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Supporting Secondary School STEM Education for Sustainable Development in Africa

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SCHOOL OF EDUCATION

Contents

List of Abbreviations

ADEA	Association for the Development of Education in Africa: ADEA
AIMS	African Institute for Mathematical Sciences
AIMSSEC	African Institute for Mathematical Sciences Schools Enrichment Centre
AMI	African Maths Initiative
AVU	African Virtual University
CAP	Common Africa Position
CESA	Continental Education Strategy for Africa
CPD	Continuing Professional Development
CPE	Continuing Professional Education
DfID	UK Department for International Development
DRC	Democratic Republic of the Congo
FDI	Foreign Direct Investment
FTTEP	Fast Track Teacher Education Programme
GEMR	Global Education Monitoring Report
HDR	Human Development Report
ICT	Information and Communications Technology
ITT	Initial Teacher Training
JICA	Japan International Cooperation Agency
LSTT	Language Supportive Textbooks and Teaching
MoEST	Ministry of Education, Science and Technology (Kenya)
NAMTOSS	Namibian Technology Outreach to Secondary Schools initiative
PTR	Pupil to Teacher (or Textbook) Ratio
R&D	Research and Development
RiSE	Robotics inspired Science Education
SDG	Sustainable Development Goal
SDGs	Sustainable Development Goals
SMASSE	Strengthening of Mathematics and Science in Secondary Education
SSA	Sub-Saharan Africa
STEM	Science Technology Engineering and Mathematics
TIMSS	Trends in International Mathematics and Science Study
TESSA	Teacher Education in Sub-Saharan Africa
TTISSA	Teacher Training Initiative for Sub-Saharan Africa

TVET	Technical and Vocational Education and Training
UNDP	United Nations development Programme
USAID	United States Assistance for International Development
WAAW	(Foundation for) Working to Advance STEM Education for African Women

Executive Summary

Background and introduction to the study

This study provides the MasterCard Foundation (MCF) with strategic options for improving the quality of Science, Technology, Engineering and Mathematics (STEM) secondary education across Sub-Saharan Africa, which is essential if countries are to achieve the Sustainable Development Goals (SDGs) and close the gap between Sub-Saharan Africa (SSA) and the rest of the world in these fields.

Data suggests that there is low student attainment at secondary level, which leads to low enrolment at post-compulsory level. To combat this, the African Union has set out extremely ambitious targets for enrolment in STEM subjects which will require addressing the current poor quality of secondary education. Problems in attainment are evident at primary level, but it is at secondary level that pupils begin to specialise in STEM subjects; hence, the focus of this report.

The specific objectives of the report are:

- To consider the role of STEM education in addressing issues around sustainable development and youth unemployment.
- To outline practical challenges facing delivery of STEM education in secondary schools in SSA.
- To understand the barriers to attainment for pupils in STEM subjects.
- To consider examples of successful innovative practice in SSA.
- To consider barriers and facilitators for the scale-up of these practices across SSA.
- To make recommendations to MCF and outline opportunities for future interventions in STEM education.

Methodology

This study was a predominantly desk-based literature review, considering both academic and grey literature. Country-specific information was also obtained from the country scoping exercise undertaken within another area of the project. It considers STEM education to include traditionally academic subjects as well as more vocational subjects, and STEM-related extra-curricular activities.

It should be noted that there is an extensive body of research on STEM education outside SSA, from which lessons can be learnt.

The role of STEM education in sustainable development

National vision documents across SSA, mainly produced in the 1990s and early 2000s, focused on industrialisation and diversification as the way to achieving middle-income status. These priorities both depend on improving STEM knowledge, which is also vital to responding to the challenges produced by climate change. The more recent SDGs acknowledge three intertwined dimensions to the development process: human development, economic development and the environment. The African Union, through Agenda 2063, has responded to the SDG goals by setting out a vision of a continent with a diversified and industrialised economy which is environmentally sustainable and has good governance. National policies value STEM education for its role in developing human capital to achieve these goals and it is assumed that the general education provided at secondary level will lay the foundations for STEM education at the tertiary level.

Lower secondary education is now considered to be part of the basic education that all children are entitled to, under SDG 4. As such, it should be free and compulsory. In SSA, it usually takes the form of general education organised into subject disciplines that are taught discretely. For students who do not want to or cannot access this, there is often vocational provision (either formal or informal) which develops skills for artisan trades such as building or tailoring. Upper secondary education usually allows pupils to specialise, at least to some extent, and choose between academic and vocational routes. Both lower and upper secondary education are viewed as preparation for training or an apprenticeship leading into the world of work. There appears to be no real idea of STEM as a subject or disciplinary area.

In order to achieve economic, social and environmental development, the notion of 'sustainable work' adopted by the United Nations is used. Here, work is about more than jobs/employment, but includes unpaid care work, voluntary work and creative expression. STEM education has a role to play in all these areas.

Jobs/employment:

- Teaching of discrete science subjects prepares pupils well for becoming STEM professionals in, for example, research and design, engineering and mining or environmental protection.
- Work in human development (e.g. education, healthcare) and artisan or trade occupations may require a different type of STEM education, including applied technology.
- The shortage of formal employment opportunities means there is a need for skills for self-employment and entrepreneurship, such as business and problem-solving skills.

Unpaid work and non-specialist jobs/employment – 'everyday science':

- Currently, 'everyday science' (for example, about health and hygiene, and the impact of activities on the natural environment) is usually taught in more vocational courses at lower secondary level (e.g. domestic science, agriculture), which are non-compulsory and not universally available.
- Offering this type of knowledge, and building on their own indigenous knowledge, could make the STEM curriculum more relevant to all pupils.
- Teaching Combined Science, covering all three discrete natural science disciplines, could make science knowledge more accessible (although teachers would need to be trained in its delivery). This is increasingly important as enrolments increase.

Voluntary work and creative expression

- Voluntary work may include the communication of scientific ideas, for which pupils need to be able to use scientific language and concepts with confidence.
- STEM knowledge can enable creative expression, such as audio-visual editing, production of textiles – which may lead to self-employment.

STEM education at secondary level, then, has a vital role to play in sustainable development and the provision of sustainable work opportunities. Crucially, it needs to be relevant, attractive and accessible to all pupils, especially as secondary education becomes mass education.

Overcoming systemic challenges to a good quality STEM education

Suitably qualified mathematics, science and ICT teachers

The general shortage of qualified teachers in SSA is felt most acutely in STEM subjects. This is partly the result of rapid increases in enrolment, which has massively increased demand for teachers, which cannot be met. As a result, unqualified teachers are employed, and this is particularly problematic in STEM subjects which are especially vulnerable to being misconceived and misunderstood.

Recruiting teachers for STEM subjects is difficult for two reasons:

- There is a shortage of people with sufficient subject knowledge.
- People who do have sufficient subject knowledge go into other, more attractive, careers.

One solution, employed in a range of countries, is to encourage the study of STEM subjects at tertiary level. In Senegal, new programmes have been developed for this purpose. In others, such as Zambia Côte d'Ivoire fast track teacher training programmes have been established.

An additional problem is teacher retention, for which a number of solutions have been proposed, including higher salaries, differentiated salaries, smaller class sizes and mentoring.

Class size and level

Problems relating to high pupil teacher ratios and mixed level pupils in single classrooms, found across SSA, are particularly difficult to cope with in STEM subjects, particularly science and technology subjects which require students to works hands-on with scientific equipment. Teachers are often untrained in mixed level teaching, leading to a mismatch between teacher expectations and pupil abilities.

Resources

STEM subjects, particularly science and technology, have high resource needs, including equipment, consumable materials and textbooks. This puts a strain on systems that already struggle to provide the basic infrastructure. Textbooks are critical, but they are often of poor quality and in very short supply in SSA.

Ambitious curriculum plans which make ICT and other STEM instruction compulsory in secondary schools are often not matched by resources, with teachers relying on theoretical explanations and teacher-centred content delivery.

Where resources have been committed, there are also problems. For example, in Malawi a commitment to delivering 700 science kits to schools saw only 200 being delivered, and in South Africa a set of well-received workbooks are still only being used by 80% of teachers, due to problems with delivery and concerns about quality.

Programmatic responses

There are two examples of programmes that seek to address interrelated systematic challenges. Both are from South Africa and both identify well managed schools and willing teachers as critical to their success.

- Dinaledi Schools programme: aims to raise attainment in secondary mathematics and science by providing 500 selected schools with a variety of inputs, based on the needs of the school, including additional teachers, in-service teacher training, textbooks, scientific calculators, computers and other learning support materials. The programme has successfully raised attainment in mathematics and science.
- Inkanyezi Project: provides for high ability disadvantaged learners to improve attainment in mathematics and science and gain entrance to university courses by supporting them in a range of ways, including placing them in particular schools and paying for holiday camps. There is also an element of teacher training. The programme has been successful in improving numbers of pupils with passes good enough to gain university entrance.

Outdated curricula and curricular change

Problems with existing curricula:

- Tension between the different aims – of the country and employers, of the pupils, and of the subjects.
- Have not been adapted to wider ability range due to increased enrolment.
- Have been overloaded with new material, e.g. relating to HIV/AIDS, with no old material being removed.
- Are now often competency based with learner-centred pedagogy, but teachers lack the skills or resources to deliver lessons in this way.
- Do not acknowledge the debt owed to Indigenous Knowledge Systems, and so lack relevance and can be alienating.

Examples of existing solutions:

- In South Africa, pupils are offered the opportunity to study mathematical literacy instead of mathematics at upper secondary level. Despite the best efforts of curriculum designers, this is seen as an easy option, and has resulted in some schools not offering mathematics at upper secondary at all.
- iSPACES framework in Tanzania sets traditional scientific work in the context of real problem solving, fostering innovation and entrepreneurship and contributing to the achievement of the SDG goals.

Examinations in STEM subjects

Examinations in SSA are very high profile, but have not kept pace with educational change, requiring rote learning and low level thinking. There appear to be no initiatives aimed at changing this, although this could potentially be a very cost-effective approach.

The data generated by examinations could also be useful in increasing attainment, but currently this is not the case, except for the West African Examinations Council, which publishes model answers and comments on the performance of candidates, and Mauritius, which also publishes high quality subject-specific examination reports. These examples could be used as a model for the rest of SSA.

Overcoming classroom challenges in providing good quality STEM education in sub-Saharan Africa

Teacher subject knowledge

Research shows that good teacher subject knowledge is particularly important in the teaching of STEM subjects. Subject knowledge is deepened at University level, but is also address through ITT and CPD.

ITT is offered by both government and non-governmental organisations. A UNESCO report looking at five countries across SSA found it to be ad hoc, fragmented, and vulnerable to changes in external donor funding.

CPD is offered through a range of organisations and methods:

- JICA projects to strengthen Mathematics and Science in secondary education (SMASSE) exist in a number of countries. They use the Japanese Lesson Study model which requires teachers to work in face-to-face teams to discuss and improve their practice. These have had variable success, which appears to be partly dependent on the teachers’ willingness to commit to the programme.

- Distance or blended learning programmes in Senegal and South Africa enable more teachers to participate, but suffer from high dropout rates and difficulties in access due to limited Internet access.
- Institute of Physics supports teachers to do practical work with pupils through STEM centres which use low cost, available and appropriate resources. This has been successful and is popular with teachers.
- There are many initiatives aimed at improving teachers' ICT skills such as UNESCO's TTISSA, African Virtual University's Teacher Education Project, Namibian Technology Outreach to Secondary Schools initiative.
- Mathematics Teacher Training Program at AIMS in Cameroon is using a cascade model, with master trainers training school maths teachers, to improve content and delivery. Anecdotal evidence suggests that the programme would have benefitted from more research-based planning.
- Provision of free online resources (e.g. TESSA initiative); uptake is low, but could provide a cost-effective approach.

Teachers pedagogical skills

The introduction of child-centred learning and inquiry driven approaches across SSA policy poses real challenges to teachers, often due to high pupil teacher ratios, hierarchical school structures and examination requirements. In the Gambia, the Progressive Teaching Initiative has been introduced to deal with this issue. The Mindset Learn programme in South Africa models good, learner-centred teaching by supplying videos of lessons. Also in South Africa, there is a '1+4' scheme where teachers meet up with colleagues and subject advisors for one day per week to discuss content knowledge and share strategies; this is very challenging to administer.

This overview shows numerous schemes to improve both content and pedagogy, but they lack robust evaluation and coherence.

Language of instruction

Learning STEM subjects is linguistically challenging for any pupil. Learning STEM subjects through a language that is less familiar to pupils is even more challenging. Teachers often deal with this, against school policies, by switching to indigenous languages in explanations. The difficulties mean that pupils often gain only a superficial understanding of the content. The LSTT project in Tanzania, which supplies language accessible textbooks, has improved pupils' engagement and knowledge. Extending this could be a highly cost-effective strategy.

Formative assessment

Formative assessment is often written into policies in SSA, but implementation is weak.

Assessment Resource Banks in South Africa have had some success in improving practice by supplying materials, although there were problems with photocopying and differentiation.

Formative Assessment in Science and Mathematics Education (FaSMEd) in South Africa has provided a formative assessment toolkit including lesson ideas and a set of professional development modules.

The South African Innovative Learning Intervention (SAILI) is helping schools make more effective use of assessment data to develop strategic priorities for interventions, with substantial improvements in attainment. This is another cost-effective strategy in countries where assessment data is readily available.

Attitudes and values towards education, mathematics, science and ICT

Some research indicates that the values and attitudes towards STEM subjects in SSA countries contributes to poor performance. A range of strategies have been employed to counter this, although they lack rigorous evaluation. Initiatives include Science Circus Africa (travelling exhibitions, science shows and teacher workshops), African Maths Initiative (week-long residential maths camps), and Robotics inspired Science Education (two-day workshops with theoretical lectures and practical activities).

Resources to help pupils self-study have also been developed. The Microsoft Maths service helps upper secondary pupils in Tanzania and South Africa with revision and homework, and is reported to have improved attainment. A series of study guides in South Africa has had success in improving attainment in life sciences and is being developed for other STEM subjects.

The African Maths Initiative also helps pupils to set up Maths clubs in their schools.

Gender

Girls do less well in STEM subjects than boys and are under-represented in science-related careers. Research in Zimbabwe indicated that teachers need more training in gender responsiveness, as well as a need for positive female role models in STEM classrooms.

Initiatives to tackle this, by the Foundation for Working to Advance STEM Education for African Women, include week-long camps for girls in Nigeria and Kenya, which have been shown to make a positive change in pupils' attitudes.

Conclusions and implications for future MCF support for secondary school STEM

The challenges faced

- The challenges are wide-reaching and inter-related, including problems with teacher recruitment and retention, poor resources and infrastructure, inappropriate curricula and poor assessment practice. These problems translate into teachers with inadequate subject and pedagogic knowledge, and disengaged and unenthusiastic pupils.
- These problems, while being continent-wide, manifest themselves differently in the different countries.
- There is limited systematic evaluation of different interventions, so it is impossible to compare within or between national contexts.
- There is little internationally comparable data on performance in STEM-related subjects.
- Tackling these problems requires a strategic, holistic approach.

Possible areas for future intervention for MCF

- Act as a repository for successful practice, collating information about successful interventions and disseminating this across SSA.
- Contribute to the existing evidence base by commissioning further research into the impact of interventions on learning outcomes for disadvantaged learners.
- Contribute to the development of curricula and assessments by commissioning research into curriculum design and providing expert advice and guidance, which take into account international best practice.
- Act as a 'broker' for different initiatives using existing networks to bring together stakeholders to produce coherent initiatives.

- Contribute to the development of communities of practice made up of the different stakeholders (see above), and sharing practice and providing training through, for example, webinars, conferences and workshops.
- Develop value-for-money resources, building on existing initiatives, e.g. successful textbooks, science kits, virtual laboratories.
- Develop hubs of excellence in STEM, bringing together the areas outlined above at different scales, e.g. single secondary schools, regional centres and national centres. These could include policy makers and officials as well as practitioners.

Chapter one: Background and introduction to the study

The MasterCard Foundation commissioned this study as one component of the “Improving Secondary School Teacher Quality in Sub-Saharan Africa” project, being conducted by the University of Bristol, UK, in collaboration with the MasterCard Foundation (MCF). This study focuses on one core aspect of improving the quality of secondary education – the teaching of STEM (Science, Technology, Engineering and Mathematics) subjects.

Developing relevant skills in STEM is critical for achieving the Sustainable Development Goals (United Nations, 2016). However, there is a serious skills shortage in STEM areas such as engineering and technology that limits the capacity for African-led development and increases dependency on foreign expertise (African Union, 2014). Further, according to a recent World Bank report (World Bank & Elsevier, 2014) although African universities have made progress in the amount and quality of their research outputs in STEM subjects, the continent continues to lag behind much of the rest of the world as does Africa’s share of innovation in science and technology (UN, 2016).

The problems, however, begin much earlier with worryingly low performance in mathematics and science at school level (African Union, 2014; Bethell, 2016). Understanding the scale of the problem facing school based STEM education is a challenge due to a lack of accurate, comparable performance data. What limited data there is paints a worrying picture. For example, only a small number of sub-Saharan African (SSA) countries have participated in the Trends in International Mathematics and Science Study (TIMSS) comparisons on student attainment at secondary level. In the 2011 assessment Ghana, South Africa, and Botswana presented as three of the four lowest attaining countries in both mathematics and science. On average, even the best performing SSA students achieved considerably lower marks than the global average percentage in both subjects for 2011 and 2015. Again, in 2015, South Africa and Botswana were two of the lowest-scoring three countries in both subjects. This cursory review of student attainment at secondary level indicates a continent-wide trend of low student attainment, which provides context for the similarly low STEM enrolments at the tertiary level. The Planet Earth Institute, an NGO that states its goal as ‘working for the scientific independence of Africa’, claims that ‘only 1 in 10’ students are choosing STEM subjects at university (Planet Earth Institute, 2016).

In order to address the shortage of STEM skills, the recent Africa 2063 Framework Document (AU, 2015) has set out an ambitious vision for an African Renaissance with STEM at its heart. The vision is that at least 70 per cent of all high-school graduates go on to have tertiary education, with 70 per cent of those graduating in subjects related to sciences and technology. To put this in context, the ambition is twice the current global average enrolment of 32 per cent and more than eight times the current Sub-Saharan African average of eight per cent. The report acknowledges, however, that in order to achieve this vision, Africa must address the challenge of a poor quality of STEM education further down the education system.

In considering the need for STEM professionals in the sustainable development of the continent, it is essential to understand the inhibiting factors that preclude students from reaching a level where they are able to even enrol in STEM subjects at the university level. To some extent the problem lies in the poor quality of primary education in SSA. Basic competency in mathematics and literacy is a prerequisite for attainment in STEM subjects at secondary and tertiary level but are seriously lacking amongst many secondary school learners[1]. It is at secondary level, however,

[1] For example, in Francophone countries, PASEC (2015) assesses competency in mathematics for end-of-primary students against a ‘sufficiency threshold’. In the entire SSA Francophone region, 59% tested below this threshold, with Côte d’Ivoire at 73.1% and Senegal at 41.2% below the threshold. Similarly, SACMEQ (2010), which has measured changes in numeracy and literacy levels from 2000 to 2007 in ten Anglophone Southern and Eastern African countries provide an equally bleak picture although with significant variations between countries. Malawi and Zambia presented with the lowest scores, though

that students begin to specialise in STEM subjects and where the biggest bottleneck occurs in progression to higher levels of the system, hence the focus of the current report.

The overall purpose of the study is to provide MCF with strategic options for strengthening secondary school STEM education in SSA. The specific objectives are:

- To consider the role of STEM education in relation to contemporary global policy debates including the skills required for sustainable economic, social and environmental development and for tackling youth unemployment;
- To outline the practical challenges facing STEM teachers within secondary education in Africa;
- To understand the barriers to ensuring all secondary school students perform well in STEM subjects;
- To consider evidence of successful innovation in STEM education for raising learning outcomes for disadvantaged learners in difficult delivery contexts;
- To consider evidence of the barriers and facilitators for the adoption, implementation and scale-up of successful STEM innovations and examples of successful practice;
- To make recommendations for future interventions in quality STEM teaching and learning and how these might best be supported by MCF;
- To outline areas of opportunities in STEM education in Africa.

The study is predominantly a desk-based literature review of the current state of STEM education in SSA. This included academic as well as grey literature accessed through the Internet. The study also draws on grey literature and interview data collected as part of a country scoping exercise undertaken by the Bristol team (Doyle, Barrett, & Reeves, 2017) in five sub-Saharan African countries, Zambia, Malawi, Cote D'Ivoire, Malawi and Senegal. Drawing on evidence from specific country contexts allowed for a more grounded approach towards understanding the issues.

The report takes a working definition of STEM at secondary level to include the natural sciences (physics, chemistry and biology), mathematics and technology-related subjects, including ICT and more applied vocationally-oriented subjects, such as agriculture, technical drawing, domestic science, which usually, where they do appear on school curricula, are offered as optional subjects. It also includes extra-curricular activities, such as science or technology clubs, and linkages with science or technology-based industries, e.g. through internships for secondary school students. Engineering, as such, is not taught at secondary level as a school subject. STEM skills lay the foundation for the development of higher order scientific, technological, engineering and mathematical skills at tertiary level and in the formal and informal economy.

Achievement in STEM subjects and attracting young people into STEM subjects at post-compulsory level are concerns in many geographical areas outside SSA. Much has been written about the current state of affairs and many recommendations have been made (for a synthesis of reports about mathematics education in the UK, for example, see Joubert, 2016; and for a report on STEM education for engineering in the UK see Morgan, Kirhy, & Stamenkovic, 2016). Many initiatives to address these concerns have been implemented, and lessons could and should be learned from these.

Chapter two positions STEM capabilities relative to global and regional visions and aspirations for sustainable development and outlines the priorities these generate for secondary education. Hence, it provides a rationale for an overall focus on secondary level STEM education. Chapters

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Tanzania's scores were significantly above average for the region. Despite this apparent improvement, an additional study conducted in Tanzania (Uwezo, 2016) surveyed 7-16 year olds on their ability to do simple numeracy operations at standard 2 level. This study found that results had declined slightly since 2012, and varied greatly between urban and rural areas, with pass rates being considerably lower in rural areas.

three and four focus on some of the key challenges towards developing STEM education in SSA and discusses how governments, donors and NGOs are responding to these, identifying gaps. Whereas Chapter three focuses on systemic issues, Chapter four hones in on the classroom level and the pedagogical challenges involved in delivering a good quality STEM education. Drawing on the insights developed in the previous chapters, Chapter five sets out options for MCF for strengthening secondary school STEM subjects in SSA.

Chapter two: STEM education for sustainable development

This chapter considers the role of STEM education in relation to contemporary global policy debates including the skills required for sustainable economic, social and environmental development and for tackling youth unemployment. International policy agendas along with the governments of many SSA countries, have for many years been concerned with economic growth and human development. They have been underpinned by shared ideas about development that have shifted from a main focus on modernisation to notions of knowledge economy and knowledge society to sustainable development. Each placing a slightly different emphasis on the purpose and relative importance of each educational level and how STEM capabilities contribute to development. Recognising that the Sustainable Development Goals (SDGs) will influence the direction of national level policy making focuses attention on the contribution that teaching and learning of STEM at the secondary level makes to sustainable development and, conversely, the implications of the SDG agenda for the content and processes of secondary STEM education.

The chapter starts by briefly setting out an understanding of the UN sustainable development agenda. It then looks at the regional vision for development, set out in the AU's Agenda 2063 (AU, 2015) and its response to the post-2015 development goals.

Then the meaning and sub-levels of secondary education are clarified. The main body of the chapter draws on the notion of sustainable work set out in the latest Human Development Report 2015 (UNDP, 2015b) to highlight the main purpose of secondary school STEM education and implications for quality of STEM teaching.

1. Sustainable development visions

Development Visions, the highest level of policy document, for low or lower middle-income sub-Saharan African countries tend to follow a similar pattern. They set out an aspiration to achieve middle income status through industrialisation and diversifying the economy. Value added manufacturing and service industries depend on mathematical and scientific knowledge, advanced levels of proficiency in literacy, cognitive skills (e.g. abstract thinking, problem-solving, e-literacy) and non-cognitive skills (e.g. self-regulation, organization and planning skills) that are developed through secondary education (Lewin, 2008).

Many of these Development Vision documents were written in the late 1990s or early noughties (Doyle et al., 2017). Ideas about the knowledge economy backed by evidence from rates of return analysis reinforced the role of secondary education in developing the cognitive skills for the uptake of new technologies, in agriculture, in industry but most especially through benefiting from the rapid development and geographic penetration of information technologies (Chen & Dahlman, 2005; Robertson et al., 2007). Our environment is also changing quickly, through climate change, environmental degradation and acceleration of urbanisation and this too multiplies up the benefits of a secondary education that prepares socially responsible citizens with the knowledge, skills, attitudes and values to respond to uncertainty creatively and with resilience (Bangay & Blum, 2010).

At the international level, the SDGs flag a realignment in how social progress and international development is viewed and measured. At its core, the sustainable development agenda is an acknowledgement of the interlocking relationship between human and natural systems (Sachs, 2015; Stiglitz, Sen, & Fitoussi, 2009). In UN documents this is expressed as development with three dimensions – the economic, social and environmental (UN, 2016). The 17 SDGs include goals for human development (poverty eradication, hunger eradication, health and wellbeing, education, peace and justice); economic development (decent work and economic growth; sustainable production and consumption; industry, innovation and infrastructure) and the environment (affordable clean energy, climate action, ocean conservation, protection of terrestrial ecosystems). Although the three dimensions are sometimes represented as pillars, they are increasingly viewed as intertwining complex systems, “integrated and indivisible” (UN, 2016: 3). Several of the SDGs cut across more than one dimension (gender equality, clean water, reducing inequalities, sustainable cities and communities).

African leaders have responded to the SDG agenda by setting regional priorities within the ‘Common Africa Position (CAP) on the post-2015 development agenda’ (African Union, 2014) and then later, Agenda 2063 (AU, 2015). Both emphasised structural transformation for inclusive economic development through modernisation of agriculture for food self-sufficiency, improved nutrition; industrialisation that adds value to primary commodities and diversifies the economy; developing the service sector and infrastructure development. Education is recognised to contribute to the development of human capital for realising this vision. Commitment to environmental sustainability focuses on improving natural resource management, access to safe water, mitigating and responding to climate change, environmental degradation and natural disasters. CAP also included a commitment to effectively managing conflict and preventing armed conflict. Agenda 2063 reinforced this vision for development but placed a greater emphasis on peaceful societies and good governance. It highlighted the opportunity presented by the availability of renewable energy sources for environmentally sustainable development through global forums. Most strikingly, however, Agenda 2063 leads with a coherent vision for a continent united through mobility of people and free trade made possible through an extensive communications structure and harmonization of education qualifications, particularly at the tertiary level. It also puts forward a confident projection of Africa as major political voice, which with a unified voice can demand its partners join in “sustainable management of the global commons” (African Union, 2014, p. 17), including the planet’s natural environment, cross-border communicable diseases, multilateral trade and international financial systems, and global knowledge for development.

In our country scoping studies of Zambia, Malawi, Tanzania, Senegal and Cote d’Ivoire, we found that at the national level policy rhetoric justifying expansion of secondary education aligned with the first of the seven Agenda 2063 aspirations, that of a diversified and industrialised economy. Indeed, this has been a consistent theme of regional policies and plans over the last 30 years (Kinyanjui & Khoudari, 2013). Hence, mass secondary education has been seen as necessary for developing human capital for modernizing and diversifying agricultural, for growing industries that add value to primary commodities produced by agricultural or resource extraction and for growing and strengthening the service sector. How secondary education contributes to this economic vision, however, was poorly articulated. We found little evidence of inter-sectoral planning that considers how secondary provision articulates with access and availability of primary and tertiary education; or how and whether expansion of secondary should be coordinated with investment in industry and demand for labour. Mathematics and science subjects were promoted, particularly in Tanzania and Senegal, as important for industrialisation and ICT as important for entrepreneurship. However, there appeared to be little debate about technology, other than ICT, in the secondary curriculum. It was taken for granted that within a general secondary education, mathematics and natural sciences laid the foundations for learning about technology at the tertiary level, an assumption that national policy makers shared with the authors of Agenda 2063 and CESA (African Union, 2014).

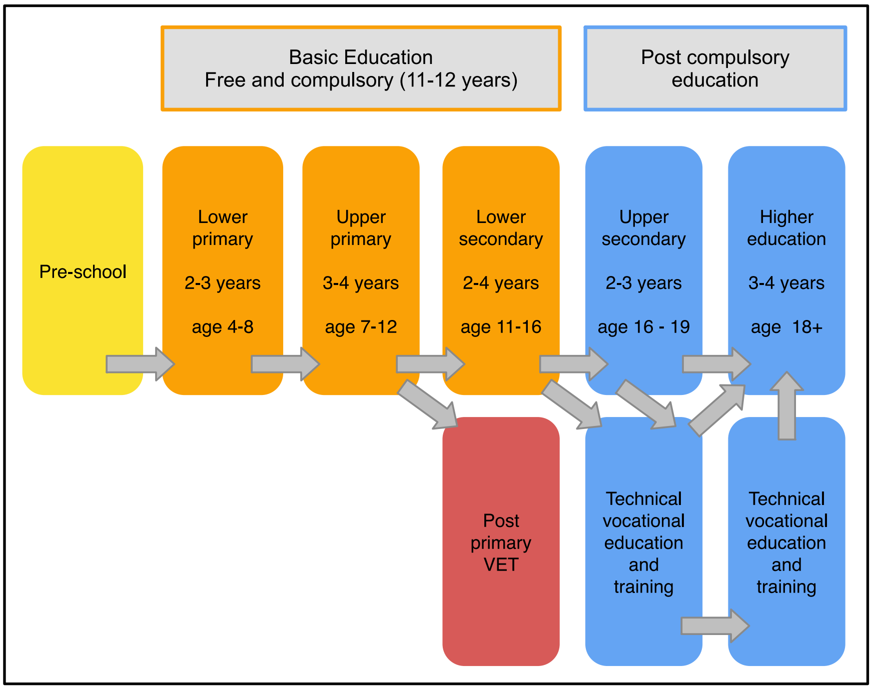
2. Organisation and purpose of secondary education

Typically, secondary education follows 6-8 years of primary education and is divided into two stages, lower and upper secondary (see figure 2.1). The Education Sustainable Development Goals (SDG4) is the first UN development goal to include lower secondary as part of the basic education cycle, which should be free and compulsory for all children. It is usually 2-4 years in duration and it “extends and consolidates the basic skills learned in primary school” (UNESCO, 2016b). Generally, countries such as Kenya and Malawi that have longer primary education cycles of 8 years have shorter secondary education cycles, a total four years for lower together with upper.

It is either at the lower secondary or upper primary level that subject disciplines are taught in discrete periods of the school timetable by subject specialist teachers. Sociolinguists have observed that at lower secondary, children start acquiring formal registers of the language of instruction and academic language (Halliday, 1995). In other words, lower secondary is when children start to engage with formal codified knowledge and make connections between formal knowledge and the informal common sense knowledge of the home and community, often associated with disciplines. Lower secondary then, is about extending general education and laying the foundation for the skills, knowledge, values and attitudes that young people will need in their everyday lives. It takes them a step closer to an academic career or vocational education, training or apprenticeship.

In many rural African communities, where access to lower secondary is far from universal and a high number of learners are over-age for their grade by the time they complete primary education, post-primary vocational is a preferred and more accessible alternative to lower secondary. Vocational education and training at this level tends to focus on developing skills for an artisan trade, such as building, carpentry, tailoring. Post-primary vocational education may be provided by local government, community organisations or variously formal/informal small scale entrepreneurial providers.

Figure 2.1



Specialisation typically begins at upper secondary and it is at this level that young people have to choose between an academic or technical/vocational route. Within the academic route, they are usually constrained to choose between sciences, humanities or modern languages. Typically students may study around three subjects to advanced level but may be required to also pursue between one and three subsidiary studies (e.g. general studies, entrepreneurship, computer skills, basic mathematics). As an alternative to secondary education, more specialised vocationally oriented tertiary education is often available. Upper secondary education is often viewed as preparation for higher education and vocational education as preparation for work. However, some specialised tertiary institutions focus on preparing students for access to specific higher education degree programmes offering Diplomas in Law, Computer Sciences etc). Upper secondary is about deepening general education and acquiring specialised academic knowledge, usually as preparation for higher education.

Both lower and upper secondary then lay a foundation for the knowledge, skills, values and attitudes that young people need as they enter the world of work and start to contribute as adults to their communities. It does not usually provide the technical skills for an occupation or profession but should prepare learners to start training or an apprenticeship that leads to a recognised occupation or profession. 'Work' here is understood broadly according to the definition of 'sustainable work' in the latest Human Development Report (UNDP, 2015), which is explained in the next section. Even technical and vocational pathways at the secondary level do not usually develop the complete set of technical skills and knowledge needed for a specific trade or profession. However, selection of optional subjects and levels of achievement do have implications for tertiary level education and training opportunities, whilst laying down a foundation for life-long learning.

3. Secondary education for sustainable development

The hybrid nature of secondary education as a broad-based general education but offering some specialisation seems to lead to weak conceptualisation of its contribution to STEM capabilities. Agenda 2063 includes the following action concerned with education:

> Catalyse education and skills revolution and actively promote science, technology, research and innovation, to build knowledge, human capital, capabilities and skills to drive innovations for the African century …

Eight specific actions follow under this headline action, four of which concern universities. Secondary education is only specifically mentioned within the first action, alongside early years and primary education. In other words, secondary education is treated as part of the general basic education cycle. Nonetheless, in most African countries and indeed, many countries around the world including industrialised countries, upper secondary is a post-compulsory offering and is far from accessible for all. CESA's strategic objective for TVET specifies "opportunities at both secondary and tertiary levels". The six bullets that follow make no explicit mention of secondary education but only refer to polytechnics, tertiary and vocational training. A close reading of CESA suggests four ways in which secondary education may contribute to developing STEM capabilities for the Agenda 2063 vision of development. These are:

1. Relevant and inclusive mathematics and science curricula that build on indigenous knowledge
2. Offering Technical and Vocational Education and Training (TVET) opportunities
3. Expanding linkages with the world of work
4. Extra-curricular activities

However, only the first in this list is firmly pegged to school education within the text. It is worth noting that alongside its concern with science and technology research and innovation driven by universities, Agenda 2063 also aspires to a 'scientific culture' within a 'knowledge society' although it does not elaborate on what is meant by 'scientific culture'. It also emphasises the need to build on indigenous knowledge.

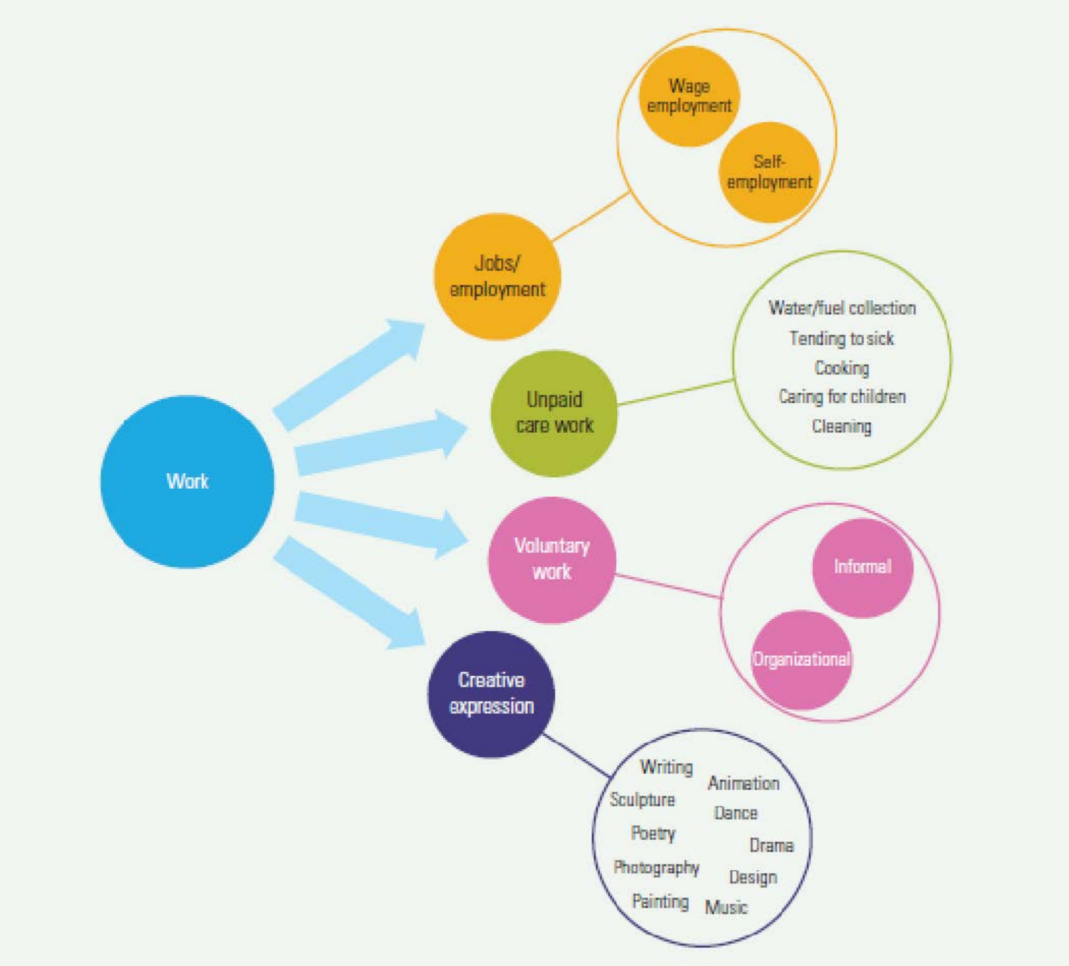
International literature on education for sustainable development, points out that the uncertainties of rapid technological and environmental change demand the preparation of flexible, creative, critical thinkers (Bangay and Blum, 2010), prepared to learn throughout their lifetime and with the skills and values to engage in sustainable work that has social as well as economic purpose and minimizes impact on natural environments (UNDP, 2015a). Secondary education bridges between a broad-based general education and specialised academic or vocational tertiary education and hence has a crucial role to play in building societal capabilities for sustainable development. Drawing the natural environment into the sphere of concern for international development, has been argued to reinforce the place of natural sciences and mathematics in the secondary curriculum and expands their purpose (Wals, Brody, Dillon, & Stevenson, 2014). Secondary education lays down a broad foundation of scientific knowledge and methods of inquiry. It is the level of education where young people take their first steps towards specialisation. Through its curriculum, it broadens students' cultural horizons beyond their local and national contexts and brings an appreciation of their position within regional and international systems. At the same time, secondary education can also develop skills for teamwork, use of digital technologies and problem solving (UNDP, 2015). Indeed, the breadth of secondary education should allow for interdisciplinary inquiry that applies scientific knowledge and to pressing social and environmental issues and their relationship to local and global forces (Matthewman & Morgan, 2013). However, much depends on curriculum design, assessment and how teachers understand their role as educators.

Hence, secondary education has a powerful role to play in developing STEM capabilities for Africa's vision of industrialisation and a diversified economy. It also has the potential for developing knowledge and values to support sustainable development. In order to understand how secondary education articulates with tertiary education to achieve this the next section uses a framework for sustainable work from the 2015 Human Development Report (HDR2015) (UNDP 2015).

4. Sustainable work for economic, social and environmental development

HDR2015's notion of sustainable work is used here to explore the purpose of STEM learning in secondary education and the various ways in which it lays a foundation for various forms of formal and informal, paid and unpaid work. The notion of 'sustainable work' encourages a break with the view of work as being solely for financial gain or profit and recognises the many forms of work that are not paid, as well as informal work that is for profit, but nonetheless make a valued contribute to society and/or the natural environment (see figure 2.2). Figure 2.3 expands HDR2015's categories of work to identify the forms of STEM knowledge demanded by each. The discussion explains how secondary education contributes to developing these forms of STEM knowledge.

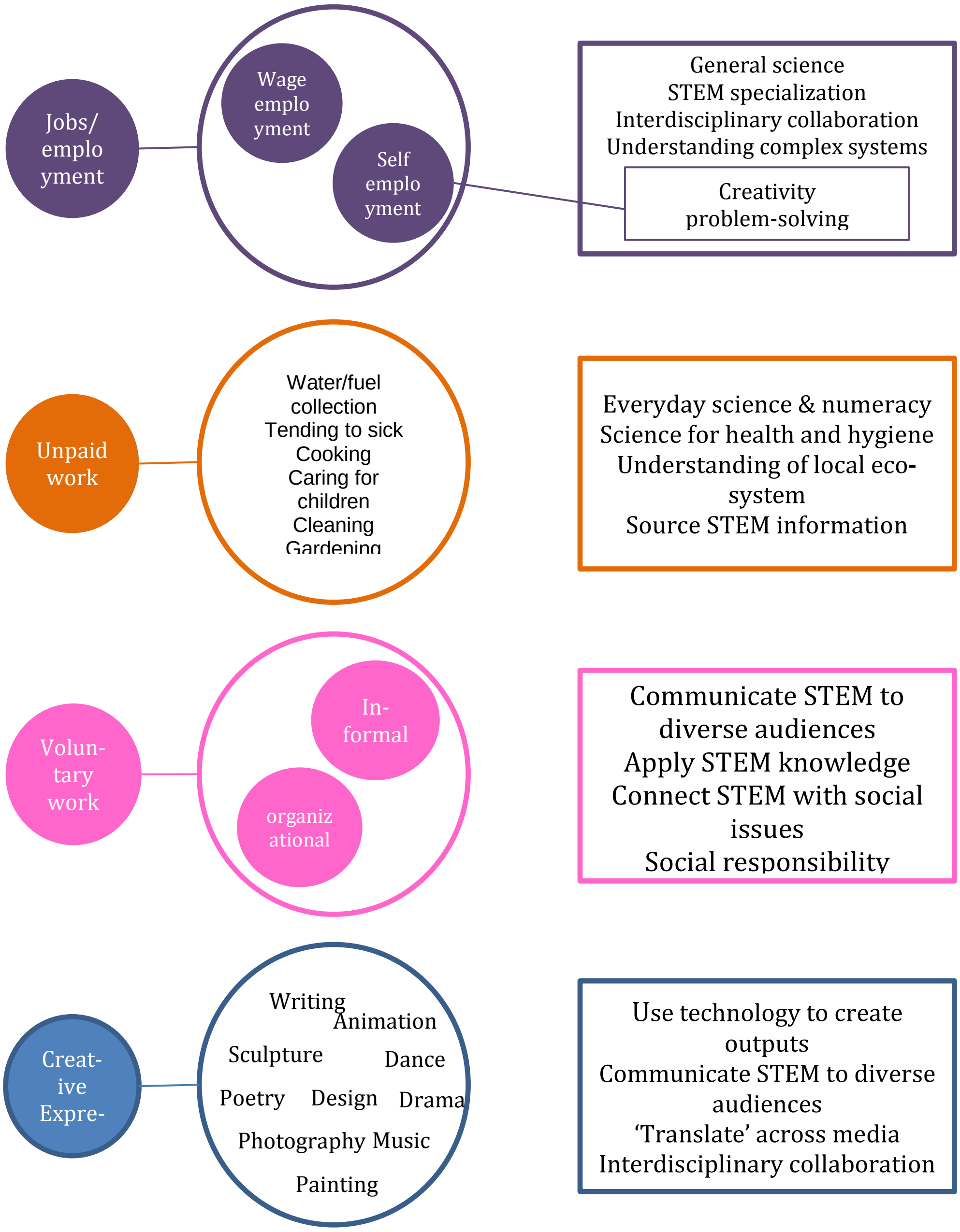
Figure 2.2 Sustainable work is more than jobs (Source: UNDP, 2015: 31)



5. Jobs/Employment: secondary education as preparation for STEM work

Jobs/employment is clearly a very wide category that includes employment that requires a high degree of specialisation in skills and knowledge to those that are unskilled. Of interest here is the jobs that require STEM specialisation. These fall into the categories of research and design (R&D); manufacturing and productivity, including in agriculture, engineering and mining; training, education and communication; environmental protection and social care and development. For STEM professionals working in any of these roles (and they often overlap), upper secondary is the first step in an extended educational career that involves several years of higher education to acquire advanced highly specialised skills and knowledge.

Figure 2.3: STEM education for sustainable work (author's adaptation)



STEM R&D: an academic curriculum

The need for independent STEM R&D led from within the African continent to solve 'African problems' has been highlighted by the lobbying organisation, the Planet Earth Institute, and, as pointed out above, is theme within the AU's Agenda 2063. A recent study by The World Bank and Elsevier (2014) found that the quantity and quality of STEM research is much lower than that emerging from any other world region, that research tends to depend on international collaborations and be heavily skewed towards agriculture and health sciences (World Bank & Elsevier, 2014). Shortage and high mobility of researchers in STEM subjects, particularly physical sciences, is one reason for this. Whilst Agenda 2063 places emphasis on agricultural research for food security it also highlights research for manufacturing, natural resource exploitation, development of bio-energy and communications infrastructure.

The reading of AU documents above, shows how a vision for a diversified industrialised economy is the dominant, although not only discourse, running through regional policy relating to science, technology and innovation. This together with the heavy emphasis placed on STEM R&D and, in the 1990s, the notion of knowledge economy, creates a pressure for an academic, theory-oriented secondary school science curriculum as a preparation for disciplined based higher education. Hence, natural sciences are delivered as three discrete subjects, each with its own subject specialist teachers. However, this is not necessarily the best preparation for the vast majority of secondary school graduates, many of whom may move into professions that apply STEM expertise alongside other types of knowledge and skills.

Currently, it is not the quality of the secondary education curriculum that impedes STEM R&D so much as the sharp inequalities in access and quality of secondary education, which prevent the majority of talented young people from disadvantaged communities from accessing higher education. Scholarship programmes, such as the one sponsored by the MasterCard Foundation, are designed to address this through singling out promising students for financial support early at some point during the secondary education. Needless to say, these need to be complemented by initiatives that improve access and quality for all in educationally disadvantaged communities.

Social professions: critical STEM education for health and education

Human development requires a professional workforce that has completed both a secondary and tertiary education. HDR2015 conservatively estimates that achievement of the SDG education and health targets for the sub-Saharan African region require an additional 5.7 million teachers (2.1 million for primary and 3.6 million for secondary) and 3.8 million health workers respectively, not taking into account pre-school teachers, trainers and managers. Supply and preparation of entrants for specialised tertiary training for these professions clearly depends on availability of quality lower and upper secondary education. Secondary school graduates aiming to work in social professions do require a grounding in science and mathematics. However, for education and patient facing roles within health provision, interpersonal skills and communication skills are also paramount, including the ability to communicate scientific knowledge effectively to people, who may not have completed secondary school and may not be fluent in a national language. Consideration of these destinations highlights the need for a curriculum that develops written and verbal communication skills, makes connections with local knowledge systems or worldviews and considers ethical and social issues that relate to science. In short, a critical education that is concerned with the cognitive, creative, affective and moral development of leaners (for more on this see section 2.7 below).

Technology-based occupations: technical and vocational options

Currently, in many low income countries, the formal sector cannot absorb all the graduates from formal basic education. In sub-Saharan African countries, as well as much of agricultural work, 66% of non-agricultural work in sub-Saharan Africa is informal (UNDP, 2015: 63). Secondary education, therefore, should lay the foundational skills for self-employment and entrepreneurship. This includes business skills, problem solving and creativity but also confidence and leadership skills. Poor language skills of students and insecure subject knowledge of teachers contribute to superficial learning, where students learn to reproduce memorised text, rather than the production of meaningful written or spoken outputs by the learner (Barrett and Bainton, 2016). Contextually relevant, linguistically accessible learning resources that relate scientific knowledge examples and problems within their own environment can support the development of problem-solving skills.

Artisan or trade occupations, e.g. building and construction, motor mechanics, electricians, textiles, also require STEM knowledge, with more emphasis on technology. Training for these occupations currently takes place predominantly in technical and vocational schools or else tertiary TVET institutions. Variously formal/informal provision is available for young people, who do not continue onto secondary education, for example, delivered by local government, NGOs, or small-scale local businesses and enterprises. Universalisation of secondary education raises key questions around to what extent applied technology subjects (e.g. technical drawing, design and technology, agriculture, domestic science) should be included in secondary education. Should they be offered as options within general schools or should students be selected into academic and vocational schools? Should vocational and academic streams start at lower or upper secondary? Which subjects should be offered? What opportunities are there for secondary schools to collaborate with local providers of Vocational Education and Training (VET) that have a track record of training primary school leavers into locally-available jobs? These are not questions with a single answer but need to be addressed through situated analysis of existing provision of post-primary education and training, complementarity with tertiary provision, local employment opportunities, implications of diversified curricula for social inequalities and politically feasibilities.

Rapid urbanisation and the increasing penetration of computer, broadband and mobile networks is changing the nature of work and the kind of technological expertise that is in demand. Hence, most African education systems have introduced ICT as a compulsory subject at lower secondary, despite very uneven distribution of hardware and software for delivery of the subject. Employment opportunities are often in local small and medium enterprises and involve use of ICT to create outputs (e.g. graphic design, editing video or music). Hence, curricula and pedagogy at secondary education should be targeted at developing capabilities to use ICT creatively (Rubagiza et al., 2011). This implies that effective delivery of ICT in secondary schools requires higher grade equipment than is currently available in the majority of secondary schools (see Chapter three).

6. Unpaid work and non-specialist jobs/employment: everyday STEM knowledge

Lower secondary education should prepare learners with a foundational level of STEM knowledge that enhances every day lives in the domestic and work spheres. The areas of unpaid work highlighted in HDR2015 include domestic labour, care work, small scale or subsistence farming. At the primary level, science education may have a focus on knowledge needs for health and hygiene, whereas secondary education tends to have a more theoretical orientation but may include some 'lifeskills' content. For example, as well as theoretical content on cells and categories of living things, the lower secondary Biology syllabus in mainland Tanzania includes topics on disease and infection that focuses only on diseases that are widespread in Tanzania. The influence of the international SDG agenda may lead to greater emphasis on environmental science and the impact of human activities on the environment within the curriculum for Biology. Some STEM knowledge that is relevant for unpaid work is currently delivered through more vocationally oriented lower secondary subjects such as agriculture or domestic science, that are not compulsory and not offered by all schools. This may well be what Agenda 2063 means by 'scientific culture' and a knowledge society.

Kinyanjui and Khoudari (2013) in their synthesis of an ADEA theme on science, technology and innovation argue that indigenous knowledge systems together with school systems form the foundations for lifelong STEM learning that allows for adaptation and uptake of new technologies and responses to sustainability challenges. Hence, school systems need to build on indigenous knowledge and teachers need to be prepared for this. Allowing use of local languages in education in classroom makes it easier to engage with and build on the dynamic STEM knowledge that students bring from their communities. As secondary education is expanding, many older teenagers enrolled in secondary schools are also economically active, sometimes in occupations that depend on indigenous knowledge passed down between generations, such as fishing, small holder farming or cattle-herding. Building on the knowledge students bring from these activities may make the secondary school curriculum more relevant.

Within Africa, subjects viewed as vocational, such as Agriculture and Domestic Science, can have substantial theoretical science knowledge organised and presented in a way that is more immediately meaningful and obviously of practical value for older teenagers, who are already engaged in work around the home or in their family farms. In UK, schools commonly offer Combined Science at lower secondary, which covers all three traditional natural science disciplines. This can make natural sciences more accessible to more learners at this level and opens up curriculum space for exploring the interconnections between natural systems (e.g. the impact of chemical pollution on living organisms). However, where teachers are insecure in their science knowledge, do not view themselves as lifelong learners and derive a sense of self-esteem from their identity as subject specialists, they may resist teaching outside of their specialist subject disciplines.

Thinking about the STEM knowledge needs of people, who are not STEM professionals, highlights the need for STEM teaching at lower secondary level to be relevant, attractive and accessible to diverse learners with a wide range of abilities and career aspirations. As lower secondary becomes part of the universal and compulsory basic education cycle in fact and not just in policy, this will be increasingly important.

7. Voluntary work and creative expression

Within voluntary work, sharing knowledge, awareness raising or campaigning and lobbying on social issues may be key activities. Understanding of social issues can hinge on scientific knowledge (e.g. for issues related to health and wellbeing, the environment or land use). Voluntary work may demand skills in communicating STEM knowledge to diverse audiences within multilingual societies. The teaching and learning of science cannot be separated from communication skills. Indeed, within sociocultural learning theory, science learning is understood as learning *to* talk rather than learning *from* talk (Daniels, 2001: 72). The work of sociolinguists, shows that it is not enough to learn communication skills in parallel to science but there are subject specific language skills developed through learning science (Coyle, 2007). STEM education cannot be compartmentalised as separate from or independent of language and literacy. Learning to read, write and talk about science is intrinsic to learning science (Polias, 2016).

Like, the social professions that require STEM knowledge, engagement in voluntary work is often underpinned by social or morally-based motivation. So, consideration of this kind of work also highlights the benefits of a secondary science curriculum that allows for exploration of the intersection between human and natural systems and develops critical thinking that brings together cognitive knowledge, moral reasoning, creativity and a capacity for compassion (Lipman, 2003).

Creative expression, as a category of work, brings together concerns for communicating scientific knowledge and creative entrepreneurship that have already been discussed. STEM knowledge can enable creative expression through some media or enable commercial exploitation (e.g. ICT skills for audio-visual editing, chemistry for creating dyes). Therefore, a quality secondary STEM education, in which learners create and not just reproduce written and oral outputs and learn through a language they understand whilst developing their language skills further can lay down foundational skills for work in the domain of creative expression as well as entrepreneurship, self-employment and voluntary work.

8. Conclusion

To conclude, the greatest challenge presented by the sustainable development agenda for STEM education within secondary schools in SSA will be to make STEM education relevant, attractive and accessible to more learners and learners with a wider range of abilities and career aspirations as secondary education becomes a mass education. This mainly entails:

- improving access and quality for disadvantaged communities, so that the most talented have the opportunity to progress to upper secondary and higher education;
- Recognizing the interdependence between science learning and language learning, developing skills for reading, writing and talking about science in the language of instruction and also talking about science across the languages spoken in multilingual societies;
- Critical thinking skills for understanding the interdependence between human and natural systems, linking science knowledge to social knowledge and the compassion to apply science knowledge within work that promotes human development and community development;
- Connecting to indigenous knowledge systems, or the informal knowledge that secondary schools students have of science from outside school, including the knowledge older students already apply in their paid and unpaid work;
- Offering technology-based subjects that are relevant to local employment opportunities;
- Technology, particularly ICT, is changing rapidly and rapidly becoming available to more people. It is therefore with respect to technology that greatest change in curriculum may be expected, with students needing to acquire skills to use ICTs in ways that are creative and productive.

Chapter three: Overcoming systemic challenges to a good quality STEM education

As outlined in Chapter one, the key 'problems' in STEM education in SSA are low levels of attainment in STEM subjects and low uptake of these subjects at post-compulsory level. Chapter two highlighted the implications of sharp inequalities in access to secondary education of an adequate quality for achieving national and continental development visions. In this and the next chapter some possible reasons for these problems are suggested and explained and examples of initiatives aimed at tackling these are given. Although the two chapters are related, the focus of the present chapter is on systemic issues whilst the focus of chapter four is on how these problems manifest at classroom level.

1. Suitably qualified mathematics, science and ICT teachers

There is a continent-wide shortage of suitably trained teachers, with UNESCO (2016a) reporting that fewer than three quarters of secondary school teachers are trained. The problem is particularly acute in mathematics, science and ICT. The problem of poor teacher quality in Africa is highly complex and is addressed in an earlier report prepared by the Bristol team for MCF (Bainton et al, 2016). In this section some of the systemic issues relating to the supply and retention of teachers are addressed whilst some of the pedagogical challenges relating to teacher subject and pedagogical knowledge are addressed in chapter four.

Mulkeen, in a report on the supply, training and management of teachers in Anglophone Africa (2010), reported that only 17% of teachers were qualified to teach mathematics, although it is a compulsory, core subject in the curriculum. He also describes the difficulty of recruiting young people into initial teacher education courses specialising in mathematics and science in Lesotho, where in 2006 only 8% of student teachers were studying mathematics as one of their two teaching subjects and in Uganda the equivalent figure was only 15%.

In many countries, the shortage of teachers is exacerbated by the need to recruit new teachers quickly to accommodate the increased enrolment in secondary education. Malawi, for example, has responded to increased enrolment in secondary school by quickly upgrading primary school teachers to secondary posts. This has resulted in 45% of secondary school teachers being officially unqualified, and a situation in which 27% of teachers hold no tertiary level qualification (Doyle et al., 2017). Further, as reported in the Malawian study (ibid), the situation with upgraded primary teachers is problematic as the development offered to these teachers is reported to be more focused on methodology and pedagogy than on upgrading teachers' content knowledge.

Similarly, a review of the literature (Hennessy et al., 2010) on the use of ICT to enhance teaching and learning in East Africa strongly indicates that few teachers are qualified to teach ICT or equivalent subjects; there is a severe lack of ICT-specific skills and subject knowledge amongst both pre- and in-service teachers. This lack of expertise affects not only the teaching of ICT, but also the use and functioning of IT equipment. For example, as Bill Sverdlik, a computer science professor from the University of East Michigan in the USA, who helped set up and run the NAMTOSS initiative (see below) in Namibia, explains, the computer lab donated by the US government and situated in a Windhoek high school 'has been inoperable for years … the locals lack the time and training to maintain the lab' (email communication, January 2017). He goes on to state

'The computer lab has been inoperable for years…the locals lack the time and training to maintain the lab'.

that 'there are many such unused computer labs throughout southern Africa, some sponsored by foreign governments, others by industry.'

Attracting teachers into STEM subjects is problematic for two main reasons: first, there is a shortage of young people with STEM subject knowledge and second, for those young people with relevant knowledge and qualifications, teaching is not seen as an attractive profession (Mulkeen, 2010).

It seems that many countries are attempting to address these concerns by encouraging the study of STEM subjects at tertiary level. Three examples of initiatives to address a shortage pf secondary and tertiary graduates with STEM expertise appear in the five country scoping reports (Doyle et al., 2017). First, the government of Senegal which has put in place a number of measures such as creating new research-intensive universities, developed a programme to promote sciences and technical pathways. Second, in Zambia, where the shortage of mathematics and science teachers is a well-recognised problem, the government, supported by development partners DFID, JICA and USAID, launched a Fast Track Teacher Education Programme (FTTEP) in 2011. The FTTEP was aimed at increasing the supply of highly skilled teachers, particularly in the critical areas of Industrial Arts, Mathematics and Science. A different approach was adopted by Côte d'Ivoire (Doyle et al., 2017), where the Graduate School of Education (École Normale Supérieure) recruits secondary school students to take part in a five year programme directed at training them to teach mathematics and physical sciences.

In terms of the second aspect of the teacher-supply problem, retention, Pitsoe (2013) explains that, although this is a global concern, it is more acute in SSA where the usual dissatisfaction with the profession is exacerbated by low and late payment of salaries. He suggests four 'promising options' to retain teachers: higher salaries (all teachers), differentiated salaries (for teachers in shortage areas e.g. mathematics), smaller class sizes and mentoring.

2. Class size and level

In sub-Saharan African education systems it is common to find high pupil to teacher ratios (PTRs), but there are particular difficulties regarding the teaching of science subjects due to teacher shortages in STEM subjects, connected to the issues with sufficient teacher content knowledge as discussed earlier. The PTR in secondary education for Zambia in 2015 was 35.2 (Doyle et al., 2017) and 70.4 for Malawi in 2014, with a sub-Saharan African average of 24.7 (UIS, 2016). In comparison, the global average for 2014 was 17.7 and the average for developed countries was 12.9 (UIS, 2016). It is noted that the flood of enrolments in primary has resulted in a strained lower secondary system, compromising quality and student progress.

For science and ICT classrooms, if practical experiments or hands-on work are to be undertaken by students ratios must be lower to ensure safety. Even if the only practical science is the observation by students of teachers demonstrating practical experiments, ratios need to be lower so that all students have a view of the demonstration.

Within STEM-focused studies, class size frequently features in combination with multi-level students, with examples such as Waller and Maxwell (2016) in which teachers dealt with a level difference of three years in South African mathematics classrooms. The World Bank reports that the dual issues of class size and class level are commonplace throughout sub-Saharan Africa, and a STEM-focused World Bank report (Ottevanger, den Akker & de Feiter, 2007) asserted that teachers are not equipped to teach mixed ability classes, and thus that 'curriculum aims are not within the reach of the majority of students' (p. 12). Whilst the problems of large class sizes and multi-level students appear intractable, some initiatives have begun to address how the quality of STEM education can be improved for disadvantaged learners in difficult delivery contexts and these are discussed in section 4 below.

3. Resources

Large class sizes put a strain on systems that already struggle to provide adequate materials and learning spaces. The material requirements of effective STEM instruction are many: from basic needs such as level-appropriate textbooks, to laboratories for carrying out sophisticated practical experiments with expensive equipment and a stock of difficult-to-obtain chemicals and glassware which require frequent replenishment (see Gado, 2005; L. M. Semali & Mehta, 2012). Within the literature, it appears as a widespread challenge and one that is consistently mentioned in both multinational reports and academic studies, with Verspoor and Bregman (2008), for example, calling for funding reorganisation in order to provide consistent and reliable access to needed materials. Despite this, there is often a disconnect between curricular requirements, available supplies and laboratory offerings.

Textbooks are sometimes seen as a key determinant of learning outcomes (Fuller, 1987; Read, 2015; Adriaan Verspoor & Wu, 1990), and in science and mathematics they are particularly important for teachers and students as they are seen as the main teaching aid for teachers (Bethell, 2016). However, provision of a textbook in itself is not enough: the quality of the textbook matters (Bethell, 2016). In SSA, determining the quality of a textbook is frequently framed with reference to alignment to curriculum standards but there is little evidence that they are systematically evaluated in terms of their effectiveness as aids to learning (ibid). Bethell, above, argues strongly for better textbooks and for SSA perhaps 'better' also takes into account the language of instruction (A. Verspoor & Bregman, 2008 and also see below, Chapter four).

The pupil to textbook ratio is sometimes quoted as a measure of educational quality of a country and Bethell (above), amongst others, also argues for more textbooks; the evidence suggests that the textbook can be used most effectively when the ratio of children to textbook is less than 3:1. However in many SSA classrooms the ratio is much higher; for example, the World Bank (2016) recently reported on the situation in Zambia, where the student to textbook ratio is more than 5 students to one book for science and maths. Interestingly, research in SSA (Kuecken & Valfort, 2013) suggests that ownership of a textbook has less positive effect on learning outcomes than sharing, as when they are sharing, they are more likely to discuss the mathematics or science they are studying.

Material inadequacies similarly plague information technology (IT) classrooms. The government of Rwanda, for example, has required IT instruction in secondary schools since 2007; its most recent policy iteration calls for smart classrooms in all primary and secondary schools. Despite ambition, current programs such as One Laptop Per Child reach only 10% of students (Republic of Rwanda, 2016) and rural schools especially struggle to implement ambitious IT curricular goals due to a lack of available technology or the common issue of computers being locked up to prevent theft or misuse (Rubagiza, Were, & Sutherland, 2011). Even when desktop or laptop computers are available, unpredictable power and lack of Internet connectivity hamper IT class instruction.

Schools without resources for STEM instruction are doubly burdened, as this paucity of materials requires teachers to rely on theoretical explanations in the place of hands-on interaction and experimentation. Secondary school physics teachers in Lesotho directly identified the "lack of facilities, including laboratory space and equipment, and the student-teacher ratio influenced their choice of teaching strategies" with a strong reliance on rote, teacher-centred content delivery, which they identified as less than ideal for students' learning (Qhobela & Kolitsoe Moru, 2014, p. 1380).

Some national programmes to address these concerns have been put in place, such as in Malawi. However, that the actual expenditure was much lower, due to 'bureaucracy and to some extent interference by some politicians' (Doyle et al., 2017). In a related initiative in Malawi, it was planned to distribute 700 science kits; only 200 were delivered. In South Africa, in 2011, the

Department of Basic Education developed a set of mathematics and science workbooks (amongst other subject areas) and one is given to every school child. These workbooks can be used for practice, for teacher monitoring or for revision. Over time they have been reviewed and improved and it seems that generally they are well received by teachers and learners (Hoadley & Galant, 2016) but that only about 80% of teachers use them, partly because delivery of the workbooks to schools has not always been successfully achieved and partly because teachers have concerns about their quality (Outhred et al., 2013).

Malawi, in 2015/16, allocated significant funds for the construction of facilities in Community Day Secondary Schools such as laboratories... 200 science kits were delivered.

The Department of Basic Education in South Africa provides mathematics and science workbooks for every child. Generally they are well received.

Both these initiatives demonstrate not only a recognition of the problem of lack of resources but also the will to address this problem. Both, also, demonstrate practical difficulties in distribution and delivery of the resources; a well-known issue documented at length by Read (2015). Practical difficulties can be overcome, however, and this is perhaps an area in which external funding and expertise could alleviate the problem.

> *...these initiatives demonstrate the will to address this problem.... practical difficulties can be overcome, and this is perhaps an area in which external funding and expertise could alleviate the problem.*

4. Programmatic responses

This subsection presents two examples of initiatives that work directly with schools to provide support for the teaching of STEM subjects. The interventions are intended as programmatic responses to many of the issues identified above including a lack of good quality teachers, large class sizes, multi-level learners and poor resources. They also seek to address some of the pedagogical challenges including poor teacher subject and sub-specific pedagogical content knowledge discussed in Chapter four; the interventions discussed here are mainly focused on systemic challenges whereas those discussed in Chapter four focus mainly on teachers.

The first example, the Dinaledi Schools programme in South Africa was established in 2001 under the National Strategy for Mathematics, Science and Technology education and aims to address the shortage of, and ethnic imbalance of, secondary students with school leaving passes in mathematics and science. Various incentives to schools include, for example, performance awards. The Department of Basic Education monitors the schools through school visits, telephone interviews and surveys.

__Dinaledi schools__ in South Africa

provide 500 selected schools with a variety of inputs, based on the needs of the school, including for example additional teachers, in-service teacher training, textbooks, scientific calculators, computers and other learning support materials.

'target well-managed schools and willing teachers'

An evaluation of the programme found that the Dinaledi programme 'has substantially improved Senior Certificate results in Higher Grade (HG) physical sciences and mathematics' (Blum, Krishnan, & Legovini, 2010, p. 6). The study also identified the barriers that remained once the supports provided by the programme were in place. These barriers include issues such as students' negative attitudes towards STEM subjects, and a lack of success in encouraging continuing study of these subjects at post-compulsory levels. According to the Zenex report (Roberts, Mostert, & Takane, 2016), the Dinaledi interventions are most successful in well-managed schools with 'buy-in' to the programme. As reported, in the Zenex report, by a representative from this programme 'Willing school managers and willing teachers are the key to programme success, if measured in terms of pupil performance' (p.66). If the initiative is to be scaled up, or replicated elsewhere in SSA, then this may be an important lesson: target well-managed schools and willing teachers.

The __Inkanyezi Project__, South Africa,

selects learners from poor backgrounds who show potential in mathematics and science and places them in selected schools, provides financial support, extra teaching, holiday camps and career counselling.

Schools are supported financially and teachers are given professional development.

A second example, also from South Africa, is the Inkanyezi Project, funded by the Zenex Foundation. This project aims to increase the number of disadvantaged learners who are able to access good maths and science learning in successful schools, increase the number of school-leavers with good enough results in maths and science to gain them university entrance (by 405 in 11 schools, over the programme period). An evaluation of the project (Quality Projects in Education and Schaffer & Associates, 2016) states that 345 quality passes were achieved by the end of 2013. At Grade 8 level, the students participating in the project scored better, on average, than their peers in eight of the eleven schools. However, the report notes that the project selected high performing students to take part, 'who would have done well despite the project' (p. 1); and it states that the selection process was under review. In terms of the teacher development programme, it is reported that these were not well attended, and, further, that the service providers did not sufficiently take into account the particular school contexts in which the teachers were working. The report recommends that service providers should attend project orientation meetings and be given professional development to address gaps in their knowledge. Finally, the report suggests that some schools lacked the ability to manage funding and report on the project, and recommends capacity-building workshops (some of these have taken place). A comment from a representative of the project, quoted in the Zenex report (Roberts et al., 2016) concludes first that change is difficult and takes time, and then that 'Projects of this nature are so dependent on the people involved in implementing them – especially at school level. Some people at school really go out of their way to support learners and others see everything as extra or need to be incentivised.' (p 141). The implications, for other interventions, are again, that the choice of school for such an intervention is crucially important.

5. Outdated curricula and curricular change

Chapter two made the strong point that education for a sustainable future requires the development of young people's problem-solving, leadership and entrepreneurial skills. It suggested the need for 'everyday science' that connects formal science knowledge to informal or indigenous knowledge. The World Bank (Ottevanger, den Akker, & de Feiter, 2007) notes that there is still a tension between preparing students' 'society-related needs (preparing for future employment, addressing socioeconomic problems), student-related needs (developing personal skills, relevance of content to everyday life), and subject-related needs (preparing for higher education levels)' (p. 14).

Curricula in both science and mathematics have been criticised in terms of their broader utility in the SSA context. The World Bank working paper on the development of STEM education in SSA identified a number of issues related to examinations and curricula (Ottevanger et al., 2007), focusing on the complexity of the content in the science and maths curricula which is problematic, given increased enrolment in secondary schools. The curricula were designed at a time when only the most able students graduated to secondary school, and have not been updated to accommodate the much wider ability range of students who are now admitted.

Curricula also risk becoming overloaded by the addition of materials which address specific societal problems of countries, such as environmental degradation and the HIV/AIDS epidemic. The shift to the SDGs may see attempts to introduce new material related to the sustainable development goals. Curricula designers often introduce such material in order to increase the perceived relevance of the curricula, but neglect to remove other material to accommodate them (see Gado, 2005). The continual curricular evolution and yearly changes place undue stress on already-burdened teachers, Waller and Maxwell (2016) argue.

More recently, there has been a shift in many African countries towards competency-based curricula reflecting a broader shift towards learner-centred pedagogy. These curricula place greater emphasis on generic, transferable skills including problem solving and critical thinking skills. These generic skills are pertinent to the perceived role of STEM for realising the SDGs (Chapter two). In science subjects they have often involved a greater emphasis on practical work and the use of ICTs. Implementing new curricula has encountered several problems and these have been well documented (Chisholm & Leyendecker, 2008; Gauthier, 2013; Komba & Mwandanji, 2015; Schweisfurth, 2011 for example). These include lack of, or limited/ inappropriate training, for teachers to support the shift towards more learner-centred pedagogy, a lack of resources including textbooks and materials to support practical inquiry in schools; and the persistence of teacher centred approaches due to the continued washback effects of traditional examinations that emphasise rote learning of facts (below). Clearly, many issues remain around the implementation of curriculum change with implications for the way that STEM subjects are taught and perceived by learners as being 'not for them' (see Chapter four).

The shift towards competency-based curricula is also intended to address the lack of relevance of existing, content-driven curricula that often date back to colonial times. Many studies have investigated the apparent disinclination of students from non-Western cultural backgrounds to enrol in STEM subjects, and the poor performance of students who do enrol (Bethell, 2016; Ezeife, 2003). It is suggested that an important factor in this unpopularity and under-attainment is the lack of relevance of the subjects to the everyday lives of these students and the lack of value and respect accorded their prior 'indigenous' knowledge systems (IKS), which could be built upon rather than being ignored or rejected. Ezeife argues that STEM subjects are taught without acknowledging the debt they owe to knowledge from indigenous communities from all over the world, which makes students from outside Western culture feel alienated from the material. In addition, teaching materials often use examples from Western culture or no examples at all. He argues that materials and methods drawn from the local context 'are practices that students from indigenous cultural backgrounds would gladly welcome in their study of science and mathematics' (p. 333).

Students' positive response to IKS integration into science curricula has been acknowledged by Manzini (2000) in that students indicated that IKS prepared them for transitioning to 'Western' science and made it easier to understand. Similarly, Hewson, Javu, and Holtman (2009) in their study of STEM and IKS in the Western Cape of South Africa noted its potential for integrating themes of sustainable development and environmental concern, providing also a partial solution to the lack of materials in 'Western' style STEM classes. Asabere-Ameyaw, Dei and Raheem (2012) argue that teaching methods, in addition to content, also need to be more appropriate to the SSA context, instead of uncritically adhering to the Western 'scientific method' of making and transferring knowledge: 'science education, if taught in a manner that engages the knowledges and methods of knowledge production of the community may become an easier task for the student as well as the educator' (p. 16). Despite these recommendations, there is little evidence of widespread application of IKS in science education and a review of the scoping studies does not suggest that science teachers are incorporating local indigenous knowledge into their curricula.

One approach towards developing a more inclusive curriculum has been developed in South Africa, where students have to choose either mathematics or mathematical literacy in their last years of school. The latter subject is intended to develop problem solving skills within realistic contexts and was carefully developed by experts in mathematics education to provide a credible alternative to mathematics (North, 2013). However, at the time of writing this report, over ten years since the introduction of the subject, it is generally seen as a watered-down and easier version of mathematics (Bethell, 2016; Julie, 2006; North, 2013) and it is not valued by teachers, students or higher education. An unintended knock-on effect of the introduction of mathematics literacy as a subject is that increasing numbers of schools now offer no mathematics in the final years of school (O'Connell et al., 2014). It seems that, despite the best efforts of the designers of the new curriculum and the full backing of policy, the introduction of this subject has been difficult, perhaps reminding us, as discussed above, how challenging it is to re-design or invent a new curriculum.

Mathematical literacy is a completely new subject designed to set mathematical learning in contexts the learners understand.

iSPACES in Tanzania

The concept of innovation surrounds and frames STEM learning in the iSPACES framework. Real problems that occur in life can be solved through critical exploration and problem solving, informed by the principles of science, systems and entrepreneurship.

A second example of curriculum change is the ISPACES Framework in Tanzania. This is perhaps the most complete rethinking and reformulation of the potential way that STEM education might function more purposefully and coherently, whilst being more culturally appropriate for sub-Saharan Africa. While at the centre are the recognisable content and practical work of traditional science courses, these are located within, and connect to, other dimensions (industry, Government, indigenous knowledge) that in turn are engaged with through a spirit of innovation. This science of everyday life within the iSPACES framework demonstrates, according to Semali (2013), how real problems that occur in life can be solved. Such a framing directly responds to the need for STEM education to contribute to the achievement of the SDGs as well as strengthening entrepreneurial possibilities of STEM education. Semali's study (ibid) suggested that the iSPACES approach had potential to provide solutions to everyday problems relevant to the students, but emphasised the importance of teacher commitment in achieving this.

6. Examinations in STEM subjects

Examinations in sub-Saharan Africa dominate the assessment scene. They tend to be high-profile and well established and encourage 'teaching to the test' (Paulo, 2014). However, many of examinations are criticised for low-level questioning which requires students only to recall facts. The tests do not reflect the broader goals of the education system such as comprehensions and problem solving but focus rather on memorised facts. For example, analysis of mathematics examination questions in some countries reveals that most questions focus on abstract, academic concepts and require students to follow a set procedure. This does not give students the opportunity to show what they know.

The development of better examinations could be a cost-effective way of shifting teaching.

There appear to be no initiatives in SSA aimed at improving examinations themselves, so as better to encourage an emphasis on aspects of learning that are valued in the rhetoric and are needed if countries in SSA are going to educate their young people in line with the ambitions of the SDGs outlined in Chapter two. However, as Bethell (2016) suggests, given the enormous influence of examinations on classroom practices, the development of better examinations could be a relatively cost-effective way of shifting teaching away from rote-learning approaches towards problem solving and critical thinking, for example.

Further, although examinations have the potential to provide rich data about the state of mathematics and science education, the way the results are presented in many countries is not useful. Generally they provide a grade (e.g. Grade A, B or C) but without further information such as cut-off scores or performance criteria: without this information interpretation of the standard of performance is not possible. Some examination agencies produce reports, however, usually written by the Chief Examiner. Bethell (2016) suggests that these reports are 'general in nature' and generally not helpful. He also provides two examples of more helpful practice. One is from the West African Examinations council, which publishes Chief Examiners' reports online, providing copies of the examination questions followed by model solutions and comments about the typical performance of students. The second is from Mauritius, which publishes subject specific reports promptly after the examinations and containing 'high quality and potentially … useful' information. These examples suggest a useful way forward for the rest of SSA.

7. Conclusion

Attainment and take up of STEM subjects at post-compulsory levels in SSA faces a range of challenges at a systemic level. This chapter identified six challenges that recur in the literature. These were:

- Recruiting and retaining qualified teachers
- Large classes, in which students are achieving at a wide range of levels (multi-level)
- Resources for teaching and learning of science and ICT
- Outdated curricula and challenges of implementing curriculum reform
- Poorly designed high-stakes assessment
- Assessment data not analysed and used effectively to inform quality improvement

These challenges are inter-related. Managing large, demanding classes with inadequate resources can be a disincentive to teachers and hence contribute to attrition. Poorly qualified teachers are more likely to struggle to understand and adapt to new curricula and the knowledge-recall demands of high stakes examinations seem incompatible with the learner-centre aspirations of competencies-based curricula. When they are provided to schools, teachers may not have the capabilities or time to maintain new resources, particularly ICT resources. Inevitably, educational inequality follows the contours of socio-economic disadvantage. It is often most difficult to retain teachers and distribute resources to schools serving the most disadvantaged communities.

Tackling these apparently intractable challenges will require strategic, multi-pronged, bold and far-reaching approach informed by successful quality improvement programmes. Two such 'programmatic responses' – the Dinaledi programme and Inkanyezi project – were considered. These select promising schools and provide a suite of support for the schools, including physical resources, professional guidance for teachers and support for students. These initiatives have shown promising results, most especially in well-functioning schools with willing teachers. This is unsurprising, school effectiveness research has consistently evidenced the strong influence of school leadership on school quality (Schereens, 2000).

All of this points to the need for interventions to strengthen STEM teaching that are underpinned by multidimensional situated analyses taking account of how these factors interact within a given context. Such analyses might seek to identify which challenges need to be addressed, how feasible it is to address challenges and how risks arising from challenges that cannot be addressed may be mitigated. For example, an intervention targeted at a small number of schools may be able to provide resources for teaching ICTs but this is likely to be unfeasible at large scale. Teachers' salaries are generally controlled by government and so other incentives may need to be put in place to retain teachers, such as participation in certified professional development programmes or improved access to health facilities. Where curriculum reform is being implemented at national level, an initiative might well need to include related professional development. Any project, may have to pay attention to school leadership, for example, by providing leaders with software tools and training to enable them to use assessment data to improve STEM teaching and learning.

Chapter four: Overcoming classroom challenges in providing good quality STEM education in sub-Saharan Africa

STEM teachers face a particularly diverse set of inter-connected challenges in their efforts to deliver quality teaching.

Teachers require at least three kinds of knowledge for teaching, as pointed out in the report produced for the MCF on improving teacher quality in SSA (Tikly et al, 2016): content or subject knowledge, pedagogic knowledge which is knowledge about how to teach, and pedagogic content knowledge which is knowledge about teaching a specific subject. In this chapter we begin by discussing the first two of these forms of knowledge in the context of secondary STEM education in SSA. One particular challenge for teachers in SSA is the language of instruction, which is frequently not the first language of either the teacher or the students. This is considered to be such an important issue that it is in a separate section. Formative assessment is also given a separate section for similar reasons. The chapter finishes with a section on attitudes towards STEM subjects and a last section on gender.

1. Teacher subject knowledge

The issue of teacher subject knowledge and content delivery is complex as the situation is different in different countries and a variety of aspects of subject knowledge need to be considered. In some countries, there is a vicious cycle of poor subject knowledge: students who are poorly taught at school go on to become teachers, with little improvement to their knowledge of subject content.

In many countries, a shortage of qualified teachers in STEM subjects, as discussed above, is dealt with by requiring teachers to teach out-of-subject. A Commonwealth report into in-service education in sub-Saharan Africa (Ibn Junaid & Maka, 2015) found that there is significant 'out-of-subject' teaching of science and mathematics in Nigeria. In both of these cases, the teachers may not have the confidence to teach effectively and may have real difficulties in responding to their students' needs and the demand of the curriculum demands.

Unfortunately, STEM subjects are particularly vulnerable to being misconceived and misunderstood (Ottevanger, den Akker, & de Feiter, 2007) and thus require teachers to have high levels of content knowledge for effective instruction.

Initial teacher education

Clearly initial teacher education needs careful attention as it is at this stage that teachers are initially prepared for school teaching. The UNESCO CFiT report (UNESCO-China-Funds-in-trust, 2014) looks in detail at this area in five countries: Congo, Liberia, Tanzania, DRC, and Uganda. The authors found that both governmental and non-governmental organisations offer initial teacher education but the government has ultimate oversight. However, according to the report, in reality training provided by non-governmental bodies tends to be ad-hoc and fragmented; and does not always lead to employment. In the DRC, for example, USAID trained about 5000 pre-service teachers but, at the time of writing, none had been employed due to financial constraints. In all five countries, teacher training costs are in part covered by external donors; in terms of sustainability, this could be problematic as if the external donors withdraw their funding, the local governments would not be able to fund these programmes.

Professional development

There are many forms and models of delivering professional development, and they all have the overall aim of improving teaching, hence learning outcomes, in mathematics, science and ICT. The models include: country-wide attempts to reach all teachers through cascading down through district officials, to senior teachers and then to ordinary classroom teachers; courses for individual teachers; versions of Japanese Lesson Study; formal and informal mentoring in schools; and researchers or consultants working in various ways with teachers involved in projects.

The Japan International Cooperation Agency (JICA) is very active in a number of African countries, working together with governmental bodies on projects to help develop large scale teacher knowledge and skills, usually with the name 'Strengthening of Mathematics and Science in Secondary Education' (SMASSE). In some cases the focus is on development of science or mathematics knowledge and others focus more on ways of teaching. There has been considerable evaluation of this project, much of which is positive and suggests that there is an improvement in teacher subject knowledge (Irungu & Mercy, 2014). Most of the professional development activity is based on a 'Lesson Study' model, and there is mixed response to this: the Zambia scoping study reported that teachers in STEM subjects responded well to this approach, while others (Fujii, 2013) argue that teachers in Uganda and Malawi were reluctant or unable to move away from a 'workshop' approach. Further findings from both Malawi (scoping study) and Kenya (Irungu & Mercy, 2014) suggest that there is some teacher unhappiness about the programme, feeling resentful that they are required to attend, finding the approaches and resources inappropriate and not finding the professional development meetings worthwhile. As the scoping study (Malawi) says, based on interviews with an MoEST official: 'There is clearly a need to strategize the training, so that it is appropriate and useful for the audience' (Doyle et al., 2017, p. 56).

There is a need to strategize the training, so that it is appropriate and useful for the audience.

The JICA projects involve face-to-face meetings and workshops and some of the evaluation suggests that meeting in person can provide a barrier to effective professional development. Two examples of initiatives that take advantage of modern digital technologies for distance learning follow. The first, from Senegal (see scoping study) is a distance-learning course which aims to strengthen pedagogical skills of teachers. Teachers have access to resources such as lesson notes and teacher guides. The second, from South Africa, takes a 'blended learning' approach. Teachers attend a ten-day 'Mathematical Teaching' course, which mainly aims to improve subject knowledge, and then go back to their schools, where they try out different teaching approaches. They are required to complete two assignments reporting on their experiences. While both these examples provide opportunities for teachers who otherwise may not be able to undertake professional development activities, distance learning suffers from high drop-out rates and many of the teachers (particularly in the Senegal case) find it difficult to access the course and resources due to limited Internet access.

Distance learning provides opportunities for teachers who might not otherwise be able to take part in professional development activities, but suffers from high drop-out rates.

There are many further examples of courses and other professional development activities taking place in sub-Saharan Africa. For example: The Institute of Physics runs professional development courses that focus on supporting teachers to do practical work in physics, particularly using low cost, available and appropriate resources. Working through partnership institutions such as teaching colleges, the Institute of Physics supports the creation of 'STEM Centres' which then deliver training to in-service teachers. It seems that this very targeted training is successful at up skilling teachers, and internal evaluation has shown that teachers' attitudes to practical work has changed. However, as a small scale initiative reliant on volunteer 'expert teachers' from UK, the Institute of Physics has found this work to be financially unsustainable in the long run (verbal information from Tanjinder Panesor, Head of International, Institute of Physics).

There have been numerous attempts to train teachers in the use of ICT, perhaps most notably UNESCO's Teacher Training Initiative for Sub-Saharan Africa (TTISSA) and the African Virtual University (AVU) Teacher Education Project (Hennessy et al., 2010). Both these programmes, whilst with a wider scope than ICT, included significant focus on ICT. A project with a more specific focus was the Namibian Technology Outreach to Secondary Schools initiative (NAMTOSS), aimed, amongst other things, to provide professional development for secondary school teachers in the area of computing: programming in particular. They claim (email correspondence, January 2017) that a 'good' secondary curriculum exists in Namibia, but that school teachers lack the background to teach this subject.

The Mathematics Teacher Training program at the African Institute for Mathematical Sciences (AIMS) in Cameroon is a five year pilot programme in partnership with The MasterCard Foundation, AIMS, ADEA and the government of Cameroon. The programme uses a 'cascade' model: experienced maths teachers and inspectors are trained as master trainers; they will in turn train secondary school maths teachers. This is intended to strengthen the content and delivery of mathematics at the secondary level across Cameroon, which will contribute to building and strengthening the pipeline of students continuing into STEM fields at the tertiary level. Evaluation reports are not yet available but anecdotal evidence suggests that the roll out of the programme has not been as successful as hoped for and that the programme would have benefited from more thorough research-based planning.

The programme would have benefited from more thorough research-based planning.

Teacher Education in Sub-Saharan Africa (TESSA)

TESSA has developed a bank of free online resources, including mathematics and science teaching packs, for use by teachers in SSA. This is a cost effective way of reaching teachers.

Another way of supporting teachers includes providing online resources. For example, the Open University in the UK, together with African and other international partners, hosts the Teacher Education in Sub-Saharan Africa (TESSA) initiative. Teachers are able to access a large bank of Open Educational Resources (OER), including mathematics and science teaching packs, general teaching resources and handbooks for teachers and teacher educators. The resources are prepared (or adapted) by African authors, and many have been modified for use in specific local contexts.

However, in a research article on the reuse and adaptation or modification of OERs for use in specific contexts, Wolfenden and her colleagues (2012) suggest that there are some challenges associated with engaging teachers in high-level thinking related to adaptation and sharing of adapted versions. The 2012 evaluation report (Harley & Barasa, 2012), hints at slow uptake of the resources. The TESSA resources are available in English, French, Kiswahili (Tanzania) and Arabic (Sudan). While reports of take-up are not encouraging, provision of online resources does appear to be a cost-effective way of reaching teachers.

2. Teachers' pedagogical skills

Related to teacher subject knowledge is the area of subject specific pedagogic content knowledge. Policies promoting child-friendly schools and child-centred learning have been introduced in many countries in sub-Saharan Africa (for example in Zambia, Ministry of General

Education (MESVTEE), 2015). Within STEM education, 'inquiry-driven' approaches modelled on the scientific method emphasise students' development of 'scientific attitudes' through observation, asking questions, making claims, testing hypotheses, and 'first-hand experiences' (Gado, 2005). However, many teachers lack the pedagogical skills required to deliver curricula in this manner, or are required to rely on teacher-centred or traditional methodologies due to material shortages.

Several reports on pedagogic skill emphasise these findings. Atebe and Schäfer (2011) investigated secondary school geometry classrooms in South Africa and Nigeria, and found that teachers offered students "few" opportunities to learn due to lack of application, but witnessed better student outcomes when teachers tailored the material and their pedagogical practice to students' varied levels. In a comparison of Malawi and South Africa, Ramnarain, Nampota, and Schuster (2016) found that teachers in more privileged South African schools better implemented student-centred guided inquiry in contrast with the more traditional, 'didactic' orientation of Malawian teachers at more rural schools. In a study of pre-service teachers in Ghana, Lesotho, Malawi, South Africa, and Trinidad and Tobago, Lewin and Stuart (2003) similarly identify the lack of modelling for STEM pedagogical practice as gap in pre-service teacher training.

These examples positively indicate the need and potential for inquiry-based application when teachers receive pedagogical training, with programmes such as the Lesson Study approach adopted in Zambia (Jung, 2016) designed to enable teachers to develop these skills through continuing professional education (CPE).

Gado's (2005) investigation of first and second grade science teachers in Benin indicated low orientation towards inquiry-based approaches despite the apparent training received in the pedagogy. A summary of the many challenges facing these science teachers follows, causing the researcher to conclude that the obstacles of lack of materials, over-crowded classrooms, and management challenges meant that teachers reverted to traditional pedagogical practices. Secondary school teachers in Tanzania expressed similar concerns that 'pedagogical change is profoundly constrained' by issues such as class size, hierarchical school structures, and examination requirements (Vavrus & Bartlett, 2012). 'Mandated curricula and the high-stakes examination systems in most sub-Saharan African countries undermine the use of inquiry-based pedagogies', Vavrus and Bartlett state, as policy outpaces effective STEM-specific pedagogical training and implementation, and presents as a salient, large scale challenge for STEM education.

***Progressive Teaching Initiative** (PTI), the Gambia*

PTI mobilised technology in the form of Interactive White Boards and class polling devices as a tool for making large scale changes to classroom pedagogy. The use of this technology allowed detailed planning of lessons by experienced educators, which allowed teachers to act as facilitators within classrooms, thus spending more time assessing, identifying learning needs and enabling lessons that were discussion based.

In the Gambia, in an attempt to improve on extremely poor examination results, the Progressive Teaching Initiative (PTI), and in particular the Progressive Maths Initiative (PMI) and Progressive Science Initiative (PSI) was introduced to 24 schools in 2012. This initiative has four key aspects: the use of technology in the classroom; new teaching approaches; new approaches to student participation and learning; and different sequencing of STEM subjects. While the initiative begs the question as to what extent the classrooms are able to be adapted to the local needs of students, it does draw attention to the ways that support systems can be put into place to enable the teachers to consistently deliver better lessons.

Mindset Learn, South Africa

Mindset Learn has created videos of lessons which teach concepts, supported where possible by exposure to experiments, demonstrations and real-life applications. Lessons aim to model good teaching and are closely aligned to the workbooks provided by the Department of Basic Education. The videos are carefully structured to provide opportunities for student interactions and teacher interventions, hence modelling a learner-centred approach.

In South Africa, Mindset Learn is a project which supports learners and teachers in schools, focusing on mathematics, science and economics for upper secondary students. Lessons are broadcast live (via television) to classrooms during school hours and is also available on youtube. The thinking behind the classroom videos is that they support teachers in teaching topics with which they are not confident, and, further, teachers can learn by watching the videos. Mindset has also produced a series of webinars which focus on teaching upper secondary mathematics and attend to both content knowledge and pedagogic content knowledge related to the topics to be taught in the forthcoming week. A blog supports the webinars (http://teach.mindset.co.za/teaching-mathematics-blog) but it appears that this has not been updated since the end of 2014. No formal evaluation of the project is available but in the description of the project provided in the Zenex report (ibid), it is suggested that teacher commitment to the use of technology and management and support for the teacher are both essential for the success of the initiative.

In addition to formal professional development courses, as discussed in Section 1, peer support and collaboration between mathematics and science teachers can promote better teaching and learning. In South Africa, starting in 2016, many teachers of mathematics take part in a scheme known as ‘1+4’, which involves four days teaching and one day meeting other teachers and district subject advisors in every week. In their meetings, amongst other things, they discuss teaching and learning and share strategies they have found to be useful or effective. Developing teachers’ content knowledge is also important within this scheme, and teachers are tested on their mathematical knowledge after each session. Clearly, this is an ambitious scheme, involving significant administrative and logistical challenges, such as finding teachers to cover the classes of teachers who are absent from school while attending meetings, and anecdotal evidence suggests that many schools do not cope well. In some provinces, the scheme has been adapted and has become '1 + 9'. No formal evaluation of the impact of the scheme on learner outcomes has been conducted to date.

As is evident from the above, both sections 1 and 2, many opportunities for professional development for teachers exist. This report has picked out some examples, all of which are documented although most of which are, at best, only superficially evaluated. There are many further professional development opportunities which are not documented. Overall the landscape is confusing and incoherent but it would seem that developing a country-wide understanding of what is offered – or could be offered – might be valuable. This has been attempted by the South African Council for Educators (SACE) which is developing a database of all quality-assured professional development opportunities on offer.

3. Language of instruction

Language of instruction presents a further significant challenge which manifests itself frequently in a range of research studies. Even for students learning STEM subjects through the medium of their home language, the subjects are linguistically challenging. As Wellington and Osborne (2001) state, 'learning science is, in many ways, like learning a new language' (p. 5), particularly because many of the words used in science and mathematics are used with different meanings in an everyday context (e.g. 'energy', 'field', 'table'). It is impossible to separate literacy from mathematics, science and ICT, and students with poor literacy struggle to be successful in STEM subjects, since, as Prophet and Badede (2009, p. 239) state, 'cognitive development and achievement in science is heavily dependent on language'.

For students who are learning STEM subjects in a language that they are less familiar with, as is the case in most of sub-Saharan Africa, linguistic challenges become even more apparent. The 2011 TIMSS study (Mullis et al., 2012) highlighted the link between performance in the survey and the level of speaking the language of the test at home: the three participating sub-Saharan African countries, which were all near the bottom for attainment in both the mathematics and the science test, were also least likely to have the language of testing be the language spoken at home.

In Malawi, Chitera (2012) identified the gap in that teacher training programs were conducted and assessed exclusively in English and thus failed to prepare teachers for instructing their classrooms in indigenous languages. Chitera further recorded teachers' use of frequent code-switching between indigenous languages in mathematics classroom explanations, a practice commonly recorded throughout SSA which demonstrates that teachers often do not strictly adhere to language policies and make use of indigenous languages when needed for students' comprehension of subject material (see Arthur, 2001; Atweh & Clarkson, 2001; Pearson, 2013).

Poor student language skills, when combined with a lack of visual materials to illustrate subject language (as discussed later) and traditional pedagogical delivery, mean that students often memorise STEM content without deeper understanding and lack skills of critical analysis and transferability. In considering tailoring language to content, science and mathematics teachers are not familiar with second language learning methodology. Probyn (2006) noted this gap in a study of Grade 8 South African science teachers when investigating the tension between content, language of instruction, and the native languages present in a multilingual classroom. Teachers struggled to attend to students' language needs while attempting to deliver the ambitious demands of already crowded curricula. Further research has demonstrated even small modifications, such as simplifying the vocabulary and English sentence structure used in exam questions for Botswana's junior secondary school science exams, resulted in improved student performance (Prophet & Badede, 2009). Without a realistic view of the language abilities of students within STEM classrooms, current practices will continue to result in poor performance. The broad range of challenges associated with language of instruction denote its importance for continued intervention continent-wide, and demonstrate the need not only for teacher-level improvement but broader system change.

> ***Language Supportive Teaching and Textbooks, Tanzania***
>
> *has created prototype textbooks for students in the first year of secondary, to support the transition to English as the language instruction. The textbooks support teaching that builds on students' prior learning in primary school, which was all in Kiswahili and includes activities to develop proficiency in reading, writing and talking about science in English. The project demonstrated the value of collaborations between science and language subject specialists within schools, in teacher education and in the process of designing learning materials.*

The Language Supportive Teaching and Textbooks (LSTT) project, involving the Tanzania Institute of Education (the curriculum authority), two African academic partners and one British university, has the explicit aim of supporting learners making the transition from using an African language to using English as the medium of instruction. The project has developed a mathematics and biology textbook that are language accessible, i.e. use simple language, glossaries translating key words and use of illustrations to convey meaning. This helps students to read and engage with the books, and provides activities that integrate language learning with subject learning (e.g. discussion in language of prior learning to elicit prior knowledge, structured support for translating prior knowledge, reading and writing). The forthcoming evaluation report (Barrett et al., n.d.) shows that over a short period of 4-6 weeks, use of the books dramatically improved students' engagement in interactive learning processes and their knowledge of subject vocabulary. Improvement was also seen in ability to write about Biology in English. Biology teachers struggled to understand the language-learning objectives of the books without support from language-specialist colleagues within their schools. A second phase of the project is now seeking to embed language supportive practice in initial teacher education programmes. Crucially, this approach offered teachers ways of strategically using the mother tongue to support subject learning in English. Extending this initiative to textbooks for use throughout secondary schools and all over SSA represents a very cost-effective but potentially highly effective strategy.

4. Formative assessment

> ***Assessment Resource Banks***
> *South Africa*
>
> *were developed by education department officials and the Human Sciences Research Council, as a set of booklets of assessment tasks, translated into seven African languages, and designed so that teachers could write the questions on the board or photocopy them and hand them out. Posters to illustrate contexts for the questions were also provided.*

As far as assessment is concerned, it is generally recognised that classroom assessments, focusing on formative practices, can be effective in improving learning in mathematics and science. This is because teachers' use of information about their students' current levels of understanding to adapt their teaching and learning strategies.

Many countries in sub-Saharan Africa have written formative assessment, also sometimes called continuous assessment, into their education policies. There is evidence, however, that the implementation of these policies is often weak, for a number of reasons, such as poorly qualified teachers, teacher-led teaching and learning, which leaves little opportunity for student-focused activity, and a lack of resources (Bethell, 2016).

Two initiatives from South Africa aim to tackle this challenge. Although the first was directed at primary schools, it is included in this review as it is one of few initiatives that appear to address the challenge of improving formative assessment practices. Subject-specific Assessment Resource Banks (ARB) were developed to support teachers in implementing the new assessment policy, introduced in 2007, which emphasised classroom assessment. Kanjee (2009) reported on the pilot of this project, concluding that the materials were mostly valued by teachers and that they were mostly well used. They did, however, report on some difficulties of using the booklets. These included, for example, a lack of photocopying facilities and the level of difficulty of the tasks. Language presented another problem: for example some words translated into the African language (e.g. triangle) were only familiar to the children as English words.

The second innovation regarding formative assessment was the Formative Assessment in Science and Mathematics Education (FaSMEd) project. This was a complex project, funded by the EU, involving eight partners in Europe and one in Africa (AIMSSEC). The project, which ran from 2014 to 2016, has now ended, but leaves a legacy of a formative assessment toolkit for use by teachers, which includes: brief theoretical introduction to formative assessment, a range of lesson ideas (using digital or non-digital technologies to enable or enhance the processes of formative assessment) and a set of professional development modules (FaSMEd, 2016).

A specific professional development need in SSA appears to be the effective use of assessment data, as discussed in Chapter three. The South African Innovative Learning Intervention (SAILI) project works with schools to help them understand and use data from a variety of external assessments of Grade 9 students (SAILI, 2016). The SAILI team shows schools how to make sense of the data, to provide an understanding of performance and to decide where to target improvements. Importantly, as the leader of this project, Sam Christie, stated 'this is not a tech solution but a human one (lots are tempted to spend more on the machine based analytics than on the effective sharing of insights)' (email correspondence, January 2017). The informal evaluation evidence suggests that schools valued this help and used it to inform their strategic priorities. A formal evaluation, not yet in the public domain, suggests that substantial improvement over time in terms of the grades achieved by students in all subjects at the National Senior Certificate level (school leaving). The evaluation also reports that schools not yet participating in the project are asking to become involved. This is an example, perhaps, of a relatively cost-effective but impactful approach which could be replicated in countries where examination and national testing data is available to schools.

South African Innovative Learning Intervention (SAILI)

The project team shows schools how to make sense of the data, to provide an understanding of performance and to decide where to target improvements.

5. Attitudes and values towards education, mathematics, science and ICT

The report by Bethell (2016), prepared for the World Bank, suggests that in countries where students achieve well in mathematics, education is highly valued, students believe that they can do mathematics, and teachers believe that all students can do well in mathematics. In contrast, in many countries where mathematics performance in schools is lower, it seems, according to the report, that it is socially acceptable to be bad at mathematics. Bethell (ibid) implies that in most countries in sub-Saharan Africa, attitudes and values are aligned with those found in the countries in which students perform less well. In other words attitudes towards these subjects tend to be negative and individuals' beliefs in their ability to achieve well in these subjects are generally low. These attitudes reflect those of the wider society and, without changing the way society thinks, it is unlikely that attitudes amongst the young will improve. No initiatives aimed explicitly at changing societal attitudes in SSA were found, but in the UK the organisation *National Numeracy* has been tackling these same issues using a range of approaches. The organisation has some data to suggest success, reported for example in its annual reports (for example see National numeracy, 2016), but states that 'measuring the effectiveness of our work is a significant challenge, especially when it comes to assessing changes in people's attitudes to numeracy, both individually and across the population. We continued to seek better ways of doing this…' (National numeracy, 2016, p. 10). It may be that SSA could develop its own version of this organisation, to focus on all of STEM subjects, drawing on the experience of *National Numeracy* in the UK.

A set of interventions targeting learners aims to develop students' enthusiasm for STEM subjects, which also includes introducing or raising awareness of careers in STEM.

In terms of developing enthusiasm, activities tend to be extra-curricular. They include, for example, exhibitions or shows which are usually one-off events visited by students whose teachers (or parents) make it possible or them to attend. These sorts of events take place all over the world. A report on the UK STEM landscape (Morgan et al., 2016) discusses their role and effectiveness in that country, stating that evaluation is inconsistent and superficial, consisting mainly of completion of feedback forms immediately after the event, which does not provide an understanding of the longer term impact on student perceptions and performance in STEM subjects. Many similar initiatives taking place in SSA appear to suffer from the same problem.

In SSA, Science Circus Africa was a ten-week initiative that ran between May and July 2015 in South Africa, Botswana, Zambia, Mauritius and Malawi. It aimed to 'make STEM … amazing for students, teachers and communities' (The Australian National University, 2015). The initiative included travelling exhibitions, science shows and teacher workshops; it also trained and mentored staff in each country to work in partnership with the Australian team, aiming to create 'lasting, sustainable impacts'. A statement of the impact of the program reports that the programme reached over 41,000 people, mostly school students attending science shows (about 37,000) (Walker, 2015). The statement reports that in all five countries, shows continue to be run, and that in Zambia teacher training colleges now include more practical science in their courses. This impact is encouraging, insofar as it demonstrates that the science circus activities took place and in some way touched the lives of over 41,000 people. However, there appears to be no information about how it touched the lives of, for example, the 37,000+ students who attended shows or the extent to which it fostered enthusiasm for STEM subjects, or taught them any science.

A second type of activity designed to foster enthusiasm, but with longer term engagement than an exhibition on show, is provided by the African Maths Initiative (AMI). AMI is a Kenyan NGO formed by mathematicians and mathematics educators who are working to create a stronger mathematical community and culture of mathematics across Africa. AMI runs week-long maths residential camps, which have the goal of exposing students to different ways of thinking about mathematics, focusing on problem-solving, experimentation and the use of computers to explore mathematical ideas. This will, according to their website, 'spark a life-long love for mathematics in students, which will both improve their performance in school and increase the chances that they will pursue maths and science in the longer term' (AMI, n.d.). AMI also actively encourages teachers to join the camps as a way to expose them to alternative ways of thinking about teaching maths. No formal evaluation of the camps was found, but one of their blogs claimed that 'The AMI Maths Camps have proved very successful at changing students' attitudes about maths. In many cases, this has led to a marked increase in student performance in mathematics as well as in other subjects. Because of this success, the camps have spread to other countries.' (AMI, n.d.). No information is available on the costs of funding the camps or how the participants are selected (but it is highly likely that they are self-selected).

A third example aiming to engage young people in STEM activities comes from Ghana. The Ghana Robotics Academy Foundation is a not for profit volunteer organisation, founded in 2011, which runs two-day workshops named RiSE (Robotics inspired Science Education). The workshops attempt to connect theory with practice by providing theoretical lectures complemented by practical activities which involve programming robots (LEGO mindstorms). These activities appear to be designed to foster creativity and problem solving skills and develop team-working skills, as described in a report for the IEEE Control Systems Magazine (Trebi-Ollennu & Okraku-Yirenkyi, 2014). This same report suggests that the programme has a 'lasting impact' on students and quotes various students' comments, which include some related to what they have learnt and other related to possible career choices in STEM.

Finally, there have been significant efforts to provide students with the tools to help themselves learn mathematics and science. For example, the Microsoft Maths service (https://math.microsoft.com/), a free online mathematics service, is available to Grade 10, 11 and 12 learners of mathematics in South Africa and Tanzania and their teachers. Learners are presented with mathematical, science and technology problems and they are able to tools such as a graphing calculator and unit converter to solve the problems. The service is intended to be used primarily after school hours and as a homework administration and revision resource. The Department of Education in South Africa has approved the content and teachers have received approximately an hour of training to support the learners in their use of the service. An app, for use on mobile telephones, has recently been developed. The Zenex landscape report (ibid) included some evaluative comments on the initiative, suggesting that, for some learners (mostly high achieving) the service had been useful and there was an improvement in their attainment.

Also in South Africa, a series of study guides called *Mind the Gap*, for a variety of subjects, including life sciences, was developed and trialled in 2012. This series aims to help students pass their examinations: the books identify areas that appear to be most difficult for learners by analysing the reports produced by examiners and focus on these areas. The 'gap' refers to the gap in students' understanding and knowledge and that required to pass the examination. An evaluation of the study guides (Department of Basic Education South Africa, 2013), using a random control trial methodology, concluded that the life sciences guide had a positive impact on pupil performance. Further, a cost-benefit analysis, in the same report, calculated the size of the impact per $100 spent and compared this figure to other educational interventions from around the world. *Mind the Gap* was in the top five (out of 15) interventions considered. Further study guides, including some for mathematics, mathematical literacy, physics and chemistry, were produced between 2014 and 2015, and trialled in 2016. The results of the trial are not yet available.

The African Maths Initiative (AMI), mentioned above with respect to maths camps, encourages students who have attended maths camps to set up clubs in their schools. Details below are taken from the website (AMI, n.d.) which explains that the students are given a year's worth of resources for use in a weekly club and are supported by camp organisers in initiating a club. The key idea behind the clubs is that students will take responsibility for their own learning inside and outside school. The first clubs were set up in 2015, so it is too early for any kind of evaluation, but as the website states, this approach has the potential for scalability and sustainability.

6. Gender

Despite major investment in girls' education, gender parity remains an issue in secondary education across sub-Saharan Africa, and one that manifests in STEM classrooms. Boys generally attain better grades in STEM subjects than girls (Ottevanger et al., 2007), although there are a few exceptions and the gap appears to be narrowing in many countries, such as Botswana and South Africa (Martin, Mullis, Foy, & Hooper, 2016). A study of secondary school girls' attitudes to science conducted in Kenya observed that girls may experience a 'stereotype threat', whereby they under-attain in STEM subjects due to anxiety that they will conform to the stereotype that girls are bad at science. This poor attainment may then lead them to drop STEM subjects when they get the opportunity to do so (Chetcuti & Beriter, 2012). However, this same study also found that girls enjoyed science when it was relevant and context-based, and that they valued the presence of female role models – although, in spite of enjoying the subject, they were still reluctant to pursue science-related careers. Within the broad context, this is a clear area for improvement: the UNESCO GEM report states that only 29% of secondary school teachers in SSA are female (2016a).

Chikunda (2014) explores issues around gender responsiveness in Zimbabwean science classrooms and how responsive pedagogies can impact girls' self-efficacy in science. Teachers were observed to see how they evaluated students, and tension was identified in that teachers appeared aware of gender bias but were not equipped via policies or practice to effectively address these in the classroom. This speaks to the need not only for positive female role models in STEM classrooms but teacher training in gender responsiveness and pedagogical practice tailored to STEM classroom needs.

The Foundation for Working to Advance STEM Education for African Women (WAAW) was founded in 2007 and aims to increase the numbers of African girls participating in STEM disciplines. The organisation runs week-long camps for girls in Kenya and Nigeria, aiming to engage girls and develop their interest in STEM careers. The girls at the camps take part in a variety of activities including lectures, experiments, games and computer programming. Importantly, the emphasis in the activities is on problem-solving in an African context, focusing, for example, on clean water and renewable energy. The Foundation's 2015 annual report (2015) includes details of the participants' responses to surveys given at the beginning and end of each camp. While these responses do not provide information about lasting impact, they do indicate a shift in students' attitudes (e.g. 'I like doing science activities': pre-camp 77% and post-camp 100%) and their perceived learning (e.g. 'I understand what climate change means': pre-camp 45% and post-camp 100%).

7. Conclusion

Overall, the first four sections of the chapter are situated within the classroom context. Essentially, they point to a need for better teaching in STEM subjects. Better teaching, the chapter implies, puts the learner at the centre of teaching, takes into account the language barriers present in most SSA classrooms and uses knowledge of the students' current levels of understanding, knowledge and skills to inform decisions about what to do next. These are difficult to achieve without a sound understanding of pedagogic strategies to address language difficulties, to gather information about the students' learning and to know how to adapt teaching both in the moment and in the longer term. They also rely on deep content knowledge; all aspects of knowledge for teaching need to be brought together for effective teaching.

SSA countries need to focus on developing all aspects of knowledge required for effective teaching of STEM subjects. Some of this work can be achieved in initial teacher training institutions but it is crucial that the programmes they offer provide appropriate training and that the offer across each country is consistent and well supported. Currently this is not the case. One possible way forward is to assist governments in reviewing and refining their current offerings, perhaps by a team that brings together national and international experts, who can draw on their own experience and the research evidence of what appears to work well in a specific context. Teacher educators, themselves, are a valuable source of expertise, with the potential to be researchers into their own practice and programmes and to contribute towards curriculum design (Stuart et al., 2009; O'Sullivan, 2010).

The development of teacher knowledge in teachers who are already in the classroom is usually achieved by professional development in various forms. Such professional development is currently provided in countries in SSA by governmental bodies, aid agencies, NGOs, university teachers and researchers and very many formal and informal programmes exist. While many of these have high levels of success, there are two main concerns about them: one is that the overall landscape is incoherent and confused and the other is that their evaluation tends to be superficial, if it exists at all. One useful response to this lack of coherence and rigour is provided by South Africa's Council for Educators. This body produces a database of quality-assured professional development opportunities for teachers that can be drawn on by schools as they identify suitable professional development opporuntities.

The last two sections of the chapter take wider society as their context. Both are concerned with societal attitudes and values: negative and 'can't do' attitudes towards STEM disciplines and negative attitudes to girls participating in STEM careers. It is clearly extremely challenging to change societal attitudes in either of these areas and no examples of initiatives designed specifically to do so were found. However, there is perhaps potential for countries in SSA to explore adopting strategies used in other countries facing similar societal attitudes, such as *National Numeracy* in the UK, with a view to adapting their approaches for the context of particular countries in SSA.

One important approach to changing attitudes is by providing students with extra-mural STEM-related experiences and to change the attitudes of the individuals who take part in these. There are many examples of this sort of activity in the text, such as science circus and STEM camps for girls and it seems that the activities are successful in developing some enthusiasm in some young people, but it is questionable how sustained this enthusiasm is. Further, these opportunities are available to some students in some geographic areas, perhaps whose teachers are well-connected and who hear about such activities or events. However, it is likely that many millions of school students around SSA have never even heard of such events, let alone had the opportunity to attend one.

As with this sort of activity elsewhere in the world (e.g. the UK) the offerings tend to be uncoordinated, ad-hoc and piecemeal. Further, as they are largely without rigorous evaluation, little is known about how well they work and to what extent they represent value-for-money, scalable and viable approaches to attracting young people into studying STEM and considering STEM careers. One possible solution might be for funders of these activities to target the harder-to-reach schools and teachers and to consider how to make it possible for all students to have the opportunity to take part. This would require research into the development of apprpriate tools to help funders evaluate their activities.

Three final examples in this chapter provide details of initiatives designed to help students help themselves by providing them with self-study materials and, in the last example, resources to support them in establishing an after-school mathematics club. There is some evidence that high achieving students in particular benefit from using these materials; but they are available to all students. Good materials such as these will not replace a good teacher, but they do give all students the chance to cover the curriculum irrespective of the quality of their teacher. The quality of such materials is variable, and it takes time and effort to develop really excellent materials. One way forward would be to support the development of research-informed, excellent materials for use by all students.

Chapter five: Conclusions and Implications for Future MCF Support for Secondary School STEM

The aim of this section is to make some overarching observations about the challenges facing STEM secondary education and the nature of interventions and gaps in support for STEM education. This will provide an opportunity to identify, on the basis of the preceding chapters, some possible promising areas for intervention for MCF. The discussion is presented in the form of options rather than definitive recommendations that are intended to stimulate debate and possible further inquiry and that can contribute to the future development of strategy.

The wide-ranging nature of challenges faced and the need for a strategic approach

One overarching observation is the wide-reaching and inter-related nature of the systemic challenges facing the development of good quality secondary STEM education in SSA. As has been discussed in Chapter three, these include a range of deep-seated systemic issues such as a shortage of suitably qualified graduates entering the teaching profession and difficulties of retention, large classes and a lack of resources and infrastructure. They also include inappropriate curricula which neglect indigenous knowledge systems, challenges of implementing curriculum change, outdated assessment practices and lack of robust, comparative assessment data. At the pedagogical level these issues translate into a lack of subject and pedagogical knowledge on the part of many teachers, a lack of enthusiasm for STEM subjects on the part of many learners including girls and problems related to the difficulties of learning in a second language.

The importance of context

Although many of the challenges identified in Chapters three and four are continent-wide, the way that they manifest is very much linked to context, with no two countries, regions, schools or learners the same. Interviews with key informants in the country scoping studies revealed overlapping but divergent needs. Thus priorities for supporting STEM in Senegal included initiatives that make science subjects more accessible and appealing for pupils particularly in disadvantaged regions as well as girls, a focus on support for learning French or English which are the media of instruction in secondary schools, and, taking into account the recent climate of violence and radicalisation, the need for science curricula to incorporate moral, ethical, social dimensions that can promote peace. In Côte d'Ivoire by way of contrast a reported challenge was a perceived lack of curriculum structure/ articulation between levels whilst in Tanzania a major issue is the bottleneck at the end of junior secondary school which is most pronounced in STEM subjects. In Malawi, there were particular issues reported around the lack of time for professional development leading to a lack of motivation on the part of STEM teachers to develop their skills.

Limited evidence of what works

The literature review conducted for this deep dive has brought to attention the limited evidence base on 'what works' in raising the attainment of disadvantaged learners in difficult delivery contexts. Thus, whereas we are able to report evaluative evidence for some interventions in some contexts this was not universally available either on a local basis or in a way that would easily facilitate comparison within and between national contexts. This is linked in part to the unreliability and lack of comparability of national performance data in STEM-related subjects.

The need for a strategic approach

Tackling these wide ranging, deep seated problems in a way that recognises differences in context requires a holistic approach and the leadership and resources of governments supported by development partners. Recognition of the scale and complexity of the problem suggests a strategic approach on the part of MCF. The sections below discuss some of the possible implications of the preceding chapters for MCF's involvement in secondary school STEM that can be used as a starting point for the development of strategy. The discussion focuses on specific ways in which MCF can add value to existing initiatives and/or plug gaps in existing provision and in the evidence base.

Possible areas for future intervention for MCF

Act as a repository for successful practice

MCF could act as a repository for successful policy and practice in STEM education. It could collate examples of successful practice for raising the attainment of disadvantaged learners in difficult delivery contexts drawing on and synthesising existing evidence from across the continent. MCF could then find ways of disseminating successful practice in the form of traditional media such as policy briefs, online resources and social media.

Contribute to the existing evidence base

Given the limited nature of the existing evidence base about 'what works', MCF could commission further research about the impact of different kinds of interventions on the learning outcomes for disadvantaged learners in different contexts. For example, research could include meta-analyses of existing evidence of the relative effects of different interventions, the underlying processes linked to improvement in outcomes and the factors associated with successful scale up. Earlier chapters have identified specific gaps in the existing evidence base around for example, successful curriculum implementation, supporting pedagogical change, support for learning in the language of instruction and the use of formative assessment. Existing evidence could be used to support evaluation of future initiatives, for instance through the development of evaluation toolkits for use by a range of STEM activity providers.

Contribute to the development of curricula and assessments

Chapters three and four identified the need for more appropriate curricula, better examinations and high quality resources, mainly textbooks. MCF could commission research into the design of the curriculum and support countries in SSA who wish to reform their curricula by providing expert advice and guidance. It could further commission research into designing assessments, taking into account international best practice as well as the particular context of the country or region in which these will be used and paying particular attention to the issue of the language of instruction.

Act as a 'broker' for different initiatives

A recurring theme is the multitude of stakeholders and the risk of fragmentation and incoherence between initiatives. MCF could potentially see itself as a broker bringing together different stakeholders from the government, donors, NGOs, universities and the private sector. MCF is potentially well positioned to play such a role given the strength of its existing networks and partnerships. Such a brokering role could be significant in the development of national and regional responses to the challenges in secondary school STEM education.

Contribute to the development of communities of practice

Linked to the above, MCF could contribute to the development of communities of practice. This could take the form of bringing stakeholders together to discuss problems in STEM education and to share successful practice in the form of conferences, webinars and workshops. It could also take the form of being a provider of different kinds of training to support policy makers for example in the successful implementation of new curricula and/or practitioners in designing, initiating, implementing and evaluating new initiatives. In tailoring its support MCF could explore the most effective professional development initiatives already in place and draw on the features that work well to develop a set of best-practice guidelines for use in any new or ongoing initiatives.

Develop value for money resources

MCF could contribute to the development of new resources including textbooks. It could build on existing resources that have been shown to be effective such as: the OER created for the TESSA initiative; the videos and webinars created for the Mindset project in South Africa; the resources to support maths clubs created by the African Mathematics Initiative; and the science kits developed for Malawian schools. It could also potentially invest in the development of innovative resources such as the development of virtual laboratories (building on similar initiatives by the Open University in the UK) or teaching and learning materials such as textbooks that are language supportive, i.e. that are specifically designed for non-native speakers of English or French.

Develop hubs of excellence in STEM

None of the above areas of intervention are mutually exclusive. One way of bringing together the different areas outlined above is in different kinds of hubs of excellence. These could operate at different scales. They could, for example, take the form of individual secondary schools that can be supported to act as local hubs of excellence showcasing and providing training in successful practice in secondary school STEM education. This could follow the model of beacon schools and maths hubs in the UK or magnet schools in the US. The Rwandan government has recently introduced a similar model and MCF could consider the potential for scaling up this kind of initiative. MCF could consider supporting hubs of excellence at a national or regional level regional and national level policy makers and officials as well as practitioners.

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Appendix: Initiatives referred to in the text

Chapter 3

- NAMTOSS initiative Namibia - Namibian Technology Outreach to Secondary Schools initiative
- Fast Track Teacher Education Programme (FTTEP), Zambia – increases the supply of highly skilled Science, Industrial Arts and Mathematics.
- One Laptop Per Child, Rwanda – aims to supply robust basic laptops to pupils throughout the country.
- Supplying Science Kits to schools, Malawi – to help in the upgrading of Community Day Secondary Schools following the massive expansion of lower secondary education.
- Supplying Mathematics and Science workbooks for every child, South Africa – planned and carried out by the Department for Basic Education, to improve attainment in these subjects.
- Dinaledi Schools programme, South Africa – provides inputs to schools to improve number of pupils from disadvantaged backgrounds gaining entry to university to study mathematics and science.
- Inkanyezi Project – supports individual pupils from poor backgrounds who show potential, to help them access good maths and science learning and gain university entrance.
- Mathematical literacy – a new subject at senior secondary level in South Africa, designed to set mathematical learning in a context the learners understand
- ISPACES Framework in Tanzania - science of everyday life
- West African Examinations council - publishes Chief Examiners' reports online, providing copies of the examination questions followed by model solutions and comments about the typical performance of students.
- Chief examiners, Mauritius - publish subject specific reports promptly after the examinations and containing 'high quality and potentially … useful' information.

Chapter 4

- SMASSE - Strengthening of Mathematics and Science in Secondary Education (a number of SSA countries)
- Senegal – distance learning for teachers
- AIMSSEC South Africa – ten day blended learning course for teachers of mathematics
- Institute of Physics - professional development courses that focus on supporting teachers to do practical work in physics
- UNESCO's Teacher Training Initiative for Sub-Saharan Africa (TTISSA) – CPD for teachers, focus on ICT
- African Virtual University (AVU) Teacher Education Project - CPD for teachers, focus on ICT
- AIMS Mathematics Teacher Training program, Cameroon - five year pilot programme CPD for teachers of mathematics
- Teacher Education in Sub-Saharan Africa (TESSA) initiative - teachers are able to access a large bank of Open Educational Resources (OER),
- The Progressive Teaching Initiative (PTI), Gambia, mobilised technology in the form of Interactive White Boards and class polling devices as a tool for making large scale changes to classroom pedagogy.

- Mindset Learn (South Africa) has created videos of lessons which teach concepts, supported where possible by exposure to experiments, demonstrations and real-life applications.
- 4+1 professional development course in South Africa - four days teaching and one day meeting other teachers and district subject advisors in every week
- The Language Supportive Textbooks and Teaching (LSTT) project, Tanzania – develops textbooks that are language accessible
- Assessment Resource Banks were developed by education department officials and the Human Sciences Research Council South Africa - a set of booklets of assessment tasks and other resources to support effective use of formative assessment
- Formative Assessment in Science and Mathematics Education (FaSMEd) project – developed a formative assessment toolkit for use by teachers,
- South African Innovative Learning Intervention (SAILI) project - works with schools to help them understand and use data from a variety of external assessments of Grade 9 students.
- Science Circus Africa - South Africa, Botswana, Zambia, Mauritius and Malawi - included travelling exhibitions, science shows and teacher workshops; it also trained and mentored staff in each country
- African Maths Initiative - runs week-long maths residential camps, which have the goal of exposing students to different ways of thinking about mathematics, focusing on problem-solving, experimentation and the use of computers to explore mathematical ideas.
- Ghana Robotics Academy Foundation - runs two-day workshops named RiSE (Robotics inspired Science Education). The workshops attempt to connect theory with practice by providing theoretical lectures complemented by practical activities which involve programming robots
- Microsoft Maths service South Africa and Tanzania - a free online mathematics service - mathematical, science and technology problems and tools such as a graphing calculator and unit converter to solve the problems
- Mind the Gap, South Africa - the books identify areas that appear to be most difficult for learners by analysing the reports produced by examiners and focus on these areas.
- African Maths Initiative (AMI), - encourages students who have attended maths camps to set up clubs in their schools.
- Foundation for Working to Advance STEM Education for African Women, Kenya and Nigeria - week-long camps for girls