* strengths rather than on their *absolute* strength (Stoet and Geary, 2018).

In order to address these barriers, clear progression pathways from all points in the education and employment system leading to a future career in engineering should be provided (UNESCO, 2017). In higher education, female students face barriers in progressing from education to professional employment. Yates and Rincon (2017) suggest that the retention of women in engineering and as entrepreneurs can be improved through work experience prior to graduation, as well as in the development of professional networks and external supports to assist with transition into the engineering workforce. The authors also noted that minority women engineers sought support from minority women mentors and professional associations to help them connect to professional career networks.

Female academics are subject to institutional barriers resulting from major inhibitors, such as reduced success rates and often substantially lower grant funding, as well as barriers to research publication (RSC, 2019). These factors limit women's access to promotion and hence to progression to professoriate positions within engineering academia. Addressing and removing these barriers is critical to enabling women to progress equitably and to reach decision-making positions in academia.

Women leaders with unique experiences and who have become what other women aspire to be, have significant power to influence women and girls of all ages. Women from all backgrounds, including those from marginalized or under-represented groups and regions, need to be trained, hired and empowered to achieve their goals.

Progression, retention and COVID-19 response

Women who successfully navigate the barriers to a career in engineering often find that non-inclusive environments in the workplace, stereotyping, unconscious bias, micro-inequalities and sexual harassment inhibit their ability to thrive in the sector and reach positions of leadership and decision-making. In many cases, these factors result in women leaving the sector. Addressing these inequalities, creating inclusive cultures and finding systemic ways to ensure women's equitable progression are vital to achieve progress in the recruitment of women. Mandatory gender pay gap reporting, the successful introduction in many countries of shared parental leave (notably led by Scandinavian countries), flexible working hours, a good childcare system, and national targets and quotas for women on executive boards are all examples of government-level interventions that improve opportunities available to women in general in the workplace.

The impact of the COVID-19 pandemic in 2020 seriously risks undoing the progress made over recent decades as women bear the brunt of increased workloads linked to childcare, home schooling, domestic responsibilities, and caring for elderly relatives who may be isolated during lockdowns. Evidence is coming to light of fewer submissions to academic journals and grant applications by women, as well as evidence of women being made redundant more readily than their male counterparts among the most recent company hires. Care should be taken to ensure that any gender disadvantages are minimized at this difficult time, and that gender disaggregated evidence is gathered that can identify inequalities. Any advantage that benefits women and retains more women in engineering should be encouraged, such as a more flexible working environment that minimizes travel and allows the workload to be organized around home and family life, where qualifications can be acquired online from home, and where a different style of leadership enables women to shine.

Conclusion

Attracting and retaining a more diverse engineering workforce is key to ensuring that the global challenges represented by the SDGs are addressed, and that engineering and technology fulfils their roles in combating climate change and global inequality. The multiple systemic and structural barriers that have historically prevented under-represented groups, notably women, from accessing the engineering sector must be removed as a matter of urgency. Drivers to achieving this include: i) coordinated methods of data collection; ii) evidence and sharing of impact and effectiveness of interventions; and iii) legislative and cultural changes, all of which are necessary. To enable women to participate and facilitate this change they must be empowered and supported to access leadership positions.

Recommendations

1. *Effective data and evidence.* Collect reliable and accessible global data on a regular basis that is internationally comparable and gender disaggregated, and use these data to inform policy and decision-making processes. Document the effectiveness and impact of interventions to encourage a more gender diverse workforce and share best practices.
2. *In education.* Use the SDGs and accompanying social justice messaging to convey the value of engineering to the next generation of young women engineers. Support women in transitions between education and employment, and facilitate intersectoral mobility from other sectors into engineering for late stage entrants. Remove systemic disadvantages to the progression of women in engineering academia.
3. *In the workplace.* Create an inclusive corporate culture where female engineers thrive and progress equitably to leadership roles, and monitor and eliminate any gender disadvantage as a result of the COVID-19 pandemic. Instead, find ways of capitalizing on more flexible working environments to attract and retain women.
4. *Government.* Strengthen government-level initiatives that support women in the workforce, such as gender pay gap reporting, targets for women on executive boards, flexible work structures, shared parental leave and good childcare facilities.

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2.3 YOUNG ENGINEERS AND THEIR ROLE

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Abstract. The United Nations *World Youth Report* stated that young people should be active architects and not mere beneficiaries of the 2030 Agenda for Sustainable Development (UN, 2018*a*). While institutions are scrambling to address the dearth of students applying for STEM degrees, transformative opportunities are too often overlooked as youth[7] can be active participants in their engineering education rather than passive consumers of standard curricula. This subsection discusses examples of models that engage young people as critical thinkers, change-makers and leaders to translate the 2030 Agenda into real practice (UN, 2018*b*).

Competitions to excite and expand the pool of future engineers

Many global and national engineering contests showcase best practices for the 2030 Agenda. Global contests foster pathways to diversify and increase the number of students taking up STEM subjects by providing a broad, exciting image of engineering practice. Working alumni continue their lifelong participation in related disciplinary societies and become role models for young engineers and change-makers who then mobilize others. FIRST[8] robotics promotes critical thinking, teamwork, STEM knowledge and problem-solving (UNESCO, 2017). Alumni are 2.6 times more likely to take an engineering course in the first year of university, and women alumni are 3.4 times more likely to take engineering courses (Melchior *et al.*, 2018). The Intel International Science and Engineering Fair (Intel ISEF)[9] inspires youth to conduct independent research in project-based science and engineering (ISEF, 2019).

A national science and engineering fair in Brazil from the University of São Paulo, called FEBRACE[10], inspires youth to propose projects and focuses on schools without the infrastructure for advanced STEM subjects (FEBRACE, n.d.). The South African Agency for Science and Technology Advancement (SAASTA) organizes the National Science Olympiad to promote the value and impact of science and technology. The China Association for Science and Technology (CAST) runs the Science Talent Programme, which promotes talented youth and leads to higher education opportunities (CAST, 2007).

Young engineers as independent stakeholders or within professional societies

Young engineers in formal university programmes are well represented in student divisions of professional societies (e.g. YE/FL[11], ASEE SD[12]) where they participate in direct conversations with relevant stakeholders, thereby accelerating progress towards achieving the SDGs. Independent youth-led initiatives (e.g. SPEED[13], BEST[14]) contribute to the development of civic leadership skills among youth, empowering them to drive change.

The student branches of the Institute of Electrical and Electronics Engineers (IEEE, 2018) actively network with professionals to develop engineering knowledge and skills. The American Society for Engineering Education (ASEE), the world's largest engineering education society, created a student division after recognizing the need for a student voice and youth leadership in the organization. The YE/FL is now a standing technical committee within the World Federation of Engineering Organizations (WFEO) that works to facilitate interactions for youth integration in the industry – a major gap identified in research (WFEO, 2018). The YE/FL programme brings a youth perspective to industry practices, the SDGs, and linkages between developed and developing countries.

The global non-profit student organization SPEED (Student Platform for Engineering Education) consists of an interdisciplinary network of students who aspire to create change in engineering education by amplifying student voices. From its inception in 2006, SPEED has embraced social justice by empowering students to take the initiative to improve engineering education and to focus on concrete action plans (Shea and Baillie, 2013). For example, SPEED's Global Student Forum 2017 fostered discussions around clean water, energy and related issues (SPEED, 2017). The Board of European Students of Technology (BEST) is a non-governmental association for European students of science and engineering that organizes events to promote an international mindset. BEST's educational committee gathers inputs from students via 'Events on Education' and surveys. Results are disseminated and new programmes are developed such as the virtual internship pathway introduced in 2014 (Christofil *et al.*, 2015).

7 UNESCO defines youth by age. For consistency across regions, 'youth' refers to persons aged between 15 and 24 years without prejudice to other definitions by Member States (UNESCO, 2017*b*). This section includes all individuals in this range, including those in secondary school, university, manufacturing/construction, postgraduate or technical/vocational education, new industry recruits and out-of-school youth.
8 For Inspiration and Recognition of Science and Technology is an international youth organization that challenges school students to build industrial-size robots.
9 Intel ISEF is the world's largest international pre-college science competition.
10 Feira Brasileira de Ciências e Engenharia.
11 Young Engineers/Future Leaders of the World Federation of Engineering Organizations.
12 American Society for Engineering Education (ASEE) Student Division (SD).
13 Student Platform for Engineering Education Development (www.worldspeed.org).
14 Board of European Students of Technology (www.best.eu.org).

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International development and humanitarian engineering programmes

Educational researchers have shown that authentic 'learning by doing' in development motivates students to persevere despite initial disorientation or frustration (Lombardi and Oblinger, 2007). A successful example is the long-term field placements of Engineers Without Borders-Australia (EWB-A). By placing volunteer engineers in real-world contexts, EWB-A addresses complex engineering challenges while building local capacity. The D-Lab at Massachusetts Institute of Technology (MIT) has trained over 2,000 students in international development, simultaneously addressing equity issues by bringing together women, minorities and LGBTQ[15] students on transdisciplinary teams (MIT D-Lab, 2018; Murcott, 2015).

Engineering for and by refugees

Given their unique knowledge, young refugees should be given opportunities to learn engineering skills. A new model for developing engineering capacity among refugee youth has been developed by the DeBoer Lab (Purdue University) in Indiana, US, in collaboration with local partners in multiple locations. The scheme offers university credits for refugees in the Azraq (Jordan) and Kakuma (Kenya) camps and uses engineering design to guide students in community-centred problem-solving. Using an active, blended, collaborative and democratic (ABCD) model (de Freitas *et al*., 2018), the students solve local problems and become agents of change.

> **'Engineering taught me how to address different needs about diversity, and working in teams. I am able to find needs, identify problems and find solutions using a multiple stage engineering design process. I am also able to communicate my solutions effectively and get feedback. Failure to me is not a stop, but a stage.'**
>
> – Kakuma, refugee, youth engineering graduate

Maker spaces and contextualized community-based programmes for out-of-school youth

As of 2019, 258 million children and youth are out of school (UNESCO-UIS, 2019), which represents a huge untapped potential. However, even informal learning can help transform these individuals into young engineers. Since 2015, the DeBoer Lab has worked with former 'street youth' at the Tumaini Innovation Center in Kenya to apply the ABCD model to pre-college engineers. Students learn foundational engineering skills and 'maker' principles to solve local problems, for example, in designing a solar PV system to power classrooms and then serving as solar maintenance consultants for the community. Vigyan Ashram in India is another successful example of a formal training programme that supports out-of-school youth through the use of hands-on problem-solving skills, and serves as a unique model for youth capacity-building in India (Kulkarni, Ballal and Gawade, 2012).

Conclusion

Formal and informal pathways for engineering provide opportunities for a wider cohort of young people to create a more inclusive cadre of engineers that better represent society. Becoming leaders and job creators themselves will help youth drive national, regional and global progress towards the SDGs. The existing elite and rigid system of formal engineering education must be phased out and replaced with a more diverse set of experiences and an understanding of socio-environmental issues. Young people motivated by social justice and environmental considerations must fully participate in this transformation in order to change engineering practice and, in turn, make engineering a tool for more inclusive development.

Recommendations

1. *Policy-makers.* Engage young engineers directly in the design of courses, learning spaces and employment. Fund programmes engaging vulnerable youth and offer incentives for participating organizations. Create standards and accountability for engineering at primary/secondary education levels. Encourage youth to solve problems by engaging with them in their communities.
2. *Industry leaders.* Engage with student organizations to directly communicate current work practices, thereby addressing a gap revealed in research (Stevens, Johri and O'Connor, 2014). Partner with programmes serving vulnerable young engineers. Apply technological and programmatic solutions to increase access to education and training initiatives.
3. *Educators.* Work with collaborators to introduce young people to engineering earlier in the curriculum (secondary education or before). Design curricula using authentic learning in formal and informal spaces, including multiple pathways for students to experience realistic, hands-on engineering work.

15 Lesbian, gay, bisexual, trans, queer/questioning.

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3. ENGINEERING INNOVATIONS AND THE SUSTAINABLE DEVELOPMENT GOALS

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Abstract. Each one of the Sustainable Development Goals requires solutions rooted in science, technology and engineering. As covering the vast array of engineering solutions is beyond the scope of this report, this chapter provides snapshots of engineering innovations that address key challenges: the COVID-19 pandemic, clean water and sanitation, as well as issues related to hydraulic engineering, climate emergency and natural disasters, clean energy and mining engineering, and leveraging emerging technologies such as big data, Artificial Intelligence and the concept of smart cities for sustainable development, all of which have shown concretely how engineering can help promote the SDGs and improve the quality of human life. These engineering solutions consist not only of technological means, they are also accompanied by ethical codes, norms and standards to ensure that engineering practices are conducted responsibly. It is also noteworthy that through its engineering programme and relevant UNESCO Category 1 and 2 Centres, UNESCO plays a particularly vital role in promoting engineering innovations for the SDGs. UNESCO has continuously worked alongside engineering societies and supported engineering solutions for implementing the SDGs with an emphasis on engineering capacity-building in developing countries, especially in the following domains: disaster management and climate risk, water engineering development, and responsible AI and big data application, among others. Although significant progress has been made in terms of engineering innovations, gaps still remain between current engineering capability and what is required to achieve the SDGs, leaving no one behind. A set of recommendations is proposed to fill the gaps. These call for the combined efforts of government, academic and education institutions, industry and engineering societies.

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3.1 ENGINEERING INNOVATIONS TO COMBAT COVID-19 AND IMPROVE HUMAN HEALTH

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Introduction

On 30 January 2020, the World Health Organization (WHO) declared a Public Health Emergency of International Concern (PHEIC) as the result of an outbreak of novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which was recognized as a pandemic on 11 March 2020 (WHO, 2020*a*). As a result of the pandemic, the workload of healthcare staff around the world has increased dramatically as they face unprecedented challenges in dealing with the rapidly growing numbers of persons infected with the coronavirus (COVID-19) who require urgent assistance from multiple domains. Biomedical engineers from industry, academia and research centres have collaborated with multidisciplinary experts to develop and provide innovative and speedy solutions for appropriate testing, diagnosis, treatment, isolation and contact tracing to mitigate the spread of COVID-19.

Objective

The objective of this section is to review engineering approaches to combat COVID-19 and improve healthcare. Some key technologies have been implemented to provide effective care to COVID-19 patients and to combat the pandemic, which include medical diagnostic and therapeutic devices, information and communication technologies (ICTs), Internet of Medical Things (IoMT), Artificial Intelligence (AI), robotics and additive manufacturing. These efforts have hastened the ability to quickly and accurately detect viral infection and made available a number of complex life-supporting devices, such as ventilators, imaging and monitoring devices, as well as efficient isolation, contact tracing and the analysis of big data, which is required to offer timely assistance within the healthcare ecosystem. Telemedicine and robotics have also been employed, alongside the use of AI to predict the potential positive cases and probable fatalities. The growing number of patients has accelerated the production of diagnostic and therapeutic devices and personal protective equipment (PPE), which has led to novel production processes. Many biomedical engineers are presently focused on mitigating the pandemic; however, the overall aim is to improve healthcare and achieve the SDGs by implementing technological advances to help in the swift diagnosis, treatment and rehabilitation of patients, while achieving greater accuracy at lower cost for the well-being of all.

Diagnostic and therapeutic devices

WHO has prioritized the medical devices required for the clinical management of COVID-19 and has also provided interim guidelines for their use, as well as technical and performance specifications (WHO*b*, 2020). The list includes oxygen therapy, pulse oximeters, patient monitors, thermometers, infusion and suction pumps, X-ray, ultrasound and CT scanners, PPE (WHO*c*, 2020), as well as related standards, accessories and consumables.

Different methods for COVID-19 testing have been carefully analysed in the hope of finding the most effective technique for detecting the virus. There are now four diagnostic tests available – rapid point-of-care, combination tests, saliva tests and at-home collection tests – providing individuals with alternative options depending on the different circumstances and scenarios (FDA[3]). The gold standard for detecting SARS-CoV-2 infection relies chiefly on reverse transcription polymerase chain reaction (RT-PCR), which has both high sensitivity and specificity in detecting viral ribonucleic acid (RNA). However, owing to its complexity, this has resulted in an increase in turnaround time. Consequently, rapid antigen tests were developed as both laboratory-based tests and point-of-care tests, offering results within 30 minutes and at low cost.

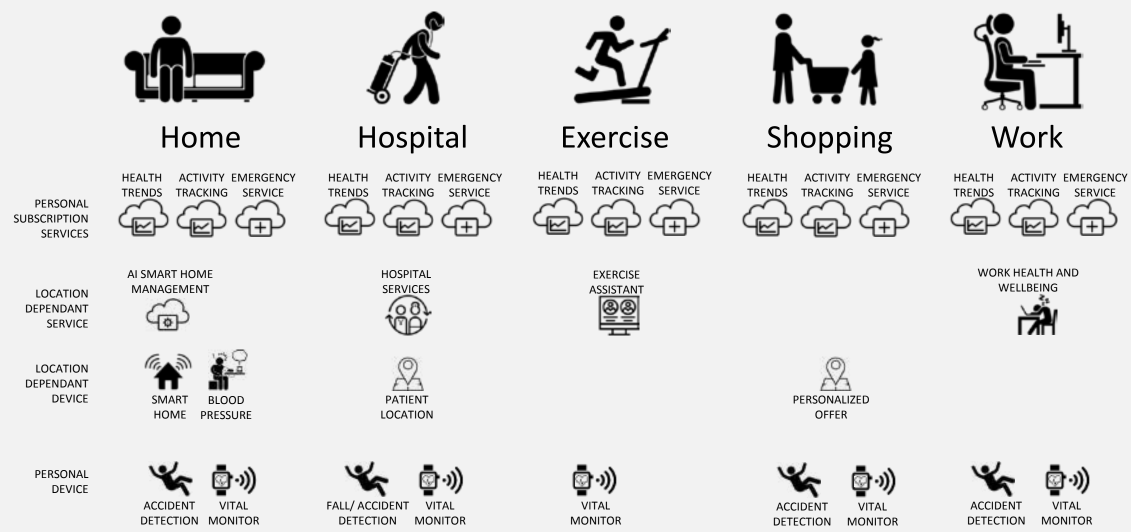
Critical patients experiencing respiratory failure need respiratory support in the form of a mechanical ventilator (Andellini, 2020) and the most suitable ventilator setting for personalized ventilation (USPHSCC, 2020). The use of 3D-printing has enabled solutions by responding to requests ranging: from spare parts to medical devices and PPE (Choong *et al.*, 2020). Patients admitted into hospital with severe respiratory problems require ventilators. However, given the low number of available ventilators, a novel collaboration between Ford, General Electric (GE) and Airon was initiated (Ford, 2020).

Information Communication Technologies

The COVID-19 pandemic has boosted the application of digital technology in society. The healthcare system has in many countries responded to the pandemic by adopting advanced digital technology tools (Golinelli, 2020). Telemedicine is recognized as an efficient and practical ICT service to collect, store, retrieve and exchange medical information without direct contact between the provider and the customer (Bokolo, 2020). The use of telemedicine technology for virtual treatment and teleconsultations has accelerated markedly since the beginning of 2020 (Brodwin and Ross, 2020; Ohannessian, 2020).

3 Read more about coronavirus disease 2019 testing basics by U.S. Food & Drug Administration at https://www.fda.gov/consumers/consumer-updates/coronavirus-disease-2019-testing-basics

Figure 1. Services across user's daily activities. IoMT applications cover acquisition of physiological, health, behavioural and other information potentially valuable to determine health status



Source: Celic and Magjarevic, 2019.

Soon after the pandemic appeared in Wuhan, China, in December 2019, patients were advised to look for medical help online rather than in person to avoid direct contact (Webster, 2020). A recent study of mobile and wireless technologies for health (mHealth) confirmed the viability of mHealth to monitor COVID-19 patients and to predict symptom escalation for earlier intervention (Adans-Dester, 2020). Interactive apps embedded in smartphones or similar devices with interactive high-quality displays, high resolution cameras and audio have facilitated contact and bi-directional communication with clinicians, as well as the acquisition of health information and guidance from diverse online services. Widespread online connectivity as well as the rapid adoption of telemedicine could potentially enable better alignment with the delivery of personalized healthcare in the future (Kannampallil, 2020). However, although screening processes for COVID-19 were available on online platforms shortly after the outbreak of the coronavirus, many individuals were not able to access the online system due to the digital divide (Ramsetty and Adams, 2020). For the purpose of understanding the spread of pandemics, position tracking of anonymized individuals through mobility indicators may be derived from aggregated mobile positioning data (Sonkin *et al.*, 2020). Internet services also provide indirect support in the fight against coronavirus by establishing awareness about pandemics, as well as clarity on important government decisions and policies affecting the public.

Internet of Medical Things

Connected infrastructure of medical devices, health systems and services is known as Internet of Medical Things (IoMT). It connects medical devices and applications to a network where 'things' communicate independently among themselves (Figure 1). The connectivity ensures the remote collection of physiological, health (Aydemir, 2020), behavioural and other information potentially valuable to determine the health status, diagnosis or treatment of persons in remote locations (Venkatesan *et al.*, 2020). The benefit of IoMT is that the communication is automated, machine-to-machine and takes place in real time. Information from wearables, home appliances and vehicles is integrated into multiparametric datasets (i.e. big data). Based on the acquired information, most common symptoms may be detected at their onset, enabling rapid diagnosis of cases in the early stages of the disease and self-isolation of the patient to prevent further spread of the infection. However, the interconnectivity of devices through cellular and home networks and Wi-Fi increases the potential vulnerability of privacy through hacking or accessing personal medical data.

Applications of AI

The application of AI in biomedicine can increase accuracy and safety in a range of biomedical fields, such as health screening, disease diagnosis and treatment, rehabilitation training and evaluation, medical services and management, drug screening and evaluation, as well as gene sequencing and characterization. These applications are driven by medical data, including images, atlases, medical records and other medical information sources, which can be rapidly processed by AI. The medical processes, including intelligent management of disease pathogenesis, precise diagnosis, safe treatment and scientific evaluation, can significantly improve the operational efficiency of doctors. In this way, it can alleviate the shortage of doctors, improve the accuracy of diagnosis and treatment, and optimize the allocation of high-quality medical resources, real-time health monitoring and warning, and the rapid development of medical IoT, wearables and medical devices, all of

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which can benefit from the use of AI. Overall, the applications of AI can aid in medical technology innovation and enable healthcare to progress to a new stage of quantitative analysis (CAE, 2019).

With prudent deployment of AI, enhanced efficiencies and quality of care can be achieved by leveraging a coupling of predictive models, decision analysis and optimization efforts to support decisions and programmes in healthcare. AI methods show promise for multiple roles in healthcare, including acute and longer-term disease management, inferring and alerting hidden risks of potential adverse outcomes, selectively guiding attention, medical care and interventional programmes, thereby reducing errors in hospitals and promoting health and preventive care.[4]

Box 1. AI Applications in combating COVID-19

Since the outbreak of the pandemic, AI has been contributing to combating COVID-19 in terms of early warnings and alerts, tracking and prediction, data dashboards, diagnosis and prognosis, treatments and cures, social control and vaccine development.

For example, one urgent challenge of COVID-19 was to break through the bottleneck of diagnosis time and assist doctors in making quick and correct decisions by using the appropriate technical tools. Having learned from many carefully annotated computed tomography (CT) images, researchers and engineers built an AI-assisted CT imaging system that can screen questionable COVID-19 cases within minutes, greatly reducing the time for diagnosis while increasing accuracy. The AI system has been used in hospitals in different countries, such as China, Japan and Italy, providing a helpful complementary check to deal with possible false-negative RT-PCR test cases.

It is worth mentioning that the Republic of Korea managed to contain COVID-19 without shutting down its economy by using the intelligent support of AI in the following steps (ITU, 2020):

- AI fasten testing kit development
- Smart quarantine information system
- Mobile phone tech data for contact tracing
- Improved diagnosis and patient classification by AI
- Mobile apps for information sharing
- Smart city hub to trace patient routes

Robotics

The coronavirus pandemic has increased interest in applying robotics as an effective technology to combat COVID-19. Robots have been considered for disinfection, medicine and food delivery, monitoring patients from a safe distance, sterilization and cleaning, all of which reduce human-to-human contact and the infection risk of personnel. Moreover, the robots that replace humans can work 24/7 and do not get infected or tired, and are thus useful in combating the overall shortage of medical and supporting personnel. Robots are also used as a protective layer to physically separate the healthcare worker and patient, and to reduce pathogen contamination in surgery (Zemmar *et al.*, 2020).

Digital health

Digital health (DH) has found increased applications in combating COVID-19. DH connects and empowers people to manage health and wellness, augmented by accessible and supportive providers working within integrated, interoperable and digitally enabled care environments that strategically leverage digital tools, technologies and services to transform healthcare delivery (Snowdon, 2020). The key components of DH include health information systems, telehealth and personalized medicine, with software, smart sensors, connectivity, IoT, AI, machine learning and efficient computing platforms. All these result in increased efficiencies, enhanced data collection, timely access to effective care and communication of data across diverse segments of the population, thereby ensuring equity, reduced costs and personalized medication for patients (FDA, 2020). DH has proven to be very beneficial to patients, doctors, nurses, physical therapists, clinics, hospitals, healthcare providers and governmental agencies.

Isolation

Essential steps involved in combating COVID-19, including testing, isolation, treatment and contact tracing. Isolation of infected patients is essential to ensuring maximum safety. Critical steps such as physical distancing, using approved PPE and a 14-day quarantine period must be followed. Innovative designs of isolation chambers and enclosures have been attempted, and practical solutions have been implemented. PPE for caregivers of COVID-19-infected patients include facemasks, NIOSH-approved N95 respirator filters, face shields, eye protectors, and disposable medical gloves and gowns. In the early phase of the pandemic crisis, PPE supplies could not meet the rapidly increasing demands. Consequently, government agencies partnering with private companies came up with fast-track manufacturing that delivered innovative 3D-printing to COVID units, hospitals and long-term care centres. Ingenious approaches in product design provided the much needed PPE and isolation facilities to combat the virus. With the collaboration of engineers and experts in multidisciplinary domains, several ‘temporary hospitals’ were designed, constructed and commissioned for treating COVID-19 patients.

Contact tracing

Contact tracing is essential to combat the spread of COVID-19. The process works to identify, monitor and support individuals who may have been exposed to a person with COVID-19.

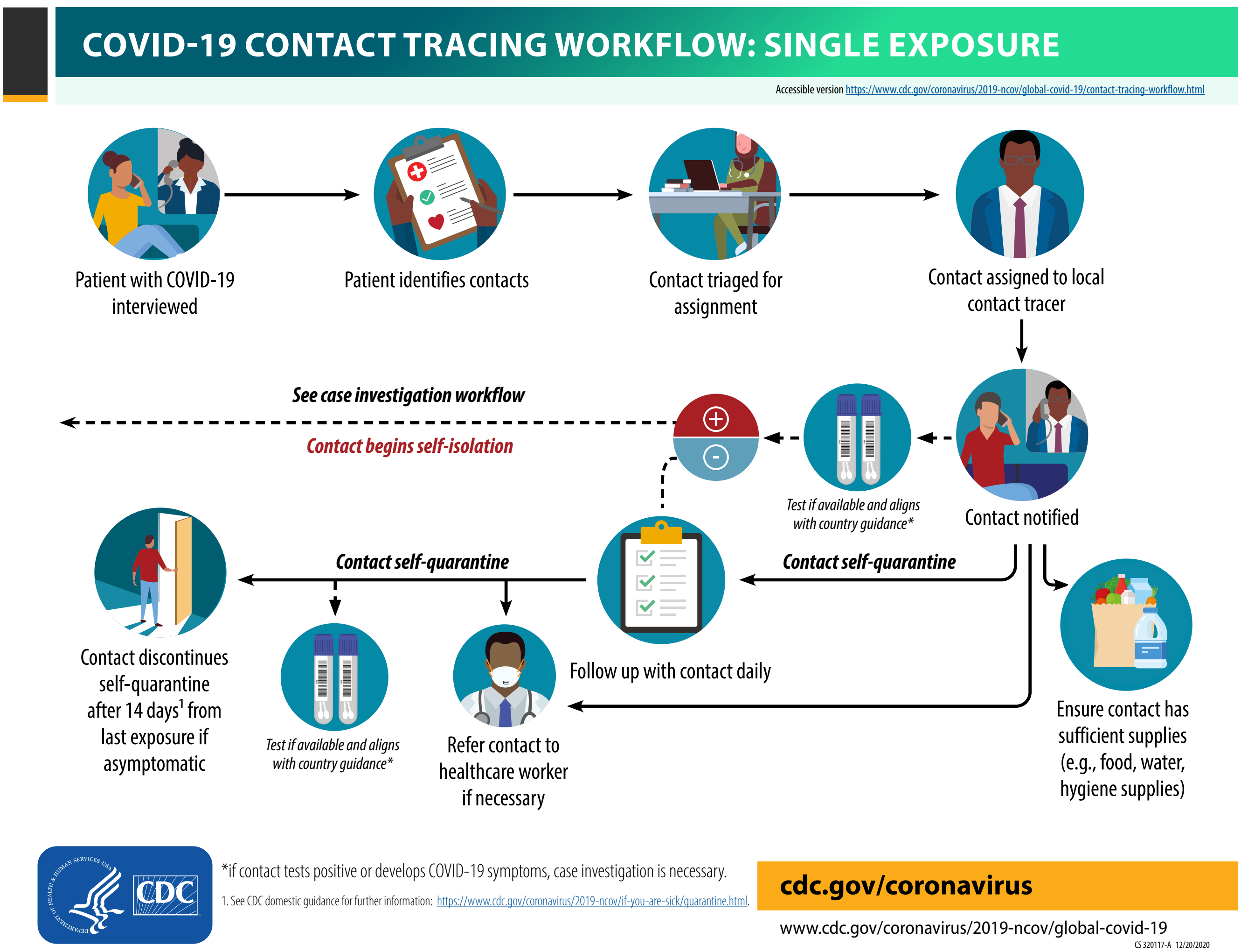
4 Private correspondence with Gong Ke is included in this section on AI.

In one contact tracing method, person A goes outside bringing a Bluetooth-enabled phone with a digital key that is able to communicate with other phones. Person A comes into contact with persons B, C and D and all their phones exchange key codes. When person A learns that they have been infected, person A's status is updated in the app and sent to the database via the cloud. Meanwhile, the phones of B, C and D regularly check the cloud database to ascertain the status of their users' contacts. When B, C and D are alerted that A is infected, they must take a COVID-19 test (Hsu, 2020). This concept was implemented successfully with 'TraceTogether' in Singapore and HOIA in Estonia (Petrone, 2020). If the subject is tested right after exposure to COVID-19, even highly sensitive PCR tests can come back negative. The average onset of symptoms occurs five days post-exposure, and the subject reaches peak infectiousness two days before and one day after the onset of symptoms (Redford, 2020).

South Korea built a centralized system that scrutinizes patients' movements, identifies people who have been in contact with patients, and uses apps to monitor people under quarantine. The contact tracers had access to multiple information sources, including footage from security cameras, and mobile base station and credit card transaction data. COVID-19 outbreaks were successfully contained without closing national borders or implementing local lockdowns (Hsu, 2020).

The steps involved in the workflow process for a partially automated contact tracing model include rapid notification of exposure, contact interviews, quarantine/isolation instructions, testing quarantine/isolation instructions, assessment of self-quarantine support needs, medical monitoring and monitoring and isolation instructions (Figure 2).

Figure. 2. Contact tracing workflow



Source: Centers of Disease Control and Prevention (CDC, 2020)

Facility reconfiguration and remote learning

Engineering approaches and new configurations have been designed and implemented in hospitals, schools and colleges. Redistributing the placement of students and faculty in labs and classrooms was a difficult exercise. A similar de-densification scheme was required in offices and public places such as libraries, restaurants, gyms and religious centres. Diligent application of video conferencing technologies such as Zoom provided vital support to all those in schools, colleges and universities, leading to large-scale use of remote learning. Without virtual and hybrid learning environments, students of all ages, as well as their educators and administrators, could not carry out their expected functions. Advances in engineering and technology have contributed significantly to keeping 'life' as close as possible to an acceptable 'new normal'.

Applications of multiple emerging technologies

Emerging technologies, such as 5G networks, IoMT, telehealth, mobile health, nanotechnologies, additive manufacturing, flexible electronics, wearable sensors, cloud computing, AI, machine learning, predictive analytics, cybersecurity and precision medicine, are all being applied to meet the needs of combating COVID-19, as well as to improve healthcare for all. The logistics technologies used by Amazon, FedEx and UPS, among others, have greatly facilitated the efficient transport of supplies, including PPEs, ventilators, drugs and essential supplies to user sites, playing a very useful role in combating COVID-19. In the clinical setting, biomedical engineers created an efficient bed management system to reduce wait times by way of faster discharge and admissions of patients, shortening the length of stay, improving efficiency and reducing costs. Analysis of COVID-19 patient data suggests a disproportionate impact on the lower income group and older population, especially with pre-existing conditions in nursing homes. Using government and private sector resources, Operation Warp Speed (OWS)[5] has been employed to accelerate the testing, supply, development and distribution of safe and effective vaccines, therapeutics and diagnostics to counter COVID-19.

Biomedical engineering to achieve SDG 3

Sustainable Development Goal 3 (SDG 3) aims to 'ensure healthy lives and promote well-being for all at all ages'. Biomedical engineering provides tools, techniques, devices and systems to aid in the diagnosis, treatment and cure of diseases and to make people healthy. The dedicated efforts of biomedical engineers in collaboration with other engineers and scientists have contributed towards ending the epidemics of AIDS, tuberculosis, malaria, and fighting hepatitis and other communicable diseases, in addition to reducing global maternal mortality and premature mortality from non-communicable diseases.[6]

Wearable medical devices can be used to track the correlation between patient behaviours and outcomes. Engineers can also help the healthcare system by promoting prevention. The combined efforts of engineering experts working cohesively with a broad spectrum of researchers from the life sciences, medicine, business and regulatory agencies have contributed towards productive actions to treat diseases and prevent illnesses. It is envisioned that engineers and technologies will play a meaningful role in keeping people healthy and promoting well-being for all at every age.

Challenges

As a result of surges in the daily total of confirmed cases, hospitalizations and deaths from the virus, hospitals and health systems have experienced financial havoc, negatively impacting on operations. Shutting down elective surgeries and non-essential services has led to lasting impacts, trigging a vital need in the United States for federal funding. While the results from clinical trials will demonstrate the safety and efficacy of several vaccines, large-scale manufacturing, distribution, prioritization, and mass vaccination represent global challenges, particularly in view of the need to comply with stipulations from various forms of public health governance in different nations. The severe cases of COVID-19 have led to critical shortages and an increasing need for intensive care unit (ICU) beds, and invasive and non-invasive ventilator support in ICUs.

Some of the main challenges encountered in digital health are digital literacy, robust software, training, interoperability, inequity in resources, funding and a skilled workforce (Taylor, 2019). The shift to remote, solitary working without social interactions during the pandemic is likely to cause a deterioration in mental health. In addition, the delivery of virtual courses may pose problems with respect to learning and teaching.

5 Read more about Operation Warp Speed of the US Dept. of Defense at https://www.defense.gov/Explore/Spotlight/Coronavirus/Operation-Warp-Speed
6 Read more about SDG 3: https://sdgs.un.org/goals/goal3

There have been cases of mental health issues as a result of stress triggered by remote learning, and the long-term impact of learning outcomes has yet to be determined.

Some core barriers to compliance with regulatory guidelines are related to practical issues, selfishness and a shift in responsibility. While emerging technologies are adapted to healthcare applications, implementation on a wider scale requires efficient collaboration between engineering and global health coupled with cooperation by the global community with diverse and inequitable resources (Clifford and Zaman, 2016). Timely analysis and the sharing of valuable information, which is collected using smart technologies and software platforms, are essential for leadership to mitigate and control the spread of COVID-19, and to treat patients and plan for the well-being of the public at regional and national levels.

Conclusion

Engineers in multiple disciplines have collaborated with scientists, physicians, healthcare personnel, mathematicians and other experts to design, develop and implement solution strategies and approaches to combat the unprecedented, multidimensional problems associated with COVID-19. There have been some successes, and ongoing and innovative efforts will continue with strong commitments to mitigate the disastrous impacts of the pandemic. Researchers at colleges, universities, industries and government centres continue to collaborate with multi-disciplinary teams forming public-private partnerships to use the emerging technologies to develop intelligent solutions to improve the quality of human life and to achieve good health and wellness for all persons at all ages.

Recommendations

Engineering-based recommendations to improve healthcare include the following:

1. Cohesive and concerted efforts undertaken across multiple layers and spheres of the healthcare ecosystem to improve healthcare for all.
2. The adoption and implementation of technological advances to help in the detection, diagnosis, treatment, data analysis and the rehabilitation of patients infected with COVID-19 and persons suffering from other illnesses.
3. Novel techniques for performing numerous processes in healthcare at faster speed, greater accuracy and lower cost will need to be developed and made available for all.
4. Similar to the innovative approaches used to combat the pandemic, superfast processes must be employed in design, development, manufacturing and implementation to prepare for future challenges.
5. Multinational members of the International Federation for Medical and Biological Engineering (IFMBE)[7] across academia, biomedical industries and healthcare systems, as well as regulatory, governmental and non-governmental organizations, should continue their contributions to developing effective solutions to combat the complex problems posed by the pandemic, as well as contributing towards sustaining good health and wellness for all.

7 International Federation for Medical and Biological Engineering official website: https://ifmbe.org/

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José Vieira[8]

3.2 WATER ENGINEERING FOR SUSTAINABLE DEVELOPMENT

Suspended footbridge in Haiti

8 President-elect, World Federation of Engineering Organizations.

The United Nations Sustainable Development Goals (SDGs) are supported by scientific and technological advances in the implementation of policies and actions for peace and prosperity, for people, and for the survival of all forms of life on Earth.

Water, as a prerequisite for life, assumes a special focus in terms of sustainable development. Global water problems, including droughts and floods, pollution caused by natural and anthropogenic-driven events such as extreme rains, rising sea and river levels, bushfires and untreated domestic and industrial effluents, are key challenges globally which require adequate and efficient water management in order to meet the growing demand for clean water.

The hydrological changes induced by climate change will present challenges to the sustainable management of water resources, which are already under severe pressure in many regions of the world, aggravating the situation of regions that are already experiencing water stress, while at the same time generating water stress in regions where water resources are still abundant today.

SDG 6 on clean water and sanitation includes the 'water goal', which aims to provide universal access to clean water and sanitation by 2030. According to United Nations statistics from 2017, and despite the progress made, an estimated 2.2 billion and 4.2 billion people still lack safely managed drinking water and decent sanitation, respectively. In recent years, a new approach – known by the acronym WASH (water, sanitation and hygiene) – includes handwashing as a main element of good hygiene practices, which has shown to be an effective method to prevent the spread of COVID-19. However, an estimated 3 billion people still lack basic handwashing facilities at home, which may have negative consequences for the prevention of COVID-19.

Universal access to WASH will not be achieved for a long time in a great number of developing countries at current rates of progress. These countries also experience rapid and often unplanned urbanization which has put a strain on clean water supply and sanitation services. As access to clean safe water and decent sanitation is recognized as a basic human right by the United Nations, there is pressure on local and national authorities to meet their political and social commitments in this regard. Engineering can help explore innovative solutions for physical infrastructure to deliver water supply and sanitation, combining traditional approaches of large centralized systems with decentralized non-sewered solutions, ranging from more effective design of septic tanks through to waterless toilets.

Water engineering is multidisciplinary and benefits from progress in technological innovation in areas such as microelectronics, nanotechnology, fine chemicals, biotechnology, data acquisition, satellite-based earth observation, hydro-environmental modelling and remote sensing.

This chapter presents examples of engineering contributions that address these global challenges and seek to achieve the SDGs, in particular SDG 6, which emphasizes the mutually integrated advances made in hydrology concerning clean water and human health.

3.2.1. Clean water and human health

José Vieira[9] and Tomás Sancho[10]

Abstract. The close relationship between human health and the well-being of communities with access to clean water is a determining factor for economic and societal development. Despite the human right to safe, clean drinking water and sanitation, as recognized by the United Nations in 2010[11], there are still major challenges to implementation, particularly in less developed countries. Currently, clean water has garnered unprecedented focus in public policy in efforts to contain the spread of COVID-19. Historically, civil and environmental engineers have played a prominent role in the design and construction of large infrastructure projects to provide clean water and adequate sanitation systems. Significant progress in water and environmental engineering in recent decades has led to the development of new and more efficient water technologies, such as advanced oxidation, adsorption, reverse osmosis, and nano- and ultra-membrane filtration, which are used in the removal of priority substances in advanced water treatment. In addition, innovations in engineering disciplines, such as aerospace, satellite technology, hydro-environmental modelling, electronic and computer engineering as well as remote sensing technologies, all contribute to identifying trends in the water cycle, which is of paramount importance for comprehensive assessment of quantitative and qualitative water-related climate change impacts.

Introduction

It is relatively safe to say that throughout human history serious public health problems have frequently been due to the transmission of infectious diseases through pathogenic microorganisms (bacteria, viruses, protozoa and helminths), related to an absence of safe water. In fact, through various routes of infection, either by ingesting food or water, by inhalation or aspiration of aerosols, as well as by exposure to contaminated water and carried by arthropods or molluscs, these waterborne diseases have been responsible for serious widespread public health crises (Vieira, 2018).

From the middle of the nineteenth century, following the devastating epidemics of cholera and other gastrointestinal diseases in Europe, there was a gradual and definitive change in thinking and attitude towards the economic, social, environmental and health aspects of daily life with regard to public policies. The creation of the Poor Law Commission in Great Britain in 1834, and the studies developed within the scope of its activity (Chadwick, 1842), were decisive for medicine and public health engineering. This act from an intervention perspective aimed to help find technical solutions for the supply of cleaner water supply and sanitation in the urban environment with the aim of preventing and controlling disease. It was thus believed that disease would be combated more effectively if technical solutions that were preventative in nature were implemented, rather than relying on interventions by the individual for the promotion of health. In this context, steam – the new energy source – enabled the development of revolutionary drinking water networks and sanitary sewer systems in buildings, introducing new technological advances in the fields of wastewater collection and treatment, and assuming a strategic role in promoting health in the urban setting.

Progress in medicine and microbiological sciences was first needed to identify and isolate the pathogens before 'safer' water could be envisaged by advances in engineering. The disinfection of drinking water, introduced at the end

9 President-elect, World Federation of Engineering Organizations.
10 Chair of Working Group on Water, World Federation of Engineering Organizations.
11 In its Resolution 64/292, on 28 July 2010 the United Nations General Assembly recognized water and sanitation as a human right, and acknowledged that clean drinking water and sanitation are essential to the realization of all human rights.

of nineteenth century, considerably reduced the spread of cholera and typhoid fever (Rose and Masago, 2007).

Currently, water pollution continues to exert pressure on public health due to growing industrialization, urbanization and the intensive use of chemical products in agriculture. Learning from the past, it is vital to use engineering advances to address the issue of global clean water, which is crucial to controlling emerging and re-emerging waterborne diseases, as well as to enhancing the quality of life in modern societies.

The human right to water and sanitation, and the focus of water for sustainable development

In 2010, the United Nations General Assembly recognized the right to safe, clean drinking water and sanitation as a human right essential for the full enjoyment of life, reflecting the fundamental nature of these basic needs. It was agreed that the lack of safe, accessible, sufficient and affordable water and sanitation and hygiene facilities has a devastating effect on the health, dignity and prosperity of billions of people worldwide with significant consequences for the realization of other human rights (UNESCO/UN-Water[12], 2020). This was a political act of high strategic significance, contributing decisively to significant investments worldwide for the construction and maintenance of the infrastructure needed to support drinking water supply and sanitation systems.

On the occasion of the United Nations Summit for Sustainable Development in 2015, an ambitious document, the 2030 Agenda for Sustainable Development, presented a strategic vision for the orientation of national policies and international cooperation activities until 2030. It proposed 17 Sustainable Development Goals (SDGs) with the aim of implementing the specific principles of health, and human and social dignity in various areas of activity. For example, SDG 6 establishes the principle of ensuring 'availability and sustainable management of water and sanitation for all'. Beyond SDG 6, several other goals are closely related to water, namely SDG 1 (End poverty in all its forms), SDG 2 (End hunger and achieve food security), SDG 3 (Ensure healthy lives and well-being for all), SDG 7 (Ensure affordable, reliable, sustainable and modern energy), SDG 11 (Make cities and human settlements inclusive, safe, resilient and sustainable), SDG 13 (Combat climate change), and SDG 15 (Protect and restore biodiversity, forests, and halt deforestation).

However, despite the advances made in the last decade, there are still major challenges to overcome before the Agenda is fully implemented, particularly with regard to less developed countries. In fact, recent estimates regarding the coverage of water supply, sanitation and hygiene systems among the world's population (UNICEF/WHO, 2019) reveal relatively slow progress that casts doubt on whether the proposed objectives will be achieved by 2030.

- *Drinking water*: 5.3 billion people have access to safely managed services. An additional 1.4 billion have at least access to basic services, 206 million people have limited services, 435 million have unimproved sources and 144 million still use surface water.
- *Sanitation*: 3.4 billion people have access to safely managed services. An additional 2.2 billion have at least access to basic services, 627 million people have limited services, 701 million have unimproved facilities and 673 million still practise open defecation.
- *Hygiene*: 60 per cent of the global population have basic handwashing facilities with soap and water available at home. Three billion people still lack basic handwashing facilities at home, 1.6 billion have limited facilities lacking soap or water, and 1.4 billion have no facilities at all.

This stark analysis brings to light the hygiene-sanitary reality of billions of people around the world, revealing the enormous global inequalities between developed and less developed countries with serious social, economic and public health repercussions for those populations.

To accelerate the realization of SDG 6, which is alarmingly off course, the United Nations launched the SDG 6 Global Acceleration Framework[13] to assist countries in raising their ambition to rapidly move towards national targets for SDG 6 and, in doing so, contribute to progress across the 2030 Agenda in areas such as poverty reduction, food security, good health and well-being, gender equality, peace and justice, sustainability and climate resilience of communities, ecosystems and production systems.

The Framework contributes to realizing the human rights to water and sanitation. It builds on ongoing processes, including the Water Action Decade 2018–2028, as well as the United Nations Secretary-General's global call to action for water, sanitation and hygiene (WASH) in all healthcare facilities, and the Agenda for Humanity[14].

12 UN Water official website: https://www.unwater.org
13 Read more about the SDG 6 Global Acceleration Framework at https://www.unwater.org/publications/the-sdg-6-global-acceleration-framework
14 Read more about Agenda for Humanity at https://agendaforhumanity.org

Engineering responses to clean water challenges

In order to ensure water security, realize SDG 6 and build resilience to climate change engineering must provide the necessary knowledge and technology to lead efficient water governance and management.

Almost one-tenth of the total burden of waterborne diseases worldwide could be prevented by improvements to drinking water, sanitation, hygiene and water resources management. The following examples refer to global diseases that are preventable if these conditions are met: diarrhoea (1.4 million preventable child deaths annually); malnutrition (860,000 preventable child deaths annually); intestinal nematode infections (2 billion infections affecting one-third of the world's population); lymphatic filariasis (25 million seriously incapacitated people); schistosomiasis (200 million people with preventable infections); trachoma (visual impairments in 5 million people); and malaria (half a million preventable deaths annually) (WHO, 2019).

In addition to these well-known waterborne diseases, emerging and future biological threats can be anticipated, for example: i) other known diseases that can re-emerge; ii) 'new' diseases identified due to new, more sophisticated laboratory methods; iii) real new diseases; iv) changes in disease behaviour; v) changes in environmental conditions; and vi multidrug-resistant microorganisms that may emerge.

Anticipated climate change can make these numbers even more dramatic, though their possible spread is so far unlikely. However, the ability to spread infectious diseases via vector arthropods increases with rising water temperatures. Regions such as Europe and North America, which were previously too cold to support transmission, may experience an inversion of this trend as the rise in water temperature creates favourable conditions for the reproduction of the aforementioned vectors.

New and emerging chemical pollutants are ubiquitous in water resources and the environment, and include: i) pharmaceutical waste; ii) endocrine disrupting compounds; iii) nitrosamines; iv) pesticides; v) biocides; vi) algal toxins/cyanobacteria; vii) personal hygiene products; viii) fragrances, and so on. For the majority of these pollutants, there is no information on their effects on human health, and their ecotoxicology is not included in official lists of parameters for regular water quality monitoring. Moreover, there is no evidence regarding the behaviour of these priority substances during water and wastewater treatment processes.

Solutions to the complex issues related to clean water have been addressed in a multidisciplinary way by engineers from different disciplines, applying scientific knowledge and providing innovative solutions to global water problems. Historically, civil engineers have played a prominent role in the construction of large infrastructure projects and water resources development. Other engineering disciplines, such as mechanical, chemical, biological, environmental, agricultural, electronic and computer engineering, have also contributed by offering new technological solutions and enhancing options for sustainable water management policies (see Box 1).

In addition to the design of water infrastructures (dams and reservoirs, channels, pipelines, pumping stations, water treatment plants), engineering contributions include the technification of systems, providing them with 'intelligence' that enables better operation and management through research and development, and knowledge transfer (Trevelyan, 2019). Some examples include:

- supporting water governance with an integrated water resources management approach;
- improving water-use efficiency and reducing losses in municipal distribution networks and industrial and energy cooling processes;
- implementing nature-based solutions in rivers, aquifers and sustainable urban drainage;
- protecting and restoring water-related ecosystems;
- introducing alternative water sources, such as safe wastewater reuse (a significant untapped resource for industry and agriculture), storm runoff and desalination, which can also relieve water stress; and
- assessing and managing risks of extreme events (floods and droughts), which are natural phenomena that cause major human and economic losses.

Significant progress in water and environmental engineering in recent decades has led to the development of new and more efficient water technologies, such as advanced oxidation, adsorption, reverse osmosis, and nano- and ultra-membrane filtration, which is used in the removal of priority substances in advanced water treatment.

Advances in wastewater treatment processes have been made in removing usable substances (e.g. phosphorus and ammonium) and other products for further processing, for example, using organic matter to produce biogas or base chemicals, which can be used in the pharmaceutical industry, and in promoting a circular economy while also preventing the discharge of harmful substances into water resources and the environment.

The Internet of things (IoT), Artificial Intelligence, new data-driven analysis and control algorithms are currently transforming water systems from passive, single-purpose urban infrastructure elements into active and adaptive units making them more efficient, more innovative and more sustainable.

Innovations in engineering disciplines, such as aerospace, satellite technology, electronic and computer engineering, as well as in remote sensing technologies contribute to identifying trends in the water cycle that are of paramount importance for the comprehensive assessment of quantitative and qualitative water-related climate change impacts.

Box 1. Innovative engineering contributions to global water problems

Engineering developments offer innovative solutions to global water challenges, provide vital information on sustainable water resources management, support scientific research on new and emerging water issues, and promote science-based decision-making on water issues. Furthermore, engineering advancements can help mitigate and anticipate future water challenges, and contribute to a comprehensive assessment of climate change impacts related to water.

- *Advances in chemical engineering and environmental analysis.* Contributions to the development of wide-spectrum and high-precision analytical tools, which have brought to light the presence of ever greater types of pollutants in water resources, have made it possible to detect and quantitatively assess new pollutants that were not previously known to be present in the environment. With high-precision and high-sensitivity analytical equipment, it has also become possible to detect pollutants at much lower concentrations than those detectable with low sensitivity conventional techniques that were used in the past.
- *Developments in biochemical engineering.* Advanced oxidation and adsorption technologies provide solutions for the pre-treatment of specific pollutants such as pharmaceutical residues and chemicals in wastewater from hospitals and industrial facilities prior to discharge to municipal sewers.
- *Innovations in environmental engineering.* Cutting-edge engineering technologies such as ultrafiltration, nano-filtration and reverse osmosis are used in advanced water and wastewater treatment and have also proven effective for the removal of emerging pollutants from wastewater.
- *Advances in remote sensing.* Wireless sensors for monitoring water consumption have been developed and are increasingly used to allow for remote water metering. Evolutions in the field of data acquisition have been facilitated by high-speed internet networks and global coverage, as well as cloud computing and the enhancement of virtual storage capabilities. Applications of big data analytics can help to obtain knowledge by processing the collection of continuous streams of water-related information and data. Citizen science and crowdsourcing have the potential to contribute to early warning systems and to provide data for validating flood forecasting models.
- *Innovations in hydro-environmental modelling.* Specific and advanced models have been developed for the management of integrated water resources, floods and droughts, precipitation-run off and recharge of aquifers, floodplain estimations, damage previsions, infrastructure resilience, and energy and economic optimizations.
- *Advancements in aerospace and satellite engineering.* Satellite-based Earth observation (EO) can help identify trends in precipitation, evapotranspiration, snow and ice cover/melt, as well as runoff and storage, including groundwater levels. The use of EO imagery coupled with rapid progress in computational engineering has immense potential for water quality monitoring at the basin, national, regional and global levels. The launch of advanced environmental satellites has improved the spatial resolution of satellite images and opened up new frontiers for research on satellite-based water quality monitoring in inland freshwater bodies. Moreover, the open accessibility of most EO satellite images, such as Landsat and Sentinel, further facilitates research and applications, contributing to a better understanding and knowledge of the impacts of climate change and human activities on water resources. Furthermore, the use of EO satellites and drones, makes it possible to monitor water quality and water withdrawals in areas without infrastructure or inaccessibility, especially in developing countries.

The epidemiological context of the COVID-19 pandemic in 2020 and the unknown scientific characteristics of the SARS-CoV-2 virus has resulted in the lockdown of entire cities and the social isolation of billions of people, as well as the closure of vital economic activities. Consequently, civil society has recognized the relevance and value of clean water, safe hygiene and dignified sanitation to protect public health. Never before has the message about the importance of frequent and correct handwashing to prevent infection been so pronounced. The focus on WASH in containing the spread of the pandemic is unprecedented, particularly among the most vulnerable communities that do not have ready access to clean water.

As we face these challenges, technological innovation, knowledge management, advanced research and capacity development will generate new tools and approaches, and equally importantly, will accelerate the implementation of existing knowledge and technologies across all countries and regions (UNESCO/UN-Water, 2020).

Recommendations

1. Clean water is at the heart of any public health policy and an integral part of sustainable development. Governments and policy-makers should take urgent action to accelerate the realization of SDG 6 and solve the problem of inaccessibility to clean water which creates vicious cycles of poverty, inequality, food shortage and forced migration, particularly in less developed countries.
2. Anticipated global water challenges related to the impacts of increasing water pollution and climate change need to be addressed, while benefiting from advances in science, technology and innovation in areas such as hydro-environmental models, decision support systems, microelectronics, nanotechnology, fine chemicals, biotechnology and information technology.
3. The social and environmental relevance of clean water and the holistic nature of the 2030 Agenda for Sustainable Development demand an integrated and systematic approach when dealing with the specificities of each of the 17 SDGs which require intensive interdisciplinary analysis and multi-sectoral expertise in their implementation.

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3.2.2. Hydrology for the SDGs

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Abstract. The science of hydrology provides practical knowledge and information for society about water fluxes, transport and management, and thus has intertwined linkages with engineering applications. In the four decades after 1930, the development of hydrological science as a separate field of scientific inquiry (Horton, 1931) coincided with an enormous increase in engineered water infrastructure development. Furthermore, the rapid increase in hydro-infrastructure development triggered engineering applications across the globe. Hydrology and engineering thus essentially developed in tandem. In this section, the mutually integrated development of hydrology and engineering towards meeting global challenges, including the implementation of the Sustainable Development Goals (SDGs) is presented from the programme perspective of UNESCO's Intergovernmental Hydrological Programme (IHP).

Global water challenges

The world's population is projected to grow from 7.7 billion in 2017 to nearly 10 billion by 2050, and two-thirds of the population is expected to live in urban areas (UNDESA, 2017). This will lead to a corresponding increase in water demand in sectors such as agriculture, energy and industry, and will be manifested in engineering applications for water-related infrastructure development. In addition to population growth and economic development, climate change is also a major factor in water security. Climate change adaptation and mitigation through water management is therefore critical to sustainable development and necessary to achieving the goals of the 2030 Agenda for Sustainable Development, the Paris Agreement and the Sendai Framework for Disaster Risk Reduction (UNESCO/UN-Water, 2020).

In addition to water supply and sanitation, the management and reduction of uncertainty and the risks associated with flooding, sediment erosion, transport and deposition, and droughts are also key challenges globally. Since these fields mutually integrate hydrology and engineering, case studies in these areas are presented in this section.

How hydrology and engineering address the SDGs

Water is explicitly addressed in Goal 6 of the SDGs (clean water and sanitation). However, goals related to poverty reduction, food, health, gender and education, and targets for water-related disasters and climate change adaptation are also linked to water. The original role of hydrology in addressing water goals has thus evolved from a primarily engineering approach to an integrated approach involving natural sciences, the social and human sciences, and engineering. Engineered and nature-based infrastructure needs to be combined with water management approaches involving stakeholder engagement and bottom-up climate adaptation. These activities require the mobilization of international cooperation for research, the strengthening of the policy-science interface and capacity-building. Through its various programme sectors (education, science, culture, and communication and information), UNESCO has a unique mandate to address these interlinkages among the water-related SDGs.

15 Division of Water Sciences, UNESCO.
16 International Center for Integrated Water Resources Management (ICIWaRM).
17 International Research and Training Center on Erosion and Sedimentation (IRTCES).
18 International Centre for Water Hazard and Risk Management (ICHARM).
19 Division of Water Sciences, UNESCO.

UNESCO's unique role in hydrology and addressing the SDGs

UNESCO played a crucial role in this development by sponsoring the International Hydrological Decade (IHD 1965–74), which provided a mechanism for a global study of water resources available for engineering works, including social aspects, water quality and land use. The objectives of the IHD, and the Intergovernmental Hydrological Programme (IHP) that followed, were to strengthen hydrology's scientific and technological bases through the development of and training on the methods, techniques and guidelines for sustainable water management.

IHP is the only intergovernmental programme of the UN system devoted to water research and management, and related education and capacity development. The main objective of IHP's eighth phase (2014–2021) entitled, 'Water Security: Responses to Local, Regional and Global Challenges', is to mobilize science for water security. All of its activities support the SDGs. The upcoming ninth phase of IHP (2022–29) will reflect even stronger links for the realization of the SDGs, the Paris Agreement and the Sendai Framework.

The three case studies below were undertaken by IHP and three UNESCO Category 2 Centres: ICHARM[20], IRTCES[21] and ICIWaRM[22]. These centres host the secretariats for the International Flood Initiative (IFI), the International Sediment Initiative (ISI) and the Global Network on Water and Development Information for Arid Lands (G-WADI), and focus on water management and engineering applications based on hydrological services (flood control, sediment transport and drought, respectively).

Flood control, dam operation and water management in Asia and West Africa

ICHARM has developed the Water and Energy Budget-based Rainfall-Runoff-Inundation (WEB-RRI) model to analyse water-related hazard phenomena with a high level of accuracy. The model integrates the Hydro-SiB2 model, which is capable of calculating the dynamics of water and energy balance, with the Rainfall-Runoff-Inundation (RRI) model that is able to perform 2D runoff/inundation calculations. Use of the new model in combination with atmospheric models has enabled the evaluation not only of flood hazard impacts but also of drought hazard impacts due to future climate changes. By applying an integrated optimization scheme to the current operation procedure for hydroelectric dams, ICHARM is working together with electric companies to reduce ineffective dam discharges, improve power generating efficiency during a flood, and secure the storage capacity of a dam reservoir after a flood.

Real-time flood forecasting systems for the Kalu River in Sri Lanka and the Pampanga River in the Philippines were developed using the Data Integration and Analysis System (DIAS) in collaboration with ICHARM and the University of Tokyo, which has started to provide flood forecasting information to related organizations in both countries. Similarly, as part of an Asian Development Bank (ADB) project on climate change impact evaluation, ICHARM applied a series of forecasting methods, which take into account uncertainty, to three cities of Viet Nam: Hue, Ha Giang and Vinh Yen. In this study, four general circulation models (GCMs) were selected for their high responsiveness in regard to meteorological factors. The uncertainty originating in GCMs concerning future prediction was evaluated by applying statistical downscaling, while, future climate scenarios were created using dynamic downscaling, and flood risk evaluation was conducted using the RRI model.

In West Africa, flood disasters often occur in the Niger and Volta river basins resulting in deaths and hindering economic development in the region. In an effort to reduce human damage, UNESCO proposed to develop flood monitoring and prediction systems for these basins and their surrounding areas. After concluding a partnership agreement with UNESCO within the framework of the Water Disaster Platform to Enhance Climate Resilience in Africa, ICHARM developed a flood early warning system for the Niger and Volta river basins to help reduce water disaster risks. Simultaneously, ICHARM invited engineers from AGRHYMET, a specialized institute of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS) and the Volta Basin Authority (VBA), to Japan and provided training on the system.

Application of hydrological services to flood control and sediment management in the Three Gorges Project

Located in the middle reach of the Yangtze River, the Three Gorges Project (TGP) in China is one of the world's largest hydraulic projects. Since 2003, the TGP has been producing comprehensive flood control, navigation, power generation and

20 International Centre for Water Hazard and Risk Management official website at https://www.pwri.go.jp/icharm/
21 For more information on International Research and Training Center on Erosion and Sedimentation (IRTCES), see https://uia.org/s/or/en/1100024285
22 International Center for Integrated Water Resources Management official website at https://iciwarm.info

water resource benefits. Its annual average power generation capacity is 84.88 billion kWh, equal to about 50 million tonnes of coal. Average annual runoff and sediment loads of the river at the dam site are 451 billion m^3 and 530 million tonnes, respectively. The total and flood control storage capacities of the TGP are 39.3 billion m^3 and 22.15 billion m^3. Long-term and real-time hydrological records are used to determine its operational flood control and sediment management modes.

The TGP controls 96% of the inflow to Jingjiang – the most dangerous river section during floods – and over two-thirds of the inflow to Wuhan. The flood control standard of the Jingjiang section is raised once every 100 years by storing flood water, decreasing the flood peak flow rate and flattening the flood peak. Between 2003 and 2019, the TGP has stored a total of 153.3 billion m^3 in flood water inflow, and plays an indispensable role in mitigating floods overall and reducing massive flood levels in the Yangtze River basin.

In the summer of 2020, serious flood events occurred in the basin. Through flow regulation of the TGP, the peak discharge was reduced from 70,000 m^3/s to 40,000 m^3/s, and the water level along the main stem of the middle reaches of the Yangtze River decreased by 0.45–2.55 m. According to the Chinese Academy of Engineering, the TGP's annual flood prevention benefits alone amount to RMB 8.8 billion yuan.

The TGP is operated in 'Storing Clear Water and Releasing Muddy Water' modes. In the flood season, the water level is kept low to allow the large sediment concentrations to be transported through the reservoir and discharged downstream; during the rest of the year, the reservoir operates at the water level of 175 metres. From 2003 to 2019, the amount of sedimentation in the reservoir was 1.8 billion tonnes, and the sediment delivery ratio of the reservoir was 24%. According to current predictions of sediment inflow, the reservoir sedimentation balance period can be extended from 100 years to more than 300 years.

International training workshops have been organized by the International Research and Training Center (IRTCES) to develop practical design and management strategies that will facilitate the sustainable development of hydropower and dams through reservoir sedimentation management. For example, the 'International Training Course on Integrated Sediment Management' and the 'International Workshop on RESCON 2 and Numerical Modelling for Assessment of Sediment Management Alternatives' were held in Beijing in 2018 and Chengdu in 2019, respectively.

Drought, water scarcity and water management in California

Southern California is a leading agricultural producer, a major manufacturing centre and home to 23 million people. With an average annual rainfall of only 375 mm/year, water must be imported from outside the region in most years. In fact, on average, Southern California receives over half of its water through aqueducts from Northern California and the interstate Colorado River. Engineered infrastructure includes pipelines that convey water, dams that store it and protect major cities, distribution plants that supply drinking water, facilities that treat and distribute wastewater for reuse, and injection wells that form a hydraulic barrier to seawater intrusion.

The task of the water resources engineering community is always challenging, but in drought years, every drop of water counts. Some of the starkest trade-offs involve balancing flood risk management and water supply during droughts. From about 2011–2017, California's worst drought in a millennium placed intense pressure on water managers. However, hydrologists of many sub-disciplines have contributed to alleviating some of this pressure. First, hydrometeorologists estimated the volume and distribution of the scarce precipitation using satellites (including systems co-developed by UNESCO), ground-based Doppler radar and precipitation gauges. Second, snow hydrologists measured the meltwater equivalent in snowpack in the mountains using snow surveys assisted by satellite and airborne imagery. Third, land-surface and surface-water hydrologists translated the rainwater and melt-water runoff into inputs to reservoirs. Finally, groundwater hydrologists analysed the safe yield of the state's aquifer systems, which many irrigators turned to as surface water sources dried up, as well as the potential for managed aquifer recharge. These studies together helped prevent a major disaster.

Still, more can be done by hydrologists to improve the management of engineered infrastructure in the next drought. Field experiments are underway to test Forecast-Informed Reservoir Operations (FIRO) using data from watershed monitoring and weather and water forecasting to help manage releases in a manner that reflects both current and forecasted conditions. At the Prado Dam in Southern California for example, FIRO could be used during inevitable future droughts to allow greater capture of scarce stormwater for managed aquifer recharge, while maintaining acceptable flood risks for the highly urbanized regions downstream.

The path forward

Neither engineering nor hydrology are static. Both have been impacted by technology and societal needs (Sivapalan and Blöschl, 2017); a trend that will likely continue in the future (Blöschl *et al.,* 2019). To respond to these drivers, the International Association of Hydrological Sciences (IAHS) has identified 23 'unsolved problems in hydrology' (Blöschl *et al*., 2019). Recent studies also highlight advances in hydrological science and innovation, and engineering in water management, as well as solutions to improve this relationship, particularly with a view to contributing to the 2030 Agenda for Sustainable Development, the Paris Agreement and the Sendai Framework.

Despite the many advances in engineering and hydrology achieved to date, comprehensive integrated data and multidisciplinary approaches are required to provide solutions for the implementation of the SDGs and their water-related targets. The breadth of UNESCO's mandate in the natural and social sciences provides it with unique strengths to respond to these challenges. By bringing innovative, multidisciplinary and environmentally sound methods and tools into play, while fostering and capitalizing on advances in water sciences, IHP and the UNESCO water family act at the science-policy nexus to help meet today's global water challenges.

Recommendations

1. Recent research should highlight advances in hydrological science and innovation, and engineering in water management, as well as solutions to improve this relationship, so as to contribute to the 2030 Agenda for Sustainable Development, the Paris Agreement and the Sendai Framework.
2. Engineered and nature-based infrastructure need to be combined with water management approaches involving stakeholder engagement and bottom-up climate adaptation.
3. Engineers need to be trained in recent advances in hydrology, intertwined with externalities such as technology and societal needs, in order to develop approaches for the implementation of the SDGs and other water-related goals.

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3.3 CLIMATE CHANGE – A CLIMATE EMERGENCY

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Abstract. Climate change, manifested through changes in atmospheric and oceanic conditions, will impose increased and new risks on many natural and human systems, notably through changes in climate variability and in the frequency and magnitude of extreme climatic events. All infrastructures are designed and built to the codes and standards that existed when they were constructed. However, embedded within these codes and standards is the assumption that climate is stationary, which is now being called into question with climate change.[24]

A system fails at its weakest link, and the weakest links must be identified and mitigated

The world is facing a challenging future. The impacts of the changing climate are real and this crisis must be addressed; the seriousness of which cannot and should not be underestimated. The United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) concluded that the world is experiencing climate change, which requires a re-assessment of the relevance of the climate criteria currently being used to design all infrastructure. These assessments are crucial to determining vulnerability to climate-induced impacts and implementing adaptive actions to mitigate their risks and effects. It is this threat to existing infrastructures that constitutes the climate emergency. Water, transport, power, communications and built infrastructures are all at risk, and a failure in one infrastructure can severely impact economies, safety and ways of life. The magnitude of the threat of climate change to the world's infrastructures is enormous. Existing infrastructures are the mainstay of the developed world, providing populations with the necessary means for a safe and healthy life. It is thus important to identify these vulnerabilities and to mitigate increasing climate risks that can jeopardize this balance.

Climate-related disasters affecting infrastructure can only be mitigated if systemic improvements to the delivery of infrastructures are implemented. Policy-makers and citizens, administrations and other entities must fulfil their roles appropriately, while emphasizing the importance of awareness-raising and disaster prevention education in order to fully adopt a culture of prevention.

It will take the best efforts of engineers to understand, quantify and adapt to these changes, so as to minimize the impact of increasingly severe weather that adversely impacts the delivery and sustainability of infrastructure systems.

WFEO Declaration on Climate Emergency – the response of the world engineering community to the climate emergency

The crises that are unfolding as a result of the changing climate represent some of the most serious issues of our time. While human-induced climate change is a phenomenon acknowledged by the scientific community and by most countries in the world, the world is still lacking positive, collective action and leadership on climate resilience to prevent a business-as-usual scenario and emissions increases. Engineers and the engineering communities have a role to play in raising these issues and proposing pragmatic and feasible solutions to address both mitigation and adaptation to climate change. The primary purpose of engineers has always been to seek progress and solutions to enhance societal well-being. Member States, engineering organizations, designers, constructors, practitioners, academia, researchers and stakeholders need to acknowledge that the climate emergency is a serious threat to the sustainability of humanity on the planet.

The UNFCCC provides a stable structure within which engineers can advocate for the need for cooperation in building sustainable and resilient infrastructures by using proven and newer technologies vital to mitigate the consequences of the climate crisis and achieve carbon-neutral economies and the transformation of industries. During meetings of the Conferences of Parties (COPs), the engineering profession has been represented by members of the WFEO Committee on Engineering and the Environment. It was during the framework of the UN Climate Change Conference (COP 25), held in Madrid in December 2019, that WFEO expressed its deep concern on the matter of climate emergency. It summarized its position and commitment to act quickly through the WFEO Declaration on Climate Emergency, which was signed by 27 regional and national engineering institutions in 2020 (WFEO, 2019). This global communication campaign to raise awareness about the immediate and long-term consequences of climate change seeks to support innovative technologies in the face of these challenges and to build resilient infrastructures and communities (Box 1).

24 Read the WFEO-CEE Newsletter, April 2010 at https://www.wfeo.org/wp-content/uploads/stc-environment/All_WFEO-CEE_Newsletters.pdf

Box 1. Commitment of WFEO and the world engineering community to climate action

1. Continue to raise awareness of the climate emergency and the urgent need for action.
2. Extend the sharing of knowledge and research to promote and incentivize capacity-building in climate change mitigation and adaptation.
3. Strive for an engineering community where a diverse and inclusive membership can work collaboratively towards innovative climate mitigation strategies.
4. Support developing countries on engineering knowledge in climate change mitigation and adaptation best practice.
5. Use WFEO's global influence and connections to gather evidence to illuminate the effect of climate change on women and disadvantaged groups worldwide.
6. Apply and further develop climate mitigation and adaptation principles as key measures of the engineering industry's success.
7. Upgrade existing built infrastructure systems when that is the most efficient solution for whole-life carbon and inclusive social outcomes.
8. Include life cycle costing, whole-life carbon modelling and post-construction evaluation to optimize and reduce embodied, operational and user carbon and other resource use.
9. Adopt more regenerative design principles in practice with the aim of providing engineering design that produces complete infrastructure systems to match the goal of becoming net zero economies by 2050.
10. Increase current levels of collaboration between UNFCCC, WFEO and its members, associates and partners, and all other professionals involved in the design and provision of complete infrastructure.
11. Work with our members, associates and partners in making this commitment real.

Elements of systemic improvement

Existing norms need to be revised to prepare engineers for the changes required to address the impacts of climate change on the world's built infrastructures in view of the need for climate resilient infrastructures. These proposed changes are embedded in two elements and their subsequent outcomes, as outlined below.

Element #1: To develop and implement engineering tools, policies and practices for risk assessment and adaptation of existing and new civil infrastructure to climate change.

Outcomes element #1

- The Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol for Infrastructure Climate Risk Assessment (PIEVC, 2020) was developed and is in use by practitioners worldwide. It is a recognized, tested methodology for assessing climate risk and supporting infrastructure resilience.

Engineering vulnerability/risk assessment serves as a bridge between the codes and standards used in engineering designs and tools such as the PIEVC that are used pending new standards, thereby ensuring that climate change is considered in engineering design, operations, and in the maintenance of civil infrastructure. Identifying infrastructure components that are highly vulnerable to climate change impacts enables cost-effective engineering/operations solutions to be developed.

The Protocol is a structured, formalized and documented process for engineers, planners and decision-makers that recommends measures to address the vulnerabilities and risks associated with changes, in particular climate design parameters and other environmental factors resulting from extreme climatic events. The assessments help justify recommendations for design, operations and maintenance, and provide documented results that fulfill due diligence requirements for insurance and liability purposes.

- Model Code of Practice on Principles of Climate Change Adaptation for Engineers (Box 2).

This Model Code of Practice and interpretive guide (WFEO, 2013) explains the link between ethics and professional practice by considering engineering within the wider context of sustainable development and environmental stewardship.

Engineers are encouraged to keep themselves informed about the changing climate conditions and to consider potential climate impacts in their professional practice. The Model Code serves as guidance to consider the implications of climate change so that engineers can create a clear record of the outcomes of those considerations. It consists of nine principles that constitute the scope of professional practice for engineers in initiating climate change adaptation actions, particularly in the case of civil infrastructure and buildings.

- Updated codes, standards, guidelines are science-based and are used by and relied upon by engineers to reflect the changing climate conditions.

National and international agencies have addressed deficiencies in existing codes, standards and guidelines that reflect the changing climate criteria. An example is ISO Guide 84:2020 which provides guidelines for addressing climate change in standards (ISO, 2020), so that developers of standards can consider adaptation to climate change (ACC) and climate change mitigation (CCM) in their standardization work. Considerations related to ACC are intended to contribute to increasing preparedness and disaster reduction, and have an impact on the resilience of organizations and their technologies, activities or products (TAPs).

3

Box 2. The nine principles are summarized in three categories

1. **Professional judgement**

Principle # 1: Integrate adaptation into practice

Principle #2: Review adequacy of current standards

Principle # 3: Exercise professional judgement

2. **Integrating climate information**

Principle # 4: Interpret climate information

Principle # 5: Work with specialists and stakeholders

Principle # 6: Use effective language

3. **Practice guidance**

Principle # 7: Plan for service life

Principle # 8: Use risk assessment for uncertainty

Principle # 9: Monitor legal liabilities

Element #2: To build knowledge, experience and appropriate techniques to enhance the technical capacity of engineers to adapt civil infrastructure to climate change, particularly in developing and least developed countries.

Outcomes Element #2

- Engineering Protocol training workshops.

Workshops are available for engineers and other professionals on the theory and application of risk management approaches and the PIEVC Protocol for Infrastructure Climate Risk Assessment. The workshops include presentations on the principles of risk assessment and examples of case studies.

- Engineering vulnerability assessment case studies of individual infrastructure.

When completed, the conclusions of infrastructure engineering vulnerability assessments provide valuable insights into their respective infrastructure type, such as water and wastewater systems, bridges, dams, airports, ports, highways, electrical transmission and distribution networks, and buildings, including hospitals.

Example case studies in developing countries include a pre-construction assessment of the future impacts of climate change on sluice gates in the Mekong in Asia, assessment of a port and a power transmission line in South America, preparation of a practice framework approach in the Nile Basin in Africa, and the assessment of bridges, water and wastewater in Central America.

- Engineering and climate risk assessment play an important role in National Adaptation Plans (NAPs). A project by GIZ, 'Enhancing climate services for infrastructure investment (CSI)'[25] provided a case study.

Engineering, climate services and policy can be brought together in a collaborative effort to broaden the scope for adaptation actions to include governments, regulators, climate scientists, engineers, infrastructure owners and other practitioners.

The CSI project helped process climate data and showed how climate products and advisory services can be developed for infrastructure planning, for example, through climate risk assessments (GIZ, 2017). Particular attention was devoted to improving cooperation between those providing and refining climate data, decision-makers, planners and engineers in the infrastructure sector. During this process, tailor-made climate products were developed to carry out a technical risk analysis of selected infrastructure.

The methodology of this analysis is based on the PIEVC Protocol that sets out how objects of infrastructure and their operational procedures are affected by various climate factors, and it forms the basis for selecting meaningful adaptation measures. The experience gleaned from the risk assessments helps to consider climate change in existing country-specific infrastructure planning methods and guidelines.

All activities can be integrated into the National Adaptation Plan and Nationally Determined Contributions (NDCs) to promote their development and implementation.

The Climate Risk Informed Decision Analysis (CRIDA) was launched to integrate climate change uncertainty into the identification of (ecosystem-based) adaptation strategies and to enable flexible decision-making processes (UNESCO, 2018).

25 See the CIS product landscape at http://climate-resilient-infrastructure.com/wp-content/uploads/2020/08/CIS_GIZ_product_landscape_8.pdf

Box 3. CRIDA principles

1. Identify problems and opportunities about uncertain future change.
2. Inventory and forecast conditions that lead to chronic failure.
3. Formulate alternative plans that are robust or adaptable. Based on previous assessments and the use of science to assess plausibility, four distinct strategies guide the collaborative plan formulation:
    i. Standard planning guidance and safety margins are sufficient. No change in current procedures is necessary.
    ii. The formulation of plans to mitigate incrementally plausible stressful futures that require more robust alternatives at different levels of magnitude.
    iii. There are conflicting sources of evidence, lack of consensus on the evidence, and/or a low risk aversion by stakeholders that chronic failure is plausible. A recommendation for collaborative strategy to formulate 'win-win' plans with options for adaptability (i.e. ensure future alternatives, not taken today, are still possible tomorrow).
    iv. There is sufficient cause for concern for action but conflicting sources of evidence and lack of consensus on the evidence leads to disagreement on the magnitude for a first investment. A strategy to formulate acceptable initial robust alternatives with additional options for the future is recommended.
4. Collaboratively evaluate robustness or adaptability. Under the CRIDA process the use of the vulnerability domain helps all parties understand plausible futures that would impair a project.
5. Compare robustness or adaptability of alternative plans.
6. Select a robustness or adaptability plan.

Recommendations

1. Countries can identify, understand and manage climate-change risks by prioritizing adaptation planning and actions, including by implementing operational and maintenance procedures that extend the life of infrastructures that: i) are at critical risk of failure; ii) service high demand; iii) are reaching the end of their life cycle; or iv) exceed the risk tolerance level and require significant investment to refurbish or replace.

2. Internationally and nationally inter-sector actors across government, industry, academia, civil society and the media must cooperate to address the climate crisis.

3. Teams that already design, manage and run infrastructures should provide the essential human resources to identify climate-related challenges and to implement adaptive or remedial actions.

4. Updating of national codes, standards and guidelines, enhancing national climate services, developing engineering and planning tools to standardize approaches to climate risk assessment, and utilizing multi-actor teams provide the pathway for societies to address the risks posed by the changing climate to existing and future infrastructures.

5. Special attention should be given to developing vulnerable countries in building their capacities to deliver climate resilient infrastructures by updating their national codes, standards and guidelines, and building capacity in their climate services, engineering and delivery capabilities.

6. Cooperation coupled with engineering research should be sought to identify and provide innovative solutions, including nature-based solutions. Mobilizing the world's engineering capacity to implement the solutions worldwide is an important step in addressing the climate crisis.

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3.4 ENGINEERING: A CRUCIAL TOOL FOR DISASTER RISK REDUCTION

Kurniawan Rizqi/Shutterstock.com

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27 Division of Ecological and Earth Sciences, Section on Earth Sciences and Geo-Hazards Risk Reduction, UNESCO.

Abstract. Advances in engineering, science and technology dedicated to disaster risk reduction (DRR) provide knowledge about the mechanisms of natural hazards including the processes that transform them into disasters. Ultimately, it is this scientific knowledge that will provide solutions to mitigating the vulnerability of infrastructures and societies. This section summarizes UNESCO's areas of intervention and how the organization uses engineering across its DRR actions.

Introduction

From 2005 to 2015, natural hazards caused US$1.4 trillion in damage, claimed 700,000 lives and affected 1.7 billion people worldwide (UNISDR and CRED, 2018). With the frequency and magnitude of occurrence increasing due to climate change, losses associated with natural disasters are on the rise. For example, it is estimated that by 2050, the number of people in urban areas who are exposed to cyclones will increase twofold to 680 million people, and those who are at risk of suffering a major earthquake will amount to approximately 870 million people (World Bank, 2010).

Efforts to address disasters form part of the UN 2030 Agenda for Sustainable Development, and many of the related goals cannot be achieved without DRR (UNISDR, 2015). Advances in engineering, science and technology dedicated to DRR provide knowledge about the mechanisms of natural hazards, including the processes that transform them into disasters. Ultimately, it is this scientific knowledge that will provide solutions to mitigating the vulnerability of infrastructures and societies.

UNESCO assists countries in capacity-building for the management of disasters and climate risk, and provides support to Member States in particular on: i) early warning systems; ii) safe critical infrastructures; iii) risk prevention for UNESCO-designated sites; iv) the use of science, technology and innovation, including Artificial Intelligence and big data; v) the built environment; vi) risk governance; vii) nature-based solutions; and viii) post-disaster response. Engineering plays a crucial role in addressing all aspects of UNESCO's interventions in DRR[28]. The following sections provide some examples of practices using engineering for DRR.

Early warning systems

UNESCO works to address various hazards, notably tsunamis, earthquakes, floods, drought and landslides.

Tsunami early warning systems are based on observation networks of seismometers and sea level measuring stations, which send real-time data to national and regional tsunami warning centres (TWCs). Based on these observations, TWCs are able to confirm or cancel a tsunami watch or warning. It is essential that communities at risk know the actions that need to be undertaken in the event of imminent danger. UNESCO is a key stakeholder for tsunami DRR at the global level. Risk reduction for tsunamis requires a variety of forms of engineering, including soil engineering, coastal engineering and behavioural engineering for both forecasting and implementing solutions such as evacuation planning. Four Intergovernmental Coordination Groups (ICGs) corresponding to the Pacific, Caribbean, Indian Ocean and Mediterranean regions have been established to address particular regional needs.[29]

Struck by a tsunami on 7 May 1842, Fort-Liberté, the capital of the northeast department of Haiti, has been classified as a probable risk for future tsunamis. With UNESCO support, warning signs were installed and preparedness materials were distributed. The city now has operational tsunami procedures in place, and 50 local and national focal points have been trained on the reception and dissemination of alerts. Significant efforts have been undertaken to strengthen seismic observation and tsunami modelling capacities across the country.

Education and school safety

UNESCO promotes a multi-hazard school safety assessment methodology known as VISUS (Visual Inspection for defining Safety Upgrading Strategies), which is based on the use of visual inspections to assess relevant hazards potentially affecting schools, and the application of pre-set algorithms that replicate expert reasoning to make judgements. The methodology also allows for the evaluation of available resources for the effective application of required safety upgrading interventions. The assessment is based on the application of structural engineering to previously damaged buildings as a result of natural hazards.

The VISUS methodology – which incorporates a strong capacity-building component for decision-makers, technical staff and universities – has been successfully tested in seven countries: Italy (2010), El Salvador (2013), Lao People's Democratic Republic (2015), Indonesia (2015–18), Peru (2016), Haiti (2017) and Mozambique (2017).

28 For more information on UNESCO activities on disaster risk reduction: www.unesco.org/new/en/natural-sciences/special-themes/disaster-risk-reduction
29 For more information on work on the tsunami DRR unit: www.ioc-tsunami.org

Overall, the security of more than 500,000 students and educational staff has been assessed (UNESCO and Udine University, 2019).

DRR in UNESCO-designated sites

Cultural heritage plays a significant role in the economic and social development of a country and represents an asset for resilience and recovery following a disaster.

The Swayambhu hillock, which forms part of the Kathmandu Valley World Heritage property, has experienced landslide events since the 1970s. Every two to three years, the hill slope undergoes debris flow, soil slumps and slides due to creeping of the soil mass. These events threaten the integrity of the religious ensemble of Swayambhu, which includes the oldest Buddhist monument (a stupa) in the valley. UNESCO carried out a geological study using soil engineering to analyse the soil, which provided essential information for the design of an engineering slope stabilization solution and recommendations for future infrastructure development in the area.

Science, technology and innovation for resilience

Science, technology and engineering help identify and explain risks, and provide relevant solutions.

Higher forms of technology include Artificial Intelligence, while less technological solutions include civil science, participatory research and local indigenous knowledge. All the data UNESCO gathers are made publicly available.

Water-related disasters account for 90 per cent of the 1,000 most severe disasters that have occurred since 1990 according to *Making Every Drop Count: An Agenda for Water Action* (UN DESA, 2018). UNESCO works with Member States to foster resilience in coping with hydrological extremes, such as floods and droughts, as well as their capacity to assess and monitor changes in snow and glaciers, which act as unique, key indicators of global warming and climate change.

UNESCO has developed various examples of data, tools, methodologies and knowledge-sharing systems to support Member States in their efforts to enhance their capacities and resilience, which are described in Chapter 3.2, 'Water engineering for sustainable development'. For example, under these initiatives, a Latin American and Caribbean Drought Atlas was produced in 2019, and a Drought Atlas for Africa is currently under development employing techniques such as hydraulic engineering, river engineering, environmental engineering and soil engineering.

The built environment

Earthquakes are among the deadliest natural hazards, with more than 80 per cent of the resulting casualties caused by the collapse of buildings.

UNESCO supports its Member States in securing buildings and building back better via enhanced building codes and building control policies. UNESCO also hosts a secretariat of the International Platform for Reducing Earthquake Disasters (IPRED), a group that gathers centres of excellence of national institutes or universities that actively conduct research on seismology, seismic engineering and structural engineering from 11 earthquake-prone countries. IPRED members develop engineering guidelines and address policy relevant issues (UNESCO, 2014; 2016).

Risk governance and social resilience

UNESCO promotes civil society engagement, targeting groups such as youth and women in DRR planning and implementation at both community and policy-making levels.

UNESCO also supports Member States in working together to encourage youth and young professionals to contribute to DRR through science, engineering, technology and innovation (SETI). UNESCO has initiated a programme entitled Youth and Young Professionals in SETI for DRR (U-INSPIRE). With the support of UNESCO, professionals involved in U-INSPIRE from Afghanistan, India, Indonesia, Central Asia (Kazakhstan, Tajikistan and Uzbekistan), Malaysia, Nepal, Pakistan and Philippines took part in a two-day forum in Jakarta during September 2019 where they agreed to formally launch the Asia Pacific Youth and Young Professionals Alliance in SETI for DRR and Climate Change. The outcomes of this forum will contribute to the development of a toolkit showcasing best practice examples, and provide guidance on how youth and young professionals in SETI for DRR can link with and contribute to regional, national and global DRR activities and frameworks (UNESCO, 2019).

Ecosystem-based DRR

UNESCO promotes the implementation of ecosystem and nature-based solutions and technologies to reduce disaster risk.

UNESCO works closely with international experts to mainstream this approach in development planning at global, national and local levels. UNESCO actively participates in the ongoing activities of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Partnership for Environment and Disaster Risk Reduction (PEDRR).

UNESCO is also actively involved in the OPERANDUM project[30] which aims to reduce hydro-meteorological risks through co-designed, co-developed, deployed, tested and demonstrated innovative green and blue/grey/hybrid nature-based solutions. Engineering plays a crucial role in potential solutions through environmental engineering, river and coastal engineering, and soil engineering.

Post-disaster response

In the aftermath of a disaster, and together with other UN agencies and international partners, UNESCO assists Member States in post-disaster response to assess damage and losses, and to identify recovery and reconstruction needs.

UNESCO has established a system to dispatch engineers and seismologists to earthquake-stricken countries in order to carry out post-earthquake field investigations and draw lessons for future risk reduction by utilizing the expertise of International Preparedness & Response to Emergencies & Disasters (IPRED). Engineering analysis is applied to collapsed buildings with the aim of understanding the cause of the collapse. The findings are then used to create better building codes and practices. Missions have been sent to Kermanshah in Iran (2017), Bohol in the Philippines (2014) and Van in Turkey (2012) (UNESCO, n.d).

Recommendations

1. Utilize engineering and sciences to understand disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment.
2. Strengthen multi-stakeholder cooperation with engineers, other technical disciplines, policy-makers, civil society and the private sector to reinforce disaster risk governance and improve disaster risk management.
3. Invest public and private funding in disaster risk prevention and reduction engineering activities through structural and non-structural measures in order to foster resilience.
4. Utilize engineering to enhance disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation and reconstruction.
5. As the impact of natural disasters becomes more serious, affecting in particular those who are most vulnerable – especially countries in Africa, small island developing states (SIDS), women and youth – ensure that engineering is seen as an important tool to define preventive preparedness measures.

30 For more information on the OPERANDUM project: https://en.unesco.org/operandum

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3.5 DEVELOPING SUSTAINABLE AND RESILIENT ENERGY SYSTEMS

Solar panel in Africa

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Abstract. Energy is today at the heart of many reflections and debates. It is unquestionably a major component of economic development and social progress to which everyone on the planet aspires. Energy is intimately linked to transitions in societies and economies, whether in terms of lifestyles, food or transport. It is also at the heart of the transformation of productive systems; a modernization that includes the development of digital technology. The list could be long, but a consensus seems to be emerging that the climate emergency should be given top priority given its dramatic consequences, some of which have already been observed.[32]

Energy and the SDGs

The challenge is therefore to move towards sustainable energy systems in line with the United Nations Sustainable Development Goals (SDGs). The SDG 7 on affordable and clean energy highlights two major challenges: i) physical and economic access to energy, given that between 2.5 and 3 billion people worldwide have no access to satisfactory cooking methods and around 1 billion have no access to electricity; and ii) the prevention of environmental damage as no form of energy is produced, transported or used without negatively impacting on the planet and its inhabitants. However, a focus on SDG 7 to the exclusion of other goals would provide an incomplete analysis. A number of the other goals are in fact highly dependent on decisions concerning the development of energy systems. A few examples of the linkages of energy to the SDGs are given below.

- Some solutions are based on the use of bio-sourced energy sources, whether used directly (wood for cooking or heating), or indirectly (when biomass is transformed into fuels or combustibles). There is an obvious link with SDG 2 on zero hunger as there can be competition between the use of arable land for crops for food and as energy sources, which can result in conflict.
- In some countries, access to essential resources such as wood or water is difficult. Women and children are often responsible for these chores and for ensuring domestic supplies. The time spent on these chores is often taken away from time spent on school activities for children, or women's professional or other activities. There is thus a strong relationship between energy and SDG 4 on quality education and SDG 5 on gender equality.
- Water and energy are closely linked and are therefore connected to SDG 6 on clean water and sanitation. Almost all energy production technologies need water. This is evident in the case of hydropower, but it is also true for hydrocarbon exploitation or for electricity production across almost all technologies. It is even essential to clean solar panels with water to preserve their efficiency. Some secondary energies use water; this is true of heat but also of hydrogen produced by electrolysis. However, energy is also needed to produce water (for pumps for example), and to transport and treat water, both before and after its use. In some countries that have to manage water scarcity, desalination technologies are being implemented, which also use energy.
- One of the causes of global warming is the use of fossil fuels. This highlights the strong relationship between energy and SDG 13 on climate action. The decarbonization of energy systems is obviously a major challenge for energy companies. It is essential to promote decarbonized energies (renewable and nuclear), or technologies that make the use of fossil fuels acceptable, such as carbon capture and storage. However, the adaptation of energy systems to the consequences of climate change is also a major challenge affecting both energy production (through water stress, which will occur in many parts of the world) and energy demand (through the development of certain uses, such as air conditioning).
- Mention should also be made of the relationship between energy and SDG 16 on peace, justice and strong institutions. Many of the world's conflicts originate from access to energy resources; with oil being the most well-known but not the only example. Indirectly, the management of flows of certain rivers by dams has provoked real 'water tensions' due to the consequences on production of electricity or irrigation in neighbouring countries.

Sustainable energy systems

Sustainable energy systems can thus make substantial contributions to prosperity and protection of the planet. While many energy solutions are well known, they require informed choices to produce the necessary energy (IEA, 2020; WEC, 2016; IPCC, 2018*a,b*). Some examples are presented below.

- Renewable energies, including hydroelectricity, are favourably viewed and comprise a wide variety of energy sources with very different advantages and disadvantages, none of which are without environmental consequences, although these can be less apparent than other forms of energy. While the integration of some energy sources into electric networks can be difficult owing to their variability (e.g. wind or photovoltaic

32 Read the WFEO Declaration on Climate Emergency at http://www.wfeo.org/wp-content/uploads/declarations/WFEO_Declaration_on_Climate_Emergency_2019.pdf

energy), others are virtuous in terms of stabilizing the system (hydroelectricity). Most renewable energies have a very large footprint and can give rise to local opposition, but they all have the advantage of being low in carbon.

- Nuclear energy, like renewable energies, is an almost non-carbon energy. Like hydropower, it is capable of producing massive quantities of carbon-free electricity and can thus contribute substantially to the fight against climate change. In fact, many international organizations, governments, private enterprise and experts consider nuclear energy to be essential in the fight against climate change (IPCC, 2018*a*), and the main challenge is to restore it to its rightful place through information and debate.
- Fossil energies (coal, oil and gas) are responsible for most CO_2 emissions, yet they still represent about 81% of the world's energy mix. While it seems utopian to try to rapidly and completely eliminate fossil fuels as a source of energy, especially in sectors such as transportation or in certain countries, they can contribute to achieving the desired objectives when combined with the use of carbon capture and storage technologies.

On the energy demand side, the search for energy efficiency also deserves further analysis to fully understand the most effective policies and measures. Some energy efficiency potentials are easy and inexpensive to exploit; others may require large investments with high payback times, or require behavioural changes that are expected to take time as they are funnelled through information channels and education. Lastly, the COVID-19 pandemic has elicited changes in behaviour, at a heavy cost in terms of the economy and jobs, and it will be interesting to observe the sustainability of these changes. Countries differ in terms of natural resources, geography, level of economic and social development, history and culture, and thus priorities and policy choices will differ depending on the country. Consequently, the paths towards sustainable energy systems will be unique to each.

Energy and resilience

The COVID-19 pandemic has not diminished the urgency to combat climate change or the importance of modernizing economies. It does however shine a light on the importance of resilience in an energy system, a resilience that needs to be emphasized (WEC, 2020).

The resilience of an energy system is illustrated in the examples below:

- resilience to health risks, not only to COVID-19 but also to other health risks that could affect societies to an even greater extent;
- resilience to the scarcity of energy production inputs, such as rare metals, water, land or skills;
- resilience to natural disasters, such as floods, droughts, earthquakes or tsunamis; and
- resilience to new risks that are often linked to the modernization of economies, such as cyber-attacks or systemic risks.

It is thus at the interface of sustainability and resilience that the work of the engineer will be situated. In a particular context of strong budgetary constraints, linked to the historic economic crisis we are currently experiencing, the role of the engineer is decisive. Faced with a multitude of innovations, alongside known and operational solutions, the engineer a rational and rigorous method for selecting technologies that contribute to the development of sustainable and resilient energy systems, far from any dream, ideology or trend.

An engineer's contribution will be based on four rules:

1. **Adopt a systemic approach**. Considering only one link in a chain of technological inputs can lead to error due to a failure to appreciate other linkages. This can be easily illustrated by considering a secondary energy, such as electricity, hydrogen or heat, whose use is scarcely polluting, but whose production can significantly modify the qualities of the system.
2. **Give priority to mature technologies**. The temporal availability of technologies is well known and can be assessed by such tools as the TRL (technology readiness level) scale. However, the degree of maturity of a technology must be linked to climate urgency (IPCC, 2018*a*). Numerous studies – primarily those of the IPCC – reveal a clear message: it is vital to act now to curb greenhouse gas emissions by 2030. Responding to the climate emergency, requires the adoption of mature technologies in the industrial environment together with the necessary skills. Less mature technologies will be developed to consolidate or amplify the initial results.
3. **Encourage significant contributions**. It is essential to ask about the extent of the contribution a candidate technology will actually make to achieving the set objectives. This potential contribution is a crucial deciding element the selection and must be considered for its various facets: the adaptability of the technology or the ease of technology transfer are two criteria to be taken into account if the technology is to make a significant contribution to the global energy mix. It must be weighed against the resources needed to develop the technology. These are invariably limited whether in terms of research and development, deployment efforts, material or human investment, and often the mobilization of public aid.
4. **Promote a simple economic criterion: the cost per tonne of CO_2 avoidance**. The economic and social crisis caused by COVID-19 has left everyone paying the cost; governments,

local authorities, companies and households have all been left financially impaired. In order to make the right trade-offs within a constrained budgetary framework, it is necessary to have a simple but robust criterion that best represents economic efficiency. Comparing the costs per tonne of CO_2 avoided (or its CO_2 equivalent for other greenhouse gases), which are calculated using a systemic approach for all technologies can help guide choices towards more efficient technologies to combat climate change. However, economic efficiency, which is only one criterion among others, must – in the current period of crisis – become a requirement.

Recommendations

1. In order to help achieve the SDGs, it is essential to develop sustainable and resilient energy systems. Reflections must be based on rigorous facts and without preconceptions. To achieve these objectives, all energy options are open, depending on national contexts.
2. Engineers have a role to play in informing choices by adopting systemic approaches that put forward mature, immediately available technologies that contribute significantly to combating climate change.
3. In the current context relative to the COVID-19 pandemic, it is important to use simple and transparent economic criteria such as the cost per tonne of CO_2 avoided.

3

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3.6 MINING ENGINEERING FOR THE FUTURE

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Abstract. Mining can contribute positively to the achievement of the 17 Sustainable Development Goals, but first the industry has to re-invent itself. During the last 30 years a huge number of visions, objectives, methods, technologies, processes and other measures have been developed by academia, industry and governments to improve the sustainability of mining activities. However, given the challenges mining engineers will face globally in the future, a quantum leap towards better and sustainable mining is necessary.

Introduction

A sufficient supply of raw materials under fair market conditions is essential for sustainable socio-economic development, as their supply links almost every business value chain (SOMP, 2019). The global mining industry has expanded over two centuries and today it is more important than ever. The global population increased by 54.43% between 1985 and 2018 from 4.9 to 7.5 billion people, while the world mining production increased by about 84.5% from 9.9 billion metric tonnes in 1985 to 17.7 billion metric tonnes in 2018 (Reichl and Schatz, 2020). Futhermore, the world's rapidly growing population of 7.8 billion people demand a greater standard of living, which together with a trend towards urbanization worldwide will likely lead to a disproportionate increase in mining activities in the future. Despite the necessary optimization of recycling processes ('urban mining'), there will be a strong demand for certain raw materials to develop a more sustainable world, such as copper and rare-earth elements for renewable energy production, or nickel, manganese, lithium and cobalt for batteries.

However, mining companies, and especially engineers, are facing tremendous challenges (Drebenstedt, 2019), as outlined below:

- deeper, steeper or unconventional deposits (as easily accessible deposits are decreasing) which present geotechnical challenges;
- lower ore grade or quality and an increase in mining waste;
- isolated mine sites and infrastructure challenges;
- extreme mining conditions;
- a range of social and environmental challenges;
- lack of human resources and skill shortages; and
- adverse community reaction to mining projects and conflicts.

Globally, the minerals industry is experiencing rising costs and increasingly difficult conditions. As many internal and external factors continue to exert pressure on mining companies, engineers and their operations, there is a growing need for more than just incremental change. The minerals industry of the future must embrace new approaches to sustainable mining systems and technologies that represent quantum leaps for the extraction and processing of minerals (SOMP, 2019).

Technological quantum leaps in improving mining engineering are inevitable

In the last centuries, mining has developed from an artisanal small business (mining 1.0) to a digitalized high-tech industry (mining 4.0). Naturally, this development assumes technological innovations, and this incremental change in mining and its continuous improvement will only endure. New technologies, different and changing orebody or deposit characteristics, market forces, and issues of social license incorporating public acceptance, governmental approvals and standards, as well as self-imposed improvements in safety performance and expectations all need to be considered. The application of innovative big data digital-based systems (mining 4.0) will also drastically improve the possibilities in mining engineering.

It is thus imperative to obtain geological and economic assessments of the operational and financial effectiveness of planned mining projects. Furthermore, risk management must be defined, evaluated and assessed thoroughly so as to ensure safe and environment-friendly mining endeavours while planning and managing the complete mining cycle: from deposit exploration to mine design, the production of minerals, to subsequent post-mining activities after closure (Kretschmann, 2020). In addition, performance that includes energy and material resource optimization, as well as operational efficiency towards real-time mining (i.e. intelligent mining) must be taken into account (Litvinenko, 2019). Consequently, key characteristics for improvements in mining engineering include the following:

- extremely high health and safety standards;
- limited effects on the landscape and environment;
- low specific carbon dioxide emissions;
- high level of recovery of the useful components from ores;
- maximal use of remote controlled technologies to allow staff to remain at a distance from the extraction zone;
- storage of waste rock without removal to the surface; and
- high resource efficiency and increased competitiveness.

The high-tech mining industry needs to face challenges with holistic and integrative solutions addressing the complete mining cycle from exploration to design, to production and post-mining activities. Furthermore, improvements in safety, environmental impact, emissions, recovery rate, remote controlled operations, efficiency and competitiveness are all essential.

Feasible business models for sustainable mining are needed

In their systematic literature review, de Mesquita *et al.* (2017) described the state of academic research on mining, sustainability and sustainable development. They identified 1,157 articles published in 491 different journals written by 3,230 authors who have links to 1,334 institutions in 93 countries. It is therefore beyond doubt that there is ample knowledge available to employ sustainable mining practices. In their book, *Mining, Materials, and the Sustainable Development Goals (SDGs): 2030 and Beyond* (Parra, Lewis and Ali, 2021), the authors describe their vision of how mining engineers and companies can contribute to achieving all 17 SDGs and the 2030 Agenda for Sustainable Development. In addition, they name no fewer than 18 international sustainability initiatives in mining. Consequently, no active international mining enterprise has a corporate mission without mentioning sustainability as a main objective in their mining activities. Still, Parra, Lewis and Ali observe that no top-down framework currently exists to assess whether or not the cumulative effects of such academic or business contributions is significant enough to help achieve the SDGs in a meaningful way.

There are currently no standardized methods to measure the impact of an activity to determine if and how these key contributions significantly improve in a measurable and meaningful way towards the global accomplishment of the 2030 Agenda. Moreover, *who* should evaluate quality and effectiveness should be determined. Would it be possible for mining companies to determine their 'responsibility' towards a specific goal or sub-goal? Is it feasible to base this determination on revenue, profit, production volume or other metrics?

Last, but not least, who decides whether a mining project is contributing positively to the SDGs or not, and what are the consequences of this decision? Decisions on mining projects are currently made mainly in a bottom-up approach by stakeholders. The necessary investment to realize a large-scale mining project can easily reach several billion US dollars (Litvinenko, 2019). To date, there is a strong trend impacting the mining industry with the global rise of ESG (environmental, social and governance) investments. This is based on the idea that incorporating an analysis of a potential investment's environmental, social and governance factors in addition to traditional financial metrics may help to improve returns.

It is recommended that mining companies reframe or reposition their business by implementing business models that work towards sustainability and thus secure their attractiveness to potential investors. Moreover, an industrial survey by EY in 2020 concluded that the greatest risk to the mining industry is the loss of its 'social license to operate'. This describes the evolving relationship between the mining industry and its local or regional stakeholders, encompassing the concepts of procedural and distributional fairness, trust and acceptance (Laurence, 2020).

Stuck between regional activists and international investors, the mining industry has to develop sustainable strategic business models to balance the competing and complementary interests of key stakeholders. In general, people agree that a world without mining is not possible, but what does that mean for a specific project in their community, especially if the processing and use of a raw material takes place in foreign countries, and the mining waste, the pollution and sometimes even environmental disasters remain 'at home'? The *2020 Global Mining Survey Report* revealed that 75 per cent of its respondents share the opinion that the mining industry needs to redefine success using a more holistic group of measures that take into account the values of *all* its relevant stakeholders (KPMG, 2020). The consequent use of sustainable mining business models is thus a necessity, and a competent and strong mining authority needs to take control at all governmental levels.

Focus on education, research and development

For 2030 and beyond, it should be a primary aim in mining engineering to foster and nurture a research and development culture that also includes new job opportunities for more highly qualified engineers able to implement new technologies in the industry. Furthermore, present and future mining engineers must aim to improve and/or learn to adopt scientific knowledge, technological innovations and emerging technologies from other disciplines. In addition, they should be able to enhance business capability and growth, ensure the minerals industry's sustainability in a rapidly transforming technology landscape, and build effective and engaging strategic partnerships. In line with this, a future mining engineer needs the following attributes (SOMP, 2019):

- high-quality technical skills;
- an understanding and ability to use, optimize and adapt to rapidly changing and innovative technologies, particularly digital technologies;
- high data literacy and capable of working with large datasets to achieve effective management and control systems;
- the capability to plan and operate mines with more socially acceptable surface footprints and environmental impacts;

- an understanding of the full value chain of the mining operation through a more holistic and systemic approach to planning and operations;
- the ability to adopt a risk-based approach to planning, decision-making and management;
- a global or international perspective, while being capable to work in a local environment and with a clear understanding of local constraints; and
- the capability to work in and lead multidisciplinary teams.

The role of a mining engineering school is to develop mining engineers for the future through curricular changes and educational experiences. This requires a collaboration between the mining industry and technological experts to accelerate both innovation and commercialization so as to create added value for the minerals industry. This is achieved by developing leading research initiatives and advocating for mining engineers with the highest ethical standards and integrity (SOMP, 2019), thus ensuring the realization of the SDGs. Consequently, current mining curricula around the world need to be evaluated in order to ascertain if and how they meet these attributes so that improvements can be initiated where necessary.

Recommendations

Based on a state-of-the-art approach in sustainable mining engineering, three initial actions for a sustainable mining industry worldwide are proposed:

1. A vast variety of suitable technologies have been developed, and governmental institutions, engineering educators, the industry and professional engineering institutions in these countries should be empowered to ultimately use these technologies to realize a more sustainable mining profession (UNDP and UN Environment, 2018).
2. The implementation of a work group lead by UNESCO could provide suggestions for sustainable business models applicable to mining enterprises, ranging from artisanal, low technology, informal operations to large-scale multinational enterprises. These models should be discussed with government representatives from mining countries, the industry, financial investors, NGOs and professional mining engineering institutions to develop the framework that is needed and to apply measurement methods that take into account the SDGs.
3. Governments and higher education institutions should take action to improve mining education and lifelong learning possibilities in mining. Specific research-education centres (Litvinenko, 2019) should be established to foster sustainable mining practices globally and to also encourage more young people, especially girls, to consider mining engineering as a career. This can address the recent shortfall in the number of engineers and ensure the diversity of thought and inclusive participation that is essential to achieving all the SDGs.

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3.7 ENGINEERING AND BIG DATA

wavebreakmedia/Shutterstock.com

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Abstract. The availability of large amounts of heterogenous data from multiple sources growing in an exponential manner has made it imperative to formulate strategies and develop processes and algorithms to analyse large data sets in an efficient manner. This has opened up new opportunities for researchers, engineers and entrepreneurs across a variety of domains and is indicative of the fact that traditional databases and tools used mainly to process structured data have been rendered inadequate. The strategic perspectives of data have thus changed radically, leading to the evolution of big data (Table 1). The utilization of collected data is the essence of big data technologies, which have shown great potential to enhance engineering practice in terms of efficiency, safety, resilience and eco-friendliness, leading to a new data-driven paradigm for engineering.

Big data systems incorporate multiple evolving technologies and skill sets, the latter of which include domain knowledge, data analysis, statistical knowledge and advanced data visualization skills. This ecosystem is quite different from the earlier concepts of data warehousing, business intelligence and structured query language (SQL), which were the forerunners of the big data paradigm (Mohanty *et al.*, 2013).

YouTube generates about 100 petabytes of new data every year (Stephenson, 2018) and about 72 hours of video every minute (Chen *et al.,* 2014), while Facebook generates over 10 petabytes of log data every month. Online trading data of tens of terabytes is generated by e-commerce platforms such as Taobao, and data from the internet was projected to increase to about 2 zeta bytes per year by 2020 (Stephenson, 2018). There is a plethora of sources from which multi-format data are generated, including from sensors embedded in a variety of devices ranging from mobile phones to industrial machines under the overall paradigm of the Internet of Things (IoT), as well as through cloud computing technologies (McKinsey, 2011) (Figure 1).

Figure 1. Common data sources

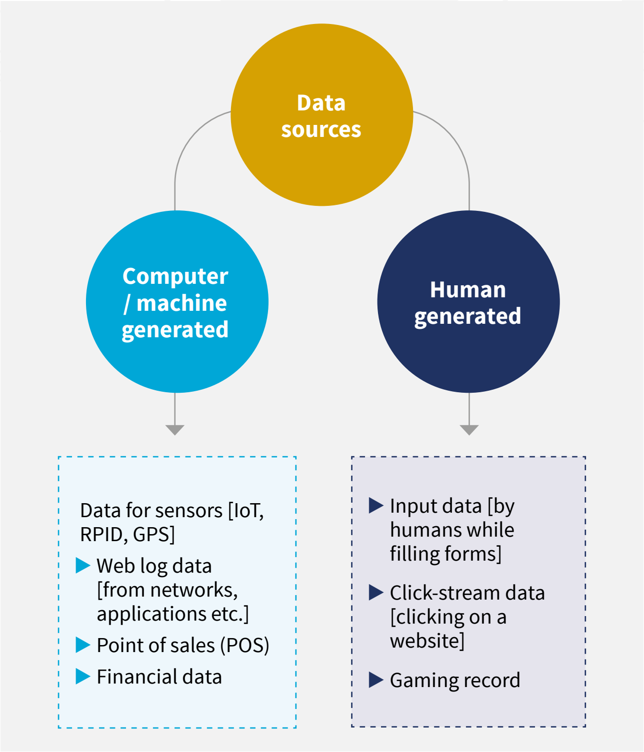


Table 1. Strategic perspectives of data: analog versus digital age

Analog era	Digital era
Data are expensive to generate	Data are continuously being generated through a plethora of sources
Challenges in data storage and management	Challenges in transforming data into valuable information
Only standard data used for analysis	Unstructured data are increasingly usable and valuable
Data managed in functional silos	Value in data sourcing, storage and processing is across functional silos
Data are a tool for optimizing processes	Data are a key tangible asset for value creation

Big data as a technology facilitates decision-making, spanning areas in innovative ways, such as business to biomedicine and engineering, and forecasting and analysis irrespective of data size. For example, big data technology was used effectively by scientists to collect and analyse massive amounts of data leading to the discovery of the Higgs boson at the CERN research facility in 2012 (Stephenson, 2018).

Big data imperatives

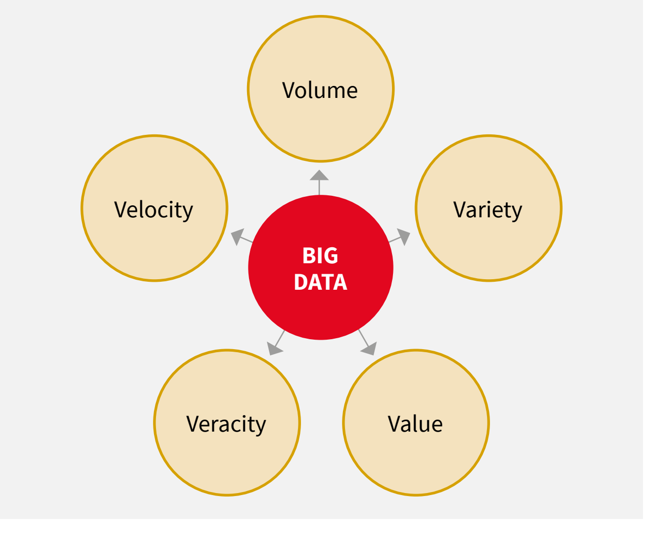
Big data has been defined as a 'high volume, high velocity and/or high variety information assets that demand cost-effective innovative forms of information processing that enable enhanced insight, decision-making and process automation' (UN, 2012). The three characteristics, or the 3 'Vs' of big data, are:

- Volume: the scale is very large due to the generation of large amounts of data from multiple sources.
- Velocity: the rapid collection and analysis of data is needed to maximize the value of the process.
- Variety: the varied data, are involved, structured, semi-structured (XML, EDI etc.) and unstructured (video, web pages, text, etc.).

There are also two other characteristics that have been commonly associated with big data: 'veracity' and 'value'. Veracity refers to the quality of information from multiple sources and 'value' denotes the significance and relevance of the data available and their amenability for data analysis (Diebold, 2012; Kambatla *et al.*, 2014) (Figure 2). It may be surmised that 'Big Data is less about data that is big than it is about a capacity to search, aggregate and cross reference large data sets' (Boyd and Crawford, 2012).

Security and privacy issues remain a matter of concern along with the standardization of frameworks and architecture involving big data. To this end, the National Institute of Standards and Technology (NIST) of the United States Department of Commerce has set up a Big Data Public Working Group (NBD-PWG) to specifically address the important fundamental concepts related to big data[35], and many engineering organizations, such as WFEO, have also called for responsible conduct with big data in engineering practice.[36]

Figure 2. Characteristics of big data



Big data analytics

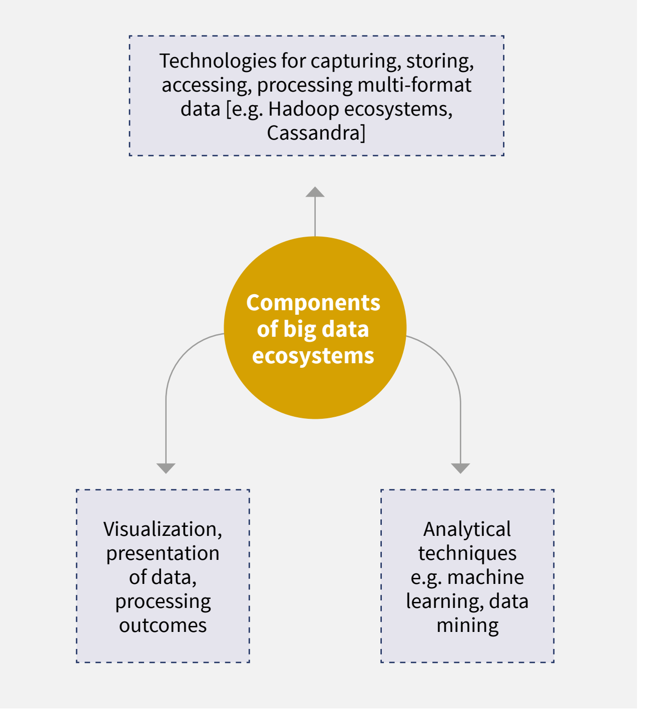
Value creation from the big data ecosystem remains the primary motivation for its further development, indicating the need for economizing the entire process from collection to processing and visualization (Figure 3).

The increased usage of search engines such as Google has increased the need to rapidly search large databases and data sources to make data available to users in real time. Various algorithms have been elaborated for this purpose and Google developed a software framework (Hadoop) that functioned as a precursor to many other such systems.

The various tools available and under development can be categorized under the following functional elements of big data generation, processing and outcomes (Oussous *et al.*, 2018):

- data integration for data uploading and system integration;
- distributed storage such as Direct Attached Storage (DAS), Network Attached Storage (NAS) and Storage Area Network (SAN);
- centralized management including diagnostics, monitoring and in enterprise scenarios;
- analysis including machine learning tools; and
- security and privacy access control especially for multi-proprietary data sources.

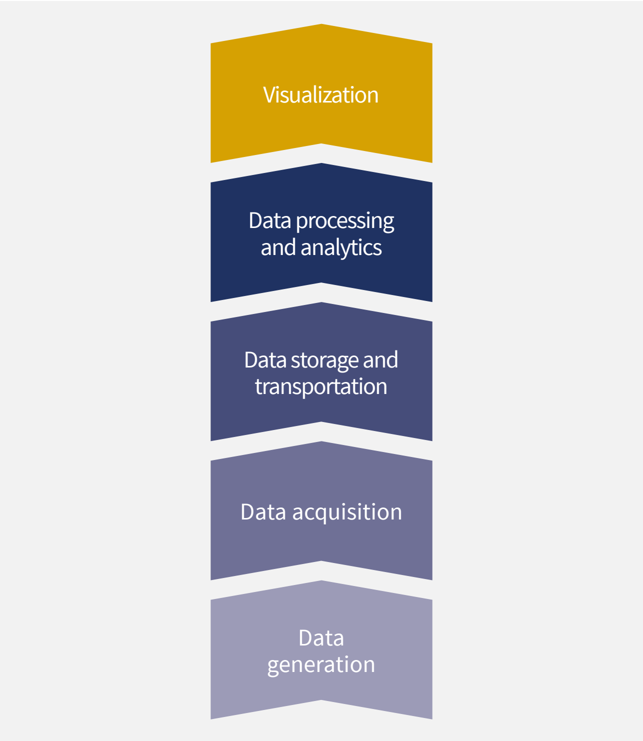
Figure 3. Components of a big data ecosystem



35 National Institute of Standards and Technology (NIST) official website: www.nist.gov
36 For more information on big data and AI principles in engineering by WFEO: http://www.wfeo.org/big-data-and-ai-principles-in-engineering

Artificial Intelligence (AI) and machine learning (ML) technologies have benefited tremendously from these advances as large amounts of data are now available to facilitate ML (such as deep learning and artificial neural networks). Tools for the big data paradigm further enable computers to achieve performance levels previously expected from super computers (Stephenson, 2018). In turn, AI techniques enrich big data analysis, especially in processing unstructured data. One key element of the big data system are the databases, which are designed to handle non-SQL data access. These fall under the category of NoSQL, which are unique in 'characteristics and design philosophies' (Mohanty *et al.,* 2013). Visualization of data analytics outcomes, in an easily and effective manner, is imperative and calls for innovation and creativity across the entire big data value chain (Figure 4).

Figure 4. Big data value chain



Big data applications

The transformative potential of big data in healthcare, public sector administration, retail and manufacturing, and personal location has been widely accepted (McKinsey, 2011). At present, big data applications are mainly used in the business sector, however, this is fast changing as others are also realizing the tremendous value accruing from this technology. Governments the world over for example are leveraging big data analytics to identify and address challenges and to plan effective programmes, especially in the developing world. It has been noted that big data has the potential to 'track development progress, improve social protection and understand where existing policies and programs require adjustment'.[37]

Realizing the significance of big data driven development, the UN Statistical Commission in 2014 created the UN Global Working Group on Big Data for official statistics, which includes a compilation of Sustainable Development Goal (SDG) indictors for the 2030 Agenda for Sustainable Development[38]. Some of the areas in which big data is creating significant value are given below.

- Big data analysis is extremely valuable in the manufacturing sector enabling the integration of data from various departments to facilitate concurrent engineering, which in turn enhances quality and productivity (McKinsey, 2011).
- Big data has immense application in infrastructure design, leading to optimal results and cost effectiveness.
- Supply chain management has been greatly enhanced by increased visibility of logistic movements as well as in utilizing user feedback, and is an oft quoted example of big data technology application.
- In the retail industry, big data enables consumer satisfaction to be enhanced by managing public perception, brand management, customer response, analysing buying trends and focused product innovation.

Data obtained from patients are being used effectively to administer optimum care, ranging from diagnostics tests to medical dosage. Gene sequencing for disease treatment relies on big data technologies due to the vast amounts of data that needs to be processed. During the ongoing COVID-19 pandemic, big data technology is being used widely in the identification of cases and in planning the treatment of those affected.

- Big data in education is effective in the performance evaluation of both teachers and students, and in measuring teaching outcomes among other variables.
- In the energy sector, smart meter readers enable data to be collected frequently and this in turn is used to analyse consumption patterns, leading to optimum deployment and usage of utilities.

While it has been established that big data will be fundamental for efficient and sustainable development in the future, there are challenges revolving around the availability of a specialized workforce, computational power and deployed resources (Espinosa, 2019). Some of the key challenges in big data for

37 As defined in the Gartner Glossary: https://www.gartner.com/en/information-technology/glossary/big-data
38 For more on the UN Global Working Group on Big Data: https://unstats.un.org/bigdata

analysis are given below (Ekbia *et al.,* 2015; Chen and Zhang, 2014; Jagdish *et al*., 2014):

- extraction of data across multiple platforms and integration;
- processing a large amount of data in real time;
- forecasting and creating predictive models and the creation of suitable algorithms for the purpose;
- having suitable processes in place to ensure decision-making based on big data analytics;
- ensuring that big data analytics is robust enough to discern underlying anomalies in the large data set used – availability of data management techniques is a critical imperative to ensure collection and updates of secure and real time data, and to ensure data security; and
- visualization of data in a cogent manner, especially keeping in mind the heterogeneity of data usage that is structured, unstructured and hybrid.

The future of big data

The convergence of data and analytics is evolving rapidly and it is envisaged that this process willl necessitate wider collaboration and communication.

Techniques and algorithms are continually being developed to analyse large heterogenous data from multiple sources. However, the validation of results of analysis remains a major issue (Kambatla *et al.,* 2014). New system and software architecture are needed to handle the gigantic amount of data being generated and made available for analysis (Espinosa *et al.*, 2019) requiring special skill sets, innovation of a very high order, agility in design, and also a governance and security framework to manage this growing ecosystem. The rapidly evolving blockchain technologies will be an enabler for big data analytics.

For engineers, the outcome of big data analytics in the future will be especially relevant in various domains, such as predictive and preventive maintenance and product and structural design, among others, leading to more efficient project management and cost effectiveness in an environment of sustainable development.

Recommendations

1. To harness the benefits provided by big data in various engineering applications, engineers need to increase their competency in the domains of data technology.
2. Governments and data owners need to make data findable, accessible, inter-operable and re-useable in an ethical way.
3. Rules and standards need to be developed based on global consensus to enable efficient data-sharing and data-exchange.
4. Security and privacy of data has increased in relevance and should form part of the design process across all stages of the big data paradigm.
5. Regulatory frameworks along the lines of the General Data Protection Regulation (GDPR) are needed to harness data while upholding privacy and fundamental rights, which should enable borderless collaboration.
6. Business entities and regulators need to revisit the standards and protocols for the capital value of data to encourage, incentivize or penalize data generation and prevent abuse when used for malicious purposes.

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3.8 ENGINEERING AND ARTIFICIAL INTELLIGENCE

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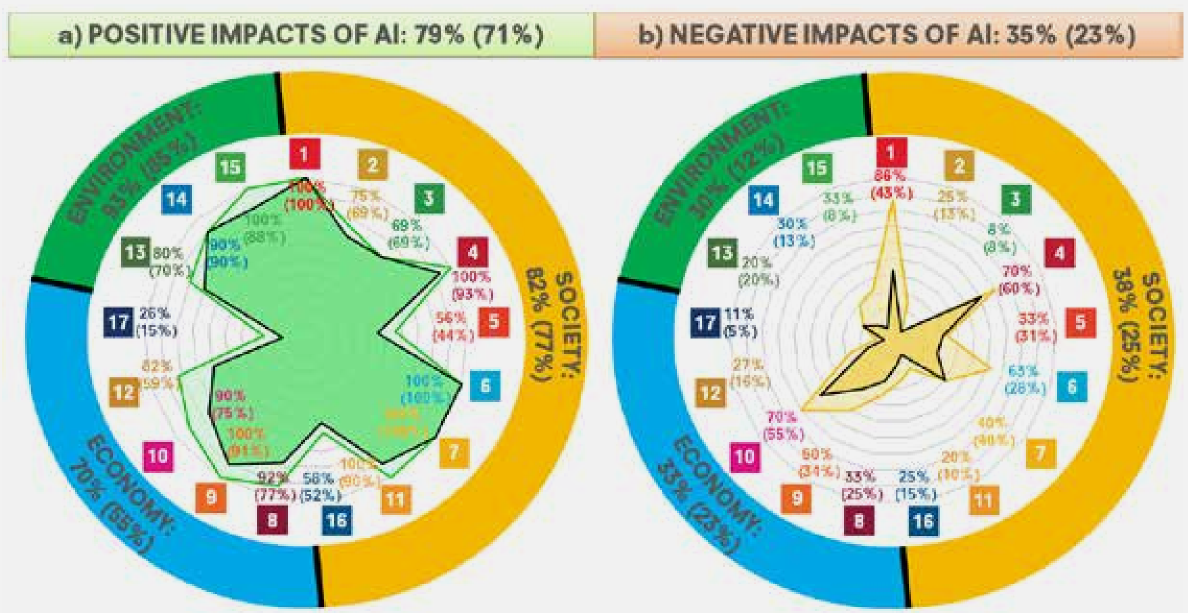
Abstract. Artificial Intelligence (AI) is playing a core role in the Fourth Industrial Revolution and impacting all aspects of economic and social development, from advanced manufacturing, energy supply, transportation, healthcare, education and agriculture to different kinds of commerce, social services and household functions. As a powerful form of general technology, AI can empower engineering for the Sustainable Development Goals, but it can also bring about negative impacts in terms of privacy and security, among other things. It is therefore the responsibility of engineers to ensure that AI applications are good for all people and for the environment.

AI is the ability of machines and systems to acquire and apply knowledge, and to carry out intelligent behaviour (OECD, 2016; UNCTAD, 2017). AI impacts on society, the economy and the environment in a broad way, and is a key driver of the Fourth Industrial Revolution (Schwab, 2017). McKinsey survey data suggests that the adoption of AI could raise global GDP by as much as US$13 trillion and add 16% to global GDP growth by 2030 (McKinsey, 2018).

After more than half a century of development, AI – driven by deep learning algorithms and big data – has now entered engineering applications. It is empowering and transforming every aspect of engineering. AI has incredible potential to improve the productivity, quality, safety and efficiency of various engineering projects. In addition, it holds great promise and potential to accelerate progress on all 17 SDGs, but it may also have negative impacts, as shown in Figure 1 (Vinuesa *et al*., 2020).

While the progress of AI is significant, it is not perfect. Intensive research and development, and the broad engagement of stakeholders are needed to ensure that human values permeate AI for sustainable development (UNESCO, 2019) for the good of humanity and for the environment (Hawking, 2017).

Figure 1. Summary of positive and negative impacts of AI on the various SDGs



Documented evidence of the potential of AI acting as: a) an enabler or b) an inhibitor on each of the SDGs. The numbers inside the coloured squares represent each of the SDGs. The percentages on the top indicate the proportion of all targets potentially affected by AI, and the ones in the inner circle of the figure correspond to proportions within each SDG. The results corresponding to the three main groups, namely 'society', 'economy' and 'environment', are also shown in the outer circle of the figure. The results obtained when the type of evidence is taken into account are shown by the inner shaded area and the values in brackets.

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AI empowering engineering for the SDGs

AI is penetrating, empowering and transforming all engineering fields. It promotes engineering innovation to optimize workflows and processes with improved productivity, increased efficiency and reduced costs in a more intelligent and automatic way. At the same time, it helps to improve the working conditions of workers by releasing them from dangerous and repetitive works, and by creating new jobs. AI helps people understand and leverage the explosion of data, and assists people in their efforts to solve a constellation of challenging real-world problems. Some examples below show how AI is promoting the delivery of the SDGs.

Healthcare

As mentioned in Chapter 3.1, the potential for AI in health is profound. From clinical uses in diagnostics and treatment, to biomedical research and drug discovery, to 'back-office' and administration, it would seem that there is almost no facet of healthcare provision and management where AI cannot be applied – and the number of potential applications is growing every day. With healthcare systems facing significant longer-term challenges, including populations that are rapidly ageing, multiple chronic diseases, gaps in workforce supply and skills, and growing health spending (a share of which is wasted or even harmful), as well as new threats like COVID-19, AI could make a huge difference in the coming years and even weeks. The potential to tackle unwarranted variation in care, reduce avoidable medical errors and inequalities in health and health care, and minimize inefficiencies and waste is particularly promising. AI could have significant benefits not only under business-as-usual conditions, but also for better resilience and emergency preparedness, making health systems and societies more capable of responding to disease outbreaks like COVID-19 (OECD, 2020).

Agriculture

Food supply is critical to human life. However, it is expected that the world's population will reach 10 billion by 2050, with environmental degradation due to climate change placing current agricultural systems under ever-growing pressure. Integrating AI with agricultural big data gathering by onsite sensor networks, satellites and drones has helped to confront pressing challenges. AI is able to analyse data on both global and local scales in real time to extract useful information about crop growth, soil characteristics and weather conditions to support farmers in making the right decisions. AI enables the transformation of farming from the mass customization of agricultural services to precision or digital agriculture. For example, AI supports increases in productivity through the accurate use of fertilizers and pesticides, as well as in the careful use of natural resources and the adoption of water-saving measures (di Vaio *et al*., 2020; Patrício and Reider, 2020 ; Paucar *et al*., 2015; Sheikh *et al*., 2020; Viani *et al*., 2017).

It should be noted that the different regions of the world will have specific needs and requirements in the development and introduction of ad hoc AI-based solutions. For example, 80 per cent of farmers in sub-Saharan Africa are smallholder farmers who have limited resources. Hence there is a need for low-cost AI-based technologies that farmers can quickly adopt and adapt to their conditions.

Transportation

Transportation systems are key infrastructures linking social and economic activities. Empowered by AI, transportation is gradually evolving through the implementation of smart, resilient and low-carbon systems. In recent years, AI applications in transportation have been on the increase, for example, in the fusion and mining of traffic data, traffic flow prediction and incident detection, connecting vehicles and roads, as well as for traffic control and management under emergencies. In the context of the rapid development of computing power and interconnectivity powered by 5G communication, intelligent transportation systems will rise from the level of infrastructure construction to the level of true intelligent management and control in the near future.

For example, powered by AI, Alibaba's City Brain analyses information, such as video from intersection cameras and GPS data on the locations of vehicles, in real time as it coordinates more than 1,000 road signals around the city of Hangzhou, China, with the aim of preventing or easing gridlock and accurately predicting traffic flows through traffic-sensitive routing. This has helped the metropolis of 7 million people drop to 57th from 5th among China's most congested cities (Toh and Erasmus, 2019).

Manufacturing

AI is helping the manufacturing industry transform their operations, better serve customers and offer new opportunities to their workers. Schneider Electric's platform is leveraging Microsoft AI tools to help a range of customers stay ahead of maintenance problems in applications as varied as coffee roasters in the developed world to schools and clinics in developing countries. In Nigeria, historical data have helped the AI system learn to identify possible drops in electricity generated by solar panels and to issue a warning when a panel needs to be cleaned or a battery checked within 12 hours to prevent it from failing. In this way, Schneider can identify trends in its solar panels so technicians can address issues before they lead to outages (Shaw, 2019).

Energy

AI has been successfully used with renewable energy systems to enable more efficient matching to working conditions such as the strength of lights and winds to customer demand. AI is also able to help the traditional energy providers be more eco-friendly.

Data and computing make it possible to see beneath layers of soil, sequence DNA and therefore make drilling more precise, not only minimizing the number of wells that need to be drilled but maximizing the production life of the wells. All of this helps reduce the time from acquisition of the site to when the energy is commercialized (Shaw, 2019).

Challenges in AI technologies and governance

Despite prominent progress in AI technologies, existing AI is still at an initial stage and remains largely limited to solving specific problems – mostly in developed regions – and far from realizing its full potential. There are therefore big gaps between their technical and applicable capabilities and meeting the requirements to achieve the SDGs.

Among many issues, widely used deep learning algorithms remain 'black boxes' that do not explain their predictions in ways that humans can understand. The lack of transparency and accountability of predictive models can have (and have already had) severe consequences. Moreover, this round of AI relies heavily on large amounts of human labour to label data, and ever-larger computing power consuming a lot of energy. Global data centre electricity demand in 2019 was about 200 TWh, or around 0.8 per cent of global final electricity demand (IEA, 2020).

In addition to technical gaps there are also gaps between AI applications and social expectation, which raises public concern about the possible negative impacts of AI, such as job loss, privacy violations, bias, malicious use, and the possibility of exacerbating the digital divide and inequality.

Closing these gaps needs intensive engineering research and the development of AI governance with the engagement of government, civil societies and industry. It is essential to recognize the gaps in current AI technologies and relevant regulation, standardization and education, and realize that AI must be developed responsibly for the good of humanity and the environment. Many efforts have been made, not only in intensive technical research and development, but also in necessary governance. To date, a number of guidelines for responsible conduct with AI have been proposed by governments, industry, universities, and scientific and technical communities, such as the ongoing UN initiatives on Ethics of AI (UNESCO, 2020), the EU Ethics Guidelines for Trustworthy AI (AI HLEG, 2019), the OECD Principles on AI (OECD, 2019), the WFEO Principles promoting responsible conduct of Big Data and AI innovation and application in Engineering (WFEO, 2019), and the OpenAI Charter (OpenAI, 2018).

Recommendations

To accelerate the development of AI with human values for sustainable development, a number of recommendations can be made to governments, policy-makers, industries, academia and civil society, among others, as presented below.

1. Promote international and interdisciplinary cooperation between academic institutions, universities and industry, as well as civil society across the world, and advance AI innovation and applications for the implementation of the Sustainable Development Goals.
2. Promote international dialogue to reach a global consensus on AI governance, and adopt global principles, guidelines and standards for the responsible conduct of AI.
3. Promote AI education and literacy to help people adapt to the AI era, engineers to conduct responsible application and innovation, and all actors, especially business leaders and policy-makers, to make informed decisions, with special efforts to narrow the digital divide between rich and poor countries to ensure that the benefits can be shared by all and 'leaves no one behind'.

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3.9 ENGINEERING FOR SMART CITIES

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Introduction

Cities around the world are facing daunting challenges such as growing congestion, worsening air quality, insufficient availability of water, lack of proper waste disposal and management, public health concerns, increased crime rates, and so on. At the same time, cities are projected to account for about 70 per cent of the global population and contribute 85 per cent of global economic output by 2050, with the potential to create a huge impact on the environment (UN, 2019).

To address such challenges, governments at city level are fast adopting smart technologies and advanced engineering applications to enable faster, reliable and affordable urban services. The rapid application of digital and engineering technologies is changing the nature and economics of infrastructure required to deal with these urban challenges. This also opens up enormous opportunities for future engineers and technologists to innovate ideas and implement cost-effective applications for the comprehensive development of cities and to improve the quality of city life. The *Global Sustainable Development Report 2019* also identifies urban development as an essential entry point for integrated implementation of the Sustainable Development Goals (SDGs).

A few indicative areas where advanced technology applications are transforming urban infrastructure and services are shown in Table 1. The creation of differentiated citzen-centric services generates significant social, environmental and economic impacts. These are are helping cities and regions meet their commitments to the SDGs, especially SDG 11 on sustainable cities and communities.

Table 1. Examples of technology applications in smart cities generating high SDG impacts in developing countries by improving key Quality of Life indicators

Area	Technology/ Engineering Applications	Impact
Faster, secure and affordable commute	• Use of digital signage and mobile apps • Intelligent traffic management • Congestion pricing • Real-time information • Predictive maintenance of transportation infrastructure • Autonomous vehicles	• Commute time saved by 15-20% • Commuting time for healthcare/ government work reduced by 45–65%
Smarter and faster public health response	• Remote patient monitoring systems • Use of infectious disease surveillance systems	• Health burden reduced by >4% • Cities in developing countries achieved 5% reduction in spread of infectious disease
Cleaner and more sustainable environment	• Building of automation systems • Air quality monitoring • Water consumption tracking with advanced metering/sensors/analytics • Smart waste management systems • Circular economy for reduce-reuse-recycle of waste materials that create economic value	• A 6% reduction in building emissions • Air pollution related negative health effects reduced by 3–15% • Water consumption reduced by 15% and water loss by 25% • Unrecycled solid waste reduced by 30–130 kg/person
Smarter, affordable and sustainable access to energy	• Reducing consumption/shifting load to off-peak periods • Smart meters to reduce losses, theft, better demand prediction and load forecasting	• Usage of carbon intensive peak plants reduced • Usage of green energy increased • Power outages reduced
Improved public safety and information security	• Predictive policing, real-time crime mapping, and gunshot detection • Optimized dispatching and synchronized traffic lights • E-hailing and reduced impaired driving	• Incidents of assault, robbery, burglary lowered by 30–40% • Emergency response times cut by 20-35% • Traffic fatalities reduced by >1%
Innovation and economic opportunities	• Smart technologies can play a role in making local job markets more efficient, supporting local business growth, and building skills that make people more employable	• Smart city technologies to boost employment by 1–3% by 2025
Disaster resilient infrastructure and applications	• Early warning systems • Making urban civic amenities more disaster resilient • Faster disaster recovery and response mechanisms	• Reduction in disaster impact • Reduced loss to economy, environment and human life • Durability of infrastructure

Source: McKinsey Global Institute, 2018.

The rate of adoption of digital technologies and IT-enabled solutions is found to be fastest in cities of emerging economies. With a large volume of sensor-based infrastructure, citizen-centric solutions enabled by big data analytics are being implemented in smart cities at a rapid scale. The Internet of Things (IoT) ecosystem provides the right platform to manage and monitor modern urban services, enabling opportunities for smart cities to adopt predictive technologies to enhance the efficiency of various urban services and to augment the quality of life of its residents by creating an interconnected network of machines and sensors which can transmit messages, resulting in the automation of repetitive tasks.

How digital technologies and advanced engineering applications can transform smart cities

With the effective use of IoT, a smart city can make optimal use of public resources by improving the quality of service delivery while reducing its cost. A key objective of using IoT in smart cities is to provide easy and unique access to public resources so that better utilization and optimization of transport surveillance, water, power and the maintenance of public areas can be achieved. The concept of smart cities is also being used to increase transparency around actions undertaken by Urban Local Bodies (ULBs) while catering to the needs of the public. A few IoT-based applications implemented in various smart cities are given below.

- ***Smart health.*** Sensor-enabled health screening machines are used to improve primary health diagnosis services. In Glasgow, sensors are placed in homes to diagnose and manage health conditions and provide early diagnosis.
- ***Intelligent traffic management.*** Adaptive traffic management is based on dynamic modelling with the help of real-time data from traffic sensors with cameras used to prevent congestion. For example, in Barcelona smart buses are connected to the city's internet network and display real-time bus timetables, tourist information, destination route maps and congestion updates.
- ***Smart utility supply grids.*** In Singapore, the installation of sensors and analytic tools within the water grid provides real-time monitoring and a decision support system to the utility provider, thus making water available 24/7 for consumers.
- ***Smart meters.*** Automated meter readings and the transmission of utility consumption data to consumers and the departments concerned enables remote monitoring and billing in near real-time mode. Nairobi has 90,000 smart meters installed to combat water theft.
- ***Smart parking.*** In the city of Kolkata, the city traffic police have launched a mobile application that provides real-time updates on available parking spots within the city, allowing drivers to pre-book them.
- ***Smart waste collection and circular economy.*** Monitoring of waste containers gauge utilization and fill levels to optimize waste collection schedules and routes. For example, in Prague, smart bins were introduced as a part of waste management plans to save energy and money. The smart bins had sensors attached which transmitted data to authorities regarding their fill levels.
- ***Smart lighting.*** In Copenhagen, the remote lighting management programme has achieved 65 per cent energy savings by controlling the dimming of streetlights when the lights are not needed.

In addition to the applications listed above, there are several more areas where IoT is helping cities achieve efficient operations and improve the quality of life for its citizens. Figure 1 highlights several more such applications of IoT in smart cities.

Figure 1. Emerging engineering applications in relevant areas of smart cities

SECURITY
- Predictive policing
- Real-time crime mapping
- Gunshot detection
- Smart surveillance
- Emergency response
- Body-worn cameras
- Disaster early-warning systems
- Personal alert
- Home security
- Data-driven building inspections

ECONOMIC DEVELOPMENT
- Digital business licensing and permitting
- Digital tax filing
- Online retraining programs
- Personalized education
- Local e-career center
- Digital land-use and building permitting
- Open cadastral database

HEALTHCARE
- Telemedicine
- Remote patient monitoring
- Lifestyle wearables
- First aid alert
- Real-time air quality information
- Infectious disease surveillance
- Data-based population health interventions: maternal and child health; sanitation and hygiene
- Online care search and scheduling
- Integrated patient flow management systems

MOBILITY
- Real-time public transit information
- Digital payment in public transit
- Predictive maintenance of transport system
- Intelligent traffic signals
- Congestion pricing
- Demand-based micro transit
- Smart parking
- E-hailing
- Car sharing
- Bike sharing
- Integrated multi-modal information
- Real-time road navigation

ENERGY
- Building automation
- Home energy automation
- Home energy consumption tracking
- Smart lights
- Dynamic electricity pricing
- Distribution automation

COMMUNITY
- Local citizen engagement
- Local connection platforms
- Digital administrative citizen services

WATER
- Water consumption / quality tracking
- Leakage detection
- Smart irrigation

WASTE
- Digital tracking / payment for waste disposal
- Route optimization

Source: KPMG, 2019.

Emerging engineering applications and skills for smart cities

ULBs and city authorities are developing smart city plans and leveraging various digital technologies to enable their overarching strategy and to meet operational and community challenges. IoT applications are expected to make urban services faster, efficient and affordable, and to become the vehicle for economic development in future smart cities. A few examples of such technology applications are given below.

- **Mobile internet** is the foundational digital infrastructure of IoT, allowing machines to communicate and automate. With the onset of 5G and other several short-ranged wireless technologies, mobile internet is expected to drive the implementation of IoT in smart cities.
- **Machine learning and Artificial Intelligence** (AI) can help convert large volumes of data collected by machines into actionable information.
- **Cybersecurity** promotes trust by enabling the secure exchange of data.
- The advent of **edge computing** is allowing faster decision-making and reaction times for machines. This has enabled the application of IoT in areas such as accident alert and response, health monitoring and surveillance.
- **Predictive analytics** is serving as a proactive tool to improve the efficiency and productivity of business, as well as myriad government actions, for example, weather prediction, traffic congestion, pollutant intensity and so on. Improved algorithms and statistical techniques are the backbone of the IoT-enabled real-time information and intelligence system used in multiple citizen services.
- **Cognitive computing** allows for an enhanced IoT experience by using computerized models to simulate the human thought process in complex situations, thereby improving the intelligence of smart devices. The next economic impetus for IoT is expected to come from machine intelligence.
- **Digital literacy** is helping more people become technology friendly, improving their familiarity with, and the rate of adoption of, smart machines.

- **IoT platforms** enable the delivery of IoT applications and the management of devices at reduced cost and time. The platforms provide a wide range of features to onboard devices so as to connect them securely and handle data exchange.

It is estimated that the global IoT market specific to smart cities, which was valued at US$79.3 billion in 2018, will reach US$330.1 billion by 2025 at a compound annual growth rate (CAGR) of around 22% (Zion Market Research, 2019). This is a clear indicator of the size of play for technology and engineering firms, institutions and networks, and for engineers in this domain.

Engineers and technologists equipped with future-ready skill sets will play a critical role in this technological landscape. While new skills and expertise in specialized engineering disciplines will be important, typically in a situation like a smart city the most crucial aspect of an engineer's role will be to integrate, coordinate and synthesize advanced capabilities from multiple domains to design holistic solutions to citizens' problems and issues. Some of the emerging domains, where traditional engineers and practitioners may need rapid upskilling, are presented below.

- ***Power engineering***. As renewable energy penetration increases, expertise in understanding grid integration and grid stability will become extremely important. In addition, as more electric vehicles come into the system, a deep understanding of grid balancing techniques and operational practices will be critical.
- ***Civil engineering and urban planning***. As more efficient public transportation modes like Bus Rapid Transit (BRT) or Mass Rapid Transit (MRT) are adopted by the transport sector, civil engineers along with transport and urban planners will have to work in tandem to design the smart city.
- ***Robotics engineering***. This interdisciplinary branch of electrical engineering and mechanical engineering – together with the increase in intelligent machines – is an upcoming area and possibly one of the most important to enable a smooth transition to intelligent cities.
- ***Computer and IT engineering***. This area of engineering is important for developing IoT and other IT-related applications, such as virtual reality design, cloud science and cyber security, among others.
- ***Structural, environmental and corrosion engineering***. Integration of these disciplines will be needed to ensure that construction and building materials are environmentally sound, as well as disaster resilient. Moreover, cities will need to be more climate resilient, which will require urban planners and engineers with the sufficient skills and expertise to predict climatic impacts using climate models so as to adopt design standards to reduce the climatic vulnerability of city infrastructure.
- ***Other areas***. These include nano-engineering, material/molecular engineering, biotech/biomedical engineering, corrosion engineering and mechatronics, all of which are increasing in importance daily.

Considering the scale and the complexities of the challenges faced by modern cities, developing appropriate and effective solutions will require multi-disciplinary thinking at an in-depth system level. This is where engineers and technologists need to collaborate and engage with a diverse group of experts and professionals to a greater extent, not only in terms of interdisciplinary cooperation within the engineering domain, but also with stakeholders outside their domain, such as policy-makers, regulators, finance professionals, economists, sociologists, environmentalists and others to develop more practical, out-of-the-box solutions that are affordable and can be easily implemented.

Challenges hindering faster adoption of IoT in smart cities

Despite the numerous advantages provided by IoT, digital technologies and advanced engineering applications for improving the social, economic and environmental quality attributes of a city, there remain a few challenges which currently impede the large-scale and seamless adoption of these technologies, as outlined below.

- **Lack of adequate resources**. The components used to manufacture IoT and digital devices (e.g. microprocessors, chips, printed circuit boards (PCBs) and so on) cannot be easily manufactured everywhere. The lack of easy availability of raw materials such as lithium and heavy rare earth metals poses further challenges with respect to the manufacture of IoT devices.
- **Data security and privacy**. High dependence of IoT devices on the internet exposes users to the risk of cyber-attacks, which could result in a loss of data and privacy, but also financial losses. This concern needs to be adequately addressed by strengthening cyber security across these devices. It is also important for governments to establish as early as possible the data governance terms for ownership, privacy, usage and sharing as a central pillar of data security.
- **Capacity constraints of governing bodies**. The pace at which technology is evolving far exceeds the capacity of government at various levels to formulate policies and a governance framework to support, regulate and monitor technology applications. The governing bodies often lack technical know-how, institutional strength, flexibility and human resources to regularly update policy frameworks in line with technological advancements.
- **Deepening global inequality**. Whereas some cities have been able to scale up and adopt advanced technology solutions to serve their citizens, a vast majority of cities around the world are still struggling to provide basic infrastructure, security, safety and hygiene facilities to their citizens. This widening global inequality

is preventing city authorities from accessing the resources required to implement modern day technologies.

- **Job loss**. Digital technologies often result in the replacement of several low-end and repetitive jobs like traffic management, waste collection and so on. However, in many cities this would result in large-scale job losses as these activities are manual in nature and offer a source of livelihood to thousands of people who may not have adequate skill sets to take up other activities. Governments across the world have initiated various re-skilling and up-skilling programmes to mitigate the short-term adverse impacts on the livelihoods of their citizens.
- **Re-skilling the workforce**. Skill gaps across all industries are poised to widen in the Fourth Industrial Revolution. Rapid advances in AI, robotics and other emerging technologies are occurring in ever shorter cycles and changing the very nature of the jobs that need to be done and the skills needed to do them. Access to skilled workers in local markets will be a key factor in determining the successful implementation of technology interventions.

Though there are challenges it is expected that growth in the global economy and the enhancement of human capital will see more cities around the world increasingly turn to technology-based solutions to meet the needs of their citizens.

The way forward

The application of IoT in smart cities is not only limited to the use of robust technology, it also covers social aspects pertaining to its ease of use, utility and digital equity that will allow greater acceptability and improved efficiencies within cities. However, for these technologies and engineering applications to be successful in smart cities, they must follow certain attributes and principles. These principles, outlined in the recommendations, are also important for the future alignment of engineering skill sets to enable engineers to play a bigger, wider and more responsible role in smart and future cities.

Recommendations

1. **Creative**. Governing bodies like ULBs need to carefully select futuristic solutions that utilize state of the art technology, while at the same time remaining cognizant of local standards and adoptability. This would require a creative balance between cutting edge, state of the art technology, human resources and urban infrastructure development.
2. **Correlated**. Instead of undertaking development in silos, ULBs will need to work in tandem with various departments like transport, education, and healthcare, among others, to enable knowledge- and data-sharing in order to create a network of interconnected smart solutions focused on providing holistic citizen-centric services.
3. **Collaborative**. The development of several private-public partnerships (PPP) models can be envisaged to leverage private sector know-how and resources. ULBs can also induce participative and equitable behaviour, allowing for a strong sense of ownership among citizens availing themselves of IoT services.
4. **Certified**. The IoT services and technologies used can be certified (e.g. ISO[45], GDPR[46], DPO[47]) to develop trust among users and to promote standardization. Obtaining certification would enable secure and safe usage of technology while protecting the privacy of citizens.

Global platforms will also play a key role in coordinating and channelling international public and private efforts towards adoption, penetration and governance of technologies in smart cities. Multi-sectoral stakeholders, including technical, financial, political, social and business partners, can collaborate and coordinate together through such platforms. This would also create common understanding, forge relationships and drive commitments for new approaches and partnerships as a foundation for technological advances in cities.

Smart cities create opportunities for the integration of digital technologies with myriad engineering applications to create efficient citizen-related services and to solve citizens' problems and issues. They also allow for opportunities to combine multiple technological and engineering applications towards finding common solutions to problems. With digital technologies playing a major role, more comprehensive, real-time data will become available, giving agencies and stakeholders the ability to watch events as they unfold, understand how demand patterns take shape, and respond with speed, agility and flexibility.

Smart engineering technologies and applications change the nature and economics of infrastructure. Starting with the new generation of transport and healthcare facilities, and encompassing disaster resilient infrastructure and low-carbon sources of energy, smart cities could become the vehicles of purpose-driven innovation and test-beds for new applications and solutions. This in turn will open up further avenues for engineering research and development, and the scaling up of commercially viable solutions. Urban development overall needs to proceed in a sustainable, integrated and inclusive manner, and this requires city authorities working together with businesses, civil society organizations, individuals and even with other global cities to facilitate the exchange of knowledge and best practices. The result is not only a more liveable city, but also a more productive and eco-friendly one where economic and innovation activities can flourish and thrive.

45 International Organization of Standardization official website: https://www.iso.org/home.html
46 Read more about General Data Protection Regulation compliance at https://gdpr.eu
47 Data Protection Officer.

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4.
ENGINEERING EDUCATION AND CAPACITY-BUILDING FOR SUSTAINABLE DEVELOPMENT

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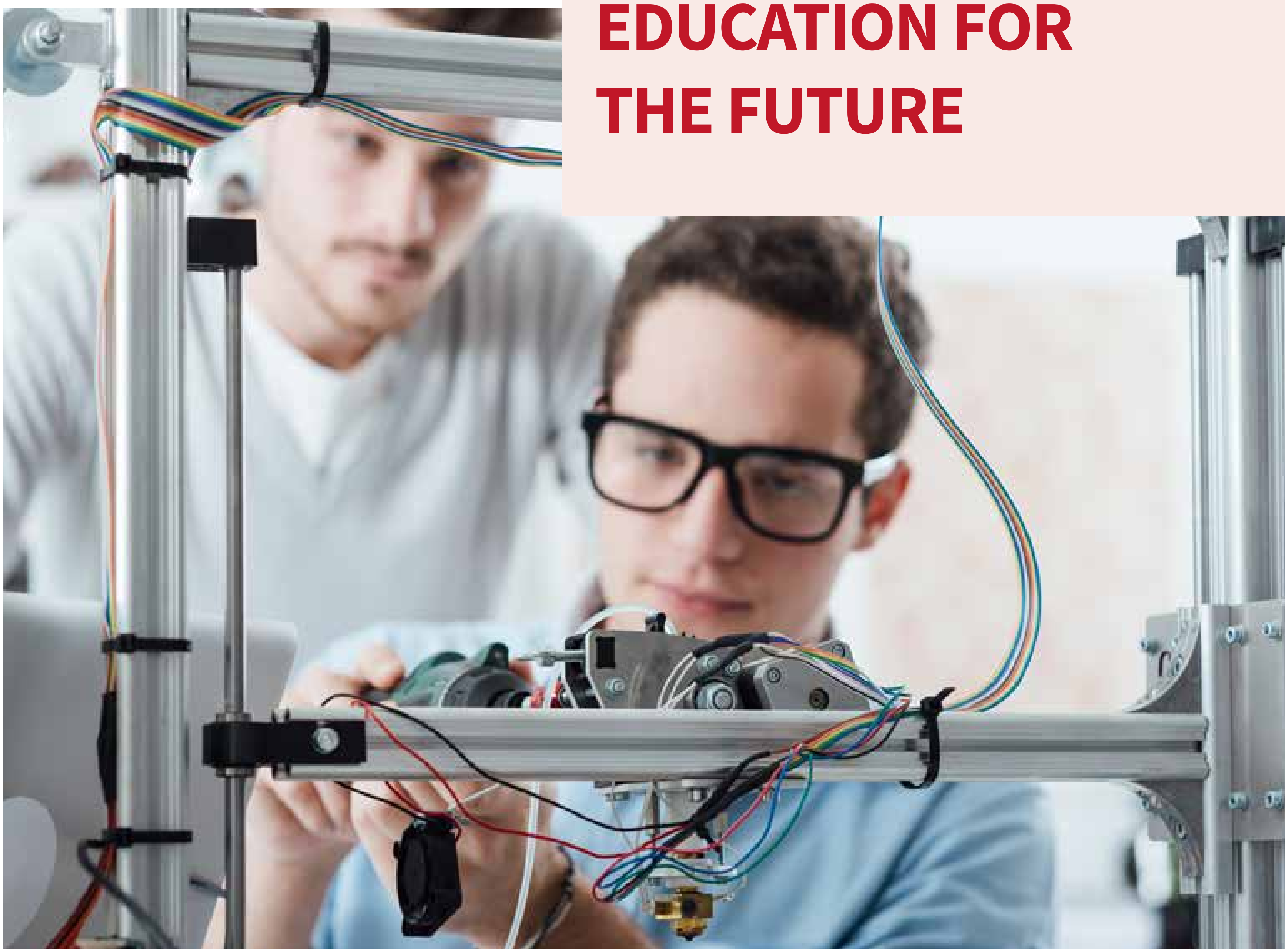
Deep Learning
SIMPLE DEEP LEARNING NETWORK
Input Layer
Hidden Layer

4

Abstract. Chapter 4 discusses engineering education, a topic essential to delivering on the SDGs. Starting from science, technology, engineering and mathematics (STEM) in school, to higher education and continuous professional development (CPD), through to opportunities for upskilling and reskilling, engineering education is a sum of all these things, enabling today's engineers to deal with the challenges ahead, and equipping them with the tools and skills needed to transform this dynamic world into a place that is respectful of the planet and that can provide good health and well-being for the benefit of all. Section 4.1 focuses on how higher engineering education can meet the requirements for new engineering competencies for sustainable development, and discusses why and how engineering education is changing from its traditional focus on disciplinary technical knowledge to a much broader interdisciplinary and complex problem-solving approach that combines societal and sustainable problem analyses with academic technical knowledge and solutions. Section 4.2 further discusses the necessity for lifelong learning in engineering, so that engineers are able to keep up with the rapid development of technologies and the ever-growing expectations of society, and respond to the world's problems. This section also analyses the current state of lifelong learning in engineering, as well as future approaches for creating a framework for policies, infrastructure and quality assurance. Section 4.3 deals with CPD and the certification systems that play a fundamental role in adapting engineers to technological innovations and new working methods to better fulfil their commitments to global sustainable development. Chapter 4 shows how engineering capacity-building is a continuous process, working hand in hand with the development of science and technology, the social aspects of modern engineering and quality assurance at every stage of this evolving process. A key requirement on this long journey of engineering education from school study to professional development is to 'ensure that all learners acquire the knowledge and skills needed to promote sustainable development' (SDG 4).

Anette Kolmos[1]

4.1 ENGINEERING EDUCATION FOR THE FUTURE



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4

Abstract. Engineering education plays a crucial role in overcoming the challenges posed in achieving the SDGs. Achieving these goals necessitates a shift in engineering education away from a focus on academic technical knowledge towards a much broader interdisciplinary and complex problem-solving approach that combines societal and sustainable problem analyses with academic technical knowledge and solutions. Engineering students need to learn how to analyse and solve complicated and complex problems, and to be able to collaborate in a variety of teams. This chapter focuses on the need for new engineering competencies, as well as emerging trends demonstrating how engineering institutions can respond to the challenges of sustainability through student-centred and problem-based learning. Steering engineering education in this direction will require educational leadership and research. Curriculum change should be approached in a systematic way, which includes promotion and faculty development.

How is the engineering sector changing?

Engineering is a problem-solving profession and requires a problem-based approach to learning. From early school education and throughout the educational system, science subjects will benefit from a more inquiry-based approach combined with design thinking and interdisciplinary collaboration with other school subjects (Box 1).

Engineering students need to learn how to analyse and solve the problems facing by society and to develop technologies that will improve sustainable living. These needs are reinforced by major trends shaping engineering education, like emerging technologies and the employability agenda, as well as diversity issues such as gender balance.

Box 1. The importance of early STEM education

The steady decline of enrolment among young people in science and the shortage of engineers is a cause for concern. UNESCO, together with its partner Intel, has developed online Science Technology Engineering and Mathematics (STEM) education resources for inclusive distance learning in response to COVID-19 with a view to making STEM education more accessible than ever. These free online resources provide coding challenges for all ages, as well as mathematical problems and solutions, a variety of micro-science hands-on experiments, instructions, descriptions, guides, magazines and interactive design opportunities with scientists via Skype. The objective is to increase the interest of young people, especially girls, in engineering and science disciplines that stimulate their critical thinking, innovation and problem-solving skills. Examples of UNESCO's online programmes in STEM education include learning from scratch how to build and programme a robot out of household materials and a smartphone.

Educators can access a number of specially developed units on the principles of STEM for the classroom here: http://www.unesco.org/new/en/natural-sciences/science-technology/engineering/engineering-education/stem-resources/

Engineering and technology are of vital importance to achieving the 17 SDGs and thus to the future of the planet. As noted in the first UNESCO Engineering Report *Engineering: Issues, Challenges and Opportunities for Development*, engineering education faces a number of challenges that include attracting and retaining students, and responding to changing forms of knowledge production and application (UNESCO, 2010). Engineering education is key to addressing the majority of the SDGs and also plays an essential role in integrating humanitarian, social and economic development, for example in the societal processes underlying peace and justice. An example of this is illustrated in the case study from Colombia (Box 2). It is therefore important for engineering education to find ways to educate engineers who can incorporate sustainable values into the development of technology.

Engineering education needs to move quickly to make progress in these areas, not least because it takes five years to train an engineer. Students starting their engineering education today will put their learning into practice beyond the horizon of the existing SDGs. Technology will become more complex and the learning outcomes for engineering education should follow suit, which will involve changes to both the content of education and the method of learning. Any future direction should involve an integrated understanding of complex problem identification and problem-solving in order to enable engineering students to learn the necessary technical skills, as well as how to deal with the challenges of sustainable development in relation to their discipline and societal impact.

Box 2. Engineering education for sustainable development

Problem and project-based learning in engineering for peace

The PEAMA programme (*Programa Especial de Admisión y Movilidad Académica:* Special Program of Admission and Academic Mobility) at the Universidad Nacional de Colombia in Bogotá is a recent example of how public universities and engineering education can contribute to peace processes, such as the one currently ongoing in Colombia after decades of internal conflict. The overall aim of the programme is to increase the education level of the population in rural and poor areas, and to improve performance in admission exams. The four-semester programme operates within the areas of nursing, agricultural engineering, agronomic engineering, and veterinary and animal husbandry. In the case of PEAMA Sumapaz, project-based learning is the main teaching methodology. Each semester, students develop a concrete product that represents a solution to the problems affecting the rural areas so as to develop competencies related to complexity, creativity and innovation in developing appropriate solutions (Agencia de Noticias UN, 2018; Ordóñez *et al*., 2017).

The SDGs and complexity in the curriculum

Addressing the SDGs and the sustainability challenges will require more 'complexity' in the curriculum. The Cynefin framework is a useful way of understanding how teaching and learning methods are combined with the increasing need to understand complexities (Snowden and Boone, 2007). In this framework, situations are classified as simple, complicated, complex and chaotic. In the *simple* category, the system behaviour is well understood and best practice is implemented; most engineering disciplines are taught within this domain. The *complicated* domain requires *expert* behaviour where there are multiple right answers. For example, the design of a bridge or a mobile phone falls into this category where a few new features are added to a known technology. *Complex* situations are the domain of *emerging* new competencies where the nature of the problem or the kind of solutions to be applied is unclear. Sustainability belongs to the *complex* domain which defines a range of criteria for analysing and solving problems. *Chaotic* situations are often the result of a disaster, whether natural or human-induced. Immediate actions are needed to stabilize the situation before applying methods from the complex, complicated and simple domains.

The normal engineering curriculum responds to the *simple* and *complicated* domains. The challenges of sustainable development, the Fourth Industrial Revolution (Society 5.0) and employability call for possible learning competencies within all four domains: i) chaotic; ii) complexity and emergence; iii) complicated; and iv) obvious. The educational strategy for the *complicated* and *complexity* domains will involve the application of design or problem-oriented projects which can be scaled from less to more open-ended, along with variation in the curriculum structure and pedagogy (Figure 1).

Figure 1. Combining elements in curriculum development with degrees of complexity

	Type of problem	Knowledge and competencies	Curriculum structure	Teaching and learning methods
Obvious	Known problem Known solution e.g. statics	Disciplines	Subjects/courses	Lectures, active learning and flipped classroom
Complicated	Known problem Unknown solution e.g. zero carbon house	↕	↕	↕
		Multi-disciplinary	Collaboration among several disciplines	Academic problem-based projects across disciplines
Complex	Unknown problems Unknown solution e.g. energy zero buildings in energy zero cities	↕	↕	↕
	New IoT, AI, Bio technologies and sustainability challenges	Inter-disciplinary	Re-organization of the curriculum and development of new student-centred and blended learning models	Complex problem analyses and problem-based projects across disciplines and together with stakeholders Mega-projects
Chaotic	**Disasters beyond complexity**	**Training in immediate action by bringing experiences/ problems from chaotic situations into education**		

Which educational approaches have proven effective?

How do engineering institutions respond to these challenges and what emerging trends can be identified for future curriculum models? Accreditation institutions respond to this by referring to the professional competencies such as those identified in the Washington Accord of International Engineering Alliance (IEA), and the American Board of Engineering and Technology (ABET) criteria for American engineering education, along with Australian engineering competencies (attributes). Some countries, for example Sweden, regulate education at the governmental level with explicit requirements for engineering students to learn sustainable knowledge and related competencies (Holgaard *et al.,* 2016).

During the last 20 years, educational institutions have moved from a teacher-driven system towards a student-driven learning environment, which involves the following.

- Active learning in the classroom (the 'flipped classroom') and problem and project-based learning (PBL).
- Practice-related learning with the inclusion in the curriculum of elements devoted to later work situations, such as internships, industry projects, entrepreneurship and innovation hubs, and learning professional competencies.
- An increased number of institutions changing to a more system-oriented approach where entire institutions change their curriculum instead of single courses (Graham, 2018*b*).

The flipped classroom has dominated the online learning approach to on-campus education. It combines online and on-campus learning with elements of active learning to engage students in the classroom. The online aspect normally takes the form of structured preparation such as a video, quiz, reading or a collaborative activity before the classroom. As a result, classroom time is used for activities instead of presenting lectures (Jenkins *et al*., 2017; Reidsema *et al.,* 2017). The full potential of digital learning has not yet been reached, and the COVID-19 pandemic has seen a faster shift towards blended learning environments as the new standard.

Problem- and project-based learning (PBL) involves a more complex learning process with students in teams working to identify problems and to select methodologies, while developing prototypes of solutions. In general, the research literature indicates that PBL leads to stronger motivation for learning, lower dropout rates and increased competency development (Dochy, *et al.,* 2003; Strobel and van Barneveld, 2009). Another field where PBL seems to have a positive impact is knowledge retention (Norman and Schmidt, 2000; Strobel and van Barneveld, 2009). PBL has also been viewed as a way to bridge the gap between engineering education/work and developing professional competencies (Kolmos *et al.*, 2020*b*; Lamb *et al.,* 2010; RAEng, 2007). Finally, research results indicate that PBL increases awareness of sustainability among engineering students (Kolmos *et al.,* 2020*b*; Servant *et al.,* 2020).

The question today is not whether PBL works, but rather the quality of PBL implementation. Practice varies tremendously within a single subject or course. Problems presented in projects are mostly formulated within an academic context – what many authors characterize as course-based PBL (Chen *et al.,* 2020; Gavin, 2011; Hadgraft, 2017; Kolmos, 2017). Course-based PBL has its limitations in terms of complex learning, encompassing both sustainability and societal issues, but such academic-initiated projects may prove very useful in gaining an understanding of complicated issues. Variation in problem and project types can thus be a strategy to allow students to work on complex sustainability challenges.

More open and longer team projects demand a systems approach that allows for the possibility of organizing projects of various sizes and types of problems and learning outcomes (Box 3). Problems can range from academically and theoretically initiated projects to those initiated by different societal actors with real-world issues. This often takes the form of a student project in collaboration with a company or member of the broader community, or a project identified and formulated by the students themselves. Collaboration with companies and other stakeholders allows students to understand the type of complex problem situations they will encounter at work. Such externally initiated projects are often very hard to control as part of an academic curriculum as problems can lead in directions not anticipated at the outset. However, research indicates that motivation increases when students work on company projects, as they experience these learning situations as more authentic and exciting because there is an identifiable customer (Kolmos and de Graaff, 2014; Zhou, Kolmos and Nielsen, 2012).

Box 3. Types of projects

Aalborg University has long experience of running a coherent problem and project-based learning model in engineering and science. Students spend half their study time on various types of team-based projects and the other half on more traditionally taught subjects. Aalborg has been an inspiration to many other institutions around the world and has served as a living laboratory for alternative ways of organizing students' learning processes. Students have the possibility of acquiring competencies from various types of projects, ranging from addressing learning outcomes within a discipline, to interdisciplinary projects for single teams, as well as the latest initiative interdisciplinary megaprojects with several project teams working together.

The megaproject addresses sustainability challenges and is organized under a theme. During the spring semester 2020, one of the themes was simplifying sustainable living. Several challenges were identified, such as waste, green consumption, and transport and mobility. For each of the challenges, further challenges and problems were identified, like waste handling at Aalborg University or waste in private households. The student project groups, covering several disciplines, worked on the same problem, for example waste in private households, but each from their own disciplinary perspectives. For example, architecture and design students worked on the design of waste bins, environmental management students worked on the logistics, electronic engineering students worked on intelligent waste bins, and so on. During midterm sessions, the students discussed and gave feedback during the process of problem analyses, design and finding solutions related to the megaproject (AAU*; Kolmos *et al.*, 2020*a*; Routhe *et al.*, 2020).

*AAU Megaprojects, Aalborg University: https://www.megaprojects.aau.dk/

Curriculum development

The key question is how to develop education. Both top-down and bottom-up approaches are necessary, and are most efficient in combination. Accreditation is as important as the overall policy framework and top-down approach. However, educational change must take place at the institutional level and will involve a shift in culture and an understanding of learning among academic staff. Change in engineering education is often slow, and strategies should be applied to foster more rapid progress. As culture plays an important role in the change process, a more experimental approach to teaching and learning is needed to create new innovative learning environments. At the institutional level, three curriculum strategies have been identified (Kolmos *et al.*, 2016).

1. An 'add-on strategy' adds more active learning to existing courses. This is the most widespread strategy for moving towards student-centred learning, and is reflected in the extensive reporting on PBL and active learning experiments at course level in the literature (Chen *et al.*, 2020). The initiative originates from the single lecture.
2. An 'integration strategy' merges existing courses with skills and competencies, such as project management and collaboration. This is exemplified by the Conceive-Design-Implement-Operate (CDIO) community, which has developed a list of standards covering the system level, including quality assurance and academic staff development, the integration of skills and competencies into the curriculum and, at a minimum, the integration of real-life projects – mostly company projects – where students learn to conceive, design, implement and operate a project (Crawley, *et al.*, 2014; Edström and Kolmos, 2014). This strategy will require an educational leader to motivate staff to carry out the experiments and to strategically create an overview of the curriculum.
3. A 're-building strategy' concerns re-structuring at the systemic level through the establishment of a new institution or programme. The re-building strategy emphasizes the societal context, allowing for all types of active learning, including more open-ended projects. Progression through an entire programme involves an emphasis on both technical knowledge and competencies, and professional or employability competencies. Such a change will also require institutional and educational leadership and there is a need for scholarly teachers who can think outside of traditional boundaries and facilitate transformation processes.

The development of educational leadership is essential to create and sustain the needed educational changes, combined with staff training to apply more student-centred and innovative teaching and learning methods (Graham, 2017; Graham, 2018*a*). There is also a need to establish both top-down and bottom-up strategies along with the development of a promotion system that acknowledges educational experiences.

It is possible to find inspiration in a recent study on leading engineering universities that are practising new types of student-centred models (Graham, 2018*b*). Olin College of Engineering, the Massachusetts Institute of Technology (MIT), Stanford University, Aalborg University and TU Delft are perceived as current leaders in engineering education, but there are also a number of emerging leaders, such as the Singapore University of Technology and Design, University College London, the Pontifical Catholic University of Chile and Iron Range Engineering in Virginia, US. Most of these institutions implement a coherent student-centred learning model that also includes external practical work in the form of internships, company projects or consultancies for companies.

Conclusion

There is a global need to transform engineering education curricula and learning approaches to meet the challenges of the SDGs. Although many institutions are already on track for a more comprehensive engineering education recommendations can still be made for further changes. Many new institutions and programmes can serve as good examples for future engineering education, and prominent older institutions have also started to shift from a more traditional curriculum towards coherent student-centred models, paving the way for establishing change worldwide. Experiences in the transition of curriculum processes can inspire others to form their own strategies and activities for curriculum development, which can in turn be a source of inspiration for institutions and governments.

Recommendations

1. *Improving and strengthening STEM education in school*. This is the foundation of higher engineering education and lifelong learning. For all education establishments, from schools to universities, engineering departments and professional training bodies, there is also a need to integrate the topic of 'sustainability' into the curriculum in order to 'ensure that all learners acquire the knowledge and skills needed to promote sustainable development' (SDG 4.7).
2. *Interdisciplinarity, sustainable development and employability in engineering curricula*. Governments should increase the focus on interdisciplinary curricula, sustainable development and professional competencies, combining them with funding models that support these needs. National accreditation criteria should be formulated and accompanied by incentives and rewards for institutions meeting these requirements.
3. *Investment in engineering studies*. Governments should promote and support engineering education studies to develop pedagogy, teaching and learning at a systemic level. Studies should focus on interdisciplinary and complex problem-solving using student-centred, problem-based learning and online learning.
4. *Institutional change embracing complexity*. Governments should reward institutions developing new systemic student-centred and blended learning models. These include engineering institutions working to change the curriculum and learning approaches through the creation of comprehensive blended educational models developed in cooperation with industry and other societal actors. Such models make use of real-world complex problems and projects including with reference to sustainable development. Action could also be taken to reward and disseminate examples of best practice at the national and international level.
5. *Educational leadership for educational change*. Governments should invest in, develop and recognize educational leadership to facilitate and sustain the needed systemic changes in engineering education. Creating a reward and recognition system that supports, nurtures and recognizes educational impact and educational leadership is an important element in the development of engineering education.
6. *Academics as agents for change*. Institutions should develop strategies for programme change and allocate resources for mandatory academic development together with other incentives such as award/reward teaching schemes for academic staff, community-building, sabbaticals and annual grants for educational innovation.

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4.2 LIFELONG LEARNING IN ENGINEERING: AN IMPERATIVE TO ACHIEVE THE SUSTAINABLE DEVELOPMENT GOALS


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4

Abstract. Many of the 17 Sustainable Development Goals can only be achieved through the active participation and contribution of skilled engineers and technologists. However, the advent of new technologies, automation, demographic changes and employment mobility will require continuous reskilling on the part of the engineering profession. This will necessitate building engineering capacity, as well as a structured approach, quality assurance and accreditation for lifelong learning. This chapter analyses the current state of lifelong learning in engineering and future approaches for creating a framework for policies, infrastructure and quality assurance to help achieve the goals and targets set in the 2030 Agenda for Sustainable Development.

Introduction

The continuous introduction of new and improved technology and automation is changing the world at an exponential rate. New technologies brought about by the Fourth Industrial Revolution, which include Artificial Intelligence (AI), robotics, nanotechnology, 3D-printing, blockchain and digital healthcare, are changing jobs, career paths and the way people work (Schwab, 2017). Recent advances in machine learning and the availability of a vast amount of data to train machines has led to significant progress in AI, often substituting manual labour with technology. Robots have replaced – and will continue to replace – human activities in many manufacturing plants. The advent of newer, sophisticated technology is replacing routine work with machines or automation, polarizing the job market in developed countries and emerging economies (OECD, 2017). While this transformation brings challenges, new job opportunities are promoting economic growth and will continue to do so. About 9 per cent of occupations in 2030 will be new and do not exist at present (Bughin et *al.,* 2018). In short, the interaction of automation with AI, coupled with demographic changes and large sectoral disruptions, are changing the nature of work in the future (Munro, 2019).

The following trends are prevalent and foreseen for the future of engineering work (Schwartz *et al.,* 2019):

- The lifespan of a working engineer has increased dramatically as human beings live and work longer. Demographically, the workforce will include a larger percentage of older adults (Jenkins, 2019).
- Engineers are switching jobs in the same organization or moving to other organizations more frequently, thus requiring continuous reskilling and upskilling (WEF and BCG, 2018).
- New knowledge is being created at an increasing rate and technology is evolving rapidly. Engineers and technologists need to keep up with these changes and innovations in order to remain in the workforce (DeLong, 2004).
- Engineers are working on projects that increasingly span the globe or have worldwide implications, often while working for global organizations in local settings (WEF, 2016).
- While automation is and will be able to perform many human actions, soft skills such as interpersonal communication and emotional intelligence are unlikely to be replaced by machines. Engineers and technologists alike need to learn these skills to remain relevant and employable (Bughin *et al.,* 2018).

The continuing education of engineers and technologists, otherwise referred to as lifelong learning for continuous reskilling and upskilling, is therefore a necessity.

Lifelong learning (LLL) in engineering is called by various names, the most common of which are continuing professional development (CPD) for engineers and continuing engineering education (CEE). LLL or CEE takes two forms:

1. Post-secondary degrees for working professionals, consisting of face-to-face, online, blended and hybrid modalities.
2. Non-degree certificates or courses in various modalities.

This section focuses on a number of aspects of LLL in engineering and technology, such as forms of LLL in engineering that have a special focus on vocational education and training in technology, the latter being more useful in developing countries, especially for achieving the SDGs and meeting their targets. This section also examines university-industry partnerships and the role of the private sector in defining the needs of upskilling or reskilling as these arise. The second part of the section charts a pathway from apprenticeship to engineering and technology careers, and refers to quality measurement and assurance of CPD programmes and infrastructure with a view to ensuring the delivery of the highest standard of continuing and professional education and advanced engineering trainings anywhere in the world with common accreditation criteria. The third part of the section delineates various quality assurance criteria for non-formal and formal CEE.

Forms of LLL in engineering and technology

As noted earlier, LLL in engineering may take various forms and occur at different stages of working life. The following sub-section delineates these forms and notes their various advantages.

Work-based learning as a form of CEE

Work-based learning, often called apprenticeship, is defined as a system of training in a trade or profession where on-the-job learning is accompanied by study in an educational or vocational training institution. This approach is often of value in a career pathway as it enables learners to gain a license to practice in a regulated profession. It is expected that learners in work-based learning will acquire measurable competencies that may result in certification (Krupnick, 2016).

For example, Germany has widely adopted dual apprenticeship systems as a career pathway, allowing future engineers to gain valuable experiences through a structured hands-on experience.[6] These apprenticeships are considered beneficial in engineering where professional competencies, such as technical and working knowledge, skills and aptitudes, are highly valued (Dubouloz, 2016). They can also be combined with a study programme in engineering at a university – a so-called dual study programme.

There is often a contractual pay-based relationship between the employer and the apprentice. Learners may even obtain formal degrees through the completion of engineering programmes by means of a degree apprenticeship. The student alternates between periods of work in the company and study on campus, and thus benefits from supervision and support at both academic and professional levels (Singh, 2015).

Outside of Germany, a number of prestigious schools, such as Imperial College and the École Centrale de Nantes, offer degrees based around apprenticeships. These courses range from electronic to industrial engineering and cover most engineering areas of study (EUCEN, 2019).

However, work-based learning has not been systematically adopted in developing nations, and there is a need for clear policies and infrastructure. Apprenticeships in sub-Saharan African countries are often undertaken for low-skilled work and do not result in engineering training or vocational education (Bahl and Dietzen, 2019).

Non-formal and informal (NFIF) learning for engineers

Formal learning typically leads to certification or other forms of recognition. Non-formal learning is embedded in planned activities not explicitly designated as learning (in terms of learning objectives, learning time or learning support), but contains an important learning element. It typically does not lead to certification or other forms of recognition, nor is it organized or structured in terms of objectives, time or learning support (CEDEFOP, 2014).

While NFIF continuing education of engineers is common, the identification of such acquired competencies calls for certain structured processes, such as:

- the definition of competencies that can be documented and validated;
- verification of the completion of formal prerequisites for eventual validation;
- determination of desired learning outcomes/ competencies for inclusion in the system;
- decisions regarding which learning outcomes are worth documenting; and
- identification of which competencies employers want their engineers to acquire.

Although some academic institutions in the United States or France and several professional engineering organizations, including the Board of Engineers Malaysia, Engineers Ireland or the Japan Society of Civil Engineers, recognize CPD achievements, a structured process for the validation and recognition of non-degree, non-credit post-baccalaureate NFIF learning is rather rare and lacks formal quality assured procedures (Feutrie, 2012, Pardo, 2016).

The overarching aim is to have in place a system to document and validate the NFIF learning outcomes of engineers that is recognized by companies, professional organizations and society so that it contributes to increased transparency and a greater mobility of engineers worldwide. This is crucial as some world regions lack trained engineers, while qualified engineers seek placements in other regions due to unemployment.

One successful, systematic approach for engineering competency evaluation of NFIF learning is the use of an e-portfolio, as offered by the Europortfolio Competency Framework (2015), which supports the processes of competency recognition and accreditation. The e-portfolio provides an environment where engineers can:

- create a digital archive for their work;
- select specific pieces of work (hyperlinked or documents) to highlight achievements;
- set goals for future training to improve;

6 See the Apprentice Toolbox on the apprenticeship system in Germany: www.apprenticeship-toolbox.eu/germany/apprenticeship-system-in-germany/143-apprenticeship-system-in-germany

- share learning with others and receive reviews from peers as part of formative feedback; and
- gather evidence of learning over time, which can be presented to different audiences for validation, recognition or professional certification.

E-portfolios for NFIF learning offer a flexible yet robust system that provides an assessment of competencies. They also provide professional associations, accreditation agencies and engineers with a mechanism through which engineers can showcase their knowledge, aptitudes and skills acquired through NFIF learning. In the near future, wider use of blockchain activities could aggregate e-portfolios and other credentials to form a student's personal record (Roebuck, 2019).

Assessment of NFIF learning and the FEANI card

Assessment of NFIF learning can be classified into two types: i) self-evaluation, such as a personal development plan (PDP); and ii) external assessment by professional associations that keep digital records. The latter process has been implemented by several professional organizations around the world in countries such as Australia, Ireland, Japan, Malaysia and the United States.

As the professional competencies of engineers are generally established by professional associations or chambers of commerce, it is not possible to create a common set of competencies for different countries and different engineering specializations. To address this issue, the European Federation of National Engineering Organizations (FEANI) created the 'Engineering Card'. This provides information about the engineer, including formal education, professional experience and CEE or CPD. It defines the group of competencies that each engineer can deliver, and proposes an e-portfolio system to record evidence of competencies acquired in NFIF processes. Each accreditation or professional organization can use this e-portfolio to recognize competencies acquired by each engineer. FEANI also has a system in place for awarding CPD credits to engineers. This system is voluntary and is used by the professional organizations of FEANI members.[7]

Role of formal CEE providers

Formal CEE providers also play a role in the recognition of NFIF engineering competencies. They define the modules and courses to complement the education and training of candidates willing to reach a certain qualification. These courses often face the same obstacles as NFIF learning. As a result, quality assurance to support recognition of competencies by professional organizations has become mandatory in some countries (Werquin, 2010).

Quality assurance of lifelong learning and NFIF learning in engineering

Quality frameworks for formal education vary significantly around the world, a variability that extends to continuing education, LLL and NFIF learning. Even within countries, standards and requirements for LLL and NFIF learning from industry can differ according to national legislation and the requirements of professional associations. Additionally, funding sources and drivers for CEE vary significantly around the world, examples of which are shown below.

- In China, the Ministry of Human Resources and Social Security establishes the requirements for continuing engineering education, and funds the China Association for Continuing Engineering Education (CACEE)[8] to develop and deliver programmes and courses to engineers and technical professionals throughout the country; the training and the periodicity are mandatory.
- In the United States, professional societies that license engineers establish the requirements for CEE, but courses and programmes are developed and delivered by institutions of higher education, government agencies, or companies that employ engineers.
- In the European Union, the European Commission funds projects for universities or other organizations to develop and deliver courses and programmes.

This global diversity is problematic for engineers because it limits mobility and the acceptance of licences (FEANI, 2018).

Roles of professional societies

As Markkula (1995) noted, professional engineering societies and organizations have a responsibility to provide and validate the LLL of engineers. Ireland's CPD accreditation scheme for professionals is designed to support LLL by encouraging and recognizing the good practices used by engineers. Engineers are expected to have at least five days of formal learning each year.[9] In Malaysia, the Board of Engineers has imposed a system that is accredited by the Institute of Engineers of Malaysia (IEM).[10] Each engineer must undertake at least an annual average of 50 training hours per triennium. The Australian Accreditation system is identical to that of Malaysia, as both countries belong to APEC (Asia-Pacific Economic Cooperation), along with Canada, Hong Kong (China), Japan, New Zealand, Philippines, South Korea, Thailand and the United States. This group decided

7 For the list of professional members: https://www.feani.org/feani/membership-list-0
8 For more information on CACEE: www.cacee.org.cn [In Chinese].
9 For more information on CPD activities: https://www.engineersireland.ie/Professionals/CPD-Careers/CPD-activities
10 For more information on CPD: www.myiem.org.my/content/cpd-250.aspx

in 2001 to adopt the CPD accreditation scheme (the Sydney Accord) and the majority have implemented the system.[11] In the United States, periodic accreditation is made by the National Council of Examiners for Engineering and Surveying (NCEES) and is referred to as Continuing Professional Competency.[12]

Roles of governments

The role of government varies in relation to providing different types of funding and support across the world. Regarding legislative frameworks, governments may establish laws implementing CPD and LLL as functions of universities for research and the training of graduates and postgraduates, or there might be a lack of interest. A recurrent political argument in this regard is that investment in human capital is vital for the economic growth and development of society and will help sustain global competitiveness (EUCEN, 2019).

Role of industry

The relationship between universities and industry is important for LLL activities. Industries typically know the competencies and knowledge needed for their workforce and search for potential employees with this acumen. Industry further provides funding for the training and education of their employees to obtain new knowledge and skills. The core competencies of universities are to discover new knowledge and deliver learning, both of which are desired by industry. Thus, successful LLL depends on strong communication between the two parties.

Quality frameworks for LLL and NFIF validation

Universities use two models to provide accreditation for engineering CPD. Industries also accredit and evaluate CPD and modules or courses using their own procedures based on the two types of models outlined below:

- The first model accredits centres and providers of CPD for engineers for a certain period of time using a self-assessment system for quality management and continuous improvement. During this period, administrators of these centres and CPD provider organizations can use the assessed quality level for accreditation as an added value in annual reports to stakeholders such as provosts or rectors. This accreditation can also be used as a quality assurance stamp for potential engineering participants.
- The second model accredits single training actions or modules with benefits for engineers similar to the training actions of accredited providers.

Both models can be found around the world and the choice depends on cost, the working culture of companies and engineers, and the regulations and established procedures.[13] One example of such accreditation of centres is the Quality Program (QP) of IACEE.[14] The proposed model is based on the European Foundation for Quality Management (EFQM) and is used to improve the quality of centres through self-evaluation, external accreditation or an evaluating body (Wagenaar and Gonzalez, 2018).

Conclusion

The coupling of new methods for formal engineering education at traditional undergraduate and graduate levels with the methodologies described in this section will produce globally competent engineers. Neither activity by itself is sufficient in today's complex and fast-changing world. The inclusion of learning that takes place on the job via NFIF learning activities allows the focus on constant learning, reflection and the credibility of information learned to become part of the everyday life of an engineer or engineering technician, enabling the full realization of the SDGs at the global level. UNESCO's leadership, in partnership with many other organizations, should enable the continual re-education and retooling of tomorrow's workforce.

Recommendations

Three recommendations that warrant further exploration are outlined below. The rapid pace of new knowledge creation taking place around the globe will necessitate that these recommendations remain agile and subject to modification.

1. *Create a global working group*. It is recommended to convene a global working group of both academia and industry to enable the identification and gathering of existing practices for the lifelong education of the engineering workforce and related fields. A US National Academy of Engineering report (Dutta, Patil and Porter, 2012) first shed light on this issue. Furthermore, the group could recommend a methodology and process by which engineering lifetime learning credits are captured, validated, shared and considered for acceptance by governance bodies around the globe. This process should focus on the lifetime education standards needed for engineering and related fields. If UNESCO, in partnership with leading engineering professional societies such as CACEE, IACEE, the American Society for Engineering Education (ASEE) and the European

11 See www.engineersaustralia.org.au/Training-And-Development/MYCPD
12 For more information about NCEES: https://ncees.org
13 See the example of the EU/US Atlantis Programme: http://daete.up.pt
14 Read more about IACEE's Quality Programme for Continuing Education: www.iacee.org/iacee_quality_program.php

Society for Engineering Education (SEFI), calls for such a group, their responses will help mobilize these efforts.

2. *Reduce or remove real and perceived barriers*. The working group will need to consider the real and perceived barriers to achieving a globally available and accepted lifelong and lifetime engineering education practice, as well as to identify potential solutions. Some of the challenges include:
    - consistent requirements that are more globally accepted; and
    - funding mechanisms across the globe for continued engineering education rather than pockets of corporate or governmental support.

3. *The following ideas could be potential tools in future solutions*:
    - Blockchain credential storage
    - An engineering card similar to FEANI
    - New business and pedagogical models for lifetime education
4. *Create global polices and associated scorecard(s).* Global policies for sharing and recognizing CEE learning can be accomplished through conversations, proposals and the adoption of processes. The development of a scorecard(s) is envisioned to assist with tracking the progress of goals and recommendations from the group. The scorecard(s) will provide both content and context for the recommendations, ensuring that all parts of the international workforce are included in reflection and action.

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4.3 ENGINEERS' CONTINUING PROFESSIONAL DEVELOPMENT

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Abstract. The challenging environment of continuous technological evolution requires skilled and competent engineers who can contribute towards achieving the United Nations Sustainable Development Goals and who can strive for innovative and sustainable solutions. To be able to do so, engineers should continuously acquire new knowledge and skills, and update their existing skills to incorporate individual and team competencies. Continuing Professional Development (CPD) can play a fundamental role in adapting the engineer to technological innovations and new working methods to better fulfill his or her commitment to society. In this regard, engineering professional certification systems could be of paramount importance for the recognition of engineering qualifications and professional competencies worldwide by establishing minimum requirements of knowledge, skills and competencies for the engineering profession.

Trends and challenges affecting the engineer

Engineers are situated as potential problem solvers able to work towards achieving the 17 SDGs through the application of an innovative and solution-based approach (UN, 2020). To be able to contribute to a future-looking environment, engineers need to update their competencies in terms of skills, knowledge and experiences (IACEE[17]). A lot of the basics in engineering remain the same, but additional competencies and trends need to be met and addressed accordingly by engineers themselves, but also by the engineering profession as a whole. This, together with increased migration (EC, 2017; Trevelyan and Tilli, 2011), is relevant in order to assess the competencies needed for a sustainable future.

There are also megatrends that are relevant for the engineer and engineering's role. These trends are automation, Artificial Intelligence (AI) and digitalization (CEDEFOP, 2020*a*). The implications of digitalization might result in new forms of work and learning, such as platform or gig work, or remote ICT-based work (CEDEFOP, 2020*b*). Digitalization will transform engineering practice into a new paradigm, which is network-based, data driven and AI empowered.

The role of the engineers will thus change and end up higher or lower in the competency hierarchy, which may lead to a polarization of the labour market and a mismatch of skills.

In order to remain professionally competent in this world of constant change, engineers must continuously acquire new knowledge and skills, and update their existing skills to integrate individual and team competencies (WEF and BCG, 2018). CPD can be defined as the intentional maintenance and development of the knowledge and skills needed to perform in a professional context. This could mean honing current skills or developing them to a new level, or it could mean learning new ones that expand an employee's role, or that prepares them for potential promotion (CPD, 2020). CPD for engineers comprises both the acquisition of new capabilities to broaden competency and the enhancement of existing capabilities to keep abreast of evolving technology and its application. It is noteworthy that CPD is not just for updating and upgrading the technical knowledge and skills of engineers, it is also for deepening the understanding of sustainable development and its goals, and for promoting the awareness of ethical codes that evolve along with the social and technical development of engineers.

How to work with CPD

CPD is essential for the maintenance of high professional standards, and it enhances the employability and mobility of individual engineers. It assists career progression and strengthens professional satisfaction. It is the individual's responsibility to engage with CPD, but it requires the cooperation, encouragement and support of employers and professional and academic institutions. To be most effective, CPD has to be planned and related to specific objectives. It is essential to reflect on what has been learned to enable an individual's Competency Development Plan to be periodically updated.

To contribute towards enhanced use of CPD, national institutions and authorities must highlight the key role of qualified professional engineers for economic growth and the development of society. Companies, universities, professional organizations and other engineering entities must be encouraged to invest in CPD. Quality CPD must be encouraged alongside innovative practises in learning and good examples and best practices to help others find relevant ways to CPD (FEANI, 2020).

There is a continuing need for CPD for engineers to maintain and develop their professional competencies. In this regard, individual engineers are encouraged to:

- Recognize the importance of CPD for their career, employability and mobility, as well as their

17 International Association for Continuing Engineering Education official website: www.iacee.org

professional satisfaction and well-being at all ages and stages throughout their career.
- Take active ownership of their professional and personal development and invest in CPD. At a personal level, they should establish a Competency Development Plan and a broad idea of a career goal.
- With the employer, negotiate a CPD plan that is realistic and builds competencies in a systematic way, ensuring good execution of tasks and enabling career development.
- Actively work towards realizing the CPD plan. Systematically record CPD activities and achievements so that maintaining and/or developing professional competency can be demonstrated, and if needed, the competency acquired may be assessed and acknowledged.
- Strive for quality in personal CPD, as well as in the use of a variety of methods, e.g. formal courses/programmes, academic studies, professional visits, on-the job-learning.

In countries where access to professional engineering activities is subject to mandatory registration, it is already common practice to recognize and value engineers' CPD achievements in maintaining their professional status. In general, the evaluation is done through the attribution of CPD credits acquired through different types of activities: developmental, work-based and individual (ASCE[18]; EA[19]; ECSA[20]; ECI[21]; ENGC[22]).

Engineering professional certification systems

National qualifications frameworks (NQFs) have been adopted worldwide as instruments to classify a country's qualifications at different levels. Significant efforts have also been made to establish regional qualifications frameworks in order to compare skills and qualifications internationally (CEDEFOP/ETF/UNESCO/UIL, 2020). However, there is still a long way to go to establish international mechanisms for the recognition of professional skills and competencies in engineering.

The quality of engineering education is usually ensured at the national level through accreditation granted by governmental institutions or professional associations. However, for educational, social and political reasons, the recognition of engineering degrees at the international level is a complex and highly sensitive issue that hinders the mobility of professionals. Even in areas of high political integration, such as the European Union, there are still great difficulties in the mutual recognition of diplomas. Some initiatives to facilitate mutual recognition have been successfully developed by professional associations through multilateral agreements, such as the European Network for Accreditation of Engineering Education[23], and the International Education Alliance[24].

Efforts to establish continuing engineering education programmes have been developed the world over. A wide variety of teaching methods, including face-to-face or online courses, have been adopted in lifelong learning activities across different geographies: Europe and the United States (Dutta, Patil and Porter, 2012), Africa (Kirkland, Vitanov and Schaefer, 2007), China and India (Li, 2012; Singh, Sarkar and Bahl, 2018). However, there is no standard worldwide accreditation process that allows for easy mutual recognition of CPD quality and integration for engineers.

Globalization of labour markets, mobility of students and workers, increased migration, automation, digitalization, polarization of the labour market and skills mismatch are some of the challenges that engineering faces globally in making significant progress achieving the SDGs. In this context, the development and implementation of Engineering Professional Certification Systems (EPCS) could be of paramount importance for the recognition of engineering qualifications and professional competencies worldwide by establishing minimum requirements of knowledge, skills and competencies for the engineering profession.

To be an accepted, effective and useful mechanism, EPCS must respect both nationally and internationally established systems and provide confidence in quality assurance for three essential pillars: engineering education, professional competencies, and CPD and lifelong learning. Details of EPCS are given in Box 1.

Recommendations

- Work towards the development and implementation of Engineering Professional Certification Systems that could be of paramount importance for the promotion of CPD and for the recognition of engineering qualifications and professional competencies worldwide.
- Encourage employers to invest in their engineer's CPD in terms of innovation and sustainable solutions so as to ensure that their employees remain relevant and that their company's competencies are up to date.
- Encourage engineers to take an active role in their CPD to ensure their employability and mobility.

18 American Society of Civil Engineers official website: https://www.asce.org/continuing-education/
19 Engineers Australia official website: www.engineersaustralia.org.au/
20 Engineering Council of South Africa official website: www.ecsa.co.za
21 Engineering Council of India official website: www.ecindia.org
22 Engineering Council official website: www.engc.org.uk/professional-development/continuing-professional-development-cpd
23 European Network for Accreditation of Engineering Education official website: www.enaee.eu
24 International Engineering Alliance official website: www.ieagreements.org

Box 1. Engineering Professional Certification Systems (EPCS)

Characteristics of an EPCS:

- Engineering education and professional experience combine to meet a required level of engineering capacity.
- The EPCS must be based on quality assurance and values.
- The initial formal education of engineers typically takes place in universities, universities of applied sciences and technical colleges. This may take the form of first-cycle, second cycle or integrated programmes, which have either an applications-oriented or conceptual/theoretical-oriented profile.
- Professional competency does not describe the learning process of the individual but it instead assumes that learning has taken place. This may be the result of several individual pathways of non-formal or informal learning processes. For the sake of measurement/assessment, it is necessary to demonstrate the learning outcome.
- Learning outcomes and competencies integrate CPD and must be assessed and verified.

Importance of an EPCS:

- It establishes minimum requirements of knowledge, skills and competencies for the engineering profession.
- It contributes towards mutual recognition of engineering education and engineering professional capacity at a global scale.
- It facilitates mobility for professionals under a shared and accepted system in an ever-increasing scenario of economic globalization and continuous advances in technology.
- It respects established systems both nationally and internationally.

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5. REGIONAL TRENDS IN ENGINEERING

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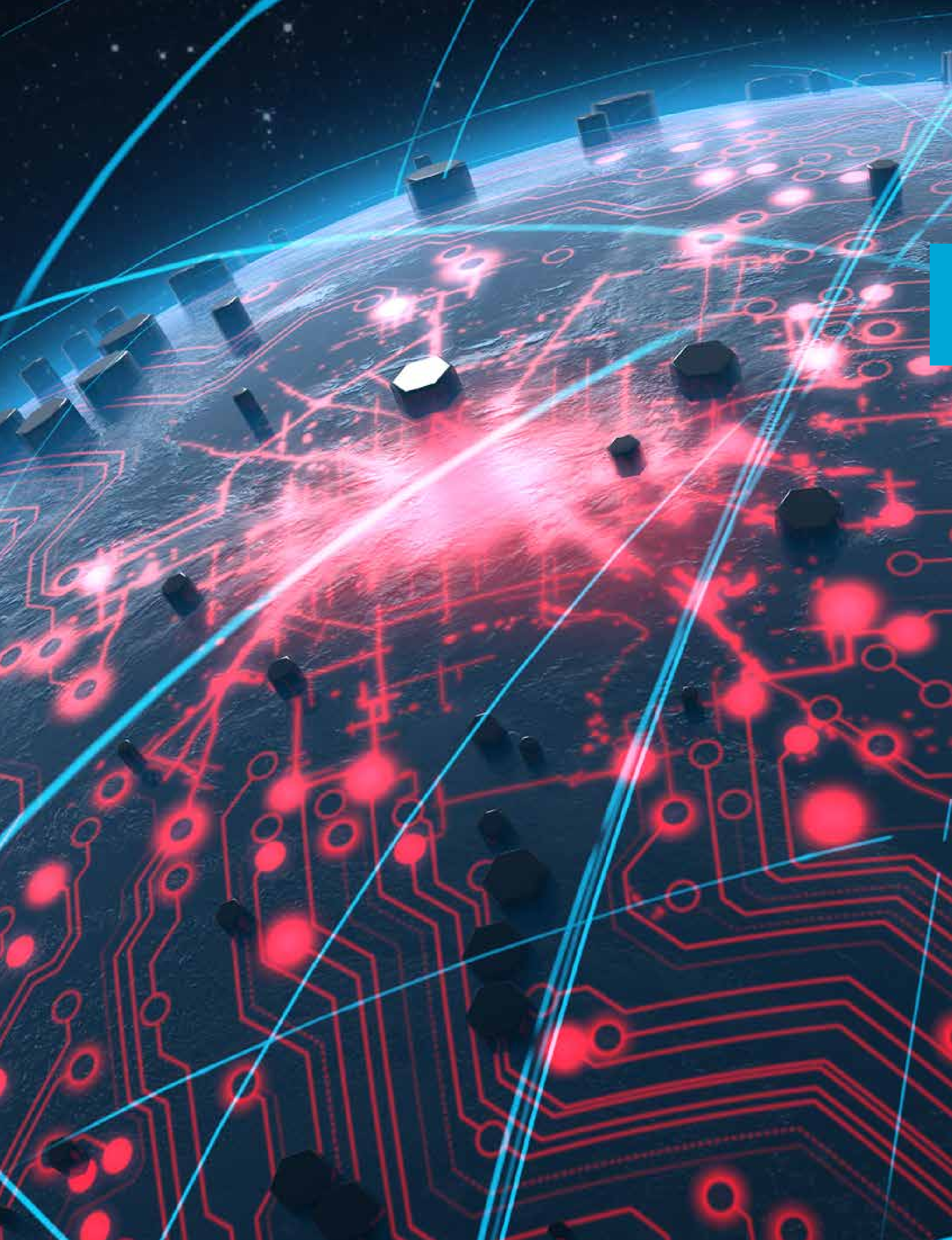

Yuan Si[1]

5.1 MAJOR INTERREGIONAL TRENDS

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Abstract. Despite the fact that engineering is an essential part of sustainable development, its precise contribution remains difficult to measure. This section explores interregional trends in engineering today and the challenges for tomorrow with regard to sustainable development. The demand for engineering expertise and education varies across continents and this section reviews the disparities in regional-level engineering skills and educational opportunities, identifying key areas for the engineering profession to build educational and technical capacity to address the regionally specific objectives of the Sustainable Development Goals.

A global effort is required to align engineering and sustainability, and facilitate the mobility of engineering professionals

The UN 2030 Agenda for Sustainable Development has united the world around the integrated vision of the Sustainable Development Goals (SDGs) with an emphasis on economic prosperity, social inclusion and environmental sustainability. Engineers and engineering underpin each of the 17 SDGs and most of the SDG targets. The 'Paris Declaration: Advancing the UN Sustainable Development Goals through Engineering' signed by WFEO and UNESCO in March 2018 made explicit this commitment of engineering for sustainable development (WFEO-UNESCO, 2019).

The World Federation of Engineering Organization (WFEO) is the peak body for engineering globally, representing nearly 100 nations and more than 30 million engineers. WFEO is committed to advancing the UN 2030 Agenda for Sustainable Development through engineering, and has elaborated the WFEO 2030 Engineering Plan to be implemented through its partners and members (Box 1).

Box 1. WFEO projects for facilitating the mobility of engineers

Under the WFEO Engineering 2030 Plan, the WFEO launched a project entitled 'Capacity Building for Engineering Education Systems, accreditation and registration to meet the needs for engineers around the world'. WFEO is collaborating with the International Engineering Alliance (IEA), the International Federation of Engineering Education Societies (IFEES), the International Center for Engineering Education (ICEE), a Category 2 Centre under the auspices of UNESCO, and other interregional engineering societies to ensure inclusive engineering education and to harmonize professional standards, a prerequisite for the global mobility of engineers.

Source: WFEO, 2018.

Professional engineering organizations are playing an increasingly important role in engineering capacity-building through interregional partnerships

Engineering has long valued partnership-building through professional societies at local and global scales. Broad connectivity visions enable the sharing of knowledge, skills, expertise and resources across nations and regions to meet development goals through concerted efforts. Professional engineering organizations have played an important role in building interregional partnerships and networks for engineering capacity-building.

Engineering and technical cooperation mediated by engineering professional organizations has underpinned a diversity of international collaborations such as North-South, South-South and triangular cooperation (Box 2). In particular, the adoption of the *Buenos Aires Plan of Action for Promoting and Implementing Technical Cooperation among Developing Countries* (BAPA) by 138 UN Member States in Argentina in 1978, pioneered South-South Cooperation (SSC) among least developed countries (UN, 1978). Today, collaborations in engineering capacity-building, especially connectivity infrastructure building, have acquired a new centrality with respect to the SDGs. Many partnerships for engineering capacity-building have demonstrated the effectiveness of the quadruple-helix of education, government, industry and civil society with regard to mobilizing and sharing value, knowledge, expertise, technology and resources. Increasingly, countries of the South are promoting cooperation through regional/international centres. Asian and African countries in particular, have expanded their networks considerably since the turn of the century.

Box 2. ISTIC for promoting South-South cooperation

The International Science, Technology and Innovation Centre for South-South Cooperation (ISTIC), a Category 2 Centre in Kuala Lumpur, Malaysia, was inaugurated in 2008 under the auspices of UNESCO. The Centre acts as an international platform for SSC in science and technology (S&T) and innovation in developing countries. ISTIC aims to facilitate the integration of a developmental approach into national S&T and innovation policies, providing policy advice, promoting the exchange of experience and best practices, creating a problem-solving network of centres of excellence in developing countries, and supporting academic and professional mobility among developing countries.

Source: ISTIC-UNESCO, 2019.

Increased investment and engineering progress accelerate infrastructure development around the world

Engineering plays a critical role in empowering sustainable development by underpinning infrastructure building. This involves both economic infrastructure such as power, transportation and telecommunication, and social infrastructure such as irrigation, sanitation and housing.

Increased investment in infrastructure, especially connectivity infrastructure, has registered as a major global trend over the past decade. The infrastructure–development link is well established: improved infrastructure drives both total productivity growth and more equal distribution of the benefits of growth, while deficient infrastructure deters both growth and equality (Bai *et al.,* 2010; Cigu *et al.,* 2019; Estache and Wodon, 2014; Kessides, 1996; Rudra *et al.,* 2014; UNOSAA, 2015). For example, in Asia, investment in infrastructure development is estimated to exceed US$26 trillion up to 2030 or US$1.7 trillion per year in order to maintain Asian growth momentum, tackle poverty and respond to climate change (ADB, 2017). However, in Africa, where rapid and significant population growth is placing increasing demands on the economic, social and natural environment, infrastructure development has grown disproportionately slower. The Belt and Road Initiative (BRI) has increased physical, digital, financial and social-cultural connectivity through infrastructure construction, transport, trade and also people-to-people exchanges (Box 3).

Box 3. The Belt and Road Initiative (BRI)/ Global partnership in BRI

The Belt and Road Initiative (BRI) has formed close links with regional development plans and cooperation initiatives such as the ASEAN Interconnection Masterplan Study (AIMS), the African Union Agenda 2063, the Eurasian Economic Union and the European Union Eurasian Interconnection Strategy. Moreover, several UN agencies including, though not limited to, UNDP, UNESCO, UNICEF and UNIDO positioned themselves early on as part of a state-level and strategic partnership on the BRI. According to the World Bank, gross domestic product (GDP) will increase by up to 3.4% for BRI participating countries and by up to 2.9% for the world (De Soyres, Mulabdic and Ruta, 2019). Currently, BRI cooperation encompasses 136 countries and 30 international organizations as of December 2019, and has created over 300,000 jobs, over US$6 trillion trade and over US$2 billion in taxes paid to the host country in 2013–18 (Belt and Road Portal, 2019).

The rise of sustainability science and engineering for the SDGs

The scholarship of sustainability science has grown substantially in the twenty-first century in response to global challenges (Bettencourt and Kaur, 2011). In particular, four enabling trends are especially important for sustainability science and engineering:

- Inter, cross and transdisciplinary knowledge is breaking down conventional boundaries to create a more holistic approach.
- Entrepreneurship, which mainly takes the form of techno-entrepreneurship, is defined as the ability to add value by generating polyvalent knowledge that integrates and synthesizes theoretical, practical and policy-oriented elements.
- The notion of diversity is expanding to mean inclusivity for all, involving not only traditionally disadvantaged groups, such as those categorized by their gender and/or social-economic background, but also personal characteristics such as physical condition, and ethnic and cultural identities.
- Human and ecological well-being are two sides of the same coin. Engineering is adopting a more sensitive, holistic and cautious approach to human-made changes to the Earth's natural environment in order to avoid a harmful and irreversible 'state shift' in ecosystems.

These trends are driving the development of sustainability engineering in order to expand the scope and scale of its disciplines, fields and practical undertakings, while facilitating greater interaction between engineering and other sciences and arts to promote sustainability.

Box 4. Global collaboration in healthy cities

According to *The Lancet* report *Healthy Cities: Unlocking the Power of Cities for a Healthy China* (Yang *et al.,* 2018), the notion of a healthy city refers to healthy physical and social collaboration across multiple aspects that ensure access to housing, well-being and public health, as well as access to natural resources, connectedness to cultural heritage and so on. The report advocates the notion of health-oriented urban development as a core approach to combating urban health challenges under the context of accelerated and dynamic urban development in China, as well as in many densely populated areas in both developing and developed countries. In particular, the report urged city planners 'to integrate health in all policies starting from urban planning, increase public participation, set up suitable local goals, assess progress periodically, and enhance research and education on healthy cities'. This report is an exemplary model of sustainability science and engineering. The report was produced by a commission led by Prof. Peng Gong of Tsinghua University and consists of an interdisciplinary team of 45 scholars and experts from around the world, including – though not limited to – the National Health Commission, the World Health Organization (WHO) and the University of California.

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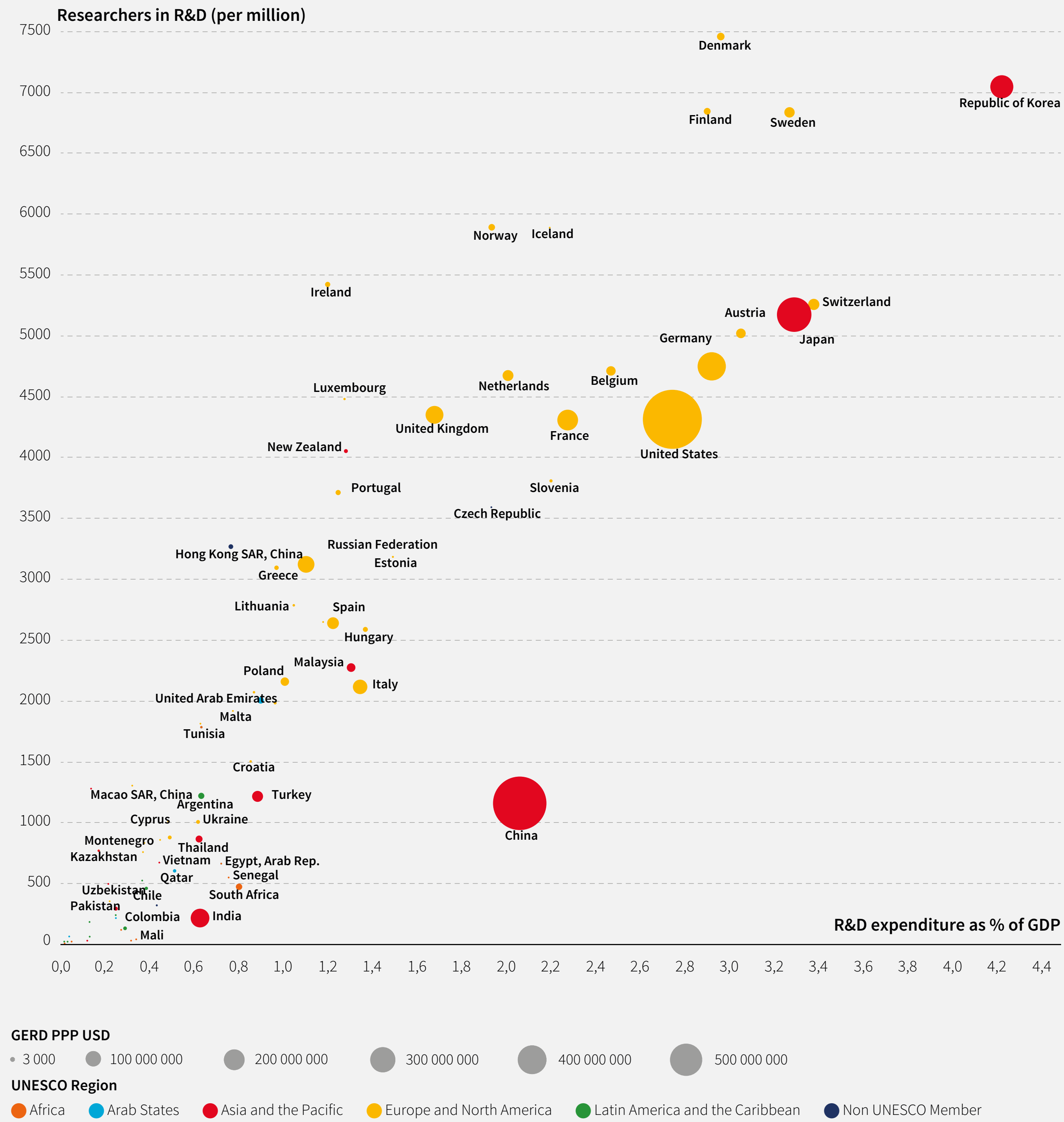
Figure 1. R&D expenditure as a % of GDP (GERD) and researchers per million inhabitants, 2018



UIS and ICEE, 2019.

Widening regional disparity in engineering capacity

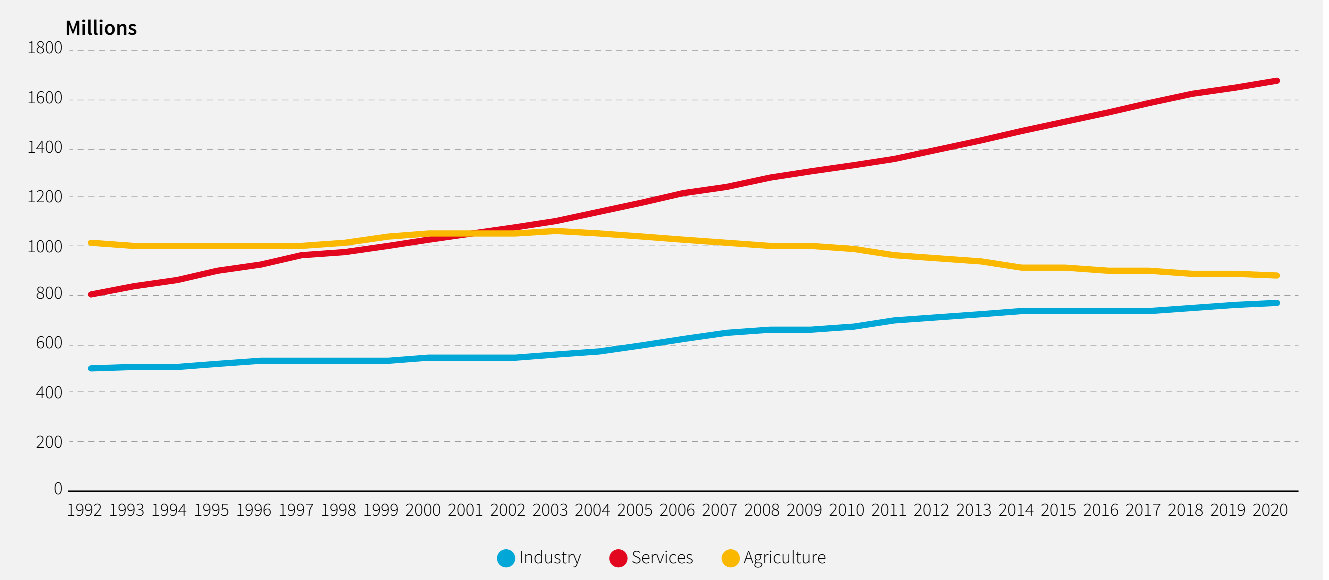
A key indicator of engineering capacity-building is research and development (R&D), which is defined as efforts to develop new or improve existing products or services. There are marked disparities in R&D across world regions in terms of expenditure and human resources. Such R&D disparities have widened over the last decade (UIS, 2019) (Figure 1). The diameter of the circles in Figure 1 show the amounts that countries are spending on R&D in purchasing power parities (PPPs) US dollars. Countries closer to the bottom of the graph have lower numbers of researchers per million inhabitants. The majority of African countries are in the lower section.

Persistent shortages of engineering talents in developing countries

Global economic structural changes have resulted in labour market expansion in both scale and scope in industry and service sectors (Figure 2). One of the main drivers is rapid scientific and technological advancement, which underpins the Fourth Industrial Revolution. Engineering talents are key to meeting such rising labour market requirements.

However, such requirements cannot be met adequately due to a shortage of professional engineers. Despite the continuous expansion of higher education in most parts of the world, the attractiveness of engineering as a career option for youth has declined in many countries. Based on available data (except for those countries with missing data, such as China and India), since 2013, although total enrolments in engineering programmes are still increasing, its ranking has dropped from second to third (Figure 3). This may mean that some students do not choose to study engineering.

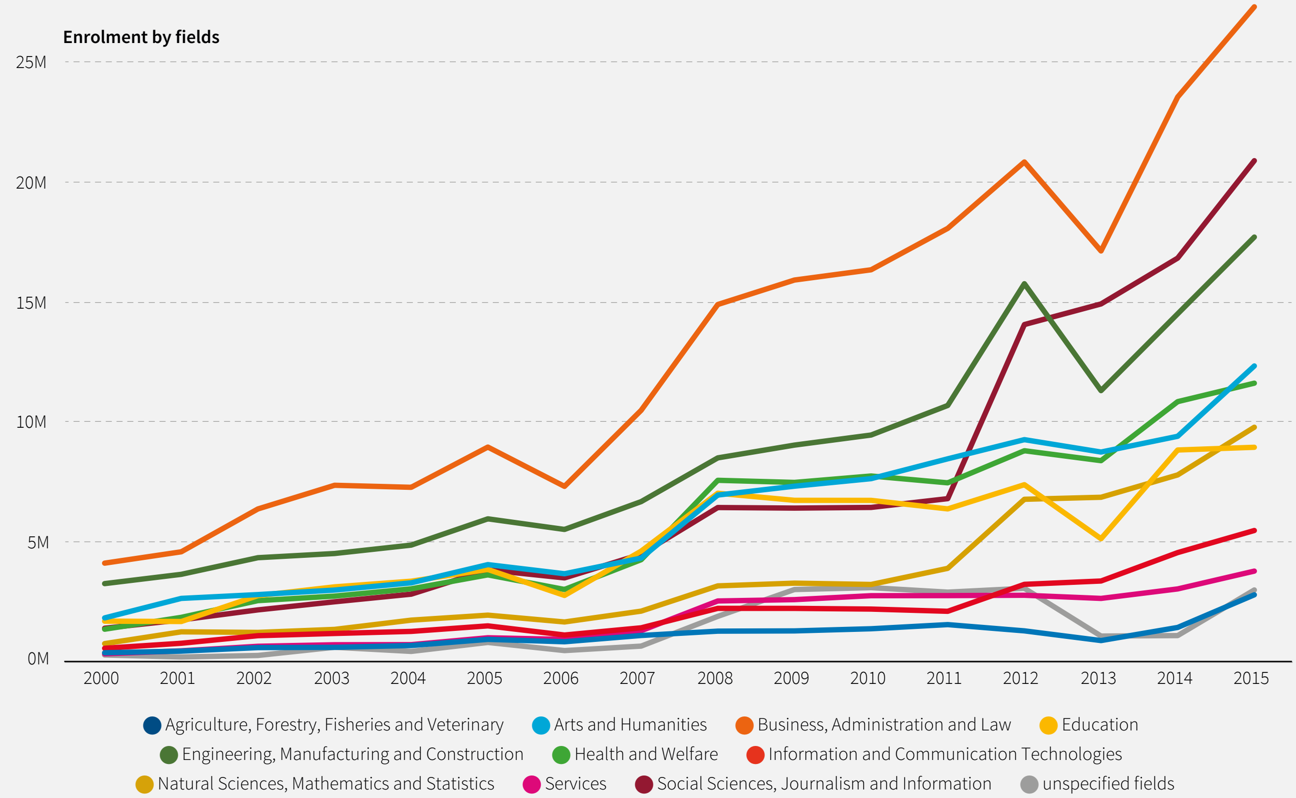
Figure 2. Employment by sector, ILO modelled estimates, 1991–2020*



*This dataset includes both real and imputed data from 1991–2018, as well as projections from 2019–20. Estimates may differ from official national sources.

Source: ILO, 2019.

Figure 3. Enrolments in tertiary education by fields, all programmes, 2000–15



Note: The visualization is based on available data. Data for some countries such as China and India are unavailable.

Source: UIS and ICEE, 2018.

Recommendations

1. Strengthen all types of interregional, regional and sub-regional cooperation for engineering capacity-building in alignment with sustainable development, including an emphasis on the engineering dimension across all SDGs, inclusive standards, the mobility of engineers and articulation of the role of the engineering-education nexus.
2. Expand and innovate engineering education globally, and particularly in developing countries, and promote sustainability competencies for all engineers through lifelong learning and training.
3. Establish diversity engineering systems and encourage young people, especially women and girls, to pursue careers in engineering. Provide support for all engineers, especially women, to establish lifelong careers in engineering.
4. Safeguard human well-being and ecological resilience by promoting an inclusive approach to infrastructure building in engineering.
5. Develop sustainable professional engineering organizations to support and maximize engineering potential, including by developing capacity in data, monitoring and accountability through engineering reporting.

5

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5.2 EUROPE AND NORTH AMERICA

Engineering student experiment

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Progress and challenges towards achieving the SDGs

Countries in Europe and North America[4] are showing good progress in many areas of sustainable development, particularly on SDG targets aimed at providing people with better living conditions. However, in other areas, such as the transition to a circular/low-carbon economy, much still needs to be done to meet the targets.

The countries of the European Union (EU) and Canada aim to be climate-neutral by 2050. In Europe and North America, the proportion of fossil fuel subsidies to GDP are close to zero. Efforts have been made to support recycling and to reduce the use of fossil fuel resources for energy production through circular economy initiatives, such as the Circular Economy Action Plan[5] (European Commission, 2020) in the EU or the Sustainable Materials Management (SMM)[6] in the United States.

The circular economy system is reshaping the high-tech industry as new approaches to the sustainable design of products emerge in many sectors. The share of value added coming from medium and high-tech industry is increasing, contributing 30–50% of all value added in Western and Central Europe and North America (UNECE, 2020). This is an indication of the extent to which developing and advancing technology, and the fostering of new ideas contribute to the economy.

Technology development, and green and digital transitions are significantly affected by COVID-19. The ensuing health crisis has proved a major challenge and has also had significant social and economic impacts. For this reason, the EU approved a recovery package of €1.8 trillion, the largest every financed through its budget. Some of the main areas – to which more than half of the spending will be allocated – are research and innovation, and fair climate and digital transitions. Gender equality is also one of the main elements of this investment package.[7]

Countries have pledged to substantially increase public and private research and development (R&D) spending to accelerate the realization of the SDGs. R&D is one of the priorities of the region as it enables sustainable, competitive and inclusive economies. Although North America and Western Europe are currently leading in terms of R&D spending, countries in Asia – led by China – may soon overtake. A number of emerging players have also been steadily ramping up their investments and numbers of researchers. EU firms account for about 20 per cent of the largest R&D companies. However, many of them lag behind in adopting digital technologies, particularly in the construction sector and Internet of Things (IoT) technologies (EIB, 2020). EU R&D spending intensity is also falling behind (European Commission, 2017) at 2.0% in the EU versus 2.1% in China, 2.8% in the United States and 2.4% in the OECD. The global share of unicorns[8] created in the EU since 2011 is only 11% versus 51% in the United States and 25% in China (European Round Table for Industry, 2020).

As part of its €100 billion research and innovation programme 'Horizon Europe', the European Commission has set five key areas of interest: i) adaptation to climate change, including societal transformation; ii) cancer; iii) climate-neutral and smart cities; iv) healthy oceans, seas, coastal and inland waters; and v) soil health and food.[9]

The regional development context in Europe and North America is characterized not only by growing environmental concerns, but also by opportunities linked to digital transformation. These trends affect engineering education and the labour market. Accurate and up-to-date statistical data are needed to investigate how projected new jobs match the current engineering labour force and the number of engineering graduates expected to enter the job market. However, there is no common approach for recording engineering profession data within Europe and between Europe and North America. Engineering is a highly diversified sector of education and professional activities, and the following facts and trends are therefore presented separately for Canada, United States and Europe.

Box 1. The role of engineering organizations in creating engineering definitions and harmonized statistics

Presenting harmonized statistics related to engineering in Europe is a difficult task as available information varies greatly in the different European countries. This complexity is demonstrated by inconsistency in definitions, engineering disciplines and differences in measuring data. In this context, a study on Common Training Framework (CTF) for Civil Engineers was conducted by European engineering organizations. According to the European Council of Engineers Chambers (ECEC), the objective of the project was to allow actors in the field of professional qualifications (e.g. professional organizations and/or competent authorities from EU Member States) to present proposals for Common Training Principles (CTP) for the engineering profession in view of having those further developed into a Common Training Framework. The proposals were developed on the basis of a mapping carried out in the Member States, as well as after broad consultation with relevant stakeholders.

The project concluded that it is not possible to find an approach that is acceptable for all or even a vast majority of the European Economic Area (EEA) countries. In order to break the deadlock and to proceed towards CTP for Engineers – which despite all the controversies is what the majority of stakeholders want – a few short and long-term approaches were suggested. CTF for Civil Engineers with a limited number of Member States could be initiated first, pending a common approach that is acceptable to the vast majority of EEA Member States over the long term.

Source: https://www.ecec.net/activities/common-training-principles-for-engineers/news-log

4 Trends and facts presented do not take into consideration the full effects of COVID-19 due to the current evolving situation.
5 For more information: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12095-A-new-Circular-Economy-Action-Plan
6 For more information: https://www.epa.gov/smm
7 Read the main elements of the agreement at https://ec.europa.eu/info/strategy/recovery-plan-europe_en#main-elements-of-the-agreement
8 A unicorn company is a start-up that is worth more than US$1 billion.
9 For more information on Horizon Europe: https://ec.europa.eu/info/horizon-europe_en

A changing engineering labour market

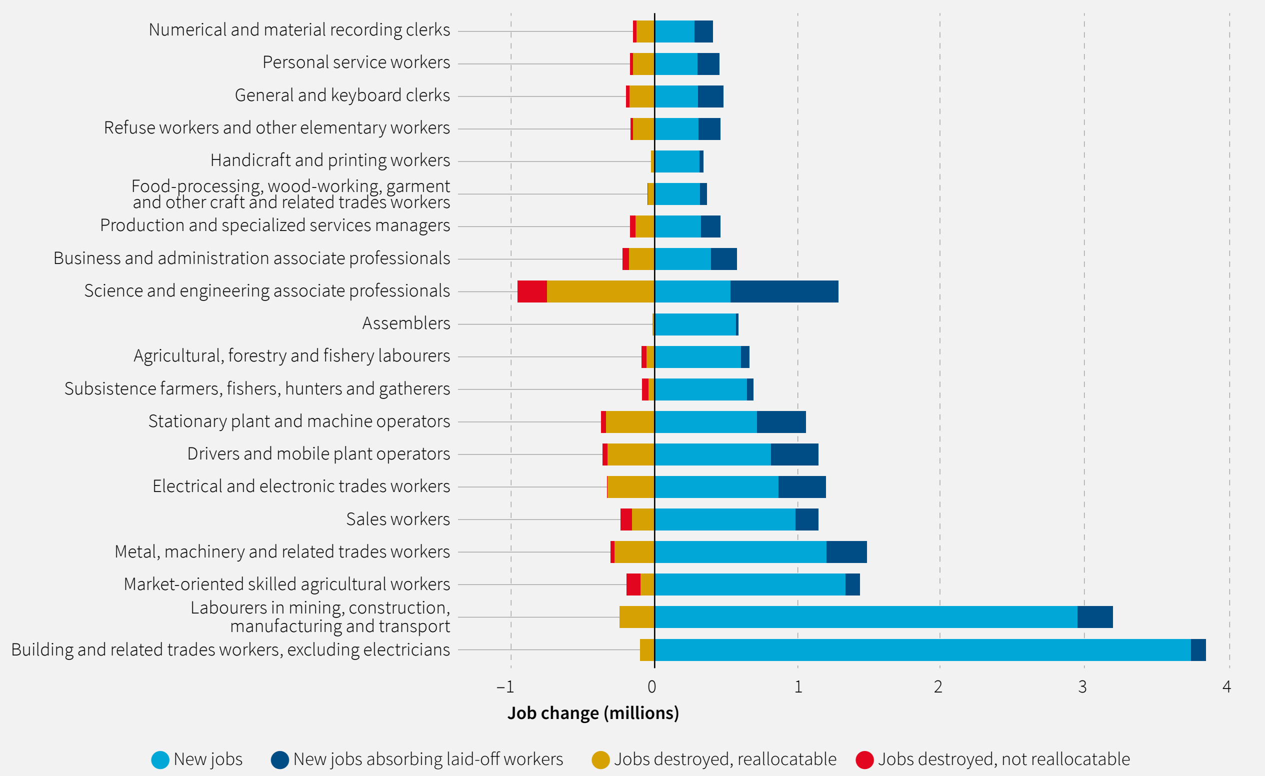
Across the world, skilled professionals are in high demand and in many countries in Europe and in North America there is a great shortage of engineers. The current situation is worsened by demographic changes, such as the ageing population in Europe and North America.

According to the European Commission, the move to a resource-efficient, circular, digitalized and low-carbon economy could create more than one million new jobs in Europe by 2030 (European Commission, 2020*a*). Already in 2017, the European Commission reported that more than half of EU enterprises that recruited or tried to recruit information and communication (ICT) specialists had difficulties in filling ICT vacancies.[10]

A number of authors are trying to estimate the effects of digitalization on employment and are predicting different ratios between new jobs created and jobs that will be replaced by new technologies (European Parliament, 2018). This clearly suggests that science and engineering professionals might undergo one of the largest changes in the labour market. For example, in energy transition these professionals are expected to have the highest rates both of jobs destroyed rather than reallocated, and new jobs absorbing laid-off workers, as illustrated in Figure 1.

Some countries are recruiting engineers from abroad. This resolves short-term recruitment problems and increases a company's diversity, creativity and competitiveness. However, it does not resolve the existing scarcity problem in the engineering workforce.

Figure 1. Occupations most in demand across industries in a global energy sustainability scenario



Note: Difference in employment between the sustainable energy scenario (the 2°C scenario) and the business-as-usual scenario (the 6°C scenario) of the International Energy Agency (IEA) by 2030 (ILO, 2018a). Detailed information on the methodology is described in ILO, 2018a, pp. 39, 172–170).

Source: ILO. 2019. *Skills for a greener future: A global view based on 32 country studies*. Geneva: International Labour Office.

10 Eurostat Statistics Explained: https://ec.europa.eu/eurostat/statistics-explained/index.php/ICT_specialists_-_statistics_on_hard-to-fill_vacancies_in_enterprises

5

Canada

Statistics Canada reports that professional, scientific and technical services continued their accelerated employment growth from 2017 to 2018. The number of employees in this sector rose by 4.5%, the fastest rate among the 10 largest industrial sectors. Concurrently, the job vacancy rate in this sector increased between 2017 and 2018 (Statistics Canada, 2018). Half of the annual employment growth was from the high-paying computer systems design and related services industry despite the fact that it accounts for roughly one-quarter of employment in the sector. This industry was also the fastest growing within the sector, followed by scientific research and development services, and architectural, engineering and related services (Statistics Canada, 2018).

United States

According to the U.S. Bureau of Labor Statistics, employment in engineering and architecture occupations is projected to grow 3% from 2019 to 2029, about as fast as the average for all occupations (US Bureau of Labour Statistics, 2020). It is expected that about 23% of new vacancies in the engineering profession will be for civil engineers. Growth in employment is also projected in mechanical and industrial engineering. These two occupations might account for about 36% of new engineering jobs between 2016 and 2026 (US Bureau of Labour Statistics, 2018).

Europe

Scientists and engineers aged 25–64 in the European Union have increased by 10% from 2016 to 2019.[11] Their total number was estimated to be 17.2 million in 2018,[12] representing 23% of all workers employed in science and technology occupations in the EU. Many of the jobs that employers may need to fill by 2030 will require a higher level of skills. The largest number (four million) are predicted to include jobs that do not yet exist, often created as a result of new technology (an AI ethicist for example), while 2.6 million projected new jobs are for science and engineering professionals (McKinsey Global Institute, 2020).

Trends in higher engineering education and lifelong learning

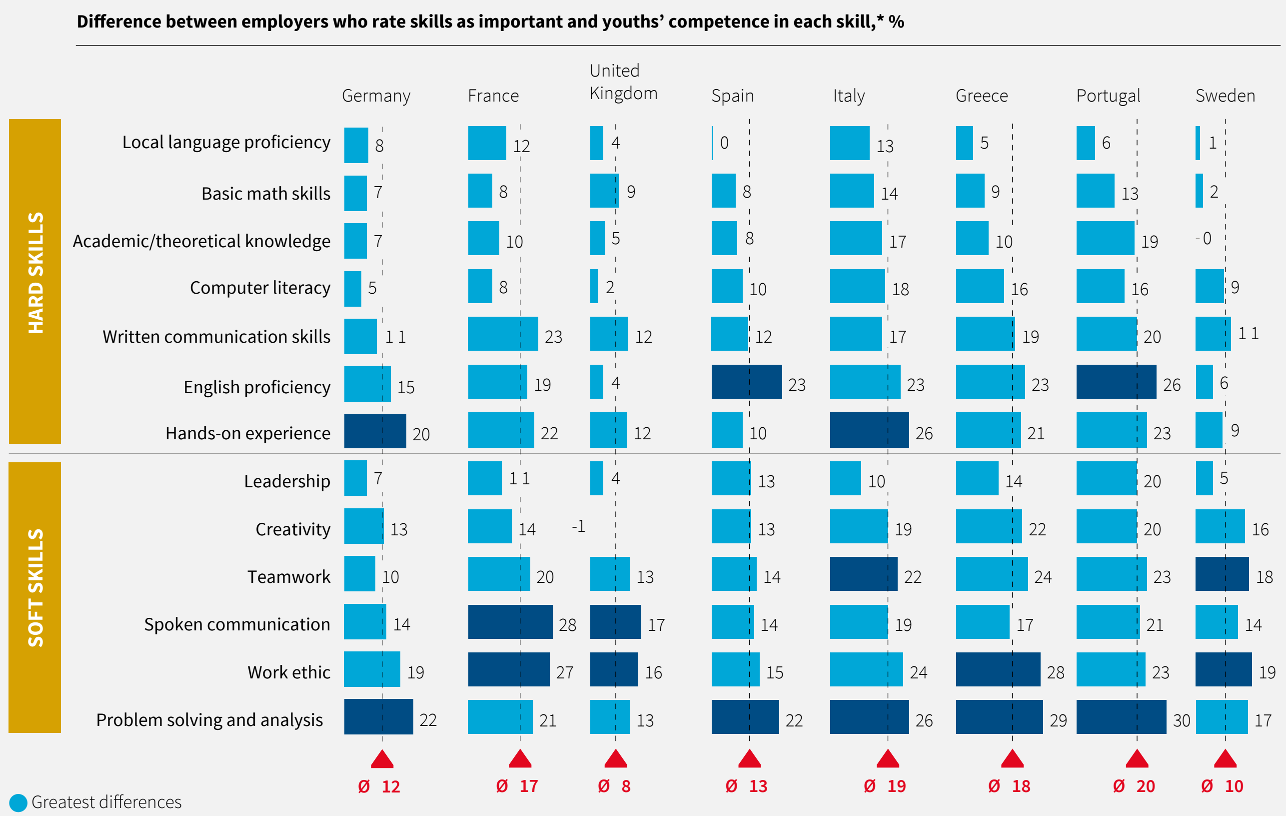
Education is pivotal to accelerating the realization of the SDGs. Overarching megatrends, such as green and digital transitions, are also re-shaping the engineering landscape and educational requirements. The engineering education system needs to be reassessed and fully shift to technological problem-solving with an holistic approach that considers the impacts of engineering innovations and activities on the environment and on society more generally.

In Europe and North America there is a growing need and recognition of future-oriented engineers who possess inter-disciplinary competencies. While engineers continue to be ‘technological problem-solvers’, they are more often seen as communicators and mediators as well. They support decisional processes and engage with a high variety of actors from local communities to policy-makers. Engineers are expected to work in multidisciplinary teams and have an aptitude for listening to all stakeholders and integrating their views into the proposed solutions. Soft skills such as being able to adapt to change, creativity and flexibility, are in high demand, as illustrated in Figure 2.

Green and digital transitions will require an upskilling of new technologies and processes including Building Information Modeling (BIM), cloud computing, AI, 3D-printing, virtual reality, IoT and blockchain technology (EFCA, 2018). Multidisciplinary approaches to technology development are also required in order to ensure socially responsible communication networks and urban governance systems.[13] The number of engineering graduates and apprentices in Europe and North America is growing; however, the current rate of increase may not be sufficient to match the new jobs created in the next decade and beyond.

11 Eurostat: http://bit.ly/eu_scientists_engineers
12 Eurostat: http://bit.ly/number_of_scientists
13 Read more on ‘engineering a more responsible digital future’: https://www.weforum.org/agenda/2018/03/engineering-a-more-responsible-digital-future

Figure 2. Employers across Europe have a similar view on where skills are missing



* "Below is a list of a number of skills regarding entry-level employees you have hired in the past year or so. For each skill, please rate how important they are for new hires to be effective at your company" minus "For each skill, please rate how competent, on average, they are."

Source: McKinsey & Company, 2014.

Canada

Statistics Canada reports that from 2006 to 2016 the largest proportion of science, technology, engineering and mathematics (STEM) graduates studied engineering or engineering technology (47.9%) (Franck, 2019). There has been continued growth in undergraduate degrees awarded, with 18.9% more engineering degrees in 2018 than in 2014. The undergraduate engineering disciplines with the highest enrolment in 2018 were mechanical engineering, civil engineering and electrical engineering. Biosystems engineering, software engineering, and industrial or manufacturing engineering show the highest growth since 2017 (Engineers Canada, 2020*b*).

United States

Enrolment in undergraduate engineering programmes increased during the last decade. The study *Engineering by the Numbers* (Roy, 2019) reveals that the top three engineering disciplines for Bachelor degrees in 2018 were mechanical engineering, computer science (inside engineering) and electrical engineering. There was also an increase in 2018 in enrolment in engineering programmes for Masters degrees in the same three disciplines accounting for 39% of all engineering Masters graduates (Roy, 2019).

Europe

Across the European Union more than one-fifth (22%) of all students in tertiary education in 2018 were studying business, administration or law. The second most common field of education was engineering, manufacturing and construction-related studies, which accounted for 15.8% of all tertiary education students (an increase from 15% in 2017), of which almost three-quarters (11.6%) were male compared with 4.2% of women.[14]

14 Tertiary education statistics at https://ec.europa.eu/eurostat/statistics-explained/index.php/Tertiary_education_statistics#Fields_of_education

Mainstreaming gender equality and diversity

Increasing diversity in engineering education and the job market is important for social justice, enhanced creativity and problem-solving capacities in this globalized profession, but also to tackling the shortage of engineers (see Chapter 2, Equal Opportunities).

There is a growing number of women in engineering reported in North America with a small increase in Indigenous people. Although the rate of female representation is growing rapidly compared to other groups, it has not reached the targets set by some countries (Engineers Canada, 2020*a*). Other under-represented groups, including LGBTQ+[15] and indigenous communities, are equally important in mainstreaming diversity. National organizations, and education and government institutions are making stronger efforts to ensure a fuller representation of society in engineering.

Canada

Women comprised 14% of the total national engineering membership in 2019 (representing an increase from 13.5% in 2018) and 17.9% of newly licensed engineers in Canada in 2019. As part of the 30 by 30 initiative[16], Engineers Canada and regulators have been tracking the number of newly licensed women since 2014. This initiative is a collaboration between engineering organizations, industry and regulators to increase the proportion of newly licensed female engineers to 30% by 2030. The representation of engineering students who identify as women grew from 23.7% to 25.2% between 2018 and 2019 (Engineers Canada, 2020*a*). Indigenous students, however, are still vastly under-represented in engineering education accounting for only 0.5% of reported undergraduate students. This is around ten times lower than the 4.9% of people in Canada who identify as indigenous (Statistics Canada, 2018).

United States

The share of female graduates of Bachelor, Masters and doctoral engineering degrees in engineering technology continues to grow. However, this proportion increased by only a few percentage points on average from 2009 to 2017 (Roy, 2019). Women earned 21.9% of Bachelor degrees, 26.7% of Masters degrees and 23.6% of doctoral degrees in 2018. However, women earned over 40% of Bachelor degrees in environmental engineering, biological/agricultural engineering and biomedical engineering in 2018. Women also earned over 30% of degrees in chemical, architectural, industrial/manufacturing systems, and metallurgical and materials engineering. The percentage of women in engineering occupations increased from 9% to 16% during the 1993–2016 period.[17]

The proportion of Black and Hispanic groups in science and engineering is less than 10%, which is slightly lower than their share of the total population. There was an increase in Bachelor engineering degrees earned by under-represented groups in 2018 with Hispanic students earning 11.4% of degrees, Black students earning 4.2%, Native American earning 0.3%, and Hawaiian/Pacific Islanders Bachelor degrees earning 0.2% (Roy, 2019).

Europe

According to the European Commission, 59% of the almost 15 million scientists and engineers in the EU in 2018 were men and 41% were women. Men were particularly over-represented in manufacturing (79% of scientists and engineers). The services sector was more balanced at 54% male and 46% female.[18] According to the study *Women in the Digital Age* (European Commission, 2018), only around 24 out of 1,000 female tertiary graduates had an ICT-related subject, of which only six would go on to work in the digital sector.[19] To promote diversity for other under-represented groups, the European Commission presented its first ever EU Equality Strategy for lesbian, gay, bisexual, trans, non-binary, intersex and questioning (LGBTIQ) in 2020 in which building capacities to prevent discrimination in education and employment is one of the goals.[20]

Box 2. Achieving LGBTQ equality in engineering education in the United States

The American Society for Engineering Education (ASEE) conducted a study on LGBTQ equality in engineering in 2016. Even though significant advances in LGBTQ equality have been seen in recent years in the United States through legislation and social acceptance, this research shows that LGBTQ students and faculty on college campuses still experience exclusion and discrimination. The study revealed that 30% of LGBTQ students seriously considered leaving their institution due to negative experiences and perceptions. This percentage was highest (42%) for faculty and first-year students (72%). This project used a transformative, cyclical mixed-method research model to provide a basis for social change. College campuses are now making gradual progress towards improving the climate for LGBTQ students through LGBTQ-inclusive policies, programming and practices.

Source: Farrell *et al.*, 2016.

15 Lesbian, gay, bisexual, trans and questioning.
16 For more information: https://engineerscanada.ca/diversity/women-in-engineering/30-by-30
17 Science and Engineering Indicators: https://ncses.nsf.gov/pubs/nsb20198/demographic-trends-of-the-s-e-workforce
18 Eurostat on women in science and technology: http://bit.ly/37ykaLG_women_science
19 Women in Digital: https://ec.europa.eu/digital-single-market/en/women-digital-0
20 Read more about the Strategy at https://www.europarl.europa.eu/legislative-train/theme-a-new-push-for-european-democracy/file-lgbti-equality-strategy

Recommendations

1. Harmonization of statistics on engineering education and profession

Engineering is a highly diversified sector in terms of education and professional activities. There needs to be a common approach to harmonize definitions and data recording, which should also reflect diversity trends in the engineering sector.

- Government institutions and engineering organizations should reinforce their cooperation to further harmonize the profession's standards of data collection and study.

2. Education, lifelong learning and upskilling

The development of soft skills will be as important as the lifelong development of hard skills in terms of helping engineers lead the transition towards more sustainable development pathways. Universities are at the core of this mission together with engineering organizations that support engineers in their professional accreditation and lifelong learning.

- With the support of engineering organizations, universities are requested to provide engineers with growing opportunities for their continuous development. These efforts should include harmonized professional accreditation across Europe and North America.

3. Engineers' contribution to better policies

The transition to the digital, green and circular economy requires inputs from engineers in policy-making processes. Traditionally, engineers have been involved mainly in the technical side of policy formulation. Increasingly, however, they are not only expected to work on the technical part of the solution but also to consider what effect technological solutions will have on society as a whole. Professional engineers are expected to have excellent soft skills and to be able to work on multidisciplinary projects. These new competencies will also enable them to impact policy at all levels of government.

- Engineers and engineering communities should adopt a proactive role in national and international engineering and industry federations, which engage with policy-makers on behalf of their members.
- Individual engineers should play a bigger role in open public consultations and surveys, which are an important part of policy-making.

4. Partnerships and collaboration

Partnerships, collaborations and networks enable progress towards achieving sustainable development. Sharing knowledge in education is the stepping stone to reaching equal civil societies worldwide within the framework of SDG 17 on partnerships, the United Nations provides a platform for collaboration with global outreach.[21]

- European and North American countries should accelerate their cooperation efforts to share knowledge and to help build engineering capacities globally.

21 For more information on the Partnerships Platform: https://sustainabledevelopment.un.org/partnership/browse/

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5.3 ASIA AND THE PACIFIC

Engineers in electrical engineering

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Abstract. Engineering plays a pivotal role in the economic development and living standards of countries and regions across the world. Engineering in Asia and the Pacific faces two inevitable challenges: acceleration of an ageing population and the deterioration of the environment. To some extent, sustainable engineering relies on the quantity and quality of engineering talent, innovation capacity and engineering education. Employment growth in the engineering sector in Asia and the Pacific has seen a steady increase since 2001, but contraction has occurred in some key markets. Women are still under-represented in industrial sectors, which limits the diversity of engineering talent. Research and development (R&D) and entrepreneurship activity across the region are emerging at different speeds. In addition, reform in engineering education has increased due to new breakthroughs that enable engineering talent to be more innovative and entrepreneurial, and geared towards addressing real-world problems. The following sections explore key trends in engineering in Asia and the Pacific.

Regional issues in the Asia and the Pacific region

The Asia and the Pacific region stretches from the western Pacific Ocean to the Indian Ocean and represents a wide diversity of economic systems, societies, geography and weather across the region. However, several trends in the region require engineers to understand the impacts and provide solutions. The following major trendsare found in the region.

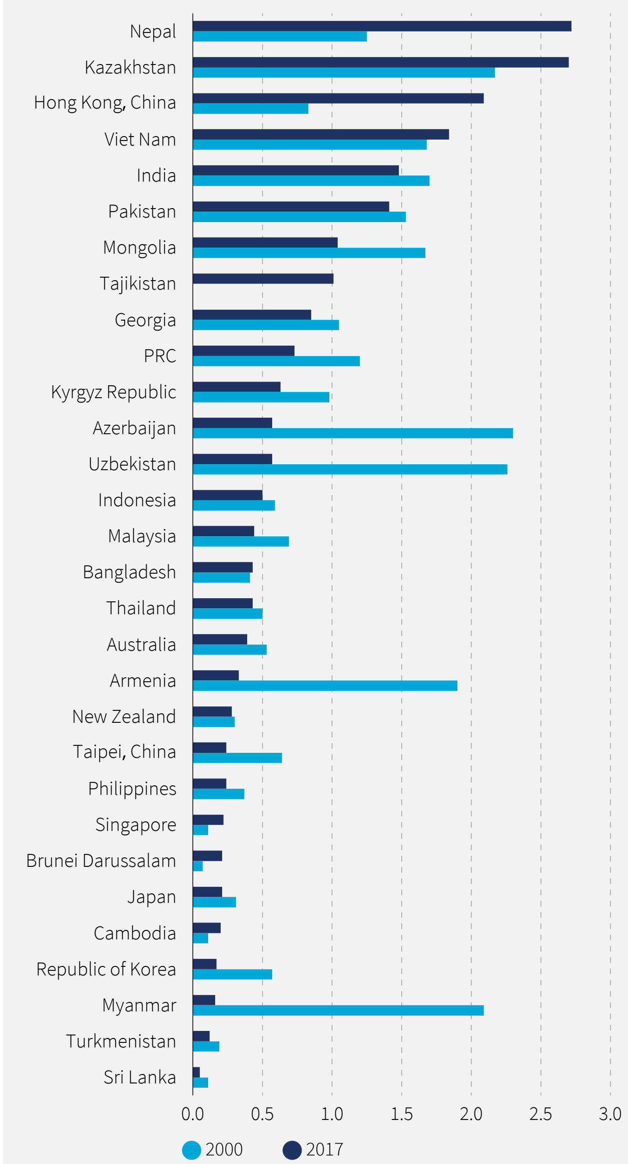
An ageing population and society

The ageing population in countries of the Asia Pacific region is growing at an unprecedented rate, presenting its own challenges. It is expected that by 2050 there will be approximately as many people in the region over the age of 65 as under the age of 15, and that the share of elderly persons in the total population will increase from 8.1% to 18.1% (ADB, 2018). Engineering can help tackle the ageing trend in the region through health, medical transportation and the built environment.

Environmental deterioration

The second challenge is that the region is still experiencing environmental degradation. Although the area of forested land increased in some countries (e.g. China and the Philippines) in 2014, Asia and the Pacific as a whole was responsible for nearly half (47.7%) of total global carbon dioxide (CO_2) emissions (ADB, 2018). However, CO_2 emissions per unit of manufacturing value added fell in more than two-thirds of reporting economies in Asia and the Pacific (Figure 1). This suggests that policies to upgrade and transform manufacturing by adopting more sustainable approaches in countries such as China are playing an active role in protecting the environment.

Figure 1. Carbon dioxide emissions per unit of manufacturing value added (kg of CO_2 per constant 2010 $)



$ = United States dollars, CO_2 = carbon dioxide, kg = kilogram, PRC = People's Republic of China

Note: Only economies with available data for both 2000 and 2017 are included. For Taipei, China, the unit of measure is kg of CO_2 equivalent per constant 2015 $. For 2000, Tajikistan has zero recorded data for CO_2 emissions per unit of manufacturing value added.
Source: ADB, Key Indicators for Asia and the Pacific 2020

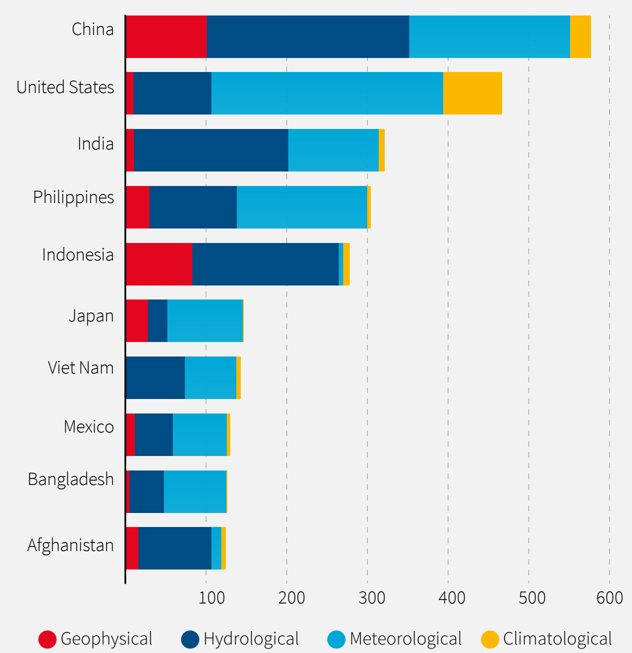
Climate change and natural hazards

According to the United Nations Office for Disaster Risk Reduction (UNDDR), eight of the world's top ten countries by occurrence of geophysical, hydrological, meteorological and climatological disasters in 2000–2019 were in the Asia and the Pacific region (Figure 2). Earthquakes, storms, tsunamis, extreme weather, floods, droughts and other disasters are hugely damaging to local lives and economies. Engineering plays a very important role in climate change resilience, adaptation and disaster risk reduction by assessing the underlying risk and providing hard and soft measures.

Employment growth in industry and change of the labour structure

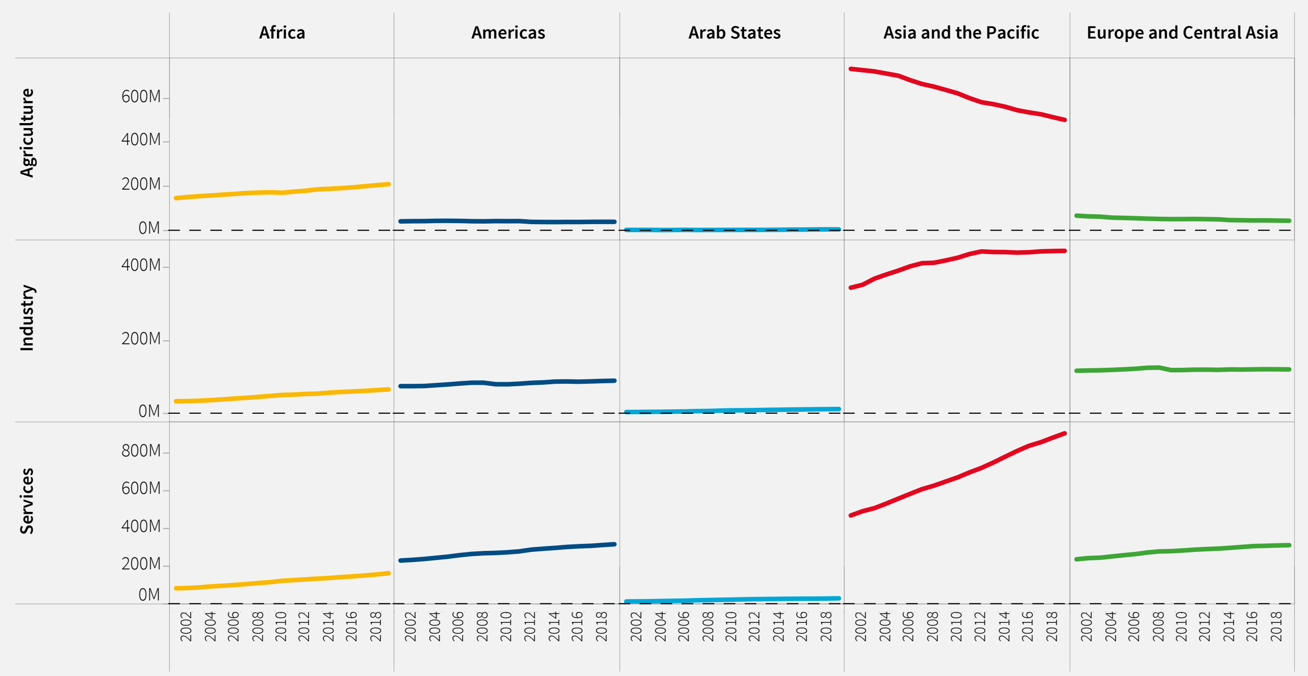
In most regions of the world, employment in agriculture, industry and service sectors experienced relatively minor changes between 2002 and 2018. However, employment in industry in Asia and the Pacific has been increasing since 2002 compared with other regions (Figure 3).

Figure 2. Top 10 countries by occurrence of disaster sub-groups (2000–2019)



Source: UNDRR and CRED, Human cost of disasters: an overview of the last 20 years (2000-2019).

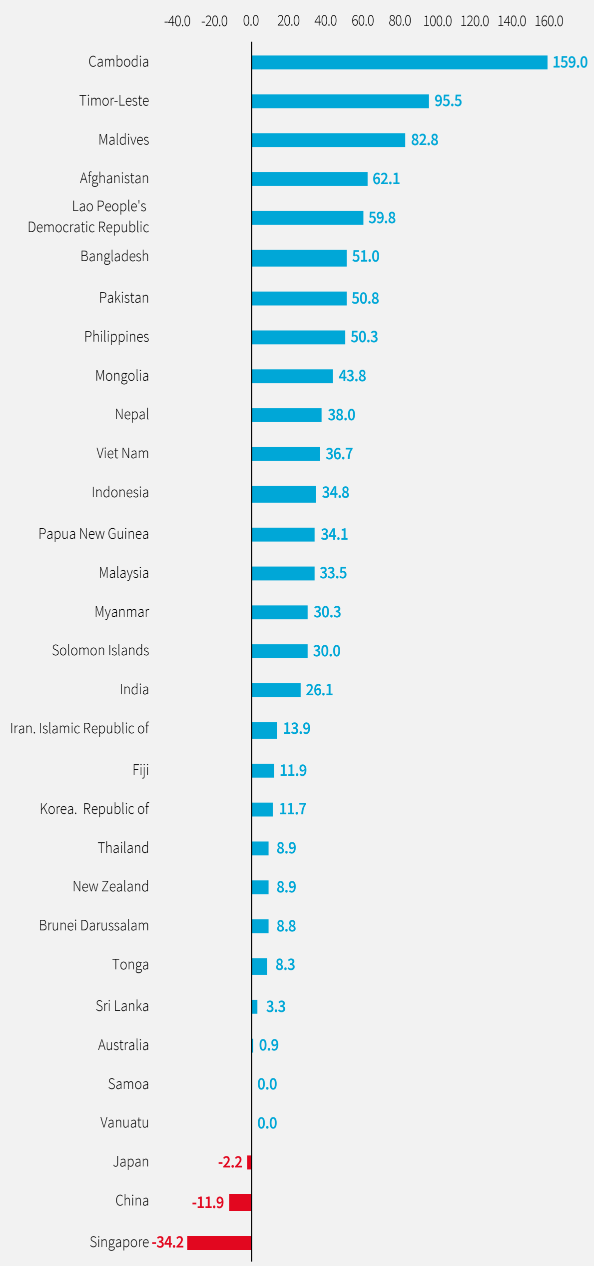
Figure 3. Employment – ILO modelled estimates, world (ILO region)



Source: ILOSTAT, www.ilo.org/global/statistics-and-databases/lang--en/index.htm

In the Asia and the Pacific region, employment growth in industry differs considerably across countries (Figure 4) driven by a range of demographic and economic factors. Between 2009 and 2018, employment in industry increased by 159% in Cambodia due partly to the establishment of export-oriented textile and shoe factories. In contrast, Singapore witnessed the sharpest contraction (34.2%) in employment in industry due to year-on-year employment gains in the service sector. During the same period, employment in industry fell by 2.2% in Japan, driven partly by weak labour force growth.

Figure 4. Trends of employment growth in industry in Asia and the Pacific, 2019



Source: ILOSTAT, www.ilo.org/global/statistics-and-databases/lang--en/index.htm

However, the sharp decrease of labour in the agricultural industry has been supported by machinery/automation. Meanwhile, labour in the service industry has increased sharply. It is noteworthy that the service industry includes not only information and technology, but also lifelines (water, gas, electricity) and the construction sector. Engineering can therefore play a significant role in this growing industry.

Environment for engineering in the Asia and the Pacific region

Investment in R&D for engineering

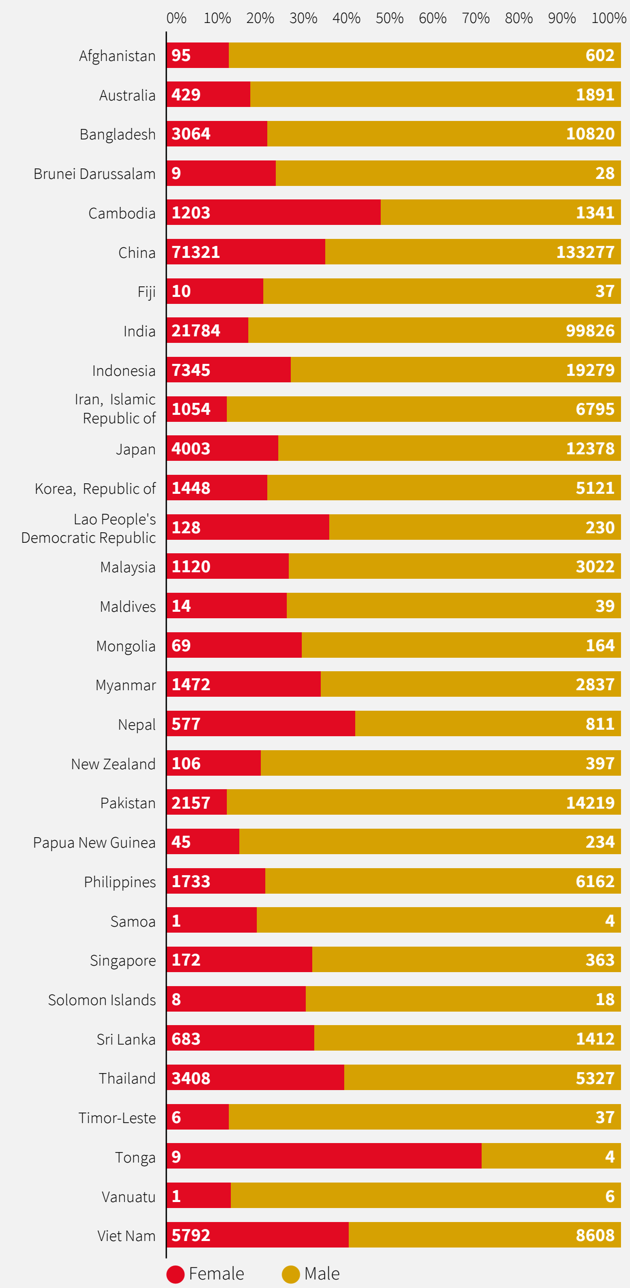
R&D has been an important driver of innovation and can predict future technology trends. The success of R&D depends to some extent on spending in this area and the number of researchers engaged in this field. Within Asia and the Pacific, there has been rapid growth in R&D expenditure and in the number of researchers. China demonstrates the most vigorous R&D growth, accounting for nearly one-third of the global increase in R&D spending over the 2000–15 period (National Science Foundation, 2018). The number of R&D workers per 1 million people in the Republic of Korea has increased greatly, from 2,914 in 2000 to 8,809 in 2016 (ADB, 2018).

Entrepreneurship is about driving innovation to market and is often facilitated by start-up communities characterized by incubation and investment mechanisms. Many influential companies have been founded by engineers, contributing significantly to the development of engineering. Over the past decade, business start-up activity has been accelerated by the simplification and deregulation of related administrative requirements. One of the biggest improvements was the decreased time needed to start a business in South-East Asia where the average number of days required fell from 75 days in 2005 to 30 days in 2017 (ADB, 2018).

Participation of women in industry

There is a wide disparity in female participation in industry among countries in the Asia Pacific region (Figure 5). In Afghanistan, Australia, India, Iran, Pakistan, Papua New Guinea, Timor-Leste and Vanuatu, women make up less than 20% of employees in industry. In Cambodia, the distribution of employment between the genders is closer to 50:50. Although Tonga has the highest percentage of women employed in industry, the total number of women workers in industry is only 13,000. Overall, women are still under-represented in industry in Asia and the Pacific. However, the difficulties women face in pursuing careers and career progression in engineering may be related to each country's specific background and conditions (ADB, 2015).

Figure 5. Employment in industry by gender in Asia and the Pacific (%), year to 2018



Source: ILOSTAT, www.ilo.org/global/statistics-and-databases/lang--en/index.htm

Engineering education system

With global challenges related to an ageing population and environmental deterioration becoming more serious, there is an urgent need to train future engineering talent to advance technological innovation and to solve complex problems. The Asia Pacific region is making great strides in reforming engineering education to enable students to be more innovative and entrepreneurial, and in building their capacity to solve real-world problems.

Many specific skill-training programmes have been set up to cultivate engineering talent with a view to taking action towards building a sustainable society. For example, Japan's Ministry of the Environment has worked with relevant government agencies to implement Environmental Leadership Initiatives for Asian Sustainability, which include developing model programmes to address leadership capacity.

Mutual recognition of engineering qualifications

The Asia-Pacific Economic Cooperation (APEC) is a regional economic forum established in 1989. Some members of APEC have signed an agreement for the purpose of recognizing 'substantial equivalence' of professional competency in engineering under the umbrella of the International Engineering Alliance (IEA). As an independent umbrella organization for the engineering institutions in the South-East Asia and Pacific region, the Federation of Engineering Institutions of Asia and the Pacific (FEIAP) is currently promoting the regional, mutual recognition of engineering qualifications within its 20-member economy. These regional organizations and agreements on engineer mobility have significantly facilitated the integration of engineering education systems and the engineering professions in the region, which is beneficial for a more inclusive and innovative regional engineering community.

Engineering advancement and solutions for regional issues

Soft measures: the education system

In addition to traditional education, open and online education is increasingly being applied through interactive classrooms. Rain Classroom, a mobile learning management system developed by Tsinghua University and XuetangX[23] in China, is commonly employed in innovation-active classroom instruction and lab activities. In Thailand, the 'flipped classroom' approach is widely used in engineering education, notably at Chulalongkorn University.

National multi-stakeholder collaboration is seen as an effective approach to enhance the quality of future engineers who are essential for the practice of sustainable development. In China for example, the International Centre for Engineering Education (ICEE) under the auspices of UNESCO has served as an inter-disciplinary platform for engineering educators around the world to work together to address complex practical challenges using engineering solutions. In 2017, a training programme at Tsinghua

23 For more information on XuetangX learning platform: www.xuetangx.com

University, organized by ICEE, provided students from Bangladesh, Kenya, Pakistan, Zambia and other developing countries with an opportunity to learn, collaborate and communicate with each other.

Hard measures: engineering advancement

In the Asia and the Pacific region, engineering technology not only plays a pivotal role in preventing and reducing risks and natural disasters, it also supports the rapid development of infrastructure and growth in the economy. In particular, transportation facilities such as highways, railways, airports and seaports not only facilitate trade across the region, reduce logistics costs and connect people in different countries, they also help with the movement of people and in developing tourism. Emerging technologies, such as Artificial Intelligence, virtual reality and big data analytics in education and health, are also helping to increase the adoption of technology and to deliver timely diagnoses and treat patients for diseases. The ageing population has a negative impact on economic development, particularly in terms of reduced labour productivity, but new technologies can help maintain productivity growth and skill augmentation (ADB, 2019).

Conclusions

Engineering technology innovation in the Asia-Pacific region is very dynamic, but at the same time there are many economic, social and environmental challenges. In order to promote engineering to better support the SDGs, governments, industry, educational institutions and other stakeholders need to forge closer and more inclusive partnerships, and take more strategic and pragmatic actions to address these key issues.

Recommendations

1. Encourage and attract more young people to study engineering and to choose the engineering profession by creating innovative engineering projects and STEM[24] initiatives.
2. Improve women's participation in industry by instituting policies that provide both women and men with more flexible and family-friendly workplaces where child-rearing responsibilities can be shared.
3. Improve innovation capabilities at the country level by increasing investment in R&D personnel and expenditure.
4. Encourage entrepreneurship by simplifying the business start-up process, and create an efficient ecosystem for the commercialization of innovation ideas, offering business classes and counselling, and building networks for sharing experience.
5. Minimize the gap between the system of education and the profession of engineering by promoting mutual recognition across the region to increase the mobility of engineers.
6. Promote partnerships to address the challenges for sustainable development by facilitating effective collaboration in engineering and education among countries across the region.
7. Ensure that new policies and practical actions are taken into account and promote the transformation of industry for sustainable development.

24 Science, technology, engineering and mathematics.

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5.4 LATIN AMERICA AND THE CARIBBEAN

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25 President-elect, World Council of Civil Engineers (WCCE).
26 Executive Director, World Council of Civil Engineers.
27 President, World Council of Civil Engineers.

Abstract. Throughout recent decades, two main factors have inhibited the realization of the Sustainable Development Goals in Latin America and the Caribbean (LAC): slow economic growth and the lack of a strong social protection system, which is reflected in a high percentage of informal employment. These factors explain why efforts by LAC countries to satisfy basic needs, such as adequate housing, drinking water access, sanitation and environmentally sustainable waste treatment, fall short of SDG targets. This section briefly presents the issues affecting LAC and explains how engineers can help overcome the existing shortcomings.

Regional issues in LAC in the context of engineering challenges

Latin America and the Caribbean has lower long-term growth rates than other regions of the developing world and it must confront these challenges if it is to realize the 2030 Agenda for Sustainable Development.[28] Such slow growth affects investment levels both in technological innovation and infrastructure, and hinders achievement of the SDGs. Since 1980, public investment as a percentage of GDP has fallen from an average of 5.9% to 4.8%. As a result, infrastructure and competitiveness have also declined. The Economic Commission for Latin America and the Caribbean (ECLAC)[29] Economic Survey of Latin America and the Caribbean (2018) concluded that 'a breakdown of gross fixed capital formation by construction asset (including residential and non-residential construction) and by machinery and equipment assets, shows that although the first component accounts for a larger share of investment and a higher percentage of GDP, the second component is growing faster', which indicates a mild recovery.

The report also mentions that wage employment has expanded significantly with economic growth in LAC, and that own-account work[30] – the second-largest category in the region in terms of employed figures – tends to show a predominantly countercyclical evolution. This is mainly explained by households' interest in generating earnings through their own employment due to the absence of new wage employment and the lack of adequate social protection mechanisms during phases of low growth rates.

Low growth rates and investment levels, coupled with development and social issues, such as lack of strong social protection and informal employment, indicate that engineers have a key role to play in overcoming the weaknesses attributed to slow growth, which is also in line with the SDGs. All these goals are interlinked, with some of them requiring the direct contribution of the engineering community. The key issues linking LAC countries to the SDGs and engineering are presented below.

Social issues and development

As mentioned above a number of social and economic growth issues in LAC hamper the realization of the SDGs and necessitate the involvement of different engineering disciplines. According to the Inter-American Development Bank (IDB) report prepared by Iorio and Sanin (2019), the LAC region has 97 per cent electric coverage[31] and ranks as one of the cleanest energy matrices in the world, but problems in other areas persist relating to core issues that affect public health and well-being, such as adequate housing, clean drinking water and sanitation.

According to the 2015 report prepared by UN Habitat there is no common definition of 'housing deficit' in the region. Any definition of adequate housing includes access to drinking water, sanitation and energy, with the 'housing deficit' affecting between 30 and 180 per thousand inhabitants. Far more distressing are water service coverage levels that show only three countries in LAC covering more than 80 per cent of their population with 'safely managed' drinking water (WHO/UNICEF, 2019). Regarding sanitation coverage levels, only seven countries provide 'safe' sanitation to over 40 per cent of their population with only one providing over 60 per cent.

Environmental deterioration

In addition to human welfare, another issue vital to sustainable development in the region is environmental preservation. LAC countries host vast environmentally sensitive areas such as coral reef barriers, large freshwater marshes and rainforests. Rural areas are home to 125 million people, including 60 per cent of the poorest people in the region. Desertification and the degradation of natural resources seriously affect nearly all countries, which is exacerbated by the expansion of agricultural activities and jeopardizes the environment and its natural resources. The United Nations Office for the Coordination of Humanitarian Affairs published an article (Milesi and Jarroud, 2016) which stated that 68 per cent of the land of South America is affected by desertification, 100 million hectares of which is deforested and 70 million is overgrazed. Water, air

28 LAC (2.6%) in contrast with sub-Saharan Africa (3.62%), Middle East and North Africa (3.92%), and East Asia and the Pacific (8.1%). The long-term growth rate in Europe and Central Asia (excluding high income) averaged 1.75% over the last 30 years. See World Bank Databank https://databank.worldbank.org/data/home.aspx
29 ECLAC official website at https://www.cepal.org/en
30 Own-account workers work for themselves and are considered self- employed.
31 World Bank. Access to electricity (% of population). https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZJ

and soil pollution are also reported, mainly associated with irresponsible mining, use of fertilizers and pesticides, urban traffic, and untreated dumping of waste and sewage effluents.

Sustainable development and environmental protection call for responsible planning, design, execution, operation and the decommissioning of management systems and infrastructure, with engineers demonstrating their expertise and commitment to protecting the environment, and thus highlighting the importance of broad-based sound engineering education and training.

Climate change and natural hazards

Climate change in LAC countries will largely affect coastlines and urban settlements (Huber 2018; Nurse *et al.* 2014; OCHA 2020). Higher ocean temperatures largely affect the Caribbean countries in the form of hurricanes[32], the rapid growth of algae and the death of corals. Inland effects of such higher temperatures are linked to episodes of extreme flooding and droughts, which alternate either by region or even within the same region. Higher temperatures provoke more frequent and larger wildfires that severely impact the affected communities. Finally, almost the entire region is either subject to seismic hazards[33], volcanic hazards or both.

Again, these facts call for the involvement of engineers to adequately assess the risks and to forecast such events using smart technologies to provide early alerts, adapt structural codes of building and construction procedures, and devise mitigation solutions.

The environment for engineering in the LAC region

As mentioned above, regional development and environmental issues call for prompt and effective engineering responses. At the same time, engineering is one of the most effective tools to address the realization of SDGs, as outlined below.

- Good health and well-being (SDG 3) and clean water and sanitation (SDG 6), can be ensured through the design and construction of sewage systems, and water and wastewater treatment plants.
- Affordable and clean energy (SDG 7) and industry innovation and infrastructure (SDG 9) are core subjects to most disciplines of engineering.
- Sustainable cities and communities (SDG 11) and climate action (SDG 13) relate, for example, to transportation engineering, construction, and factories management, among other specialties of engineering.
- Responsible consumption and production (SDG 12) is clearly linked to the implementation of recycling systems and waste treatment schemes.

Moreover, all 17 SDGs somehow involve technological development and the application of science to make best use of available resources. For instance, no poverty (SDG 1) relates directly to zero hunger (SDG 2) and both relate to food production (agronomical engineering), shipping (civil, mechanical and electrical engineering), and proper storage (mechanical and civil engineering).

If engineering is essential to attain these objectives, the needs and numbers of LAC engineers must be reviewed. However, reliable global statistics on the number of engineers in the different countries are not currently available. Current figures are incomplete as some countries do not keep an official professional registry and are unreliable owing to informal engineering practice, even in mandatory licensure countries.

The World Council of Civil Engineers (WCCE) estimates that developed countries have between 1,300 and 2,500 civil engineers per million people (Abramian, 2020). In a comparison with a sample of 10 LAC countries, the numbers of engineers range from 200 to 1,666 per million inhabitants. Except for Bolivia and Brazil, the sample countries display fewer civil engineers than the world average and much lower numbers than in developed countries (1,000 per million inhabitants approximately). Such ratios highlight a shortage of engineers in the region, a diagnostic that is confirmed by the fact that while many OECD[34] countries such as Italy, Portugal, Spain and the United States have expressed concerns regarding the shortage of engineering students, they 'export' engineering services through contracts awarded globally. However, LAC countries usually hire foreign companies to design or build large infrastructure works, indicating not only a need for more professionals but also a lack of companies with the required equity or know-how to undertake LAC's large infrastructure contracts.

Engineering advancement and solutions for regional issues

Engineering education

According to the Red Indices Panorama of Higher Education in Latin America (2018), the lower numbers of engineering graduates in Latin America are a consequence of the higher investment required to educate engineers and scientists, as well as LAC universities' main focus on humanities.

32 2017 was the worst hurricane season in terms of number of affected countries and damage.
33 In South America, 25 per cent of the larger earthquakes are over 8 on the Richter scale.
34 The Organisation for Economic Co-operation and Development (OECD) is an inter-governmental economic organization with 37 Member countries. Official website at: https://www.oecd.org

However, the future flow of engineers shown by the share of higher education graduates from engineering, construction and manufacturing is quite promising. According to the Red Indices report, enrolment in educational programmes related to 'engineering, industry and construction' has become the second most popular choice among students, with a particular increase in Chile and Colombia, accounting for up to 20% of the new student intake, within a context of a 3.8% general increase in higher education students over the period 2010–15. Women's enrolment figures have increased over this period to represent 55% of all higher education students in LAC, although such an increase may not result ultimately in a higher percentage of women in engineering practice (Box 1).

However, despite the current increase of enrolled engineering students in LAC, the overall number of engineers is still insufficient to meet the region's potential and needs.

The role of professional engineering bodies in LAC

Different engineering bodies coexist in LAC consist of national engineering regulatory organizations and engineering professional associations that have been assigned a key role to deliver the actions needed to realize the SDGs. Such bodies comprise regional and cross-regional organizations within the global umbrella of the World Federation of Engineering Organizations (WFEO).

Since 1949, the Unión Panamericana de Ingeniería (UPADI) has been fostering Pan-American engineering education and professional practice within LAC societies with a clear interest in contributing to the welfare of their communities. Based in Rio de Janeiro, UPADI currently hosts annual conventions and provides its views to WFEO.

In addition to this, the Council of Civil Engineering Professional Organizations of Portuguese and Spanish-speaking countries (CICPC), a younger cross-regional organization founded in 1992, focuses on assessing member countries' current challenges in order to provide a regional view and propose global joint action principles to the civil engineering community. National members of both organizations are shown in Table 1.

Table 1. UPADI and CICPC membership

	UPADI	CICPC
LAC countries	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Uruguay, Venezuela	
Non- LAC countries and regions	Portugal, Spain	
	Canada, Italy, United States	Andorra, Angola, Cabo Verde, Equatorial Guinea, Guinea Bissau, Macao, Mozambique, São Tomé and Principe, Timor Leste

Economic uncertainty in LAC where countries suffer recurrent economic crises requires a sound flow of engineers from crisis-stricken countries to more dynamic economies in the region who return when the host country's economy declines. Most of this flow is informal and burdens both the career development of LAC engineers and also the growth of engineering firms. The need to establish formal professional mobility procedures within the engineering sector, although addressed by UPADI and CICPC, is specific to CIAM[35], a platform hosted by MERCOSUR[36] governments. CIAM works towards the establishment of a framework to regulate professional cross-border services and licensure within the MERCOSUR Member countries for the engineering sector.

Box 1. A project to address gender equality in engineering in Argentina

Women account for 20% of engineering careers in Argentina, a trend that is rising to 25%. In contrast, according to Argentina's construction syndicate UOCRA, the proportion of women in construction works has fallen below 5%, of which 20% perform tasks related to masonry. This reduces the proportion of women's engineering posts to 4%, resulting in a mostly male environment for construction design, management and contracting.

To address this situation, Argentina's branch of Ingenieros sin Fronteras/Engineers without Borders (ISF-Ar) is developing projects with a gender neutral approach, encouraging the participation of women to achieve a balance between female/women and male/men participants.

This initiative has normalized the presence of women in construction sites, confirming their ability to undertake construction tasks during the design, management and execution phases, and providing role models for young girls interested in joining civil engineering.

35 Comisión para la Integración de la Agrimensura, Agronomía, Arquitectura, Geología e Ingeniería del MERCOSUR [MERCOSUR Commission for the Integration of Surveying, Agronomy, Architecture, Geology and Engineering].
36 MERCOSUR is the Southern Common Market, an economic block comprising 5 States Parties. Official website: https://www.mercosur.int

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Conclusion

Latin America and the Caribbean countries need to address a number of environmental and development issues to unlock the region's potential and to realize the SDGs. To this end, engineering solutions are available but are hindered by the insufficient numbers of engineering professionals in the region or the limited capacity of companies. Hence, efforts should be made towards increasing the number of LAC engineering professionals. This obliges LAC governments and universities to promote engineering programmes, paying special attention to women's involvement. LAC national and regional engineering organizations, together with their international counterparts, must help promote engineering careers, linking them to the realization of the SDGs. They should also promote the enhancement of professional mobility systems that could unlock the professional shortages of developing countries.

Recommendations

1. Enhance South-South cooperation (SSC) and triangular cooperation (TRC)[37] in engineering projects to foster knowledge transfer in the region (UNDP, 2017). Lack of investment, technologies and expertise should be addressed through regional inputs and horizontal SSC and TRC.
2. Establish frameworks to enhance the mobility of engineering students to provide opportunities for them to develop, and share knowledge and experience at institutions and organizations in different countries within LAC. Encourage regional outreach to enhance mobility and help develop a LAC engineering culture to address regional and global challenges.
3. Establish intra- and inter-regional professional mobility frameworks as a first step in promoting global temporary mobility standards and enhancing cooperation systems.

37 SSC refers to 'mutual cooperation aimed at fostering self-sustaining development, involving deepening relations among developing countries while conducting technical and economic cooperation'. TRC refers to 'Southern-driven partnerships between two or more developing countries, supported by a developed country(ies) or multilateral organization(s), to implement development cooperation programmes and projects' (UNDP, 2017).

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5.5 AFRICA

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Abstract. This section advocates for better engineering solutions for Africa by describing and exploring the current state of engineering across the continent and its challenging contexts and priorities in light of the Sustainable Development Goals. It highlights the challenges facing Africa in terms of urbanization, employment, food, water and energy security, environmental degradation, climate change, natural disasters and poverty, and shows how engineering can help the region tackle these challenges. This section also highlights the many critical issues of underdevelopment in Africa and how engineering is the key to achieving the SDGs for Africa. It argues that quality engineering education and improved standards will create good jobs and economic growth leading to the achievement of the African Union Agenda 2063: The Africa We Want.

Introduction

The continent of Africa is the second largest landmass in the world and is home to a wealth of cultures, as well as policies and strategies. Economic development varies widely across Africa's 54 sovereign nations. However, as a collective, Africa is committed to implementing a vision for prosperity: the African Union Agenda 2063.[41] A common thread in African cultural heritage is an orientation towards communities, inclusivity, peace, conviviality and long-term partnerships.

This section describes engineering in Africa and its challenging contexts and priorities in light of the SDGs. Africa has a young population and faces an array of challenges in terms of inequality, equity, service provision and justice. There are well-known difficulties relating to the provision of universal health coverage and quality education, beneficiation from natural resources and infrastructure, as well as a recognized need to create sustainable cities and to develop a holistic response to disasters resulting from the climate crisis, migration, pandemics or armed conflict. Indeed, appropriate solutions necessitate co-development. As the Special Rapporteur on extreme poverty and human rights, Philip Alston, noted in his report to the UN General Assembly, 'to reduce the harm caused by incorrect assumptions and mistaken design choices […] systems should be co-designed by their intended users and evaluated in a participatory manner' (Alston, 2019).

Regional issues in Africa

Social issues and development

The need for better engineering solutions is brought to the fore in the *2020 Africa SDG Index and Dashboards Report*, which provides an assessment of where African countries stand with respect to the SDGs and their progress toward the goals, with the additional lens of 'leave no one behind' (Figure 1). This report also includes a preliminary analysis of the impact of COVID-19 on the SDGs in Africa, which outlines this humanitarian and economic crisis with serious immediate and long-term impacts, particularly on the social and economic goals. The report posits that approximately 60 million Africans could be pushed into poverty and that food insecurity is expected to nearly double. An estimated 110 million African children and youth are already out of school, fragile health care systems are being tested, and women are at risk of being left out even more than before (SDG Center for Africa, 2020). It is also predicted that slow economic activity and lockdowns will increase unemployment and debt, while at the same time diminishing remittances, development assistance and domestic revenue create further risks in terms of financing development and the SDGs. Now is the time for greater self-reliance in Africa, and for African countries to innovate through sustainable engineering solutions and the application of local skills and its abundant natural resources.

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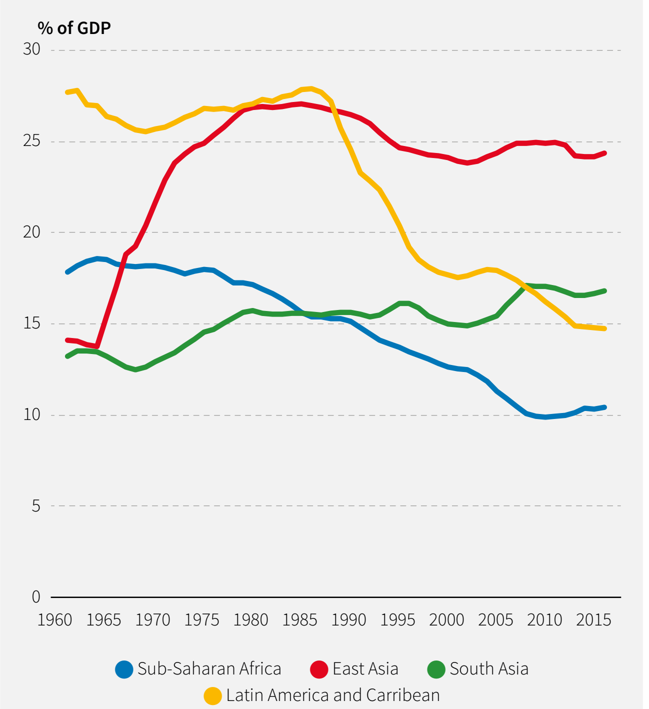
41 For more information on the Africa Agenda 2061: https://au.int/en/agenda2063/overview

Figure 1. Challenges of leaving no one behind with specific reference to Africa

Source: UN, 2019.

Figure 2. Manufacturing as a percentage of GDP by selected global regions



Source: Cilliers, 2018.

The list of challenges faced by Africa include urbanization, employment, food, water and energy security, environmental degradation, climate change, natural disasters and poverty. Engineering can help the region tackle such challenges.

Although there is a wide gap between and within African countries, studies and reports show that income levels in sub-Saharan Africa are substantially lower than those in many other countries of the world. African formal economies rely mainly on extractive industries, while large sections of the population depend on agriculture in informal settings. Africa also relies heavily on imports of machinery, and its share of manufacturing as a proportion of GDP is substantially lower than that of the rest of the world (Figure 2).

Given the strong relationship between engineering, science graduates and economic growth, several countries in Africa regard science, technology, engineering and mathematics (STEM) as crucial for development. Engineering and information and communication technology (ICT) capacity and capability are an essential component of the narrative of the Fourth Industrial Revolution with automation, Artificial Intelligence (AI), the industrial internet and big data functioning as the engines of the economy.

At present, outside of megapolises, this revolution is nascent in most African countries. In rural areas in particular, where most people reside, the Second Revolution (electrical power) and the Third (use of electronics) have not yet taken hold (Naudé, 2017). Meanwhile, the fundamentals of the Fourth Revolution such as digital platforms – around which digital realms pivot – appear to be lacking in Africa (Ministry of Foreign Affairs, 2018; Rodrik, 2018). According to UNCTAD (2019), two countries, China and the United States, account for about 90 per cent of the top 70 digital platforms. Africa and Latin America combined only account for 1 per cent. As a result of a troubled past, most information transmitted from one African location to another passes through Europe (Gueye and Mbaye, 2018).

Electricity is an integral part of modern infrastructure alongside the availability of good quality buildings and potable water. However, in many parts of Africa, electricity is not readily available. When putting Africa's electricity supply and use into perspective, the Africa Progress Panel[42] noted that '[i]t is shocking that Sub-Saharan Africa's electricity consumption is less than that of Spain and on current trends, it will take until 2080 for every African to have access to electricity' (Africa Progress Panel, 2015, p. 11). In most of Africa, electricity supply lags behind demand. In rural areas in sub-Saharan Africa, electricity supply is often absent or erratic, with frequent power cuts (Mudenda, Johnson, Parks and van Stam, 2014).

Of course, African countries have numerous universities in both public and private settings, many of which produce excellent research and development (R&D). Nevertheless, Africans are mostly absent in terms of the conceptualization of global technologies, as is evident at 5G events (van Stam, 2016). Established international practices talk *about* Africa instead of *with* Africa, with African voices rarely present in discussions. In an effort to shed inherited colonial practices and focus on local needs and solutions, curricula and R&D are turning towards integrative and dynamic relevance for local and national communities (Bigirimana, 2017). For instance, the principles underlying research at the Kampala International University in Uganda, centre around 'collaboration within context', bolstering its lead in the multi-country Virus Outbreak Data Network (VODAN) to manage African COVID-19 pandemic data within the precepts of data sovereignty. However, valiant efforts are hampered by an over-reliance on expertise and funding from outside the continent.

Environmental deterioration

Over the past decades, African countries have suffered from various issues including high population growth, multiple armed conflicts, natural disasters, epidemic diseases and political instability. These problems have left their mark on the continent's natural environment. In addition, other threats such as climate change, often uncontrolled urbanization, deforestation, pollution (of the atmosphere, water or soil) and land tenure conflicts, all contribute to the deterioration of the continent's environment. Faced with this situation, African countries must deploy initiatives to eradicate some of the causes of this ecological decay. The development of environmental science and engineering should enable Africa to build human capital capable of providing knowledge on the laws of nature, proposing intervention strategies and developing green technologies that can be used on the continent.

Climate change and natural hazards

Climate change and natural disasters have profound impacts on development sectors and societies in Africa. In fact, climate change and the hydro-climatic intensification associated with it, for example, affect all components of the hydrological cycle at all scales relevant for human activity.

In recent decades, Africa, in particular West Africa, has experienced some of the most extreme weather events in the world, challenging the implementation of different frameworks for disaster risk reduction (Hyogo and Sendai Frameworks) and the realization of the SDGs. These extreme events create particular challenges within urban contexts where better access to reliable and relevant information is essential to support effective planning towards preparedness, response, mitigation and adaptation. Improved forecasting and forecaster skills at long and short timescales can enable better preparedness for climate-related risks. In addition, the new climatic, hydrological, environmental and societal conditions that the different regions of Africa have been experiencing over recent decades are not taken into account in the development of design tools leading to under- and over-sizing of hydraulic infrastructure, resulting in the generation of new costs and materials, and human damage during extreme climatic events. To face this challenge, engineers have to develop suitable design tools that take into account the strong signals observed and projected on climate forecasts, as well as major changes in land conditions and land use.

Water, food and energy security

Africa faces many challenges that seriously hamper its socio-economic development chief among which are issues of food, water and energy security. With a population estimated at more than two billion inhabitants by 2050, or nearly 25 per cent of the world's population, Africa will have to develop strong policies and innovative initiatives to ensure the well-being of its population in an increasingly hostile environment marked by climate hazards and regional insecurity. Africa must also derive the maximum benefit from its demographic dividend, through the development of its human capital and quality education. An increasingly young population (over 60 per cent of young people are under 25) that is well-educated and trained is better able to stimulate a new development dynamic and accelerate economic growth.

The pronounced food and energy insecurity in Africa requires, in particular, the construction of hydraulic works and installations that respect adequate hydrological standards of design. To meet the challenge of food security in Africa, it will also be necessary to focus on the agricultural entrepreneurship of young Africans.

The development of training and research fields in water, agricultural, energy and environmental engineering sciences and technologies will

42 For more information on the work of the Africa Progress Panel: https://africaprogressgroup.org

thus provide Africa with highly competent engineers and managers to meet the challenges in these strategic development sectors.

Environment for engineering in Africa

Engineering technological trends

Engineering a better Africa requires a new paradigm that focuses on building capacity and rallying stakeholders to create strategies to achieve the SDGs. The Federation of African Engineering Organisations (FAEO) through its Agreement with the African Union (AU) Commission Department of Human Resources, Science and Technology envisions the implementation of engineering solutions in the AU Science, Technology and Innovation Strategy for Africa 2024 (STISA-2024) using engineering as a springboard for the right infrastructure, technological innovations and solutions to deliver the 'Africa we want' as enshrined in the AU Agenda 2063 (Manuhwa, 2020).

Alignment with global trends that include big data, AI, progress in communications and energy, robotics and additive manufacturing, as well as the urgent need to develop basic infrastructures, places a significant strain on African capacity and creative solutions. However, an array of technologies and practices exist that are particularly suited to African contexts. Examples include the exploration of dynamic spectrum (ICASA, 2020) and the utilization of TV white spaces (Johnson and Mikeka, 2016). There are many examples of communities involved in running networks in Africa (APC, 2018). This approach requires constant re-skilling and upskilling of people in local and global engineering to serve their communities and to benefit from new, global opportunities. In addition, ICTs have the potential to contribute to African economies and are essential for capacity-building, in particular, through the use of online facilities. The utilization of renewable and alternative energy sources is also growing in Africa. The continent has an abundance of solar radiation energy, hydro-energy and wind energy, and there is a focus on interconnectivity, as can be seen from the pooling of electrical power in various parts of the region.

The use and integration of digital money services shows that Africa can leapfrog industries. One example is the local assembly of cars, televisions or mobile phones using state-of-the-art management tools. Given the abundance of natural resources and labour, it is likely that Africa will see an increasing focus on beneficiation. Associated scenario-planning exercises indicate Africa's GDP growth potential, which will result in jobs and poverty alleviation (Table 1). Industrialization requires support through fair government policies, appropriate ICT, local manufacturing, available energy and transportation. This shift requires sufficient engineering and science capacity, as well as ongoing transformation.

Table 1. Comparing scenario GDP growth rates

Region	Current path average to 2040	Made in Africa average to 2040
Africa	4.8%	6.5%
Low-income Africa	7.2%	8.9%
Low-middle-income Africa	4.7%	6.4%
Upper-middle-income Africa	3.8%	5.3%

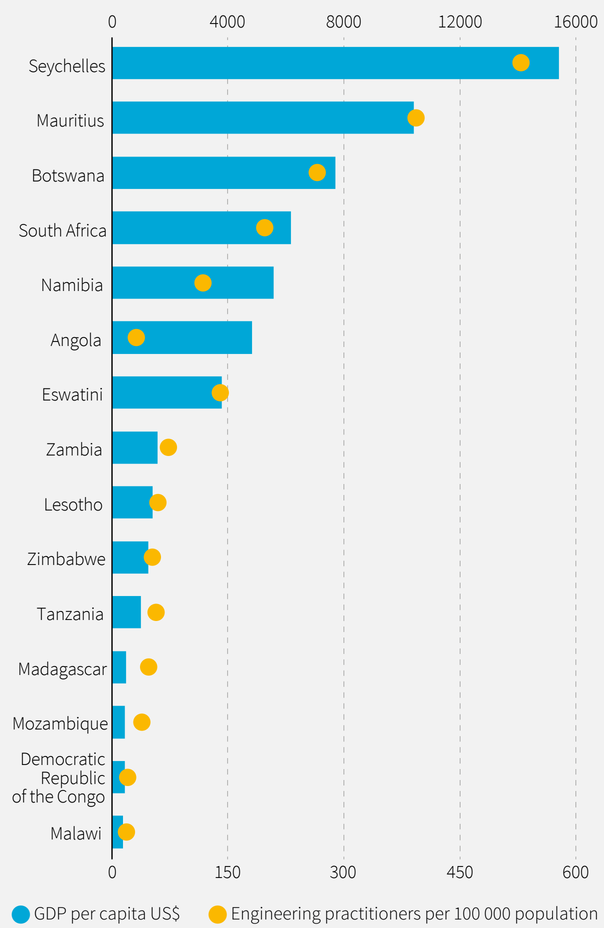
Source: Cilliers, 2018.

The ongoing transformation of engineering capacity includes the elaboration and alignment of education with local and professional needs, mobility, and appropriate national and international regulatory frameworks. Local needs and global trends have given rise to new expectations that graduates will need to be conversant with and that contextually align with R&D, as well as with internationally recognized professional competencies. Engineers play an essential role in preparing society in general as well as other professions, enabling them to adapt to a diverse world of work through the integration of local and national needs with technological advances in the global society.

In Africa, the understanding and alignment of engineering educational standards, their suitability to local and national demands, and the quality of engineering graduates in terms of international standards remain open questions. Only one country, South Africa, is presently a signatory to the International Engineering Alliance (IEA) for both educational and mobility agreements. This situation is compounded by the relatively low number of engineering graduates, well below the per capita norm outside of Africa. Recent research have highlighted 'the lack of disaggregated data for engineering across the world, with not even an occupational breakdown for engineering as a whole in many instances, let alone across the range of engineering disciplines' (RAEng, 2016). This is most pronounced in Africa, and without the necessary data to understand how 'well-stocked' African countries are with engineers of a sufficient quality, it is difficult to ensure that sufficient numbers of well-qualified engineers are emerging to meet the inevitable growth in demand as economies develop, mature and seek new ways of achieving economic growth, as is noted in the same 2016 Royal Academy of Engineering (RAEng) study. The Department of Science and Technology in South Africa commissioned a numbers and needs study on behalf of the Southern African Development Community (SADC) for its Member States.

Figure 3 shows the number of engineers per population and the GDP per capita for selected countries in Africa. While the correlation appears to suggest that more engineers are needed to increase GDP, the converse is true: increased investment in engineering activity is required to grow economies and allow more engineers to actually find jobs in relevant industries and services.

Figure 3. GDP per capita 2016 vs engineering practitioners per 100,000 population



Source: SADC/DST, 2019.

The UNESCO Africa Engineering Week

In 2014, the World Federation of Engineering Organizations (WFEO) together with the Federation of African Engineering Organisations (FAEO) partnered with UNESCO to launch Africa Engineering Week, a platform for the African continent to communicate the importance of engineering to policy-makers, society and the engineering profession. This platform gave birth to the Africa Engineering Conference, which was established to discuss critical topics in engineering and to agree on joint resolutions. The first Africa Engineering Week was held in Johannesburg, South Africa, in 2014, the second in Zimbabwe in 2015, the third in Nigeria in 2016, the fourth in Rwanda in 2017, the fifth in Kenya in 2018, and the sixt in Livingstone, Zambia, in 2019. The UNESCO Africa Engineering Week has been a resounding success, bringing together governments, professional engineering institutions, educational bodies, international stakeholders and civil society. It has not only inspired learners to take up engineering careers, it has also focused on promoting engineering among girls and young women, and has helped share engineering solutions and awareness among practitioners, society, policy-makers and international organizations. The week has also enhanced the visibility of FAEO, UNESCO and WFEO, providing an environment in which their work and activities can be promoted throughout the African continent.

African governments have accelerated narratives of self-realization and sovereignty, especially given geopolitical realities and growing contestation over technologies. Through various initiatives, countries have put in place holistic policies, regulatory frameworks, collaborative strategies and institutional arrangements for community engagement, workforce enhancement and technology transfer, particularly in the fields of engineering. Engineering is seen as a means to enhance economic growth, regional and international cooperation and partnerships, and to create synergies for political integration on the continent.

Balance in society, unity, partnerships and integration

Young people between the ages of 15 and 29 represent approximately 28 per cent of the continent's population, a large proportion of whom are unemployed, with 40 per cent of Africa's population below the age of 15. According to the FAEO President, Eng. Martin Manuhwa 'engineering is a key ingredient to economic development, therefore we need to prioritize and encourage young people into the field of science so that they have the tools to help their countries develop' (RAEng, 2016). Attracting youth to careers in engineering and providing them with support is crucial to resolving local and contextual infrastructure-related challenges. It will also pave the way towards sustainability in terms of local design, implementation and maintenance. Furthermore, such an approach provides pathways to embed thought leadership[43] about African solutions. Lastly, as with other continents, attracting women into the profession remains a challenge and will necessitate the creation of positive action in policy form to encourage young women to choose engineering as a career.

Intercultural and language barriers still restrict intra-continental partnerships in Africa. However, several initiatives are in place to improve relations and connections between countries. The

43 van Stam (2016) defines thought leadership as 'content that is recognized by others as innovative, covering trends and topics that influence an industry'.

potential for South-South cooperation projects, inside and between continents, provides exciting opportunities, especially given the historical similarities, cultural and epistemological alignments (e.g. Ubuntu and Buen Vivir), and geographic and ecological features in the Southern Hemisphere that need exploration, especially in the context of the climate crisis. Engineering education and practice can benefit from multiple ways of knowing and building intercultural competencies to equip engineers to serve their communities in an interconnected world.

Engineering advancement for and solutions to regional issues

The challenges faced by Africa present numerous opportunities, especially in the fields of engineering, research and innovation. To take advantage of these opportunities and contribute to solving these challenges, African countries must initiate systemic reforms to improve the quality of education at all levels and professionalize their education systems in order to educate and train youth, in particular, in the fields of science, technology and engineering. For Africa to achieve the goal of economic transformation, it will therefore be imperative for countries to invest strategically in the education and training of African youth. To make this happen, African synergy should be activated to promote enhanced regional integration on the one hand, and to advance science and technology in Africa on the other.

In an article in *Le Monde,* writer Myriam Dubertrand noted that 'sub-Saharan Africa is in need of more engineers' and that for Francophone Africa to realize its full potential, the continent must develop partnerships, networking of researchers and students, and the establishment of collaboration and co-construction with other, more established, engineering schools on other continents, such as cooperation with the prestigious Conférence des grandes écoles[44] (CGE). It also noted that while seven establishments are African only one is based in sub-Saharan Africa: the International Institute of Water and Environmental Engineering (2iE) in Ouagadougou, Burkina Faso (Dubertrand, 2016).

Conclusion

Engineering is the key to achieving the SDGs for Africa. Quality engineering education and improved standards will create good jobs and economic growth , leading to the 'Africa we want'. The challenges in sub-Saharan Africa are common to Francophone, Lusophone and Anglophone countries. They include reduced access to affordable energy, low industrialization, lack of standardization, inadequate infrastructure (especially transportation), low productivity, as well poor health and wellness, all of which require engineering solutions. However, there is now evidence of local engineering practices and capacity-building being implemented, offering solutions using modern technologies, such as industrial 4.0 and other disruptive technologies, as witnessed during the COVID-19 interventions by local professional institutions and universities (FAEO, 2020).

Recommendations

1. Mainstreaming local, national and continental engineering is crucial for the design, building and maintenance of sustainable African solutions to both African and global challenges. Engaged communities, stakeholders and governments are the bedrock for ensuring appropriate capacity and orientation in education and professional enterprise.
2. Enhancement of African engineering capacity requires a focus on local, national, regional and continental challenges, as well as professionals embedded in Africa's cultural heritage.
3. Expanding engineering capacity is a priority for the continent, and necessitates policies, national and international regulatory frameworks, and national and regional professional engineering organizations that focus on long-term benefits for Africa's progress and well-being.
4. African leadership and engagement in international technology development (e.g. in 6G) must be harnessed and supported.
5. FAEO should be supported in its role to unify the profession and support capacity-building and engineering regulation throughout the continent.
6. African R&D geared toward policy development is needed to provide the necessary evidence for governments to assign a legal basis and resources, aligning certification with continental and world standards for instance, and to sustain the mobility of engineers throughout the continent.
7. Without neglecting cultural diversity and histories, there is significant benefit in programmes that encourage diverse working relationships (nationalities, genders and sub-disciplines), and which work to develop intercultural competencies among Africans, particularly in support of transnational African projects in the engineering profession.
8. Countries should take urgent action to increase the number of engineers in line with Africa's needs and to close the engineering gender gap.
9. Countries should invest more in engineering and upgrade/enhance the capacity of their engineering training institutions.

44 A French association of prestigious higher education and research institutions.

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5.6 ARAB STATES

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Arab woman engineer receiving a prize

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Abstract. The Arab States are starting to leverage internal national data with comprehensive policy frameworks to effect potentially dramatic changes that will match human capital to government development goals. At the same time, they seek to encourage sustainable start-up cultures, diversity and inclusiveness with a focus on women, as well as promoting investments targeting environmentally friendly and responsible energy alternatives. The next step will be to consolidate the momentum of change and enable wider implementation to countries that have yet to start this process, while strengthening the regional position through intraregional cooperation.

Engineering, education and the quality of education

In its latest *World Development Report*, the World Bank (2019) explored how leveraging data and comprehensive policy frameworks can effect potentially dramatic changes to help realize the Sustainable Development Goal (SDGs). These shifts include aligning local and regional development goals with changing skills and the nature of production and market power to improve human capital, resilience and infrastructures. This approach requires looking beyond typical indicative improvement measures, such as the International Labour Organization's employment-to-labour ratio (ILO, 2018), to more robust and proactive assessments that map and incentivize youth towards educational careers and pursuits aligned with government development programmes.

One such instance is a study conducted by the Office of the Vice President for Planning (OVPP) at Kuwait University, which investigated and forecast (over the next five years) the balance in the supply of engineering graduates from the university to meet the demand of the Kuwaiti engineering labour market (Khorshid and Alaiwy, 2016). The market showed significant gaps compared with strategic national development and/or tactical growth plans despite the remarkable Kuwait employment-to-labour ratio of 72.4% (ILO, 2018). The outcome of this study – although focused on the engineering sector in Kuwait – found a repetitive theme across other sectors, suggesting that the high rates of education and subsequent employment may not be sufficient to meet present and future development needs in Kuwait and across the region.

It is also imperative, however, to emphasize the need to start providing quality education followed by employment to those who have been educated, with the recommended approach being to align educational programmes/courses with national development/growth plans from the outset. Currently, ILO 2018 statistics for countries in the Arab region show that Qatar (87%), the United Arab Emirates (81%), Kuwait (72%), Bahrain (72%) and Oman (69%) have the highest employment-to-labour ratios, while Jordan (33%), Yemen (34%), Algeria (36%), Syria (38%) and Iraq (39%) have the lowest. These statistics, although generally indicative, often do not provide a reliable measure of literacy levels and quality of education; for instance, Jordan currently has around 98% literacy levels but a 33% employment-to-labour ratio, which may be attributable to the high number of engineering graduates without the commensurate growth in industries.

While bodies such as OVPP (Kuwait) and similar assessments are mostly inexistent or non-operational in most other Arabian nations, some Arab States are now actively assessing this potential gap (e.g. the Jordan Education for Employment (JEFE), the Qatar Foundation for Education, Science and Community Development, and the Public Education and Training Evaluation Commission of Saudi Arabia).

Encouraging a sustainable start-up culture

The first Arab Regional Seminar on the SDGs and Gender Equality for Parliaments of the Middle East and North Africa, jointly organized by the Arab Inter-Parliamentary Union and the House of Representatives of Egypt, was held in the Library of Alexandria in September 2018, with parliamentary representatives from 15 countries in attendance. The Members of Parliament demanded regional action to address the high rates of unemployment, especially among women and youth, owing to factors that include the recent decline in regional economic growth by 6% (in 2005–10) and 3.5% (in 2011–14). The role of government in addressing this trend cannot be over-emphasized. Governments also need to explore and support internal partnerships (start-ups and SMEs) and external partnerships (private sector and governments) towards more sustainable solutions. Basic and primary literacy levels are strategic levers in this regard, while university education provides the launching pad for start-up culture and future internal partnerships.

Jordan is a good example of an Arab State with an outstanding literacy level, having reached around 98 per cent in 2018 and aiming for 100 per cent by 2020. However, while the largest proportion of the state budget is dedicated to education, graduate jobs in industry are mostly lacking, and the employment-to-population ratio is very low at 33%. The situation is similar in Kuwait, where 90% of employed citizens work in government jobs, and only 4% work in the private sector and 2% in start-ups. Outside of government employment, a multipronged approach is needed to tackle unemployment or underemployment in the Arab States with low employment ratios (Algeria, Comoros, Egypt, Iraq, Lebanon, Libya, Mauritania, Morocco, Somalia, Sudan, Syria, Tunisia and Yemen).

There is an urgent need to actively incentivize the start-up culture in the region by expanding the regular educational curricula to include entrepreneurship trainings/courses supplemented by industry exchange programmes so as to enable student interns to experience industry challenges and to provide solutions. This action has to run concurrently with the development of government policies that encourage the establishment of more private sector companies (by improving 'ease of doing business' factors across the region), especially for the creation and growth of small and medium-scale enterprises beyond home-grown companies and investment opportunities for international companies.

The integration of internships as a mandatory subject in engineering/technical educational curricula will involve the creation of an innovation and entrepreneurship ecosystem in which universities in the Arab region are transformed into real entrepreneurial hubs/universities that promote and facilitate start-up creation, innovation and technology transfer for graduates and industries. This functional ecosystem will provide students with opportunities to connect theoretical knowledge with industry practice and experience. This in turn will broaden their learning experience and make them better prepared for industry upon graduation, while also exposing them to the possibility of starting their own businesses.

All the elements required to capture business planning beyond technical expertise should be included in the educational curricula. Business courses should incorporate end-to-end business planning and maturation processes including risk and opportunity assessment and management, and exposure to corporate/government nuances such as the requirements for setting up and running a business, available support structures (policies, funding, incubators) for early phases of business development, scaling up, mentoring and so on.

Women in engineering practice

Gender equality (SDG 5) and good governance (SDG 16) were the main themes discussed at the first Arab Regional Seminar on the SDGs. The participants committed 'to include a gender equality perspective in all their work on the SDGs; to review legal frameworks to remove discriminatory legal provisions against women; and to use their oversight power to hold governments to account on SDG strategies and planning. This will help to promote more gender equality in education, training and employment as well as in economic and political leadership'.

Although the number of high-profile engagements and policies promoting gender equality in the Arab region has increased significantly in recent years, the gaps remain huge. In the Kingdom of Saudi Arabia, for instance, most women can only study engineering abroad (outside the borders of the kingdom) as most public and private universities in the kingdom do not allow women to take engineering degrees – only Effat University (in 2006) and King Abdulaziz University (in 2013) allow women to take undergraduate engineering degrees. King Abdullah University of Science and Technology (in 2009) accepts women but only to postgraduate engineering programmes. An offshoot of this statistic is the very limited (almost non-existent) participation of women in science, technology, engineering and mathematics (STEM) ventures in the kingdom. At present, there are 4,846 engineering consulting firms of which only 54 (1.11%) are owned by women.

In Bahrain, women accounted for 30% of engineering graduates in the 2018 academic year (221 women and 522 men), which is largely representative of global averages. However, this is not commensurate with the percentage of women in engineering practice. In Morocco, the female-to-male ratio is 3:20 in information technology, 3:10 in computer science and 4:10 in engineering education and qualifications. However, a UNESCO survey on the contribution of higher education to the SDGs and the mandate to 'leave no one behind' stated that '[l]ately, it has been observed in Morocco that more than half of the students in engineering universities are girls'.

In Kuwait, women are encouraged to get an engineering education and typically account for 80% of engineering graduates. This statistic is also not reflective of Kuwaiti industry STEM positions as women are generally discouraged from engineering practice. According to the engineering training and alumni centre at the College of Engineering and Petroleum (COEP) in Kuwait University, a total of 4,872 engineers graduated for the 2017/18 academic year. Among these, female engineering graduates accounted for 3,901 (80%), however the majority settled for non-engineering roles in their workplaces.

On the surface, it may seem that women are dissuaded from engineering practice for no other reason than being female. However, there may be underlying issues that need to be addressed to correct this cultural nuance. One notable example is an instance where a major company in the Gulf region modified the design of their safety coveralls (mandatory worksite clothing) to fit designs that are culturally acceptable for women, making it easier for women to choose to work openly in engineering field locations and in a more welcoming environment. This single act increased the number of female applicants, with many Indigenous communities encouraging their women to work for this company. Perhaps more innovative approaches are required to address the cultural nuances in the region and hopefully open up new vistas of opportunities for women in STEM practice, thus reversing this demography.

Alternative energies in the Arab States

The sense of urgency around the fulfilment of the SDGs was palpable at the SDG climate facility signing event for the Arab region, an event held in Cairo, Egypt, on 16 March 2019 and hosted by Ahmed Aboul Geit, Secretary-General of the League of Arab States, and Mahmoud Abu-Zeid, President of the Arab Water Council. With only a decade left to achieve the targets underpinning the 2030 SDGs, leaders at the meeting restated the need to mobilize greater levels of ambition to help countries accelerate results to produce co-benefits across the SDGs. Targets facilitating the use of more alternative energy sources in place of carbon-intensive equivalents (e.g. fossil fuels) will help to realize both Goal 13 on climate action and Goal 7 on affordable and clean energy, and thus enable the achievement of other goals, including no poverty, zero hunger, and clean water and sanitation.

The above event is one of many hosted by governments in the Gulf region to demonstrate their commitment to fast-tracking alternative energy penetration and utilization. Decisions have been made and future goals have been set by most countries in the region to meet specific alternative energy penetration targets in their energy production mixes in the upcoming years. An overview can be provided by Arab Union of Electricity data for alternative energy penetration in 2013 and 2016 (Arab Union of Electricity, 2015; 2017). Gradual upscaling is observed with more effort needed across the board to match the goals set by countries in other regions.

In Kuwait, for example, during a UN climate change conference, the Emir pledged that the country will generate 15% of its electricity from alternative energy sources by 2030. The leadership of Dubai made a similar pledge to generate 7% of the city's electricity consumption from alternative energies by 2020, rising to 25% by 2030 and 75% by 2050, underlined by the official launch of the Fully Charged Sustainable City initiative. In Saudi Arabia, the 2030 vision includes the addition of 9.5 GW of electricity production from alternative energies, following a 16 MW (27.79%) increase from 58,462 MW to 74,709 MW between 2013 and 2016. Likewise, Jordan increased its proportion of electricity from alternative energies from 3,333 MW to 4,626 MW (38.79% increase) between 2013 and 2016.

Recommendations

1. Governments should produce studies utilizing data to forecast labour market shifts, and examine past trends, strategic direction and growth aspirations to guide student choices towards particular fields of study.
2. Universities should include courses that help achieve mindset changes for the younger generation, alleviating their dependence on available jobs and enabling them to create start-ups and job opportunities for others.

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Acronyms

ABCD	Active, blended, collaborative and democratic
ADB	Asian Development Bank
AI	Artificial Intelligence
CACEE	Central Asia Centre for Engineering Education
CEE	Continuing Engineering Education
COP	Conference of the Parties
CPD	Continuing Professional Development
CRIDA	Climate Risk Informed Decision Analysis
CSI	Enhancing climate services for infrastructure investment
CT	Computed tomography
DH	Digital health
DRR	Disaster Risk Reduction
EO	Earth observation
EPCS	Engineering Professional Certification System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH [Development agency, Germany]
IACEE	International Association for Continuing Engineering Education
ICEE	International Centre for Engineering Education
ICT	Information and Communication Technology
ICU	Intensive care unit
IEA	International Education Alliance
IFEES	International Federation of Engineering Education Societies (IFEES)
IoMT	Internet of Medical Things
IoT	Internet of Things
ITU	International Telecommunication Union
FIDIC	International Federation of Consulting Engineers
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GEDC	Global Engineering Deans Council
LAC	Latin America and the Caribbean
LLL	Lifelong learning
ML	Machine learning
NAP	National Adaptation Plan
NFIF	Non-formal and informal
OECD	Organisation for Economic Co-operation and Development
PBL	Project-based learning
PPE	Personal protective equipment
PPP	Private-Public Partnerships
RAEng	Royal Academy of Engineering (UK)
R&D	Research & Development
SDG	Sustainable Development Goal
STEM	Science, technology, engineering and mathematics
ULB	Urban Local Body
UNDP	United Nations Development Programme
UNIDO	United Nations Industrial Development Organization
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
WASH	Water, sanitation and hygiene
WCCE	World Council of Civil Engineers
WFEO	World Federation of Engineering Organizations
WHO	World Health Organization

Engineering for Sustainable Development

Delivering on the Sustainable Development Goals

Today's interconnected societies must find new ways of addressing sustainable development challenges in a holistic and interdisciplinary manner, drawing on the full spectrum of scientific knowledge and disciplines if they are to realize the 2030 Agenda for Sustainable Development and deliver on the 17 Sustainable Development Goals. However, to play their full part in today's globalized world, countries must have the scientific, technological and engineering capacity to provide sustainable solutions in areas such as health, agriculture, education, communication and industrial development. This is why engineering is a major driver for sustainable socio-economic development and why engineers are a vital profession in addressing basic human needs, alleviating poverty, promoting secure and sustainable development, responding to emergency situations, reconstructing infrastructure, bridging the knowledge divide and promoting intercultural cooperation. In this regard, the UNESCO Engineering Initiative will continue to reinforce its engineering activities by promoting engineering education at secondary and tertiary levels, and highlighting the roles and accomplishments of women and youth in the engineering field so that 'no one is left behind'.

Ten years since the publication of the first Engineering Report, as COVID-19 continues to spread across the world, the pandemic has revealed the multi-faceted contribution of engineering, whether in the design of 3D-printing, face masks, respiratory machines or innovative tracking systems. This second Engineering Report provides a snapshot of the work of engineers who are leading the charge to deliver on the commitments to and challenges of sustainable development. The report highlights the leading research, innovations and visions around the world for the future of the engineering profession at the dawn of the Fourth Industrial Revolution. UNESCO with its unique mandate in the sciences plays a crucial role in supporting its Member States to advance the science of engineering and to create knowledge societies that have the power to choose the future we want for the planet and its peoples.

It is in this endeavour that this report will serve as a reference point for governments, engineering organizations, institutions of education and industry to foster scientific exchange and excellence, to encourage investment in applied research and training in engineering, and to promote and catalyse international scientific collaboration and networks for the sake of sustainable development and for a future that is inclusive, equitable and resilient, and ready to meet the challenges of our rapidly changing world.

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