FOREWORD BY SIR TIM BERNERS-LEE

Ten Frontier Technologies for International Development

Ben Ramalingam, Kevin Hernandez, Pedro Prieto Martin and Becky Faith

India, Rajasthan
Kamla, age 33, is Rajasthan's first female solar engineer. Starting her education at age 11 in night school, while carrying on with her domestic and farm work, she went on to study solar technology and now runs a rural field station fabricating solar home lighting systems and solar lanterns. Despite her humble background she has travelled to Delhi to speak at National Conferences on solar technology. Here, Kamla works on solar batteries connected to roof panels.

Credit Robert Wallis – Panos

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Informing development practice – Climate & Environment, Infrastructure, Livelihoods

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Last but not least, our gratitude is due to Sir Tim Berners-Lee for his foreword, and to Anne Jellema and Dillon Mann at the Web Foundation for their help and support with the process.

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The views expressed in the report are entirely those of the authors and do not necessarily represent DFID's own views or policies, or those of Evidence on Demand, or of IDS.

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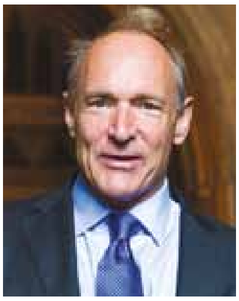
Foreword by Sir Tim Berners-Lee



When I designed the World Wide Web, I built it as an open platform to foster collaboration and innovation. The Web evolved into a powerful and ubiquitous platform because I was able to build it on a free and open network and because hard-wired into it was the power of any user to become a creator, not just a consumer.

Since then, the internet has become the central infrastructure of our time – every sector of our economy and democracy depends on it. Few would have been able to imagine this even 20 years ago. And the role of the internet in promoting development has been highlighted by the World Bank as a critical enabler, working to reduce transaction costs, improve efficiency and democratise access to services. But it can only do all of these things if accompanied by the political will to ensure that all benefit equally from the potential of technology.

This report impressively spells out a number of emerging technologies that could well carry the seeds of transformative changes of tomorrow. Some, like the internet of things and the collaborative economy, are platforms that build on existing technologies. Others, like 3D printers and unmanned aerial vehicles, offer whole new networks and new possibilities for future development progress. The report's authors are very clear that the potential and limitations of these technologies are fundamentally dependent on choices that we make, today and in the future – choices about keeping platforms open and inter-operable, choices about hardwiring users' rights and freedoms into our technologies, and choices about systematic efforts to overcome the new patterns of exclusion that new technologies inevitably create. Without due care and attention, these new technologies will become uneven playing fields, with a select few winners and many more losers.

We learn in the pages ahead that to ensure these exciting technologies realise their potential to contribute to economic growth and social progress, people in developing countries will need sustained and thoughtful engagement. Along with patient investment in novel approaches, there will need to be adaptive and intelligent approaches to anticipate and head off risks and protect users' rights, as well as creative ideas for building these technologies on open standards and applying them in ways that meet the needs of those in developing countries.

I urge all leaders – be they politicians, development policymakers, or technologists and innovators – to heed this timely call, and to come together to realise the greater promise of open and inclusive technology in creating a more sustainable and fairer world for future generations.

Sir Tim Berners-Lee, inventor of the World Wide Web and founding director of the World Wide Web Foundation and World Wide Web Consortium.

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Acronyms

3D	Three dimensional
3DP	3D printing
3DP4D	3DP for development
AM	Additive manufacturing
DFID	Department for International Development
HP	Hewlett-Packard
ICT	Information and communications technology
IoT	Internet of things
Iot4D	IoT for development
LTA	Lighter than air
NGO	Non-governmental organisation
P2P	Peer to peer
PV	Photovoltaic
RSA	Royal Society for the encouragement of Arts, Manufactures and Commerce
SMS	Special messaging service
UAV	Unmanned aerial vehicle
UK	United Kingdom
UN	United Nations
US	United States
UV	Ultraviolet
WEF	Word Economic Forum
WHO	World Health Organization

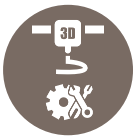
Executive summary

As new technologies and digital business models reshape economies and disrupt incumbencies, interest has surged in the potential of novel frontier technologies to also contribute to positive changes in international development and humanitarian contexts. Widespread adoption of new technologies is acknowledged as centrally important to achieving the United Nations Sustainable Development Goals by 2030.

But while frontier technologies can rapidly address large-scale economic, social or political challenges, they can also involve the displacement of existing technologies and carry considerable uncertainty and risk. Although there have been significant wins bringing the benefits of new technologies to poor consumers through examples such as mobile money or off-grid solar energy, there are many other areas where the applications may not yet have been developed into viable market solutions, or where opportunities have not yet been taken up in development practice.

Against this background, the Department for International Development (DFID) commissioned the Digital and Technology Research Group at the Institute of Development Studies to undertake a review of frontier technologies in five areas as shown below.

The development of this report formed a major element of a learning process that has led to the establishment of a new Frontier Technologies Livestreaming initiative at DFID, which over the next three years will seek to pilot a number of the technologies and recommendations of this report in practice.



MANUFACTURING AND CONSUMPTION

New digital tools that enable new approaches to manufacturing using novel materials, and new digital platforms that bring together producers and consumers in novel ways.

- **3D printing for development**
- **Collaborative economy tools**

CONNECTIVITY

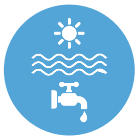
New approaches to expanding digital connectivity and growing the range of things that are online.

- **Alternative internet delivery**
- **Internet of things**

TRANSPORTATION AND LOGISTICS

Autonomous aircraft and airships, enabling more efficient and lower cost transportation and logistics to less accessible areas.

- **Unmanned aerial vehicles/drones**
- **Airships**



FRESH WATER

New approaches to sustainably extract fresh water from seawater and brackish water, and from the atmosphere.

- **Solar desalination**
- **Atmospheric water condensers**

CLEAN ENERGY AND AIR

Distributed energy generation and storage technologies, and novel ways to reduce smog in different settings.

- **Household-scale batteries**
- **Smog-reducing technologies**

Overview and methodology

This report is based on an extensive review of literature on the ten selected frontier technologies in these five areas, as well as consultations with expert informants. Each technology is explored in more detail in the second half of this report. The ten frontier technologies selected for study arose out of consultations with DFID staff and advisers. It should be noted that technologies are constantly evolving and so these reviews need to be seen as a snapshot in time, synthesising existing evidence, ideas and insights.

The first part of the report describes the nature of frontier technologies and their specific relevance to international development; presents the potential and challenges of the ten technologies; and explains key cross-cutting findings from the technology reviews. It concludes by setting out a number of potential roles for development actors in facilitating and targeting the use of frontier technologies so as to make a positive contribution while mitigating the risks these technologies may also present.

Importance of frontier technologies

Drawing lessons from across the ten technologies considered, as well as wider literature and informant interviews, the report finds clear evidence of the potential of frontier technologies to contribute to social, economic and political development gains in a number of ways, by:

- Driving innovations in business models, products and processes that provide new goods and services to 'bottom of the pyramid' consumers;
- Providing the means by which to make better use of existing underutilised household and productive assets;
- Catalysing increases in demand, nationally and internationally, which create new industries and markets, leading to macro- and microeconomic growth; and
- Changing demand for labour and capital, leading to direct job creation and transformation of the workforce.

For all of the potential upsides, potential downsides must also be considered. While it will largely be the private sector that will drive deployment of these technologies, the public sector through national regulation, as well as development financing, will have a major role in mediating the pace and direction of technological change, both to achieve development objectives, and to protect potential losers.

Drones were deployed by the United Kingdom International Search and Rescue UK ISAR to help identify the most vulnerable areas after the 2015 earthquake in Nepal. For more on drones, see p.75.

Key findings

Technology development and diffusion

Frontier technologies are defined and shaped by context – What is 'frontier' very much depends on particular economic, social and technological contexts, and the problems and challenges faced in those contexts. Although some frontier technologies are globally new, in other cases they may also be a new application or bundling of more established technologies, applied to a long-standing development problem. Catalytic converters are an good example of how a mature and well-established technology in developed country contexts can be viewed as frontier in many developing countries.

Frontier technologies are often in reality a blend of different solutions – Broadly speaking, technology blending for development involves combining frontier technologies with techniques and procedures found in low- and middle-income countries. The off-grid solar sector is an example blending internet of things (IoT) sensors and connectivity, latest renewable and battery technologies, and mobile money.

Frontier technologies can help redefine and navigate 'wicked problems' – 'Wicked problems' are seemingly intractable development challenges. Some of the technologies discussed redefine critical challenges in transformative ways that make them more amenable to change. A technological fix is not always the answer to a problem, but frontier technologies can highlight the limits of current thinking and suggest new ways of approaching challenges. For example, solar desalination has the potential to overcome water insecurity by moving beyond approaches to better management of existing freshwater sources, to focus on novel sources of fresh water, as well as being a sustainable means of accessing that water.

Diffusion takes time and can have multiple pathways – A number of factors determine the success of new technologies in achieving 'take-off' and widespread use. These include public infrastructure, government regulation and compatibility between technologies. While innovations emerge rapidly, and create continual pressures for reforms, institutions tend to change more slowly. Moreover, wider contextual factors – social, political, financial and environmental – may slow or accelerate a technology's progress. For example, the rise of collaborative economy approaches such as Airbnb and Uber has been especially pronounced since the financial crisis of 2008, and the growing need for alternative, low-cost ways to supplement income, and indeed to access services.

Managing quality and risks

Frontier technologies can lead to unequal benefits – The benefits of new technologies have tended to accrue to those people who already enjoy material and other advantages. It is vital to ensure inclusive and participatory principles are at the forefront of technological development in bridging the 'digital divide'. For example, a number of digital innovations rely on good levels of connectivity (specifically, 3D printing, the collaborative economy and the IoT). Here, existing forms of digital divides – from access to digital literacy – may inhibit their widespread dissemination among the poorest groups. Although many of the technologies may offer the potential to expand goods and services to more people, some of them simultaneously pose a threat to existing livelihoods and jobs.

Frontier technologies require skills and capacities to manage high levels of risk and uncertainty – The path from invention to innovation impact is usually non-linear and difficult to predict. Forecasts depend on a series of cascading and interdependent challenges, and are shaped by wider factors such as privacy, security, safety regulations and willingness to adopt new technology. For example, the challenge of managing uncertainty underpins how development actors deal with risk in relation to innovation, too often working to minimise risks in their investments rather than to strategically manage them.

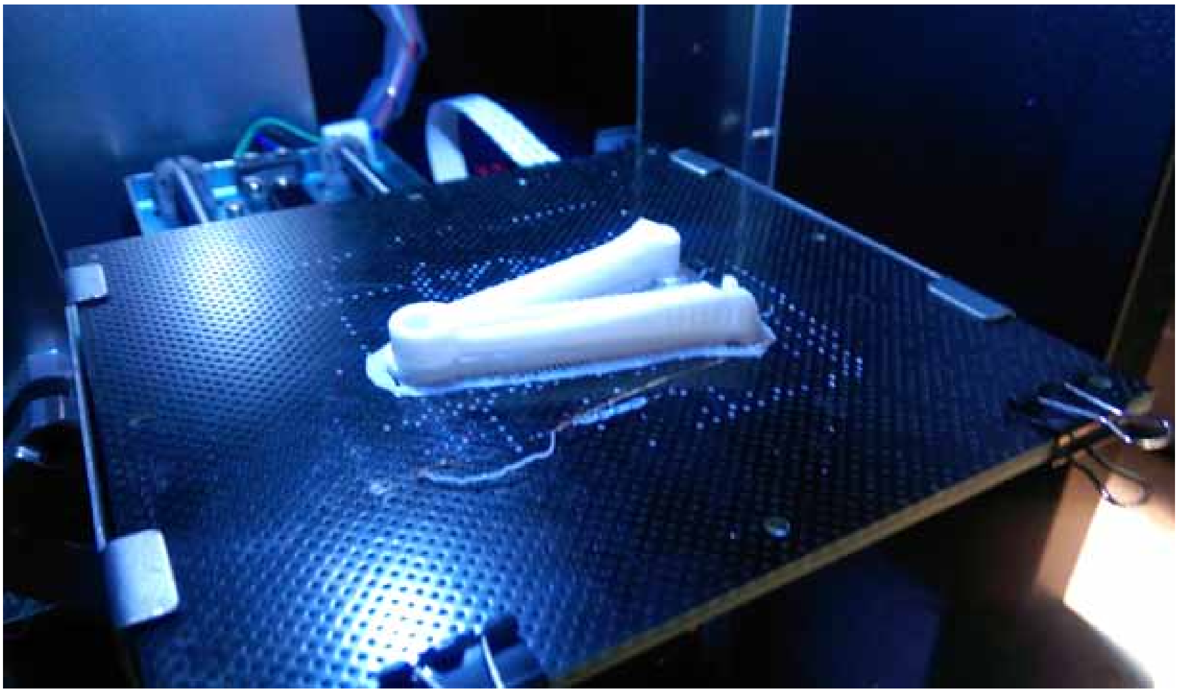
Achieving impacts

Frontier technologies can deliver many different types of outcomes and impacts – These include: providing access to essential goods and services that would otherwise be unavailable due to physical, social or economic constraints; reaching remote or excluded populations; reducing transaction costs; catalysing new collaborative business models; and generating new sources of income and welfare. For example, the Hello Tractor initiative, also known as the Uber for tractors, offers African farmers access to low-cost tractors when and where they need them, enabled by an SMS (text message) booking system that connects owners to farmers. This service, like numerous other collaborative economy tools, is making assets and services available to those who need them most, improving income and livelihoods.

The 'leapfrogging' potential of frontier technologies needs careful analysis – New technologies enable groups or sectors in developing countries to skip over or 'leapfrog' established technologies used in more developed countries, but which might be more expensive, less efficient, more polluting, of inferior quality or simply not economically feasible. But it is necessary to understand if a new technology will replace, complement or extend existing infrastructure and services. For example, aerial-based alternative internet delivery initiatives seek to overcome the need to build ground-based infrastructure in connecting the four billion people who are currently offline.

Frontier technologies can deepen and extend value chains – Frontier technologies can enable more efficient delivery of goods or services to more people, especially the poor and those living in remote areas or off grid. For example, unmanned aerial vehicles (UAVs) – commonly known as drones – provide the opportunity to transport packages the 'last mile' from areas that are served by infrastructure to areas nearby where roads may be impassable, inadequate, or non-existent, and are already being used to expand logistics infrastructure for national health systems. Greater coordination and information sharing across critical value chains are needed, as well as the ability to track where frontier technologies can: (a) fill critical gaps; (b) extend value chains to new groups or areas; or (c) enhance the nature of the value being delivered through complementary and additional services.

Frontier technologies can accelerate green transformations – Many of the technologies discussed in this report could enhance more climate-compatible strategies and approaches along major global value chains. For example, catalytic converters, catalytic paints and smog-reducing towers convert dirty gases already in the air into less harmful ones. More work is needed to understand how these and other technologies could be combined with each other and other technologies to increase their effectiveness, achieve sustainability and create a 'green ecosystem' of frontier technologies to meet the needs of the poor and underserved.



A freshly 3D-Printed umbilical clamp which will be used in a rural Haitian medical clinic to aid the safe and healthy delivery of a newborn. 3D printers can potentially lead to the wholesale transformation of material production, supply chains and logistics processes by enabling and making use of local, flexible, efficient, on-the-fly production of the supplies, parts and tools required for critical tasks. See p.40. Photo credit: Field Ready.

Recommendations for development organisations

Across all the following recommendations, increased effective collaboration at different levels – between the development sector, entrepreneurs and innovators, business and industry, researchers, governments, local organisations and target communities – will be critical to success. The figure opposite sets out the recommendations in visual form.

Enhance development, testing and diffusion of frontier technologies

- **Deepen understanding, recognition and the search for frontier technology needs and opportunities** – Undertake careful research and analysis on the challenges, opportunities and risks various frontier technologies present, working with a broad range of collaborators, and building on previous work, particularly among scientists and investors. Effort should be made to catalyse the search for appropriate frontier solutions by defining problems, establishing challenges and finding ways to share risks.
- **Build skills and capacity in understanding and using frontier technologies** – Ensure expertise and understanding of frontier technologies in the development sector are adequate and appropriate, especially at senior levels; and by building capacity in developing countries.

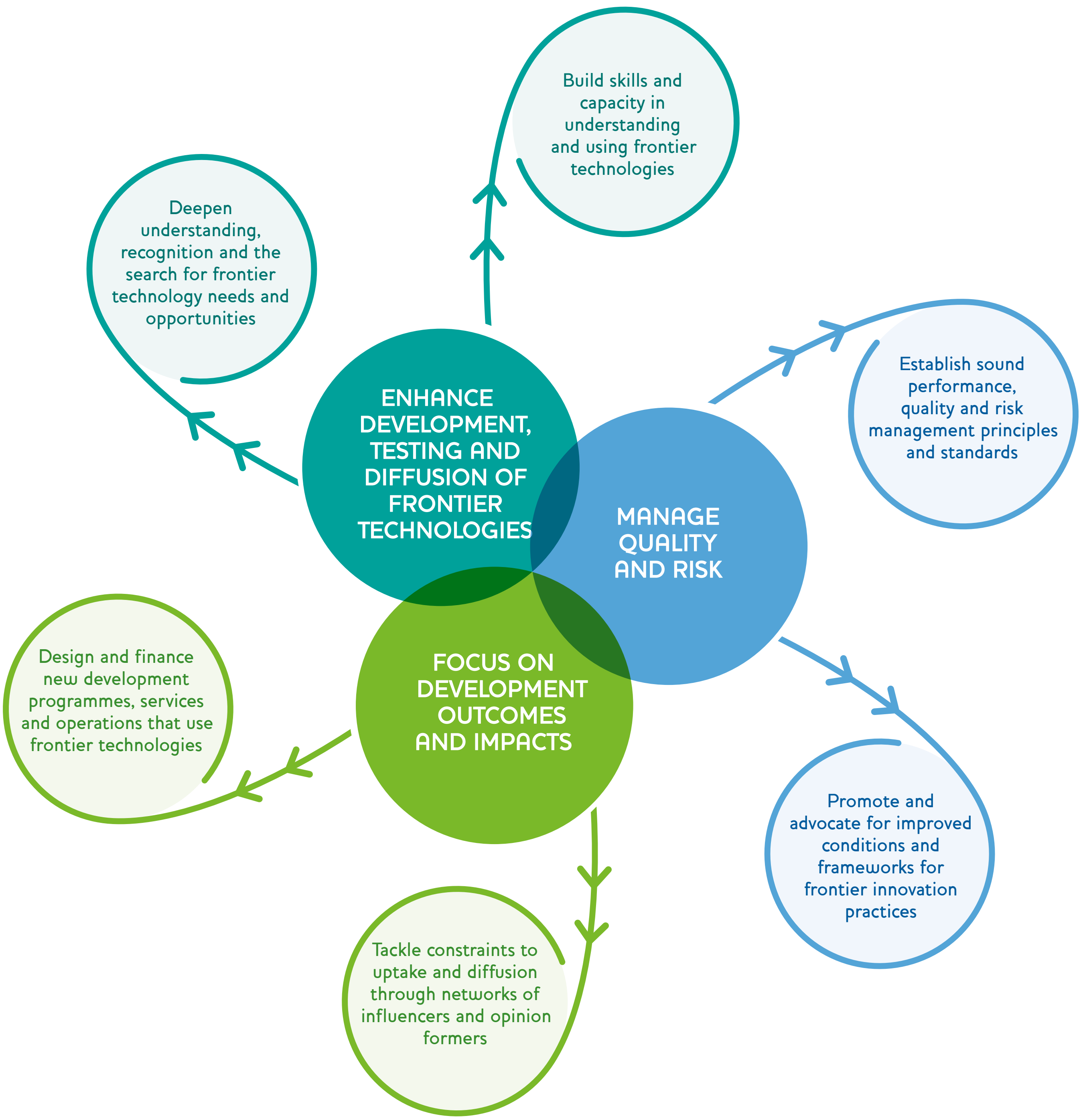
Manage quality and risk

- **Establish sound performance, quality and risk management principles and standards** to ensure that innovation is undertaken responsibly and ethically, and is specific to individual contexts. Clear and flexible protocols are needed to ensure product performance, safety and quality assurance for users and consumers, and to facilitate interoperability.
- **Promote and advocate for improved conditions and frameworks for frontier innovation practices** that promote safety and privacy, managing risks by using 'regulatory sandboxes', and overcoming obstacles that may limit frontier technologies wider uptake and use.

Focus on development outcomes and impacts

- **Design and finance new development programmes, services and operations that use frontier technologies** – Development sector finance can signal and underwrite tested technologies' market potential. Actors in the sector should also promote their use in development programmes and use purchasing power intelligently to support novel solutions in becoming mainstream. Considerable scope also exists to use frontier technologies – especially digital ones – to improve processes, leading to more agile and adaptive development programmes that flex and change as technologies improve.
- **Tackle constraints to uptake and diffusion through networks of influencers and opinion formers** – Development actors should use their influence to adopt and consolidate innovations that are useful and generate value, and to overcome non-technological barriers such as potential users' lack of financial capacity or leaders' lack of engagement.

Recommendations for development organisations



Introduction and overview

Introduction

From its very inception, a strand of international development has focused on the potential of technology to bring about positive changes in the lives of poor and vulnerable people.[1] President of the United States Harry S Truman in his 1948 inaugural address called for 'a bold new program for making the benefits of our scientific advances and industrial progress available for the improvement and growth of underdeveloped nations'.[2]

Similar calls have been made since, based on assumptions of technologically driven development. The basic premise was simple, arguably to a fault. Relevant technologies would be either available – or if not, developed and perfected – in developed countries and subsequently transferred to developing countries through the pipeline of development cooperation.

So-called 'technology transfer' models have been the subject of considerable and sustained criticism. In the 1960s EF Schumacher's stirring call for 'appropriate technology'[3] made the case for more contextually relevant, intermediate technological tools that were relevant to existing levels of development approaches. More recent assessments have emphasised the importance of technologies that are developed in developing countries over those transferred to developing countries;[4] and the role licences and intellectual property rights play in this process.

It is also important to note that new technologies are being adopted in developing countries regardless of the work of international organisations. A 2008 study by the World Bank found that 'the main channels through which technology is diffused in emerging economies are foreign trade (buying equipment and new ideas directly); foreign investment (foreign firms bringing them); and migrant communities in Western countries, who keep families and firms in their countries of origin abreast of new ideas'.[5]

However, the past few years have seen a growing interest in the potential of novel frontier technologies to contribute to positive changes in international development and humanitarian work.[6]

The past few years have seen a growing interest in the potential of novel frontier technologies to contribute to international development and humanitarian work.

Within the development sector, new technologies are seen as centrally important to achieving the United Nations (UN) Sustainable Development Goals (SDGs) by 2030.[7] In contrast to earlier efforts to transfer technology, there has been more emphasis by development actors – in principle at least – on designing with and for end users, on being responsive to social, cultural and political dynamics, and on taking an adaptive and iterative approach to innovation processes. [8] This has driven efforts to re-envision development innovation processes – from technology development and implementation to testing and diffusion – as participatory, open, and grounded in social, economic and political contexts in developing countries.[9]

Against this background, the United Kingdom (UK) Department for International Development (DFID) commissioned the Digital and Technology Research Group at the Institute of Development Studies to undertake a review of ten frontier technologies and what they might contribute to development efforts.

Overview and methodology

This report focuses on ten frontier technologies and their potential to positively contribute to development and humanitarian efforts. It also examines the critical questions and challenges posed by these technologies, and closes with the different roles development actors might play in realising the opportunities and mitigating the risks these technologies present.

The report begins by describing the nature of frontier technologies and their specific relevance to international development. It moves on to look at key cross-cutting messages within the technology reviews; and then sets out a number of potential roles for development actors in facilitating frontier technologies in ways that can make a positive contribution to international development goals. The second part of the report presents the ten technology reviews, which explore each of the frontier technologies in more detail.

The list of ten frontier technologies arose out of crowdsourced consultation process with DFID staff and advisers globally, initially casting the net wide, and then filtering the long list down through a process of internal dialogue and online voting. This initiative, although small scale and organisationally focused, followed the same kind of consultative processes other mechanisms use to identify frontier and emerging technologies, including the World Economic Forum's Meta-Council on Emerging Technologies.

There then followed a process of research and learning, based on an extensive review of the available literature on each technology, as well as consultations with expert informants and DFID staff. In total over 300 articles, reports and studies were reviewed, and over 50 experts were consulted over the course of April–September 2016.

The technology reviews and the initial synthesis findings were presented at a roundtable at DFID HQ in London at the end of June 2016 for feedback, discussion and debate. The key discussion points and outcomes of the discussion have been incorporated into the main body of the report. The technology reviews were also subject to review by selected experts for each technology, leading to a process of adaptation and refinement of the material.

Roosegaarde's Smog-Free tower has been installed in Beijing, China, one of the world's most polluted cities, as part of its world tour. See p.112. Photo credit: Studio Roosegaarde.

It should be noted that technologies are constantly evolving – frontier technologies more rapidly than more established forms – and so these reviews need to be seen as a snapshot in time, synthesising existing evidence, ideas and insights at the time of writing.

Moreover, no such review can claim to be fully comprehensive and exhaustive. Rather the aim is to provide a broad overview of prominent frontier technologies and the landscape within which they are emerging.

Explaining frontier technologies

What are frontier technologies?

According to the Organisation for Economic Co-operation and Development's most recent annual report in the *Science, Technology and Industry Scoreboard* series, **frontier technologies[10] are those 'that will reshape industry and communications and provide urgently needed solutions to global challenges like climate change' and 'have the potential to displace existing processes'.**[11] The same report finds that in the past decade frontier technologies have been especially prominent in fields related to information and communications technologies, energy and the environment.[12] These fields correspond very closely to the categories of frontier technologies explored in this report (see Box 1).

Box 1 Five areas of frontier technologies looked at in this report

MANUFACTURING AND CONSUMPTION

New digital tools that enable new approaches to manufacturing using novel materials, and new digital platforms that bring together producers and consumers in novel ways.

- **3D printing for development**
- **Collaborative economy tools**

CONNECTIVITY

New approaches to expanding digital connectivity and growing the range of things that are online.

- **Alternative internet delivery**
- **Internet of things**

TRANSPORTATION AND LOGISTICS

Autonomous aircraft and airships, enabling more efficient and lower cost transportation and logistics to less accessible areas.

- **Unmanned aerial vehicles/drones**
- **Airships**

FRESH WATER

New approaches to sustainably extract fresh water from seawater and brackish water, and from the atmosphere.

- **Solar desalination**
- **Atmospheric water condensers**

CLEAN ENERGY AND AIR

Distributed energy generation and storage technologies, and novel ways to reduce smog in different settings.

- **Household-scale batteries**
- **Smog-reducing technologies**

McKinsey Global Institute's examination of a number of frontier technologies takes a more economic perspective, arguing that they are new approaches with the potential to 'disrupt the status quo, alter the way people live and work, rearrange value pools, and lead to entirely new products and services', while at the same time 'supplanting older ways of doing things and rendering old skills and organisational approaches irrelevant'.[13] For example, collaborative economy tools that enable more efficient use of assets such as property and vehicles for example, Airbnb, CityCarClub and Uber could potentially bring about new approaches to consumption for users and business operation for would-be business people. At scale, such approaches allow greater access to essential assets for a greater number of people by overcoming costs of full ownership, while simultaneously lowering barriers to entry for entrepreneurs wanting to start up a business in a particular sector.

Although they can stem from any field or discipline, reading across comparative studies reveals a number of common features among frontier technologies.[14] Specifically, frontier technologies:

- **Address large-scale economic, social or political opportunities or problems**

  The challenges or opportunities that frontier technologies address are often very large, in terms of the economic value that might be generated, services that might be improved, different groups that might be reached, or numbers of lives that could be improved. The problems and challenges the technologies in this report seek to address include energy poverty (household-scale solar batteries), water scarcity (atmospheric water condensers and solar desalination), reaching areas inaccessible through conventional transport (drones and airships), and more.

- **Are characterised by rapid rates of technological development and advancement**

  Frontier technologies are usually at the forefront of a fast-changing technical field. This is typically manifested in a number of breakthroughs that 'drive accelerated rates of change or discontinuous capability improvements'.[15] These improvements are usually in terms of price, performance and market share compared to alternative approaches.

- **Have broad potential impacts across diverse fields**

  Frontier technologies typically sit at the interface of existing sectors or silos, and successful endeavours have implications for a variety of industries, sectors and businesses. To take one example from the technology reviews, the IoT is expected to radically improve the efficiency of a wide range of public sector, business, and social processes as connected devices are able to interact with each other directly.

- **Carry substantial potential for displacing or leapfrogging existing technologies, or previous technological pathways taken in developed countries**

  Frontier technologies have significant potential to change the technological landscape, and thereby to dramatically change the expected pathways for development gains, or be particularly appropriate in a development context. The archetypal example is how the mobile phone has become ubiquitous in developing countries despite the lack of landlines and other infrastructure that predated their diffusion in developed countries. One example from the technology reviews is the potential for off-grid home solar systems, paired with household-scale batteries, to leapfrog the need to extend the conventional power grid into remote areas.

- **Involve considerable uncertainty about opportunities, risks and future pathways**

  By their very nature, frontier technologies are not assured of success or failure, and a great deal of uncertainty and complexity surround the possible paths to success and wider diffusion (price, availability, modification, political economy, resource focus, etc.)

Why are frontier technologies important for international development?

The potential importance of frontier technologies is increasingly highlighted in policy and practice circles with reference to the growing pressures on delivering development gains, both now and in the future.

As noted by Owen Barder and Charles Kenny at the Centre for Global Development: If we are to sustainably feed a planet of nine billion, we need new crops and tools for water and nutrient efficiency. If we are to preserve and extend health gains across the world we need *new vaccines and antibiotics*. If we are to get to a planet where everyone has access to plentiful modern energy and [be free from] air pollution… we need the development of *new, cheap, and robust renewable technologies*. [16] A number of technologies have been developed that would appear to illustrate this potential, from low-cost vaccines to mobile phones. But more effort is clearly necessary to deliver on a new generation of development and humanitarian ambitions. According to the UN's work on technology and the SDGs, **'in order to eradicate poverty and reorient current unsustainable development trajectories over the period 2015 to 2030, affordable technological solutions have to be developed and disseminated widely in the next fifteen years.'** [17]

These newly developed technologies can contribute to social, economic and political development gains by a number of pathways, both directly and indirectly:

- **Driving innovations in business models, products and processes that provide new goods and services to 'bottom of the pyramid'[18] consumers.** This often happens when frontier technologies are paired with other existing or frontier technologies. For example, the successful M-KOPA business has expanded rapidly across East Africa through innovative combination of mobile money schemes and the IoT. M-KOPA is able to provide financing and service schemes that make household solar systems affordable to many of the poor for the very first time, at a lower cost than traditional, inefficient and unsustainable approaches such as the use of kerosene fuel.
- **Providing means by which to make better use of existing underutilised household and productive assets.** Collaborative economy businesses make use of digital tools to allow producers and consumers to make more efficient and effective use of a range of assets, thereby disrupting existing business models. For example, property owners can benefit from being able to market unused rooms as rental accommodation (Airbnb) or earn income from driving people in their own vehicles (Go-Jek and Uber). These services also lower costs for consumers.
- **Catalysing increases in demand, nationally and internationally, which create new industries and markets, leading to macro and microeconomic growth.** Frontier technologies can drive the emergence of novel industries, as with solar batteries for off-grid household energy, or the use of alternative fuels in producing fresh water in more sustainable ways. Digital technologies have also underpinned many new sectors and sub-sectors.
- **Changing demand for labour and capital, leading to direct job creation and transformation of the workforce.**[19] New technologies can create new opportunities for employment, skills development, entrepreneurship and investment.

Of course, for all of these potential upsides, potential downsides also exist that need to be considered. For example, along with the potential to create jobs, 3D printing (3DP) might potentially displace workers in the manufacturing sectors as less employees are needed to in the production processes. It might also make it more lucrative to build projects closer to end markets rather than in countries with low wages. The value of analysing and understanding such technologies is precisely that by doing so it is possible to 'raise awareness of their potential and contribute to closing the gaps in investment, regulation and public understanding'.[20] While it will largely be the private sector that will drive deployment of these technologies, the public sector through national regulation, as well as development financing, will have a major role in mediating the pace and direction of technological change, both to achieve development objectives, and to protect potential losers.

The ten frontier technologies examined in the research

As already described, the ten frontier technologies looked at here were arrived at through a process of crowdsourced consultation with DFID staff and advisers, which generated a long list of technologies, which were then narrowed down to a short list of ten through a process of internal dialogue and voting. The ten technologies are set out in Table 1 below.

Table 1 The ten frontier technologies examined in the research

Each of these is looked at in more detail in the accompanying Technology Reviews report, which should be read in parallel with this report. The rest of this report summarises key themes emerging from across the technology reviews.

TECHNOLOGY CATEGORY	SPECIFIC TECHNOLOGIES REVIEWED	QUICK DEFINITION
Manufacturing and consumption	3D printing See pg. 40	Printers capable of printing 3D objects directly from digital prototypes
	Collaborative economy tools See pg. 48	A range of initiatives based on enhancing the utilisation of assets by establishing horizontal networks across and between owners of assets and potential users
Connectivity	Alternative internet delivery See pg. 58	Large-scale initiatives, usually involving innovative aerial or satellite-based approaches to infrastructure aiming to expand affordable internet access globally
	Internet of things See pg. 64	Data communication technologies built into physical objects, enabling a wide variety of objects and assets to be sensed, measured, coordinated, and controlled remotely
Transportation and logistics	Unmanned aerial vehicles/drones See pg. 74	Aircraft that operate without human pilots on-board, for easier and lower-cost sharing of information and goods
	Airships See pg. 79	New aircraft designs that use alternative energy sources and do not rely on the same infrastructure as traditional aircraft, thereby expanding reach and access
Fresh water	Solar desalination See pg. 90	The use of alternative energy to convert salty or brackish water into clean drinking water around the world
	Atmospheric water condensers See pg. 97	Innovative structures and materials capable of collecting fog and rainfall as a source of clean drinking water
Clean energy and air	Household-scale batteries See pg. 104	Low-cost home battery systems that recharge using electricity from solar panels, providing energy access to off-grid communities
	Smog-reducing technologies See pg. 111	A range of technologies aimed at reducing levels of air pollution

Ten key themes from the technology reviews

Frontier technologies are defined and shaped by context

Across the technology reviews, it is clear that what might be seen as a frontier technology is very much dependent on particular economic, social and technological contexts, and the problems and challenges faced by actors working and operating in those contexts. For example, in urban centres in Kenya a frontier technology application of the IoT (see Technology Reviews Part 2) might relate to digitally enabled home energy efficiency, which makes use of broadband and wireless technology. Meanwhile, in rural parts of Kenya, a frontier application of the IoT might use mobile connectivity to allow more basic but essential access to solar energy for off-grid households (as shown in Technology Reviews Part 5).

Catalytic converters (also in Technology Reviews Part 5) are an obvious example of how a mature and well-established technology in developed country contexts can be viewed as frontier in many developing countries. There are also existing technologies where novel applications are clearly frontier in nature. For example, the growing use of unmanned aerial vehicles (UAVs) (Technology Reviews Part 3) has led to widespread use in digital mapping of landscapes and other physical features, but applications are now rapidly expanding to include logistics and transportation of goods, which could see much wider dissemination and use across a range of areas and sectors.

Therefore is seem important to think about frontier technologies in very specific and concrete ways, asking the questions: *Frontier for whom? In what ways? And with what benefits?*

Frontier technologies are often in reality a blend of different solutions

Frontier technologies almost always represent an aggregation of many different parts being blended together to address specific challenges or problems. For example, the development of the World Wide Web required the development of a whole host of innovations, including packet switching technology, internet protocol suite standards and hyper-text language protocols developed by Sir Tim Berners-Lee.[21] A number of the frontier technologies looked at here are also being applied through similar blending strategies, with particular attention paid to the way existing technologies are used in developing countries.

Such strategies have been discussed in development science and technology circles since at least the 1980s, but are worth revisiting in light of the most recent wave of interest in innovation for development. Broadly speaking, technology blending for development involves combining frontier technologies with techniques and procedures found in low- and middle-income countries. For example, 3DP will need to work hand in hand with existing manufacturing networks; UAV logistics will need to be built into existing supply chains for health and other vital products; and successful solar desalination and water-harvesting systems will need to be embedded in well-functioning water management structures and processes, whether or not they are privately operated or community run.

> What is seen as a frontier technology is very much dependent on particular economic, social and technological contexts, and the problems and challenges faced by actors working and operating in those contexts.

It is also worth flagging up the special potential of digital technologies in this regard. New ways of communicating information, sharing it and acting on it – either through automation or with human intervention – can provide a vital infrastructure for the dissemination of frontier technologies. The best example of such blending among the technology reviews discussed here is the roll-out of household-scale solar batteries that require effective financing, and which has been enabled by pay-as-you go systems underpinned by mobile phone-enabled money transfer tools. The notion of the collaborative economy is itself a frontier technology, based on the idea of blending new digital platforms with existing, underutilised assets, which may be technological in nature.

Frontier technologies can help redefine and navigate wicked problems

A number of the technology reviews focus on technologies with the potential to add value to seemingly intractable development challenges, sometimes termed wicked problems.[22] Their potential value derives from the scope of particular technologies to redefine critical challenges in transformative ways and make them more amenable to change. For example, solar desalination has the potential to overcome water insecurity by moving beyond approaches to better management of existing freshwater sources, to focus on novel sources of fresh water, as well as being a sustainable means of accessing that water. Similarly, household-scale batteries paired with renewable energy sources can help rural poor populations move away from inefficient, dirty and expensive fuels to gain sustainable and affordable off-grid access to electricity.

This is not to say that all such problems are amenable to purely technological fixes. There is substantial evidence across the history of development efforts that stacks up strongly against such a conclusion. However, what the new technologies can do in the face of such challenges is help to expand the space for possible solutions, thereby signalling that the search for solutions should not be bounded by current frameworks and mindsets. Although new technologies do not always achieve such dramatic changes in how problems are understood, and there are risks of techno-utopianism if such expectations are taken too far, it is clear that frontier technologies are increasingly useful as a way of highlighting the limitations of existing solutions, and suggesting new ways to overcome them.

Diffusion takes time and can have multiple pathways

Diffusion[23] patterns for successful technologies generally follow a distinctive 'S' shape, with the rate of adoption initially slow and confined to so-called first adopters, increasing rapidly as the technology becomes established, but then slowing as markets approach saturation, with only harder to reach or resistant adopters left. The shape of each diffusion curve is unique, but the most important difference is in the time taken to reach 'take-off', which innovation scholar Everett Rogers estimated to be between the 5 and 25 per cent adoption

> Frontier technologies are as a way of highlighting the limitations of existing solutions, and suggesting new ways to overcome them.

rates.[24] Take-off is the level of penetration from which the technology is likely to reach widespread adoption.

However, some technologies reach this level of penetration and go out of fashion or are superseded by superior technologies. Some might approach this level very slowly, taking decades, while others might accelerate past it rapidly. Research by the World Bank found that for 28 technologies that achieved a market penetration of at least 5 per cent in developed countries, 23 went on to achieve a penetration of over 50 per cent. The path from early adopter to mainstream can be rapid. In developing countries, however, of 67 new technologies that had achieved a 5 per cent penetration, only six went on to reach 50 per cent. In other words, new technologies can be adopted by a small minority of people in poor countries, but often fail to achieve widespread diffusion, so their benefits do not become more generally available.

One reason is that take-off and wider diffusion can be achieved in a number of ways. Although this was not derived from the reviews, Table 2 shows the number of different approaches for the diffusion of technologies and illustrates the diversity of approaches that can be seen across the technology reviews. In international development, it has been hypothesised that the majority of innovation processes focus on diffusion by replication, regardless of the nature of the underlying problem they are addressing or indeed the nature of the solution.[25]

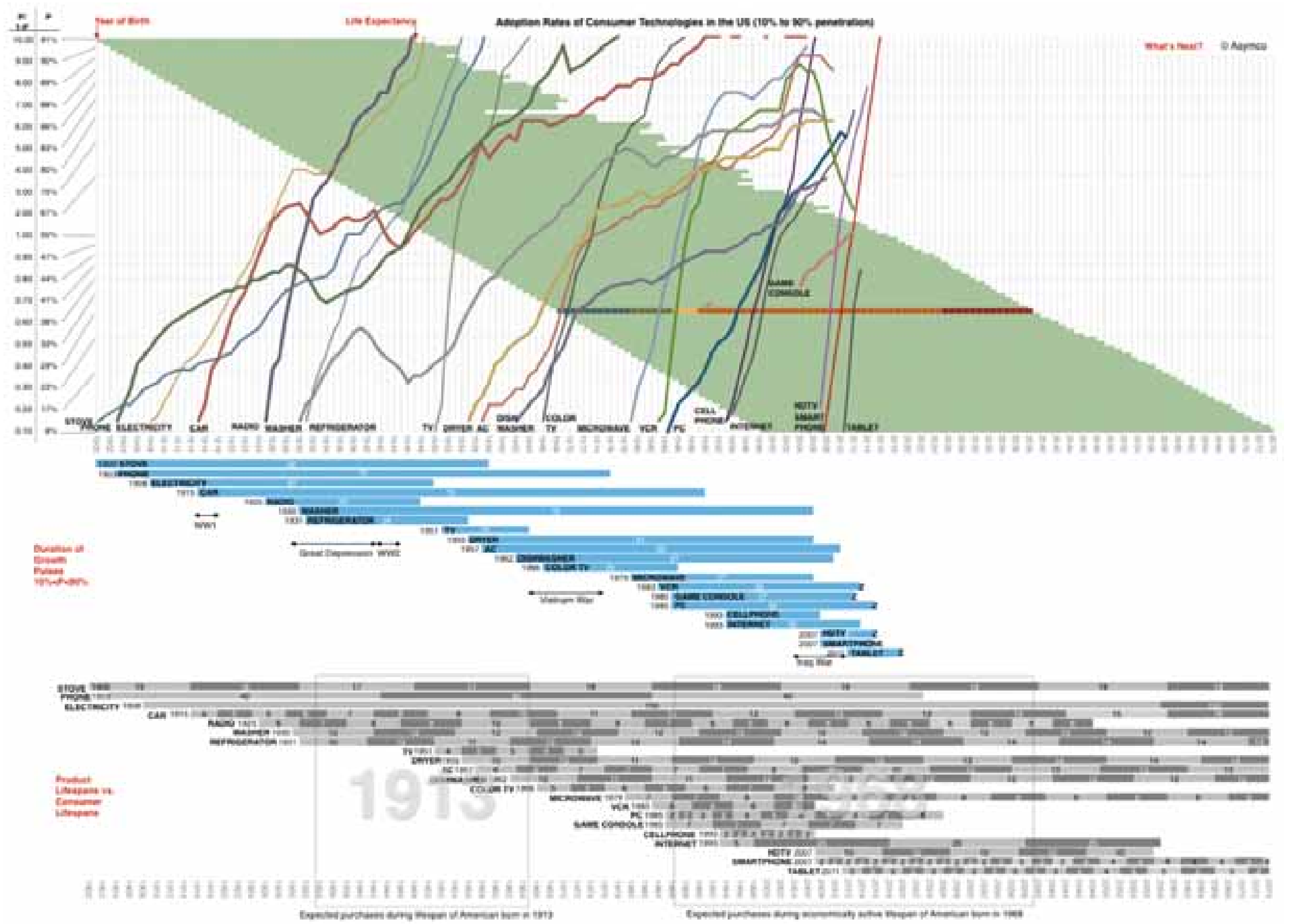
It also takes time for technologies to diffuse comprehensively across a population, as shown in Figure 1 on the next page on diffusion patterns of key technologies in the US. Other factors can affect the rate at which technologies diffuse, including public infrastructure, government regulation on competition and standards, compatibility between technologies, supportive institutional reforms, and wider contextual factors.

Table 2 Six different pathways for diffusion of technologies

ENDGAME	CHARACTERISTICS	CORE APPROACH	FUTURE ROLE
Open source	A breakthrough idea that is easy for other organisations to adopt and integrate	Conducting research and development, and sharing knowledge	Serving as a knowledge hub for research related to a breakthrough idea
Replication	A breakthrough product or model that is easy for other organisations to adopt and deliver	Defining a replicable operating and impact model. Demonstrating its efficacy, and sharing it with other organisations	Providing certification of franchise programs and training services, and servicing as a centre of excellence.
Government adoption	A model of high coverage potential, along with a capacity for integration into public sector programs	Delivering results at a sufficient scale and level of efficiency to make a case for public sector involvement	Offering services to government agencies, and maintaining research and advocacy efforts
Commercial adoption	A product or service with profit potential that solves a market failure or reduces market risks	Demonstrating the impact and profitability of a product or service, and reducing associated risks	Maintaining advocacy and monitoring efforts, targeting hard-to-reach market segments, and working to ensure commercial delivery
Mission achievement	Defined and achievable outcomes related to solving a discrete problem	Maintaining a focus on targeted intervention	Applying (where relevant) unique assets and capabilities to additional issue areas
Sustained service	A strong organisation, with a proven ability to sustain funding, that fills a market or public service gap	Creating a cost-effective model, building a strong organization, and making efficiency improvements	Continued provision of a core service at an ever-increasing level of efficiency

Source: Stanford Social Innovation Review (2015)[26]

Figure 1 The diffusion of selected technologies across US households



Source: Asymco (2013)[27]

These last two points are worth exploring in more detail. At present, although their diffusion has been accelerating (as seen in Figure 1 opposite), there is something of a lag between the development of frontier technologies and their mainstream acceptance. While new technologies are emerging at an ever-faster pace, there is often a delay before institutional norms and structures are adapted and refined so as to exploit their benefits. Perhaps the most prominent example is that the second industrial revolution – when electricity replaced steam – took 30 years or more to make a tangible contribution to the efficiency and effectiveness of industrial production. This seems to be a feature of the digital revolution as well. As Nobel Prize-winning economist Robert Solow quipped in 1999, 'you can see the computer age everywhere except in productivity statistics'. This is attributed to the fact that institutions fundamentally shape how frontier technologies are incorporated into existing organisational and managerial processes.

Electricity was first used to power factories that were otherwise unchanged from the steam era, with the factory floors stacked vertically above a large engine housing. It took a generation before the potential of electricity was fully understood, and factories were redesigned to maximise the potential of mass production, giving us the low, flat, expansive industrial factory set-ups that are still commonplace today. Today 3DP provides the opportunity to disrupt such factory set-ups, but only time will tell if it is able to maximise its production potential and how long it will take.

One common challenge across the ten technology reviews is the tendency for the benefits of frontier technologies to accrue to those actors who already enjoy material and other advantages, meaning that key groups – women, children, elderly, lower socio-economic groups, ethnic minorities – are less able to gain a fair share.

Exogenous factors also affect the diffusion of frontier technologies. The analysis underpinning Figure 1 indicates that the advent of the Great Depression (1929) and the Second World War (1939) appear to have slowed or even reversed the household diffusion of electricity, the automobile and the telephone. In contrast, a number of exogenous factors seem to have accelerated interest in selected frontier technologies. The rise of collaborative economy approaches such as Airbnb and Uber has been especially pronounced since the financial crisis of 2008 and the growing need for alternative, low-cost ways to supplement income, and indeed to access services. Meanwhile, the rising impact of climate change on water availability has accelerated efforts in solar desalination and water harvesting.

Managing risks

Frontier technologies can lead to unequal benefits

These technologies must overcome many challenges before they reach take-off, as identified previously. A number of these are not just in the technical sphere, but relate to ways of increasing the impact of the technology, if and when acceleration occurs; and maximising positive benefits while managing possible downsides. One of the most common challenges highlighted across the ten technology reviews relates to the tendency for the benefits of new technologies to accrue to those actors who already enjoy material and other advantages, meaning that key groups – women, children, elderly, lower socio-economic groups, ethnic minorities – are less able to gain a fair share.

The specific ways that this challenge can be navigated vary considerably by technology type, but one message across the technology reviews is the need to focus on the processes by which these technologies are managed and supported, to ensure end users' needs and interests are at the forefront of development, deployment, piloting and scaling efforts. This means effective engagement with developing country stakeholders – from governments, private sector and communities – in determining problems, exploring solutions, designing specific configurations of solutions, and so on. It also means working to strengthen the capacity of communities and citizens to engage with, understand and use the technologies.

Although many of the technologies may offer the potential to expand goods and services to more people, some of them simultaneously pose a threat to existing livelihoods and jobs. For example, 3DP could have the potential to displace current ways of making a large variety of goods. This may reduce the market drive towards offshoring manufacturing to developing countries with lower wages, with more work taking place in close proximity to end users and markets in developed countries. This could potentially reduce levels of foreign direct investment and other financial flows into developing countries, and create more domestic jobs in high income countries.[29]

This may be of positive economic and social benefit in the long run for developing countries, especially given the scope to disrupt and challenge existing supply chains to enable more local production. However, there are also potentially negative implications for small and medium-sized enterprises, which are integral to job creation and economic growth in developing countries, because local production through 3DP may lead to more manufacturing being relocated from developing countries to be closer to end consumers. While some firms may adapt to such shifts in global value chains, many more may not have the capacity or desire to do so, particularly given the large numbers of poor people who currently work in small-scale manufacturing and construction. The positive outcomes for development, in other words, are far from guaranteed, and potential downsides and risks should not be ignored.

Along similar lines, groups that have not already benefited from earlier investments and development processes could be marginalised. For example, a number of digital innovations rely on good levels of connectivity (specifically, 3DP, the collaborative economy and the IoT). Here, existing forms of digital divides – from access to digital literacy – are likely to inhibit their widespread dissemination among the poorest groups. Again, there are critical gender and age considerations here.

Finally, with specific reference to digital innovations, the low or zero cost of replicating software and the falling cost of computer hardware can lead to winner-take-all market outcomes in which users have a strong tendency to opt for the most popular software or application in a particular field, especially if it is accessible at no cost – as can be seen in the market share dominance of Amazon, Google and Facebook, eBay and others in their respective sectors of online retail, search, social media and online marketplaces. The same pattern is now surfacing in the collaborative economy with the rise of platforms such as Airbnb and Uber. As Harvard innovation scholars Brynjolfsson, McAffee and Spence explain:

> The returns in [digital] markets typically follow a distinct pattern – a power law, or Pareto curve, in which a small number of players reap a disproportionate share of the rewards. Network effects, whereby a product becomes more valuable the more users it has, can also generate these kinds of winner-take-all or winner-take-most markets.[30]

Digital technologies have been shown to lead to a number of 'superstars' in different settings, creating monopolies and anti-competitive behaviour that can ultimately harm the poorest consumers and workers. Investments in these technologies will need to be complemented with parallel and active efforts to address and overcome digital divides and digital downsides.

Frontier technologies require skills and capacities to manage high levels of risk and uncertainty

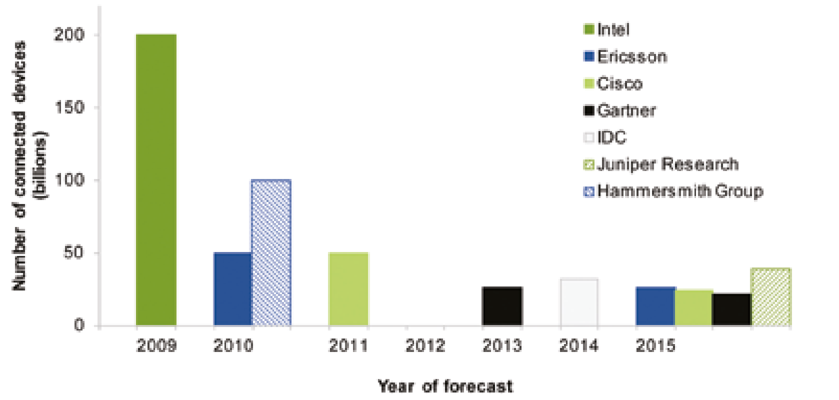
For a number of reasons, the path from invention to innovation to development impact is usually non-linear and difficult to predict. This is because of risks that relate to the technical sphere, the programmatic risks of testing the technologies, and wider social risks.

> The path from invention to innovation to development impact is usually non-linear and difficult to predict.

With frontier technologies, such risks are a continual feature, playing out not just in the technology development process, but also in their wider diffusion and use, and can strongly shape the kinds of impacts that are seen. For example, investments in the collaborative economy may seem inclusive in that they draw in people and assets that were previously not in the market. But although barriers to entry to sell goods and services in the collaborative economy are often lower than in the conventional economy, and jobs in the collaborative economy tend to be more flexible for workers, those people who start to earn a living from the collaborative economy often have to deal with uncertain incomes and benefits, and a lack of safety nets, compared with those in more formal jobs in the traditional economy.

For example, the global web-enabled taxi business Uber has now started offering UberPOOL, which maximises the use of each driver by getting them to pick up multiple commuters in the same vicinity who are going in the same direction, rather than each Uber driver picking up one passenger at a time. Although this is presented as a way of limiting fuel consumption and combating climate change, it also means that Uber needs fewer drivers per passenger and can drive up profits. Moreover, in the future Uber sees itself employing autonomous vehicles, without the need for drivers.

Figure 2 Changes in projections of the internet of things over time



Sources: Adshead (2014); Cisco (2015); Ericsson (2015); Gartner (2015); Juniper Research (2015); Postscapes (2014).

Source: Australian Government Analysis[31]

In similar ways, the collaborative economy disrupts jobs in pre-existing industries while the development benefits generated may be temporary. Any forecasts are contingent on making the right bets about a whole series of cascading and interdependent challenges, and are shaped by wider factors such as privacy, security, safety regulations and the willingness of consumers and firms to adopt the new technology.

Many of these factors remain highly uncertain, so it is hard to make any definitive decisions about what to invest in, when and how until such a time as the take-off is already clearly under way. This becomes apparent when one looks at how widely forecasts of the future size of the IoT (by number of connected devices) have varied over the past several years (see Figure 2).

The challenge of managing uncertainty underpins a fundamental limitation in how development actors deal with risk in relation to innovation, and indicates why many actors have been slow to engage with frontier technologies. In general, development actors work to minimise risks in their investments rather than to strategically manage them, and high-risk investments in particular are hard to manage and support.

The challenge of managing uncertainty underpins a fundamental limitation in how development actors deal with risk in relation to innovation, and indicates why many actors have been slow to engage with frontier technologies.

Achieving impacts

Frontier technologies can deliver many different types of impact

The frontier technologies looked at here have the potential to contribute to individuals, households and firms in developing countries in a range of ways, as shown in Figure 3 overleaf. It is vital to be aware of these potential impacts, to explore what might be possible in the context of different frontier technologies, and to continue to learn about how they might best be achieved.

Figure 3 The impacts of frontier technologies

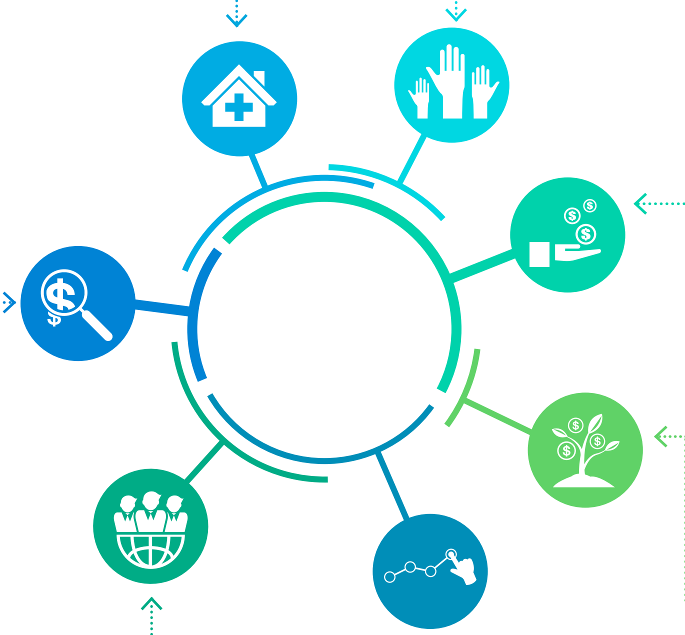
The frontier technologies looked at here have the potential to contribute to individuals, households and firms in developing countries in a range of ways as shown below.

Providing access to essential goods and services that would otherwise be unavailable due to physical, social or economic constraints – see Technology Review on Fresh Water.

Reaching remote or excluded populations with new services - see Technology Reviews on Transportation and Logistics, and on alternative internet delivery.

Generating new sources of income and welfare; this is true of many of the technologies covered here, but see especially the Technology Review on the collaborative economy.

Reducing the transaction costs and negative impacts of key market, public sector and social/community activities – see Technology Review on smog-reducing technologies.



Bringing a range of household and other assets into the market economy - see Technology Review on collaborative economy tools.

Catalysing new collaborative business models facilitated by digital platforms and technologies – see Technology Reviews on Manufacturing and Consumption.

Generating and managing data in new and innovative ways - see Technology Reviews on internet of things and UAVs/Drones.

It is vital to be aware of these potential impacts, to explore what might be possible in the context of different frontier technologies, and to continue to learn about how they might best be achieved.

The leapfrogging potential of frontier technologies needs careful analysis

The concept of leapfrogging is being increasingly used in the context of innovation for development as a way of describing how successful technologies can accelerate development processes. The concept is based on new technologies enabling groups or sectors in developing countries to skip over or leapfrog established technologies used in more developed countries. These established technologies might be more expensive, less efficient, more polluting, of inferior quality or simply not economically feasible. The country or sector would typically move directly to more advanced technologies, which would enable delivery of services and obtaining benefits without having to use intermediate technologies that were part of the historical evolution in other settings.

Perhaps the exemplary leapfrogging technology is the mobile phone, which has in a number of settings enabled the expansion of communications, financial inclusion and most recently energy systems without investments in fixed-line telephone infrastructure, banks and centralised power systems.

Observers and innovators have flagged up all the technologies discussed in the accompanying reviews as having leapfrogging potential, albeit in their different ways. For example, household solar energy system company M-KOPA (Technology Reviews Part 5) has made it is possible to reach off-grid poor households for less money than they would previously have spent on kerosene or the grid. More generally, the use of solar energy in developing countries is seen as a way of creating an energy infrastructure without having to rely on fossil fuels, allowing economies to 'jump directly into the 'Solar Age'.'[32] 3DP could enable developing countries to 'leapfrog' conventional industrial processes, bypass various elements of traditional manufacturing that are less efficient, more polluting, and require costlier infrastructure, and reduce dependence on foreign goods, because a large number of vital products could be manufactured locally on demand. In addition, aerial-based alternative internet delivery initiatives seek to overcome the need to build ground-based infrastructure in connecting the four billion people who are currently offline.

While all of these claims have some legitimacy, a degree of nuance is required. First, despite the excitement of some analysts, there is no solid evidence indicating that leapfrogging applies to all fields. It may, for example, be far more amenable to digital technologies than other forms of infrastructure.

Second, building on this, leapfrogging does not happen in a vacuum. Typically, some form of intermediate technology must be present for leapfrogging technologies to be successful. In other words, favourable conditions and the presence of 'analogue complements' are often prerequisites for widespread technology diffusion. Mobile telephony may have enabled fixed-line systems to be comprehensively leapfrogged, but the same may not be true for technologies such as airships in relation to planes. While airships will be cheaper and provide novel improvements for specific consumer groups and regions, they are likely to be a niche or partial leapfrog, which works to complement other existing transportation infrastructure.

Along similar lines, while solar energy (off grid) could in principle leapfrog grid electricity infrastructure, the capacity of such a system may not deliver the comprehensive benefits of a grid system without considerable further development. Further improvements and cost reductions in household-scale batteries are one of the key issues that will define whether this set of technologies offers a partial or full leapfrog (i.e. improving electricity service until the grid arrives, or completely displacing the need for the grid).

More generally, then, it is important to understand what exactly is being leapfrogged, and whether or not existing technologies and infrastructure are being fully replaced, complemented or extended.

Frontier technologies can deepen and extend value chains

Many of these frontier technologies provide the opportunity to deepen, extend and in other ways transform value chains, enabling more efficient delivery of goods or services to more people, especially the poor and people living in remote areas.

For example, airships and UAVs provide the opportunity to transport packages the 'last mile' from areas that are served by infrastructure to areas nearby where roads may be impassable, inadequate, or non-existent. Specific areas where impacts might be feasible include the vaccine cold chain, where investments are already being made for UAVs to fill gaps and strengthen weak national systems. In collaboration with the Rwandan government, Californian robotics firm Zipline has designed a drone delivery network for getting medical essentials to rural health facilities. Initial plans are to make up to 150 deliveries of blood a day to 21 transfusing facilities within a 47-mile radius of a delivery hub, with vaccines and other supplies to be added after the test phase.[33]

Similarly, 3DP can work to shorten the manufacturing value chain, skipping the need to transport goods – as long as necessary materials are available – and provides clients in developing countries with the potential to print customised products that fit their particular needs.

The collaborative economy changes the rules of the game regarding who can be a supplier of goods and services; gives more people the ability to rent out their idle assets or provide services; and increases their ability to participate in the global economy via open platforms that are accessible through the internet and mobile devices. An embryonic IoT is also observable, with the use of mobile money networks to create financial models for solar energy systems to be extended to off-grid households.

Solar desalination and water condensers bring the production of water to the community, bypassing the need to rely on long supply chains and can be economically viable in places where water delivery systems do not reach and transport costs are a big portion of the cost of clean water.

For these technologies to deliver such impacts, greater coordination and information sharing across critical value chains are needed, and the ability to track where frontier technologies can: (a) fill critical gaps; (b) extend value chains to new groups or areas; or (c) enhance the nature of the value being delivered through complementary and additional services.

Accelerating green transformation and expanding green frontiers

Most of the technologies covered in this report have positive environmental functions or externalities, making them potential additions to strategies for green transformations. Some have very direct relevance. For example:

- **Airships** use less fuel to carry the same amount of cargo over the same distance as planes. Moreover, prototypes have shown the feasibility of building airships that run entirely on renewable energy, making it potentially the only zero-carbon form of flight. They also make much less noise than conventional aircraft. Because airships and (most) drones do not need extensive runways, roads or airports to take off and land, they are less destructive to the environment around their points of departure and landing sites.

- **Fog collectors** are passive technologies that do not require any energy inputs to convert fog, dew, and rainwater into safe drinking water. Similarly, solar desalination provides the opportunity to desalinate brackish water using solar energy rather than fossil fuels, as is typically done with conventional methods. Both of these can make water access more sustainable.

- **Household-scale batteries** enable the storage of intermittent renewable energy for reliable use on or off the grid.

- **Catalytic converters**, catalytic paints and smog-reducing towers convert dirty gases already in the air into less harmful ones.

Others are indirect in nature, for example:

- **3D printing** reduces the waste generated from manufacturing processes, and because goods can be produced in or very near where they will be used, there is less need to burn fuel for transport.

- **The collaborative economy** allows ordinary citizens to rent out or share their underused assets with others who would otherwise have to purchase an entirely new asset, thus potentially curbing the sustainability impacts of global mass production and consumption culture.

- **The Internet of Things** allows asset and equipment manufacturers to monitor the health of assets in real time, giving birth to business models in which manufacturers provide goods as a service. This means that equipment can be repaired and replaced only when it needs maintenance, and that the manufacturer has a direct stake in limiting waste and recycling materials. The IoT also enables farmers to practise precision agriculture, ensuring that all plants across a field get precisely the amount of inputs they need, thereby maximising yields while limiting soil depletion and decreasing water wastage.

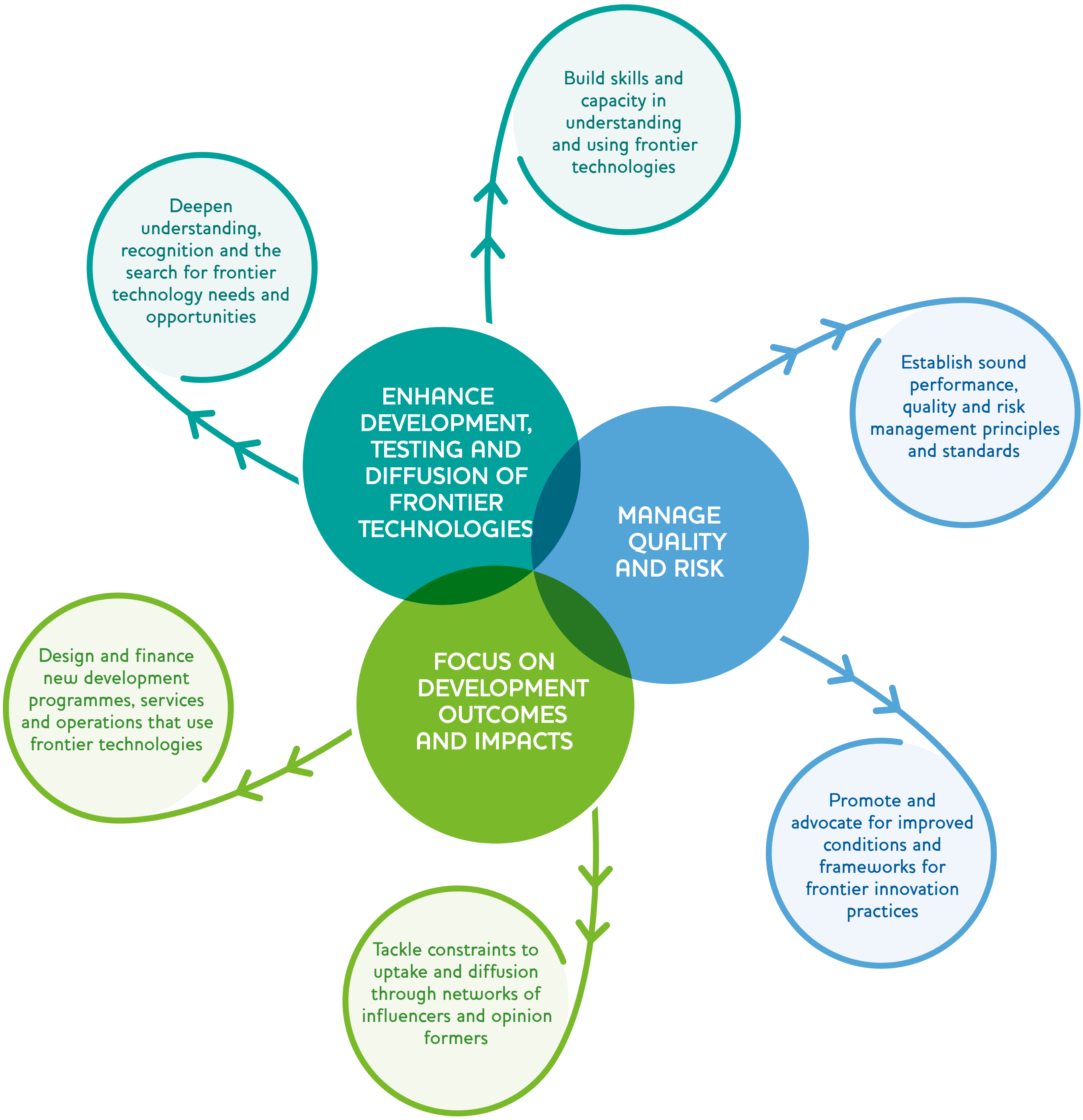
> The potential of frontier technologies to lead to a greener circular economy could be dramatically improved by combining them with each other and other technologies.

However, it should be noted that few of these frontier technologies would offer magic bullet solutions to achieving sustainability goals in developing countries, just as they do not have such status in developed countries. Instead, their potential to reduce emissions along the value chain and lead to a greener/circular economy could be dramatically improved by combining them with each other and other technologies, thereby leading to positive multiplier effects. For example, the IoT could be boosted thanks to connectivity through alternative internet delivery. The IoT could also be incorporated into solar desalination systems and atmospheric water condensers in remote areas to ensure that equipment is functioning as expected and that drinking water is safe, and if not, the required replacement parts could be ordered and transported by drones. In other words, the effectiveness of these technologies, as well as their potential to accelerate sustainability, could be increased by using them in tandem. Rather than think of these technologies in isolation, more work is need to understand how they could be combined with each other and other frontier technologies to create a ‘green ecosystem’ of frontier technologies to better meet the needs of the poor and underserved.

Recommendations for development organisations

The ideas set out in this section draw on the technology reviews and focus on two broad areas: first, how development organisations can strengthen strategies and management for specific frontier technologies; and second, how they might improve the enabling environment for frontier technologies. These are set out in Figure 4 and described in the rest of this section.

Figure 4 Recommendations for development organisations



Enhance the development and diffusion of frontier technologies in international development work

Deepen understanding, recognition and the search for frontier technology opportunities

Frontier technologies are often surrounded by hype and hyperbole about their potential impacts. It also seems as though one of the best ways for any novel technology to get instant global fame is to make unsubstantiated claims about its potential development impact. One of the first things development organisations should do is to follow the approach taken in industry and innovation management, and use careful research and analysis to deepen understanding of the challenges, opportunities and risks different frontier technologies present.

Such analysis should be used to better identify potential entry points for development actors, as well as to understand the potential positive and negative impacts of a particular technology. Building this understanding and analysis should be done by creating a broad church of collaborators, and by leveraging previous work. For many technologies, scientists and investors will already have undertaken relevant generic assessments – as indicated in the Technology Reviews report – that can be used as the basis for development-specific assessments of opportunities and risks in particular countries or regional contexts.

> Skills are needed on the development side, in terms of understanding and engaging with frontier technologies, and on the technology side, in terms of better understanding development challenges.

In many contexts, frontier technologies amount to little more than 'solutions looking for a problem', risking an overly supply-oriented, technology transfer-style approach. The danger of 'tech-solutionism' is heightened if development actors are not included in early-stage problem definition and solution design. Development actors with their institutional history and in-depth understanding of challenges in development should seek to bring a sharper focus to the work of innovators by clearly and carefully defining potential problems and specific metrics for success. This can also be linked to resources and funding, such as challenge prizes. A number of different mechanisms for funding innovation exist – for example, the Global Innovation Fund, Development Innovation Ventures, Humanitarian Innovation Fund and others – but early-stage ideas and technologies remain under-represented, because of the potential risk they pose. These existing mechanisms could coordinate and collaborate, along with actors outside the sector, to establish 'frontier challenge mechanisms' to ensure that potential frontier technologies arrive on the development radar earlier and are supported in a more systematic and clearly understood fashion, and also reduce potential risk by effective pooling across funding entities.

Framed appropriately, such 'frontier challenges' could catalyse idea generation, initial solution design and piloting of solutions on the ground. Challenges naturally serve to map and give visibility to the 'positive deviants' in the field who have achieved gains despite facing the same constraints as others, and facilitate learning from their efforts. This process should include actors within and outside of the development sector, and could initiate more collaborative learning about specific technologies.

Build skills and capacities in understanding and using frontier technologies

While innovation for development of course incurs research and development costs, it is just as important to channel and build the necessary skills and knowledge to manage effective and robust innovation processes. Such skills are needed on the development side, in terms of understanding and engaging with frontier technologies, and on the technology side, in terms of better understanding development challenges. This ranges from making sure there is an adequate supply of people with appropriate expertise in the sector, investing in training and mentoring programmes, and creating the space and opportunity to use these skills. As well as recruiting new innovation leaders with expertise gleaned from outside the sector, it will also be necessary to build up understanding of technological innovation at the most senior levels where such understanding is currently lacking.

There will also be an important capacity development role to play in developing countries. Ultimately it is local and national supply and demand that shape when, how and if frontier technologies are developed, adopted and diffused. Development organisations could support capacity development in the understanding and management of technology development processes. Brokering relations with national innovation agencies in developed country settings, and facilitating South–South learning between such agencies where they already exist is a possible, and still largely untapped, area of value.

In building the requisite skills and capacities, it will be important to recognise that efforts in frontier technologies are highly fragmented and

Development actors could tap into maker spaces and open source initiatives to collaborate with developers who understand key technologies very well and who are keen to 'build things that matter'.

disconnected. For example, many pilots may be launched with similar goals, but with a lack of coordination and communication their potential is not realised. Development organisations have a strong role to play in bringing actors together, either directly through their own organisations, or by working with existing innovation network brokers and organisers. Such collaborations need to happen in operational settings and coordinate stakeholders from the development community with entrepreneurs and innovators, industry and business, researchers, national governments, local organisations and target communities.

Lack of dialogue on frontier technologies is leading to a somewhat dysfunctional and frustrating set of interactions, wherein different actors misunderstand each other's needs, strengths and challenges. Loose networks, sector-specific communities of practice and more formal cooperation mechanisms all have a role to play. In some cases these networks already exist in embryonic form – see, for example, UAVs, IoT, fog collectors, and solar desalination in the technology reviews – and development actors could well benefit from fuller participation in the dialogue. Such networks could also be established for frontier technologies in general, either from scratch or incorporated into existing platforms with aligned strategies and agendas, such as the Sustainable Development Solutions Network developed by the UN to find novel technological approaches relevant to the SDGs.

Development organisations could facilitate the development of virtual and physical hubs where researchers, entrepreneurs and firms could meet to bring products from conception to market.

In convening these diverse groups it will be vital to bring together actors where there is already some resonance with development and humanitarian challenges. In innovation literature, this is referred to as 'brokering parallel innovations': by bringing together actors working on similar problems in different settings, one maximises the potential for constructive and productive learning. A good example in the technology reviews is the potential for development actors to share ideas and learn from the experimental efforts of the Canadian government in using airships to reach remote indigenous villages in northern Canada.

Along similar lines, development actors could tap into maker spaces and open source initiatives to collaborate with developers who understand key technologies very well and who are keen to 'build things that matter'.

Over time, there will be a need to reduce the transaction costs of establishing such collaborations. Drawing on the work of hubs for supporting innovation in other settings,[34] a hub for frontier technologies would be worth investing in, whereby a standing network could be tasked with putting in place infrastructure and capacities to match skills, ideas and capital. Development organisations could facilitate the development of virtual and physical hubs where researchers, entrepreneurs and firms could meet to bring products from conception to market.

Manage quality and risks

Establish sound performance, quality and risk management principles and standards

Shared principles and standards play an important role in facilitating the testing and adoption of new effective technologies. Minimum standards can help ensure products and processes meet a threshold for product performance and/or safety, and to avoid undue risks for users and consumers. As such, intelligent and light-touch principles and standards can help address information asymmetries between producers and consumers for new products and services. For firms trialling new products, compliance with such standards can also be used as a marketing device. In addition to the role in quality assurance, standards can also facilitate interoperability. This can be important for all technologies; but because of the network characteristics, interoperability is particularly important for innovation and adoption of digital technologies, as has been noted in areas such as mobile money

To ensure innovation is enabled and not stifled, these principles and standards need to strike a balance between being robust and flexible. There is an argument to use outcome-focused standards that are not overly complex or prescriptive. For example, the outcome-focused strengthening of motor vehicle emissions standards according to an announced timetable could serve to motivate the development of markets for catalytic converters.

Some standards are enshrined in legislation or implemented as binding regulations; for example, the compliance standards for new vehicles or automotive emissions standards. However, many are not legally binding unless referred to in legal instruments, such as regulations. Many standards and principles frameworks are used in international development, often developed by non-governmental organisations (NGOs) and used as advocacy tools; or by coalitions of organisations and used to shape practices, such as the Digital Development Principles developed by a network of international organisations in 2012. Flexibility will need to be a watchword for frontier technology efforts to ensure that innovation is undertaken in a responsible and ethical fashion, as well as in ways that are specific to different contexts, to ensure that appropriate levels of quality and effectiveness are reached.

Flexibility will need to be a watchword for frontier technology efforts to ensure that innovation is undertaken in a responsible and ethical fashion.

Promote and advocate for improved conditions and frameworks for frontier innovation practices

National governments play a major role in setting the frameworks within which markets operate through broad regulation, such as competition policy and consumer law, and specific legislation that governs the conduct of particular activities, firms, industries or workers. Specifically, they are crucial in the following areas:

- Development and implementation of regulatory frameworks within which innovators, firms and markets operate, addressing issues such as market concentration and information provision to all groups of consumers.
- Establishing enablers for effective technology development and adoption processes. This includes appropriate public infrastructure investment, setting standards to ensure a pro-poor focus and interoperability between technologies; and investing in education and training to ensure the workforce is appropriately skilled.
- Mitigating risks, establishing ways to smooth the technology adoption process by setting standards and safeguarding privacy and security.

These aspects are especially important because frontier technologies typically advance in ways that outpace regulatory and procedural frameworks. Ambiguous or non-existent regulation can in turn help or hinder investment in technologies and their subsequent diffusion. Development actors – especially international organisations – should work together to come up with standards and regulations to promote safety and privacy, and overcome other obstacles that may limit the dissemination of frontier technologies.

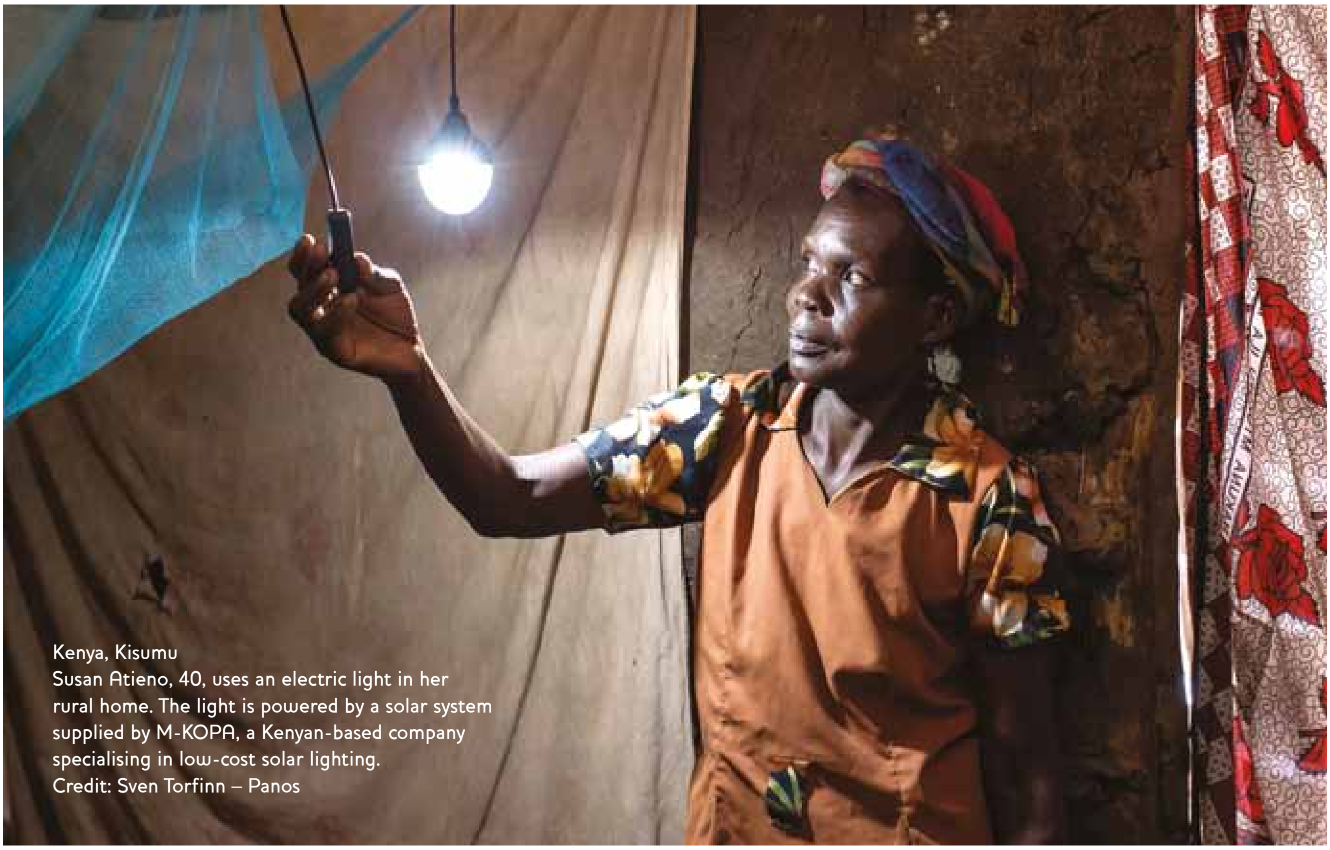
Where necessary, development actors may have to work on getting all countries to set standards. Such may be the case with catalytic converters, where the introduction in some countries of emissions standards for all road vehicles runs in tandem with the lack of regulation in others. This leads to dirty vehicles finding a home in the latter, thereby – at least partially – offsetting the impact that catalytic converters could have on combating air pollution and ultimately climate change.

In areas of rapid change where there is considerable uncertainty about the impact on individual consumers or market segments, a new approach being used in developed countries is to use a 'regulatory sandbox'. This approach, which is being tested for financial technologies in the UK allows firms to offer new products free from certain regulations to a sample of consumers, but subject to a set of criteria aimed at managing risk.

It is also important to note that many potential adverse economic impacts and risks to individuals, consumers and the environment may arise from frontier technologies. Development actors need to actively anticipate and work to mitigate these risks, in collaboration with innovators, governments and other critical partners.

A large number of risks from these frontier technologies are identical to the wider challenges of digital technologies, which relate to regulation that protects users' and customers' privacy, security and data integrity. For example, the advent of the IoT allows ever-more of our activities to generate data and thus provides more potential entry points for security breaches and hackers. However, for a number of new technologies there will be little evidence on the potential risks, and so scientific and expert opinion will need to be integrated with consultation of potential end users and beneficiaries.

More generally, more sophisticated methods for risk management in innovation development and testing are needed, which are aligned with financial and contractual arrangements. It is also necessary to recognise when development actors can manage risks on their own and when they will need to work in partnerships – with scientists, business and civil society – to better understand and deal with risks.



Kenya, Kisumu
Susan Atieno, 40, uses an electric light in her rural home. The light is powered by a solar system supplied by M-KOPA, a Kenyan-based company specialising in low-cost solar lighting.
Credit: Sven Torfinn – Panos

Focus on development outcomes and impacts

Design and finance new pilots, programmes, services and operations that use frontier technologies

Development sector finance can also help to drive the development of specific frontier technologies by signalling and underwriting market potential. Grants, taxes, subsidies and transfers can all incentivise innovators to develop and/or adopt new technologies, and to adapt as they reach and pass the take-off stage of diffusion.

After identifying the most promising actors and technologies, and supporting early-stage pilots, it is essential for development actors to roll up their sleeves and actively promote and support their use in development programmes. In some cases, especially in experimental stages, this may be done through innovation funding mechanisms; but the success of frontier technologies in this regard will be when they are able to commandeer investment from development programme budgets, and leverage funds from other external sources.

Moving from dedicated innovation funding to programme, government or private investments should be seen as an important part of the graduation process for frontier technologies. While some of these may involve stand-alone initiatives – for example, funding a new programme on humanitarian UAVs – others might include funding for frontier technologies as part of larger programme objectives – for example, a programme on precision agriculture that includes a number of IoT applications. This means not just investing in innovation, but also using broader purchasing power intelligently to support novel solutions in reaching the mainstream.

> Development sector finance can help to drive the development of specific frontier technologies by signalling and underwriting market potential… it is also essential for development actors to roll up their sleeves and actively promote and support frontier technology use in development programmes.

While there are some examples of new technologies being used within aid management processes to enhance their effectiveness and efficiency, these tend to be few and far between, and are experimental at best. One clear way of creating a more supportive and enabling environment for frontier technologies in development is to generate interest and willingness within development organisations to use such innovations. Development organisations often lag behind other sectors in their technology uptake and use, but there is considerable scope to use technologies – especially digital ones – to improve processes.

For example:

- New real-time communication technologies could make interaction and engagement between development partners less burdensome and more efficient, and create better feedback loops with end users and communities.
- New models such as the collaborative economy could be used as a way of more productively sharing development assets such as water installations or other infrastructure.
- Alternative internet delivery systems could be used to expand connectivity between country offices and remote locations.
- Drones could be used as a way of supporting enhanced operational training and learning in new and unfamiliar environments.

These technologies are becoming more mainstream within development organisations and as are likely to see greater levels of acceptance and adoption in development programmes.

As well as engaging operationally, frontier technologies should be more prominent in 'innovation for development' strategies. As development organisations become increasingly involved and engaged in innovation management and funding, growing numbers of formal strategies, protocols, directives, departments, dedicated organisational units, funding mechanisms and networks are being established. As this work proceeds the tendency is likely to be to focus on established, low-risk innovation efforts, shaped by the existing culture of many development institutions.

A special effort should be made to ensure ideas and practices of frontier technologies are at the heart of development organisations' strategies and own practices, and that these technologies are seen as an integral part of any organisation's portfolio of innovation investments. This also means recognising the often heightened risk surrounding new technology endeavours, and the need for supporters of innovation to be prepared for longer time frames, and with more patient

For frontier technologies that are proven but resisted, development organisations might work to establish steering groups or panels made up of respected individuals to undertake an objective assessment of the challenges and opportunities for diffusion.

and flexible forms of support, including financing approaches. Tapping into the potential of such technologies also highlights the need for more agile and adaptive development programmes, which can flex and change as technologies evolve.

Tackle constraints to uptake and diffusion through networks of influencers and opinion formers

Frequently, barriers to adoption exist that do not relate to the technologies but to the wider enabling environment of international development work. For example, potential users may lack financial capacity to acquire a useful technology; or lack of engagement from higher management may deter initial procurement by a development organisation. It is thus very important to use the influencing power of development organisations to facilitate adoption and consolidation of innovations that have proved to be useful and generate value.

In the case of technologies that are proven but resisted, development organisations might work to establish steering groups or panels made up of respected individuals to undertake an objective assessment of the challenges and opportunities for diffusion. These might look similar to the High Level Panel on Cash Transfers mechanism designed and set up by DFID in 2016 to establish the extent of the current evidence base and finding consensus on future directions. Along these lines, an initial high-level panel on the use of UAVs in development might help set out the existing evidence base, and indicate key gaps and high-value areas for further investments. This would also be used as an advocacy tool to drive collaborative action and strategies. Using this as a baseline, subsequent assessments by the panel could help to track progress and highlight positive and negative developments. Applied more generally, such mechanisms could provide a solid basis for overcoming institutional and attitudinal barriers to uptake and diffusion.

[1] STEPS Centre Working Paper (2009) Innovation, Sustainability, Development: A New Manifesto

[2] http://pdf.usaid.gov/pdf_docs/Pcaac280.pdf

[3] http://practicalaction.org/history

[4] Barder and Kenny (2015) Technology, Development, and the Post-2015 Settlement, www.cgdev.org/sites/default/files/CGD-Policy-Paper-63-Kenny-Barder-Technology-Development-Addis.pdf

[5] *World Bank Global Economic Outlook 2008*, summarised here: www.economist.com/node/10640716

[6] www.nesta.org.uk/sites/default/files/innovation_in_international_development_v7.pdf

[7] www.intel.com/content/www/us/en/corporate-responsibility/sdgictplaybook.html

[8] http://digitalprinciples.org

[9] http://steps-centre.org/wp-content/uploads/final_steps_dynamics.pdf

[10] Although they are not exact synonyms, the terms 'emerging' and 'disruptive' are also used in the literature and in technology policy studies as ways of describing technologies with these same features.

[11] www.oecd.org/sti/oecd-science-technology-and-industry-scoreboard-20725345.htm

[12] *Ibid.*

[13] www.mckinsey.com/business-functions/business-technology/our-insights/disruptive-technologies

[14] Drawn and adapted from www.sussex.ac.uk/webteam/gateway/file.php?name=2015-06-swpsrotolohicksmartin. pdf&site=25 and www.mckinsey.com/business-functions/businesstechnology/our-insights/disruptive-technologies

[15] https://cgsr.llnl.gov/content/assets/docs/Global_Trends_2030-NIC-US-Dec12.pdf

[16] Barder and Kenny (2015)

[17] https://sustainabledevelopment.un.org/content/documents/78192%20Technology%20Event_Concept%20note%20and%20agenda%20final.pdf

[18] The phrase 'bottom of the pyramid' refers to largest but poorest socio-economic group globally, usually the three billion people globally who live on less than $2.50 per day.

[19] See www.oecd.org/innovation/inno/50586251.pdf and www.weforum.org/agenda/2013/04/fiveways-technology-can-help-the-economy/

[20] www.weforum.org/agenda/2015/03/top-10-emergintechnologies-of-2015-2/

[21] Forman, C, Goldfarb, A, and Greenstein, S (2014) 'Information Technology and the Distribution of Inventive Activity,' *NBER Working Papers* 20036, National Bureau of Economic Research, Inc.

[22] For an overview of wicked problems and a related programme of research and learning at DFID, see Ramalingam, B, Laric, M and Primrose, J (2014) 'From best practice to best fit: understanding and navigating wicked problems in international development', *ODI Working Paper,* www.odi.org/publications/8571-complexity-wiked-problems-tools-ramalingam-dfid

[23] Diffusion is commonly measured by the rate of household penetration (the proportion of households using the technology). For some technologies, business or government penetration may be a more relevant measure.

[24] www.d.umn.edu/ lrochfor/ireland/dif-of-in-ch06.pdf

[25] Waliji, A (2016) 'Why innovation seldom scales, and what to do about it', in B Ramalingam and K Bound (2016), *Innovation for International Development Navigating the Paths and Pitfalls*, NESTA: London

[26] http://ssir.org/articles/entry/whats_your_endgame

[27] Asymco (2013) *A way to measure one's life*, www.asymco.com/2013/11/19/a-way-to-measureones-life/

[28] https://www.brookings.edu/wp-content/uploads/2016/06/199904.pdf

[29] Brynjolfsson, E and McAfee, A (2014) *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, London: W. W. Norton and Company.

[30] www.foreignaffairs.com/articles/united-states/2014-06-04/new-world-order

[31] Australian Government Analysis, www.pc.gov.au/research/completed/digital-disruption/digital-disruption-research-paper.pdf

[32] www.wupperinst.org/globalisation/html/lit_leap.html

[33] www.theguardian.com/world/2016/jul/27/africas-drone-rwanda-zipline-kenya-kruger

[34] www.openinnovate.co.uk/papers/PAPER_NESTA_NETWORKS_PPR.pdf

Technology reviews table of contents[35]

[35] Each Technology Review addresses the following aspects in turn: (i) what is the challenge or opportunity that the technology might address; (ii) definition of the technology; (iii) potential for acceleration; (iv) potential value generation and Impacts; (v) potential benefits for development (vi) enablers and barriers; (vii) what next for development sector actors?

Manufacturing and Consumption
Technology Reviews

- 3D printing for development
- Collaborative economy tools

Kenya, Kisumu
A technician solders a circuit board used for the management of power supply grids.

Credit: James Morgan – Panos

3D printing for development

What is the challenge or opportunity?

The opportunity is the wholesale transformation of material production, supply chains and logistics processes by enabling and making use of local, flexible, efficient, on-the-fly production of the supplies, parts and tools required for critical tasks. The fields that are experimenting with this set of technologies are diverse, and range from industrial design and production, to medical goods and supplies, water and sanitation and architecture.

3D printing as a frontier technology

Additive manufacturing (AM), more commonly referred to as 3D printing (3DP), is not a completely novel technology. Its origins can be traced to the 1980s, when early experimental adaptations of inkjet printing technology led to the substitution of ink with solid materials. Since then, a more or less continual stream of 3DP technologies has been developed, tested and deployed in different settings. This has led to the current 'tipping point' moment, where 3DP is 'coming of age as a manufacturing technique'[36] and is considered to be the cornerstone of a decentralised manufacturing revolution.[37]

Indeed, 3DP has potential to bring about fundamental changes in how a wide variety of products are designed, built, sold and delivered. A number of factors are accelerating the growth of AM processes:

- Rapidly **improving** technologies;
- Falling raw material costs and 3D printer prices;
- Diffusion of AM to new areas, sectors and challenges;
- A growing design-sharing community, both virtual and face to face; and
- Innovations in delivery channels for 3D-printed products.

Over the past three decades, the AM industry has grown annually at a consistent rate of just over 26 per cent, to its current global value of more than $5.1bnn. This is expected to exceed $26.5bn

The current 'tipping point' moment, where 3D printing is 'coming of age as a manufacturing technique' and is considered to be the cornerstone of a decentralised manufacturing revolution.

3D Printers have been used in Haiti for humanitarian purposes since the 2010 Earthquake. Photo credit: Field Ready.

in 2021.[38] While this growth is impressive, experts believe that it could still take a few years before the impacts of 3DP become widespread and create the large-scale transformation that its champions predict.

Definition

AM technologies use 3D printers to directly create 3D objects from digital prototypes and models. Objects that can be printed range in size from nanoscale components to entire buildings. A wide variety of 3DP techniques are currently available, employing materials that range from plastics, metal, ceramic, graphene and glass to paper, food types and even living cells. These materials are provided in the form of powders, filaments, liquids or sheets. The printing process involves forming one layer of the material at a time, each on top of the previous one until the product is complete – hence the term 'additive'. Some 3D printers might melt the material before depositing it in layers, while others use lasers to solidify the material that forms each layer. In the case of inkjet bioprinting, a combination of live cells and supportive scaffolding materials are sprayed or deposited simultaneously.

3DP confers a number of advantages over conventional manufacturing or construction methods based on moulding or subtractive techniques:

- It makes it possible to skip or shorten many conventional manufacturing process steps including design, parts production, transportation, assembly and distribution;
- It also brings considerable flexibility, by enhancing the capacity to apply improvements and adaptations to designs without incurring time or cost penalties;
- It allows the creation of objects that would often be impossible to produce with traditional techniques, including objects with complex internal structures that add strength, reduce weight, increase functionality, or in other ways boost desired performance; and
- It also minimises the waste produced during manufacturing processes.

Current limitations of 3DP, which vary between different printing techniques include:

- Relatively slow build speed;
- Limitations in object size;
- High cost of materials; and
- In some cases, limited object strength.

However, these issues need to be qualified by the fact that each passing year sees new innovations that actively address and reduce these limitations.

There are four distinct usage trends or market segments in the application of AM:[39]

- **Rapid prototyping** – Designers and architects already widely use 3D printers to flexibly create and improve product designs and prototypes.
- **Moulds and tooling** – 3DP is widely used to quickly produce moulds that are used in conventional manufacturing. This in effect combines traditional and AM, and this market segment is currently becoming consolidated
- **Digital manufacturing** – To produce final components and whole products, such as lightweight parts for aircraft or tailored dental implants. It has gained good traction in the past two years and led to unprecedented levels of mass customisation and more efficient, less costly supply chains.
- **Personal fabrication** – The latest trend, and still in a very early stage of development, it refers to entrepreneurs and individual consumers using 3DP to print, share and use or commercialise their own products.

3D printing allows the creation of objects that would often be impossible to produce with traditional techniques, including objects with complex internal structures that add strength, reduce weight, increase functionality, or in other ways boost desired performance.

Potential for acceleration

As 3DP continues to mature and grow, it has the potential to address many important needs. In consumer products markets, 3DP can meet rising expectations for high-quality design and personalisation. Direct product manufacturing using printing reduces the number of steps required for parts production, transportation, assembly, and distribution. It can also reduce the amount of material used – and wasted – in comparison with subtractive methods, thereby potentially reducing costs and negative environmental impacts.[40] In medicine, advances and applications are also accelerating and manifold; from creating models that help surgeons to test, plan and enhance operations and other interventions, through to printing implants, bone replacements, pills and even entire organs.

While the materials used in 3DP remain costly, prices are falling rapidly and can be expected to decline further as demand and volumes increase. In addition, new types of materials are being adapted for AM every year, from titanium for attaching aeroplane engines to wings, to new biomaterials for implants.

Improvements in printer speed and performance, as well as falling costs, are also anticipated to accelerate the spread of 3DP in the coming years. Costs of printers are declining rapidly as production volumes grow and competition increases. On the consumer side, prices for basic 3D printers have declined from $30,000 a few years ago to less than $500 for basic entry-level models. Unit sales of consumer 3D printers are one of the fastest-growing consumer electronic goods categories, albeit from a low base: 23,000 printers were sold in 2011 worldwide, and 278,000 in 2015.[41] Other essential supporting components of 3DP systems, such as design software and 3D scanners, are also continuously enhancing the functionality and affordability of the overall systems on offer.

In medicine, 3D printing advances and applications are accelerating – from creating models that help surgeons to test, plan and enhance operations and other interventions, through to printing implants, bone replacements, pills and even entire organs.

On the consumer side, prices for basic 3D printers have declined from $30,000 a few years ago to less than $500 for basic entry-level models.

3DP marketplaces, first introduced in 2008, are now spreading and becoming more sophisticated. These are web platforms that enable users to share, access and discuss 3D designs and, in some cases, also to commercialise them and print items on demand. Shapeways every month prints and ships more than 220,000 products in more than 50 different materials; and 3D sharing marketplace Thingiverse hosts more than half a million 3D designs at the time of writing. In this way, marketplaces contribute to spreading technical knowledge and the so-called 'maker culture'.[42]

'3D Hubs' illustrates the catalysing potential of such marketplaces. Founded in 2013, 3D Hubs is known as the 'Uber of 3D printers' because it incorporates 'collaborative economy' principles. 3D Hubs allows printer owners to locally advertise and share their printing capacities across the platform's global network, which currently lists more than 31,000 printers in over 150 countries, with hundreds more joining every week (see Figure 5 opposite). Together, they provide over one billion people with access to 3DP within 10 miles of their home, albeit mostly in developed countries.

Potential value generation and impacts

Frontier technologies are characterised not only by their current and potential rate of acceleration but also by their capacity to generate substantial economic and social value in a wide range of domains. The impact on manufacturing and supply chains, and more generally across society, is deemed to be substantial and pervasive.[43] McKinsey Global Institute has estimated a direct economic impact ranging from $230bn to $550bn by 2025.[44]

It is expected that, for a number of years, traditional manufacturing techniques will remain more efficient than AM for high-volume products and parts. However, AM's transformative impact is not so much based on replacing traditional manufacturing but on increasingly complementing and becoming integrated with it and other industrial developments, such as advanced robotics. This normalisation of AM is seen by some as happening faster than anticipated, with 3DP 'becoming mainstreamed as we witness the technology cross the threshold from 'advanced' to 'conventional'.[45]

Figure 5 Global distribution of 3D printers in the 3D Hubs network (2015)

Mirroring digital divides, the distribution of 3D printing hubs is uneven. Source: 3D Hubs, www.3dhubs.com/what-is-3d-printing

On a wider societal and economic level, 3DP's main impact will be as a result of its general capacity to improve productivity, changing patterns of consumption and creating new products, services and entrepreneurial opportunities. Some argue that it could even lead to shifts in comparative advantages between nations, decentralising manufacturing and moving production capacity closer to final consumers, thereby reducing imports of consumer and other goods.

Increased access to 3D printers is contributing to spread a global DIY/maker culture that, inspired by the open-source and hacker movements, leverages collaborative tools and practices to design and construct physical objects. Learning about and socialisation of the maker mentality happens both online, in virtual communities such as HackADay, offline in FabLabs and 'hackerspaces' all over the world and, increasingly, in formal education too. Developments in different related frontier technologies, including cloud computing, internet of things and the collaborative economy are all accelerating this trend. At the broadest cultural level, 3DP could contribute to changes in the way new generations think about how to make things.[46] These new thinking patterns could, in the long term, be the most important impact of 3DP.

Potential benefits for development

It has been argued that 3DP presents a considerable positive prospect for developing countries, because of its potential to be used to promote economic empowerment and improve the livelihoods of communities.[47] Developing countries could use AM to leapfrog industrial development processes, bypassing various elements of traditional manufacturing that are less efficient, more polluting and require a costlier infrastructure. This could reduce dependencies on foreign goods, as a large number of vital products could be manufactured locally on demand. It would also be possible to adapt product designs to make them more suited to local conditions and more culturally appropriate. However, there are also potential economic downsides: AM-enabled industrial development may not create large numbers of new manufacturing jobs because of the high automation levels associated with 3DP manufacturing.[48]

As illustrated in the previous sections, 3DP technology has a broad 'enabling character' that allows it to be used in many different contexts. Housing, emergency response, health, agriculture, sanitation and education are among the many development sectors that have been identified that could benefit from AM.

3D-printed umbilical clamps. Photo credit: Field Ready

Developing countries could use AM to leapfrog industrial development processes, bypassing various elements of traditional manufacturing that are less efficient, more polluting and require a costlier infrastructure.

In the last few years a range of initiatives and experimentation have been conducted to evaluate the suitability of 3DP in developing countries. [49,50] These pilots have shown that AM has the potential to improve response to disasters and development operations.[51] In general, 3DP self-manufacturing can only be considered economically viable in contexts where supply chains fail or are too slow. But these are situations that are quite frequent in humanitarian settings, where supply lead times for urgently needed items can be of up to 12 weeks.[52] Using AM can lead to reductions in lead times to 1–2 days, meaning that unnecessary 'just in case' transport and warehousing could be avoided. Moreover, contextually specific improvements in the design of components has enabled greater functionality and appropriateness. 3DP can therefore lead to improvements that fill gaps and complement existing supply chains, reducing complexity, and time and space requirements, and providing greater flexibility.

The capacity to print on demand is especially useful in the case of medical supplies, where the lack of availability of some low-cost supplies can have unfortunate and unnecessary consequences. Low-cost, modular prosthetics sized according to patients' needs are another promising medical application of AM in developing and conflict-affected countries. 3D-printed prosthetics could in particular better serve children with missing limbs, as they require frequent replacements and refits because they are still growing. For example, Field Ready is a non-governmental organisation that 3D-prints humanitarian supplies in emergency response settings. In 2014, the organisation set up a programme to 3D-print umbilical cord clamps for a hospital in Haiti in response to infant mortality caused by umbilical cord infections. The 3D-printed clamps take just eight minutes to produce and have replaced the often unsanitary makeshift clamps that were being used due to the prohibitive cost of ordering new supplies. The programme provided a printer and training for local staff, and the hospital continues to print enough umbilical cord clamps to keep up with the local birth rate.[53]

Housing is an area that has received special attention after several pilot buildings were constructed using AM technologies. Such initiatives produce housing stock that can that readily be adapted for local climatic conditions and incorporate other features, such as solar panelling, the use of existing natural and recycled materials, and so on. Rapid rates of urbanisation in developing countries and increases in forced displacements due to conflicts and natural disasters have led development organisations to look for new approaches to producing cost-effective emergency shelters and sustainable housing. 3D printers are therefore seen as a potential alternative to current approaches for designing and constructing short-term shelter and housing. However, existing cost structures and technical limitations mean that it is unlikely that AM will become an economically feasible method of producing affordable and sustainable housing in developing country settings for some time.[54]

Enablers and barriers

3DP technology's limitations, particularly the affordability of 3D printers, cost of materials and printing speeds, have so far limited wide-scale adoption. 3D software, scanners and marketplaces are additional and often necessary components for AM systems, and could also limit the successful spread of the technology. However, based on the current evolution of the technology, all these additional components and platforms are expected to improve dramatically in terms of performance and affordability, with key enhancements announced even in the brief period during which this technology review was written.

For example, Hewlett-Packard (HP), the company that dominated 2D printing in the 1980s, in 2014 unveiled its plan to enter the 3DP market. This marked the first entry of a large IT firm into AM. Two years on, its first 3D printers have been launched in what commentators

New models for training are required, including training materials and open source libraries with relevant 3D models, as well as support for new business models that suit developing economies and can benefit urban and non-urban areas.

consider ‘potentially the most disruptive event in manufacturing since the invention of 3D printing’.[55] The new technology introduces significant breakthroughs in 3DP speeds, which are up to ten times faster, higher definition, and with lower costs per part. The printers will also soon have multi-material and multi-colour capabilities. HP plans to invest heavily in supporting innovations, including 3D software, new materials and extensive alliances, aiming to achieve 3DP competitiveness with mass production. Other hardware companies, including Toshiba and Canon, are expected to enter the market soon. This upheaval in the 3DP industry signals that technical innovations could accelerate in the coming years, rather than slow down. With them, the manifold impacts of AM on society will also proliferate, opening up new development opportunities.

Such changes will also involve a number of issues and challenges. Risks for 3DP have already been identified that will require state action and regulation to address them. For example, intellectual property rights of products and designs will prove difficult to uphold, as 3D models of copyrighted merchandise can be obtained, modified and shared very easily. The capacity to print food, drugs, biomaterials, and in general, new kinds of products will require special attention too. Guns and other firearms have already been produced using 3D printers, which poses a whole range of security risks. Policymakers face the challenge of evaluating and addressing these risks without stifling innovation or limiting the potential value the technology provides.

In the context of developing countries, additional challenges are especially relevant. AM technologies are normally created assuming usage conditions that are not normally present in international aid and emergency response settings, such as steady power supplies, internet coverage, availability of 3DP expertise, transport and commercial infrastructure, favourable climatic conditions, and so on. The technology and its uses need to be adjusted to account for local conditions if AM is to achieve its potential in development environments.

What next for development sector actors?

The availability of 3DP skills in developing country contexts and among aid workers is an especially important barrier.[56] While 3D hubs are spreading worldwide, in developing countries they are mostly restricted to big cities. New models for training are required, including training materials and open source libraries with relevant 3D models, as well as support for new business models that suit developing economies and can benefit urban and non-urban areas and also improve humanitarian work.[57] For example, FabLabs could be established within local universities and hospitals, and networks of local ‘3D-preneurs’ could be developed and supported to extend a model of sustainable village-based networks of 3D printers.

Most of the advances in the field of 3DP are going to be commercially driven, irrespective of international development efforts. As innovation rates accelerate, and the impact on developing countries becomes more widespread, however, the development community could play an important role as a catalyst to enable the creation of social and economic value for poor and marginalised communities. Systematic projection of the evolution of the technology will be required to identify relevant opportunities and contribute to realising related benefits in development settings using horizon scanning and foresight methodologies.

Risks for 3DP have already been identified that will require state action and regulation to address them... Policymakers face the challenge of evaluating and addressing these risks without stifling innovation or limiting the potential value the technology provides.

Before leaving a site, Field Ready trains local staff to use 3D printers ensuring their ability to print whatever they need (e.g. the aforementioned umbilical clamps). Photo credit: Field Ready.

Donors, particularly, should focus their interventions on those areas and activities where they are best positioned to add value. For example, they might aim to promote innovation by fostering *collaboration between the development community and 3DP networks*, by putting in place strategies that strengthen the 3DP for development (3DP4D) innovation ecosystem as a whole, and thus foster more autonomous emergence, application and scaling-up of innovations. The 3DP field lends itself very well to this treatment. There are tens of thousands of devoted makers who are passionate about the technology and are willing to apply it to every possible situation. Makers are especially keen to experiment and to collaborate, and are motivated by a strong desire to 'build things that matter'. For example, more than 150,000 makers are currently registered with HackADay.io, a community platform that hosts more than 12,000 projects and launches technical design challenges to address 'problems faced by humanity'.[58] Thingiverse has more than 900,000 members and shares more than 560,000 designs.

Because most makers live in developed countries they lack an understanding of the kind of problems 3DP could help to address in developing country contexts. They also lack the connections with people and organisations that could test and improve proposals on the ground. There is huge potential for *mutual learning and cooperation in bridging communities of practice* that include development actors, makers and 3DP private sector actors.

Taking this perspective into account, the following actions would help development actors to catalyse and accelerate progress in the field of 3DP4D:

- **Increase recognition of the potential of 3DP for development** – Development and humanitarian actors need familiarise themselves with 3DP uses, while 3DP communities need to actively learn about the possible ways to contribute to this effort. A targeted research agenda on 3DP4D would keep track of general advances in the field, map outstanding actors and uses in the field, and consolidate evidence and learning about them. Training materials and open source 3DP4D libraries would also be instrumental for the uptake of AM in development contexts.

There is huge potential for mutual learning and cooperation in bridging communities of practice that include development actors, makers and 3DP private sector actors.

- **Convene different actors, at various levels, to promote networking and collaboration** – Devise policy instruments that facilitate network formation and development between the different actors in the field, including development organisations, maker communities, researchers and scientists, entrepreneurs and innovators, local organisations, corporations and business leaders. This would include supporting intermediaries and network-brokers to alleviate the burden of establishing and managing networks.
- **Incentivise new solutions, especially from actors outside the development sector** – Huge potential exists in this field to trigger creativity by means of challenges. Partnerships with existing makers, humanitarian communities and platforms would allow the launch of a series of challenges. Framed appropriately, the challenges would prompt idea generation, and the initial design and piloting of solutions. Challenges would reinforce community-bridging and active co-learning efforts, as well as contributing to establish and mature 3DP4D catalogues. Challenges naturally serve to map and give visibility to the 'positive deviants' in the field and foster replication of their initiatives. These challenges could be for specific 3DP-generated products, but could also be for low-cost, low-maintenance AM systems – the 3DP equivalent of the ubiquitous Nokia 3310 phone.
- **Fund promising new technologies and innovations** – After identifying the most promising actors and technologies, it is important to support their progress from an early stage up to wider diffusion of their solutions. Programmes such as USAID's Development Innovation Ventures, the Humanitarian Innovation Fund and Global Innovation Fund[59] could provide financial support and technical help to consolidate innovation projects at stages when they cannot still attract private funding. These schemes could be applied to AM projects, including mentoring, technical assistance and research to improve and scale up innovations and their associated business models. The Humanitarian Innovation Fund, for example, has provided funding for Field Ready's work mentioned above, which has expanded beyond Haiti to 3D–print a range of humanitarian supplies for emergency responses.
- **Inventive pre-commercial support and procurement of innovations** – Frequently, barriers to adoption do not relate to particular technologies in themselves but to the wider enabling environment. For example, potential users may lack financial capacity to acquire a useful technology, or lack of interest from higher management may deter a development organisation from procuring it. It is thus very important to use the purchasing and influencing power of development organisations to facilitate adoption and consolidation of innovations that have proved to be useful and generate value.

Huge potential exists in the 3D printing field to trigger creativity by means of challenges, to prompt idea generation, initial design and piloting of solutions.

Collaborative economy tools

What is the challenge or opportunity?

Rapid growth in digital social technologies and a growing diversity of approaches to gain income and support livelihoods have enabled new kinds of socio-economic processes. These are built around the sharing and trading of assets and resources, which range from property and vehicles to access to finance and even food. How might these new collaborative business models help deliver development ambitions?

Collaborative economy tools as frontier technology

Collaborative economy tools cover a range of activities designed to maximise the potential economic and social value of existing human and physical resources that may be underused, including intangibles such as skills and tangibles such as physical objects and assets. These tools leverage the power of social networks and technology to promote new models of consumption, novel employment and income generation opportunities. As well as underpinning radical approaches to economic development and growth, they also have the potential to drive greater environmental sustainability.

The promotion of collaborative economy tools in developing countries has the potential to support Sustainable Development Goal 8.3: 'Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services'.[60]

Advocates for the positive social impact of collaborative economy tools include the P2P Foundation,[61] which argues that principles of managing resources for the benefit of the common good, as popularised by Nobel Prize-winning economist Elinor Ostrom,[62] can be implemented through digitally enabled peer-to-peer (P2P) exchange between dispersed individuals and communities.

Collaborative economy tools leverage the power of social networks and technology to promote new models of consumption, novel employment and income generation opportunities.

Examples of collaborative economy approaches

Uber uses a mobile app[63] that allows customers with smartphones[64] to submit a trip request, which the software program then automatically sends to the Uber driver nearest to the customer, alerting the driver to their location. Uber drivers use their own personal cars rather than registered taxi cabs. As of August 2016, the service was available in over 66 countries and 507 cities worldwide.

Airbnb is an online marketplace[65] that enables property owners to list, and property seekers to find and rent, short-term lets and holiday homes.[66] As of August 2016, it had over 1.5m in 34,000 cities and 191 countries.

There has been a rapid expansion in profit-making platforms such as Uber,[67] which is now available in 12 African cities, and Airbnb which as of 2016 has more than 2m listings in 191 countries.[68] The growing use of collaborative economy tools by large corporations indicates a growing trend that such tools are moving away from a primary focus on principles of the commons such as sustainability, openness, and solidarity, to include business principles of competition, profitability and market share.[69] The Collaborative Consumption directory site[70] lists hundreds of businesses that use these business models, ranging from P2P pet boarding[71] to boat sharing.[72]

Definition

Broadly speaking collaborative economy tools refer to a range of initiatives based on enhancing the utilisation of assets by establishing horizontal networks between dispersed users, consumers or participants. Successful tools catalyse and enable new socio-economic systems, typically leveraging digital technologies such as the internet or mobile connectivity, to allow distributed individuals and communities to share, access and use a range of underused assets. Although there is diversity in terms of the ownership of the underlying assets – ranging from those that are collectively owned to those that are individually or corporately owned but collectively accessed – the basic principle underpinning the collaborative economy is the notion of 'distributed power and trust within communities as opposed to centralized institutions'.[73] As shown in Figure 6, collaborative economy tools have been employed in developed country settings in a number of ways, some of which are also growing in developing country settings, such as Airbnb and Uber. New kinds of tools are also emerging in developing countries that take this basic notion and adapt it to local capacities and needs, typically by taking advantage of the rapid growth in mobile phone and mobile money applications.

> Successful sharing economy innovations in developing countries often adapt existing models to fit infrastructural realities and limitations. For example, Hello Tractor in Nigeria provides access to essential farm machinery via SMS, allowing small farmers to address issues of undercultivation, poor harvests and lost income.

The key areas identified by the industry body Groupe Speciale Mobile Association (GSMA) as particularly relevant for collaborative economy tools in developing countries are transport and education. For example Go-Jek,[74] the Indonesian 'Uber for motorcycles' launched in 2011, has 200,000 freelance drivers as of July 2016. In an illustration of the 'secondary economy' model posited by GSMA, Go-Jek also offers food delivery, cleaning and beautician services. In Uganda SafeBoda[75] offers not only motorcycle taxis but helmets for passengers and riders, and reflective jackets, thereby improving safety in a country where only 1 per cent of passengers and 30 per cent of drivers wear helmets.

Successful sharing economy innovations in developing countries often adapt existing models to fit infrastructural realities and limitations. For example, in the field of education in Nigeria PrepClass[76] connects independent tutors with students to provide lessons, and provides materials for those preparing for tests. The company has partnered with more than 1,000 cybercafes across the country[77] to allow those without home internet access to access their resources. Hello Tractor[78] in Nigeria provides access to farm machinery via SMS (text message), allowing small farmers to address issues of under-cultivation, poor harvests and lost income.

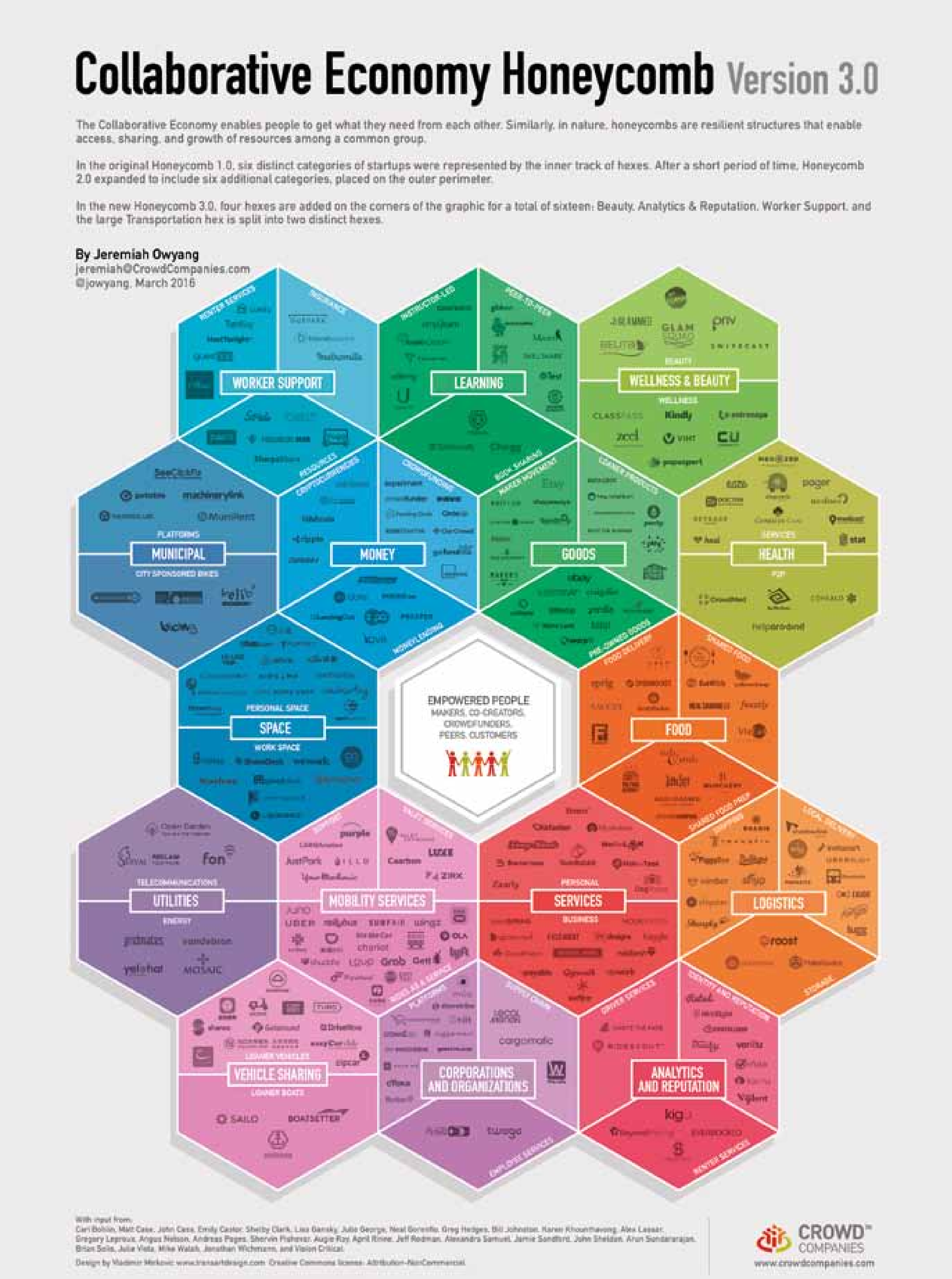
P2P finance projects such as Zidisha[79] exploit the direct communication potential of digital platforms to remove the need for field partners in micro-lending projects and enable individual donors to lend money directly to people in developing countries, using this communication model to facilitate accountability between lenders and borrowers. P2P lending could also work using Bitcoin a digital currency and payment system. Entrepreneurs from developing countries could take out loans in Bitcoin with lower transaction costs, while using the underlying database system as a means of keeping track of and assessing credit-worthiness.[80] Bitcoin and similar technologies also offer the possibility for independent short-term workers – also known as 'gig workers' – to bypass intermediaries by using decentralised cooperative sharing platforms.[81]

According to the UK Royal Society for the Encouragement of Arts, Manufactures and Commerce (RSA), there are two distinct routes to scaling and accelerating collaborative economy tools:[82]

- **Outward processes:** whereby P2P models such as co-working and bike sharing spread through replication across cities and other localities rather than through the network of a single platform.
- **Upward processes:** whereby a single network of activity grows, typically under the control of a single business, which then has the potential to expand nationally and globally through the use of technology.

Outward processes have been facilitated by technological breakthroughs such as electronically locking cars, bike racks and locks, telecommunications systems, smartcards and fobs, mobile phone access, and computers on board vehicles. More generally, P2P models have grown considerably to number hundreds if not thousands of programmes worldwide.[83]

Figure 6 Collaborative economy honeycomb



The collaborative economy continues to expand into more and more sectors. Source: crowdcompanies.com.
Design by Vladimir Mirovic www.transartdesign.com, March 2016.

The *upward* approach is clearly visible in the five main sectors that have been enabled by collaborative economy tools: P2P finance, online staff resourcing, P2P accommodation, car sharing and music video streaming. Professional services firm PwC estimates that the global revenues of these five collaborative economy sectors combined has the potential to grow to from around $15bn today to $335bn by 2025.[84] It is anticipated that this will happen as the result of broader changes in consumption and asset usage patterns and behaviours. For example, a World Economic Forum survey looking at 'technology tipping points' found that two-thirds of respondents expected people to make more journeys using car sharing than in private cars by 2025.[85]

A 2013 report shows that collaborative economy tools are starting to reach groups that were previously excluded from the global economy, and may have started to promote a type of economic development that is more connected with traditional social values and environmental concerns of local communities.

The rapid rise of smartphone ownership rates in emerging and developing nations – climbing from a median of 21 per cent in 2013 to 37 per cent in 2015[86] – might well facilitate the spread of collaborative economy tools, both outwards and upwards. A 2013 report by International Development Research Centre (IDRC) on the impact of collaborative economy approaches in developing countries shows that they are starting to reach groups that were previously excluded from the global economy and may have started to promote a type of economic development that is more connected with traditional social values and environmental concerns of local communities. In particular, IDRC's research on women at the bottom of the pyramid shows that the sharing economy might have a positive impact on issues that are key inputs for economic growth – such as trained labour, capital and technological development – through initiatives that offer training and P2P loans. However these economic models did not have the potential to affect housing, which is a significant concern for women at the bottom of the pyramid.[87]

Potential value generation and impacts

GSMA, whose Ecosystem Accelerator programme is funding mobile-focused sharing economy projects in emerging markets,[88] identifies the following economic benefits:

- Increased access to tools and other useful physical resources;
- Increased ability for individuals to live off cash flow, with less need for savings to be able to afford use of assets;
- Better asset utilisation;
- Less opportunity for long-term abuse of trust because of direct and public feedback loops; and
- Creation of secondary economies through services such as Uber drivers delivering goods or food.

Overall, there would seem to be considerable potential for collaborative economy tools to contribute to diversification of income generation, asset utilisation and livelihoods options in developing countries.

However, this value is also closely related to levels of connectivity and affordability, so it is also likely to disproportionately benefit urban, literate, educated and well-off people. IDRC points out that as crowdfunding platforms require the engagement of middle- or high-income groups, although shared resources can be important to low-income groups, existing solutions – such as bike-sharing services – can be out of their reach.[89]

It is also important to recognise the impact on established businesses that are 'disrupted' by collaborative economies. For example, in New York City alone, Airbnb's 416,000 guests[90] who stayed in houses and apartments between 2012 and 2013 cost[91] the New York hotel industry 1m lost room nights.[92] On a broader societal level, the casualisation of employment that these business models cause has an impact through the erosion of workers' rights and lack of healthcare and insurance benefits.[93]

Potential benefits for development

As noted above, the sharing economy has the potential to reach groups that were previously excluded from the global economy thanks to growing access to open global platforms, the internet and mobile phones in poor communities around the world.

In particular, granting access to millions of citizens previously locked out of capital-based marketplaces could diminish certain forms of asset-based inequalities and boost inclusion. For example, innovative projects that do not 'fit' existing funding models can access capital through P2P lending platforms such as Zidisha, which allow lenders to connect directly with borrowers in developing countries.

Projects such as Jana[95] take advantage of widespread mobile phone adoption in developing countries to pay people with airtime for contributing to research or participating in social marketing.

Samasource, a collaborative economy human resources firm, provides an entry point to employment for groups historically excluded from formal employment, such as women, young people and refugees. Samasource offers microwork opportunities to people from the bottom of the pyramid without significant work experience, and trains them to perform basic digital tasks such as image classification, data verification and content moderation, offering a living wage for completed work. The company claims that they it can raise users' average salary from $2.20 a day before joining, to an average of $8.15 after three and a half years.[96]

To ensure value for people at the bottom of the pyramid, GSMA research suggests that it is better not to let platforms co-opt people. Instead it is vital that individuals can opt in and out, with the platform simply acting as an intermediary, and that assets are owned by people, not by platforms.

Enablers and barriers

Key enablers and barriers of the sharing economy in developing countries relate to ownership of assets and the regulatory environment, as well as modifying technology models to fit local needs and access.

To ensure value for people at the bottom of the pyramid, GSMA's research suggests that it is better not to let platforms co-opt people. Instead it is vital that individuals can opt in and out, with the platform simply acting as an intermediary, and that assets are owned by people, not by platforms.

The same research also suggests that it is important that collaborative economy startups work with and not against the prevailing regulatory environment. GSMA also warns that it is vital for platforms and individuals not merely to replicate existing services, but instead seek to leverage the power of digital technologies to offer new solutions that prove a better fit in developing countries. For example, in Western Europe and the United States sharing economy platforms rely on users having smartphones, good mobile data access and a credit card. However, in developing countries these platforms must be tweaked to use technologies such as SMS, interactive voice systems, and mobile money platforms such as MPesa. Each of these technology adaptations offers potential entry points for mobile network operators, businesses, consumers and development organisations.

On a similar theme, IDRC also suggests that entrenched solutions and monopolistic companies, which these new business models of sharing, openness and transparency could displace, may put up resistance.[97] Non-existent supply chains and distribution channels, bad roads, and lack of financial access might also present barriers to the spread of collaborative economy tools, as well as low literacy rates and lack of shared languages. However, it is worth noting that in contexts where collaborative economy transactions are feasible, they could potentially lead to a decrease in financial corruption, because they are often mobile based and transparent.

Risks and downsides

The rapid growth of sharing economy platforms poses a clear risk of the rise of 'networked monopolies'. The RSA has found that some global collaborative economy-based platforms are showing signs of 'monopoly power in influencing the price, output, and investment of an industry, as well as in limiting the entry of new competitors'.[98] There is also a risk that businesses such as Uber do not contribute to an economy's overall productivity. While the company raised $350m from Saudi Arabia's sovereign wealth fund in 2016,[99] critics argued that the company's growth does not generate 'positive spillovers'[100] on a scale that might benefit other businesses.

There are also issues in relation to labour rights and conditions. A *Harvard Business Review* article from 2016 found that far from being a neutral intermediary, Uber's operations are based on a highly managed labour force:

> Drivers have the freedom to log in or log out of work at will, but once they're online, their activities on the platform are heavily monitored. The platform redistributes management functions to semi-automated and algorithmic systems, as well as to consumers.[101]

In a development context where the achievement of women's rights is a priority, it is possible that such employment models might favour men, who typically own assets such as cars, which they can leverage. Women with childcare responsibilities might not be in a strong position to take advantage of some of the flexible working models offered. Although women who do care work may be well positioned to perform gigs that could be done from home, they may find it more difficult to engage in other 'flexible' gigs outside of the home such as driving for Uber.

Such systems might also pose a threat to individuals through the erosion of workers' rights and full-time employment, and the disappearance of health-care and insurance benefits. In his research on digital work platforms Mark Graham from the Oxford Internet Institute warns of the dangers of digital work platforms for freelancers 'in which competition between workers leads to a race to the bottom in terms of wages and working conditions'.[102] World Bank research shows that unions significantly increase wages and working conditions;[103] the lack of effective workers' representation on collaborative economy-enabled platforms could pose a threat to individual wellbeing and wages.

A Go-Jek driver in Jakarta, Indonesia, checks for his next job on his phone. Go-Jek, the motorcycle equivalent of Uber, has 200,000 freelance drivers signed up and as well as providing rides, offers food delivery, cleaning and beautician services. Photo credit: Bernard Oh on Flickr,

The World Economic Forum also warns that increased employment flexibility can leave workers vulnerable and lead to what it describes as an 'agile but fragile workforce',[104] whose working lives are characterised by short-term and zero-hour contracts. This in turn has macro societal and economic impacts, with the need to overhaul traditional organisational structures.[105] Economic and political changes are required to adapt to collaborative economy models.
For example, the collaborative consumption economy is hard to tax, measure or regulate, so it will be necessary to rethink how to deploy effective tax systems, pension schemes and trade unions. Taxation and regulation will need to move ownership- or sales-based modelsto use-based models.

> Gig economy systems might also pose a threat to individuals through the erosion of workers' rights and full-time employment, and the disappearance of health-care and insurance benefits.

What next for development sector actors?

The sharing economy offers not just a means to promote the economic welfare of some of the world's poorest people, but could become a new model for development, building on values of self-help and solidarity which already exist in certain communities. This puts the onus on development sector actors to promote the social benefits of collaborative economy tools and to explore ways to ensure that hard-to-reach groups benefit from these models.

One route to this might be through funding innovation challenges and experiments to pilot new projects, taking advantage of the fact that digital sharing technologies designed for the bottom of the pyramid can be very cost effective in terms of impact. This might also have the effect of bringing together different actors to create new collaborations and incentivise new solutions.

A number of pro-poor collaborative economy businesses might benefit from investment to help them grow and reach new markets. The work done by GSMA[106] shows how the private sector can help secure the funding and direction innovators in the sharing economy need to bring their products and services to scale. This has related benefits, providing new business opportunities for mobile network operators.

Finally, development actors can play a role in brokering groups of experts to address issues such as the need for new regulatory frameworks, which are required to address critical issues such as tax system reform and quality standards.

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- Alternative internet delivery
- Internet of things

Algeria, Algiers
Satelitte dishes wall of a tenement building called 'Les Dunes', said to be the longest building in Algiers (300 m). With its sister building, it contains a total of 840 apartments. In the background is the minaret of a mosque.

Credit: Andrew Testa – Panos

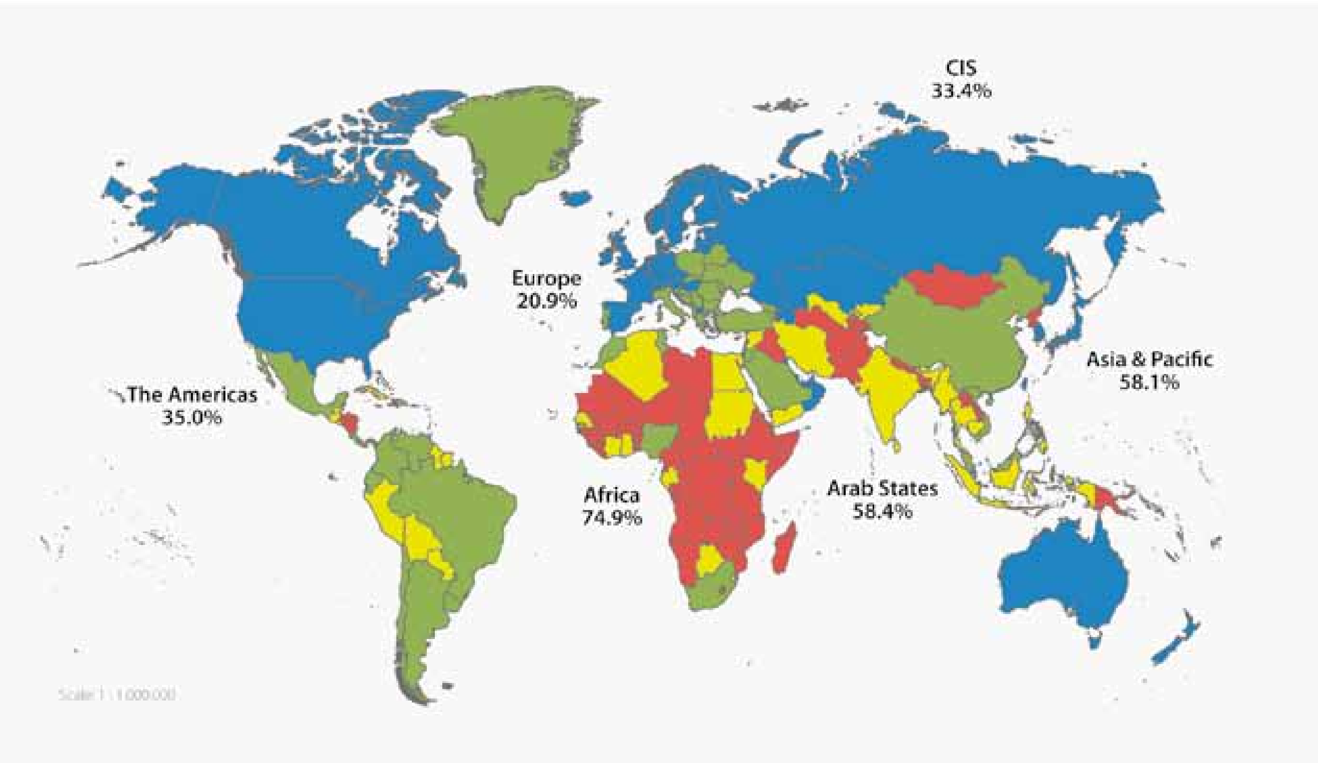

DENTISTE

Alternative internet delivery

What is the challenge or opportunity?

Affordable access to the internet remains one of the major challenges to getting more poor people online. The poorest people in the least developed countries pay more for internet access than citizens in developed countries in absolute and relative terms.[107] The World Bank's 2016 *World Development Report* estimates that four billion people do not have access to the internet, leaving them unable to reap 'digital dividends' (see figure 7).[108] A 2014 study by the McKinsey Global Institute found that because the internet is increasingly integral to the fabric of local and global economies and societies, those who are not online are likely to be increasingly disadvantaged, and risk falling further behind.[109]

Figure 7 World's offline population, 2016



% of people
NOT using the internet

- 0 – 25
- 26 – 50
- 51 – 75
- 75 – 100

At the of 2016, 3.9 billion people – 53% of the world's population – are not using the internet

In the Americas and CIS regions, about one-third of the population is offline

While almost 75% of people in Africa are non-users, only 21% of Europeans are offline

In Asia and the Pacific and the Arab States, the percentage of the population that is not using the internet its very similar: 58.1% and 58.4% respectively

Source: ITU, 2016. ICT Facts and Figures 2016, Geneva: International Telecommunication Union (ITU). Available at: www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2016.pdf (Accessed October 10, 2016).

Alternative internet delivery as a frontier technology

One of the major obstacles to expanding affordable internet access relates to the challenge of rolling out or upgrading infrastructure in poorly connected areas. This challenge has a number of facets.

First, infrastructure investment and roll-out tend to be demand driven, shaped by available markets, and typically deployed in areas where telecommunications companies and internet providers see potential profits. As a result, much infrastructure is deployed in more urban and affluent areas, where business and government activity – and therefore potential profitability – are greater.

Second, even when physical infrastructure is in place, the internet may remain out of reach of the majority of people because of the costs of operating and maintaining the infrastructure, which remains high and is often passed on to consumers.

Third is the issue of logistics. While mobile telephony infrastructure has overcome many of the obstacles of laying out fixed-line infrastructure – such as the need to lay out hundreds of thousands of miles of cables, and the need to have those cables connected to many homes – setting up and maintaining cellphone towers in hard-to-reach areas is operationally difficult. Given that private telecommunications companies typically drive mobile network expansion, there is little incentive to reach the most remote areas because the potential revenue often does not outweigh the costs. Transportation, materials and personnel are all needed, in places that are often highly inaccessible. This also raises the political issue of the need to secure and manage land rights for new infrastructure, which is seldom a straightforward process.[110]

A large number of proposals and pilots have been developed to overcome these issues through a series of aerial infrastructure innovations. The most advanced have been four efforts designed and backed by large corporate players in digital technology sectors: Google, Facebook, SpaceX and OneWeb. Each initiative claims to have the cutting edge technology that will bring the next four billion online and bridge the digital divide. More details on each approach follow below.

Project Loon

Google's Project Loon seeks to provide constant wireless internet coverage worldwide, its objective being to 'connect people in rural and remote areas, help fill coverage gaps, and bring people back online after disasters'.[111] This is achieved with a network of thousands of high-altitude balloons working in tandem with drones from its parallel Project Titan initiative. The balloon technology itself is noteworthy, with artificially intelligent sensors continually determining and adjusting the position of the balloons relative to wind currents to give optimum connectivity to people on the ground. Each balloon gives coverage of an area up to 80km in diameter. Through arrangements with telecommunications companies, Project Loon enables users to connect directly from mobile phones and other wireless-enabled devices. The signal is then passed across the balloon network and back down to the global terrestrial internet.

Project Loon's technology was initially piloted in New Zealand, California, Brazil and Australia and found to be both viable and effective. The first commercial deployment was in Sri Lanka in July 2015, with plans to expand to Indonesia and India in 2016. In 2015, MIT Technology Review research estimated that the technology was about two years away from being globally available.[112] Project Loon is the only high-profile alternative internet delivery initiative that has piloted, tested and deployed this form of technology at scale.

One of the major obstacles to expanding affordable internet access relates to the challenge of rolling out or upgrading infrastructure in poorly connected areas.

One of Project Loon's balloons is displayed at a launch event in June 2013. Photo credit: Flicker User: iLighter, Creative Commons licence: BY, https://commons.wikimedia.org/wiki/File%3AGoogle_Loon_-_Launch_Event.jpg

Internet.org and drone-based internet

Despite the large proportion of people globally who do not have internet access, a large majority – estimated at 85 per cent of people worldwide – live in areas covered by a mobile internet signal.[113] The untapped potential underpins Facebook's Internet.org initiative. This involves a package of solutions aimed at enhancing the 'accessibility, affordability and relevance' of the internet globally.

The solution that has attracted the most attention – for those who can access an internet signal – has been the Free Basics mobile phone app. This is intended to provide a free demonstration of the internet for the people who do not have internet access, with a series of 'empowering apps' that allow unconnected communities to learn about and engage with the benefits of the internet.

The idea is that after an initial taster, poor users will be incentivised to buy data and begin using the internet. In parallel, Facebook is also running a series of contests and funds seeking to introduce local languages and localised content, and relevant apps to better meet the needs of groups whose interests are underrepresented on the internet.

On the infrastructure side, to reach those not covered by an internet signal and improve affordability, Facebook is placing its bets on a combination of satellites for very remote areas; a network of solar-powered unmanned aerial vehicles (UAVs) or drones that can stay in the air for months at a time for more suburban areas; and laser technology to speed up the strength of internet signals from space.[114] Facebook is also investing heavily in innovations, aiming to bring down the cost of data 100-fold and reduce the cost of mobile phone handsets through partnerships with technology and hardware companies.

Micro-satellites

OneWeb and SpaceX are betting on planet-wide constellations of low-earth orbit microsatellites to beam continuous internet across the planet. OneWeb is owned by a consortium of actors including Greg Wyler, former CEO of internet satellite company Other 3 Billion (now owned by Google), British entrepreneur Richard Branson, Airbus group, Virgin Galactic, Bharti Enterprises, Hughes Network Systems, Intelsat, Qualcomm Inc., Totalplay and Coca-Cola. OneWeb believes it will achieve global coverage thanks to a network of 648 satellites, along with many small, portable and low-cost ground terminals.[115]

SpaceX's initiative is more ambitious than the other initiatives listed here. In addition to connecting the unconnected on Earth, the company seeks to lay down the fabric for an inter-planetary internet between Earth and Mars with 4,000 proposed satellites. This initiative is part of a larger venture aiming to establish a colony on Mars by 2025.[116]

While the overall potential market size has yet to be estimated, future digital services for the four billion who are presently not online is likely to lead a new market with future value in the order of tens if not hundreds of billions of dollars.

Potential value generation

The value of expanded internet access is dependent on a number of factors: (1) network coverage and speed; (2) cost of access in relation to income; (3) awareness and literacy (language and digital); and (4) availability of locally relevant content.

Although these will be of varying importance for different socio-economic groups adopting a given technology, 'coverage and cost are arguably the most fundamental'.[117] If these can be addressed, then the initiatives listed here are likely to yield benefits to people living in remote and other hard-to-reach places in developing countries. By bringing connectivity through aerial infrastructure, these initiatives have considerable potential to connect people who were previously never covered by a mobile signal, and overcome the limitations of conventional infrastructure described earlier. If as promised the technologies developed are cheaper to deploy and operate than current land-based infrastructure, these initiatives also have the potential to drive down costs in areas where there is already good connectivity, thereby making greater internet usage more affordable for more people.

There will also be benefits for middle- and high-income groups. One major group is likely to be air and sea passengers and transportation workers, who will benefit from internet at affordable rates when thousands of miles from terrestrial infrastructure.[118] Value is also likely to be generated through strengthening connectivity in times of network saturation – for example, at big sporting events or festivals – as well as providing connectivity when ground-based infrastructure has been damaged or destroyed, such as during natural disasters and extreme weather conditions.[119]

Some of the largest benefits from alternative internet delivery initiatives will no doubt accrue to the corporation that proves most successful and captures the greatest market share for its systems. GSMA estimates that 1.1 billion people will connect to the internet for the first time using a mobile phone between 2014 and 2020.[120] It has been estimated that because of the centrality of its search engine for internet users, Google could add over a billion dollars in revenues to its search business for every 42 million users that come on to the internet.[121] While the overall potential market size has yet to be estimated, future digital services for the four billion who are presently not online is likely to lead a new market with future value in the order of tens if not hundreds of billions of dollars.

Leaders of the firms and initiatives in question have made bold statements about the potential of these innovations to bridge the digital divide and thereby alleviate poverty, decrease inequality, improve education, empower women and minority groups, democratise knowledge, and stimulate economic growth. However, in almost all of the cases, an over-simplistic set of assumptions underpins these claims: that access to the internet in itself will almost inevitably lead to the positive outcomes described.[122]

Although these initiatives are likely to contribute to partially bridging the persistent digital divide, with the possible exception of Facebook's work, they seem to assume that the offline status of individuals is primarily about technological access. However, evidence increasingly shows that connectivity is just one of the reasons that often dictate whether or not an individual is going to benefit from digital dividends. Other factors include:

- Access to and autonomous use or ownership of adequate internet-enabled hardware devices and related software tools;

- Levels of language and digital literacy; and
- Socio-economic status (e.g. age, gender, education, class).[123]

Because digital access is interdependent with broader development challenges it cannot be fully tackled in isolation from wider contexts. For example, in rural and often patriarchal societies, the deployment of better aerial internet infrastructure is unlikely to overcome social norms that act as a barrier for women to access the internet.

Enablers and barriers

The development policy context is changing, with a growing awareness of the importance of digital access, and the scale and scope of the problem in relation to lack of such access. Influential reports such as the 2016 *World Development Report* are likely to create a positive context for these initiatives to develop and expand, and for their development contribution to be put centre stage.[124] For this to be a true enabler of positive development, a clear and transparent way of assessing the benefits that are being generated by the pilots and subsequent attempts to scale is needed.

Demand for internet access is growing among excluded groups, and this market potential is likely to drive the expansion of these initiatives. A better understanding of this market and of the nature of the demand are urgently needed.

Legislation concerning UAVs and flying objects has not kept up with the speed of technological innovation. Airspace legislation and sovereignty are likely to prove to be major barriers that prevent these initiatives from fulfilling their potential. Specifically, international law dictates that airspace belongs to the country that it covers. Failure to consult or abide by agreements with sovereign nations regarding flying objects in their airspace could result in the taking down or confiscation of those objects.

Besides the legal barriers, there are also issues of national permissions for use of airspace.[125] Some governments – especially authoritarian ones – may be less willing to promote the spread of the internet.[126] For example, North Korea deliberately keeps its population offline, while China blocks full access to certain high-profile platforms such as Facebook, Wikipedia and Google to control the content its citizens can access. More generally, governments may prefer to control infrastructure within their borders as it makes it easier to control access and to filter content.[127]

Perhaps unsurprisingly, privacy and data exploitation concerns also accompany these initiatives. There are commercial risks in Western firms accessing and selling data with commercial benefits. But there are also political and security concerns, such as widespread fears that technology companies will collaborate with intelligence agencies to spy on populations.

These initiatives are not wholly new, but instead build on past initiatives seeking to provide a global internet. A number of these failed, such as Bill Gates satellite-based venture Teledisc in the 1990s, or Motorola's Iridium, widely referred to as the single biggest business failure of its decade.[128] It is not clear that lessons from these failures have informed the design of new initiatives.

These initiatives also collectively propose to add hundreds of thousands of flying objects to an already over-crowded airspace and near-earth orbit. They will increase the likelihood of collisions in earth's orbit and could also lead to signal interference with other satellites already in orbit.[129]

All of these initiatives need access to the limited telephony spectrum to beam mobile internet access from the sky. Only OneWeb has rights to use part of the spectrum, as these were allocated to company founder Greg Wyler during a previous satellite venture. Project Loon has circumnavigated the need to apply for spectrum in Sri Lanka by providing the government with a 25 per cent ownership stake in its operations in the country. All four companies have mentioned the possibility of partnering with established telecoms companies to share spectrum, which is limited and tightly controlled and allocated to entities by governments. Each one of these initiatives will have to have its own spectrum allocated to it to avoid interfering with other telecoms operations on the ground. Project Loon has already encountered spectrum issues in India, where the spectrum it was allowed to use interfered with local mobile networks, leading the government to deny the project access to unused 'white spectrum'.[130, 131]

What next for development actors?

- **Research and analysis** – More and better targeted research investments by development actors could help enhance and deepen understanding of the needs of the four billion offline, potential markets and the range of possible solutions. It could also identify positive and negative impacts and work to mitigate these, and bring more objectivity to the claims being made. Development actors could use better research to set specific standards and targets for alternative internet delivery, and thereby drive more 'pro-poor' innovation. A particular role for evidence is to clarify the potential of existing initiatives. Because these initiatives tend to overlook the wider, non-technological factors that might keep the four billion offline, they tend to make bold statements about having the capability to 'bring everyone online' – rather than making measured projections about how many people their initiatives might in fact reach. An independent assessment of these initiatives is needed that takes into account all the factors that stop people from getting online; and makes realistic assessments of how many people will come online because of these initiatives, and how many are likely to remain offline, who will require other kinds of interventions.
- **Collaboration with development actors** – For the most part, none of the cited initiatives – with the exception of Internet.org through its Free Basics app – involves much collaboration with development organisations. These initiatives are largely deploying simple, top-down technocratic solutions – what Evgeny Morozov has termed 'tech solutionism'[132] – to complex, often non-technological problems. Technology companies would have much to gain from interacting and collaborating with development actors that are more familiar with the 'beneficiaries' they are attempting to reach, in terms of prior engagement, access and being an trusted and honest broker.
- **Cooperation across initiatives** – Some collaboration is already happening; for example, Google invested $900m in SpaceX in 2015. Development actors may be able to drive greater operational collaboration between competing firms to enhance pro-poor innovation, helping the initiatives to assess their own strengths and weaknesses and identify new partnerships that can drive access growth among those most in need.

Technology companies would have much to gain from interacting and collaborating with development actors that are more familiar with the 'beneficiaries' they are attempting to reach, in terms of prior engagement, access and being an trusted and honest broker.

Internet of things

What is the challenge or opportunity?

The internet of things (IoT) provides the opportunity to radically improve the efficiency of all kinds of public sector, business and community processes and infrastructure, thanks to a growing network of low-cost sensors, actuators, and data communications technology embedded in physical objects. This IoT enables those objects to be sensed, coordinated and controlled remotely across existing network infrastructure. The technology is instrumental to establishing and integrating a number of new innovative processes and business models, leading to multipliers in the value they might otherwise generate in isolation.

Internet of things as a frontier technology

The IoT, also known as the 'internet of everything', refers to the interconnection of physical objects embedded with sensors, electronics, software, network connectivity and actuators (see figure 8 for an illustration of the range of objects connected to the IoT). These enable the objects to collect and exchange data, which can subsequently be acted upon. From monitoring goods trucks as they travel across Germany, to measuring the humidity of the soil in Spanish vineyards, to tracking the output of water pumps in Kenya, the IoT can be integrated into virtually any process and thereby enhance efficiency, responsiveness, timeliness and intended positive outcomes.

The IoT is a frontier technology because of its enabling character. It allows a number other frontier technologies to be combined, thus multiplying their potential generated value. Following the general principles of network economics, the more 'things' are connected and the more services are integrated into the network, the more value can be extracted from the IoT as a whole, and the more its adoption will accelerate. The potential impact of the IoT is therefore enormous. McKinsey Global Institute predicts that if 'policy makers and businesses get it right, linking the physical and digital worlds could generate up to $11.1 trillion a year in economic value by 2025'.[133]

Figure 8 Range of devices connected to the internet of things

The more things and services are integrated into the Internet of things, the more value that can be extracted from them.
Source: Jeferrb on pixabay, https://pixabay.com/en/network-iot-internet-of-things-782707

The Internet of Things (IoT) allows a number other frontier technologies to be combined, thus multiplying their potential generated value. Following the general principles of network economics, the more 'things' are connected and the more services are integrated into the network, the more value can be extracted from the IoT as a whole, and the more its adoption will accelerate.

Widespread adoption of the IoT is speeding up, thanks to constant improvements in underlying technologies such as miniature sensors, wireless networks and connectivity. It is calculated that currently more than 22.9bn devices around the world are already connected to the IoT, which is expected to exceed 50bn by 2020.[134] However, this widespread adoption is not going to happen overnight in developing countries, where a relative minority of connected objects are present.

Definition

The IoT refers to the growing trend for data communications technologies to be built into physical objects – from swallowable pill cameras that travel through the human intestines, to wearable gadgets and smartphones, house appliances and smart-city sensors, and drones and satellites. These technologies comprise:

- **Sensors** – Electronic components designed to detect processes and environmental factors; and
- **Actuators** – Electronic components responsible for control or movement.

Together, they enable connected objects to be sensed, coordinated and controlled remotely by both human and automated users across existing network infrastructure. The IoT creates opportunities for the direct integration of the physical world into computer-based systems. The aggregation of information the sensors collect generates high-value big data that can be used by a variety of stakeholders for real-time monitoring and response, or collected over time to perform predictive analysis and improve processes.

The IoT has the potential for the public sector, business, communities and individuals to improve delivery of services, optimise performance, introduce new business models, and achieve goals in a very wide range of different settings. Areas where the IoT has been widely applied include, but are not limited to:

- Improving the efficiency of manufacturing and logistics;
- Enhancing counterfeit product detection;
- Monitoring movement of people, stock, vehicles and equipment;
- Analysing a wide range of infrastructure investments from water installations to healthcare facilities; and
- Monitoring the environment to ensure optimal conditions and resource allocation in water delivery systems and agriculture.

As well as enhancing existing processes, IoT technologies are increasingly used to establish innovative processes and create novel services. IoT technologies range from simple identification tags that enable tracking of items to complex multi-sensor devices and actuators. Sensors can be attached to items to track their location and condition; embedded in infrastructure to control their surroundings; included in multi-functional gadgets such as smartphones; or integrated into robots and drones to support their movement and activities.

All IoT sensors collect data, which is then transmitted using connective technologies, which include cellular networks, WiFi and Bluetooth. The transmitted data can be aggregated and processed in many different ways, from computerised analysis that triggers automated actions, to dashboard displays that facilitate operational decision making by people, and big data analytics or artificial intelligence/machine learning to support better understanding and navigation of complex problems.[135]

Potential for acceleration

The IoT is a new but rapidly growing technology, which is widely expected to continue accelerating its expansion as an essential component of the digital industrial revolution. International Data Corporation (IDC), a market intelligence firm, predicts that, in the next 2–3 years, the IoT will reshape business areas as diverse as executive decision making, marketing strategies, product design, customer engagement and aftersales service; moreover, within five years all industries will have launched IoT initiatives and incorporated IoT in their business plans.[136] The worldwide revenues generated by IoT solutions is expected to grow at a steady 20 per cent annually, rising from $2.7 billion in 2015 to $7.1 billion in 2020.[137]

The worldwide revenues generated by IoT solutions is expected to grow at a steady 20 per cent annually, rising from $2.7 billion in 2015 to $7.1 billion in 2020.

A variety of issues could potentially limit the rate of growth of the IoT, but current trends are positive on most fronts. On a technological level no major barriers are blocking the development of the IoT. Semiconductor components that are central to most IoT applications are showing ever-greater functionality at lower prices and electrical consumption. Sales of sensors are growing rapidly, and technological advances are making more capable sensors more affordable. Miniaturisation and high-volume manufacturing techniques make it possible to install sensors in even the smallest devices. Finally, the spread of high-speed wireless data networks is extending the coverage area of the mobile internet, helping pave the way to greater IoT use.[138]

The increased effort to develop formal and informal standards should facilitate interoperability between IoT applications and technologies, a critical factor in reducing the risk of lock-in that might deter future investments. Companies such as Apple and Google have entered the IoT home automation market and now provide development toolkits, contributing to the emerging ecosystem for IoT app development, which could then spark off further innovation.

The field of digital technologies for international development has seen renewed growth in interest, and many innovations are improving project outcomes and delivering services in developing countries.[139] Adaptations of IoT to the needs of low-income populations have been identified by scholars at the Berkeley Institute for Globally Transformative Technologies as one of the technological breakthroughs to drive global sustainable development.[140] While many international development actors are aware of the need to leverage the potential of IoT for development, they are still uncertain about the best way to do it. Consequently, most of the experimentation in the IoT for development (IoT4D) field is currently performed in small-scale projects that non-governmental organisations (NGOs), social enterprises and academia are driving, and is still in the nascent or 'hacker' phase of development Nonetheless, interest is growing and the field is expected to accelerate and increase in scale and scope.

Potential value generation and impacts

The IoT is expected to generate immense value, with deep and long-lasting impacts across all industries and spheres of human interaction. Health care, manufacturing, energy and infrastructure management, agriculture, home automation and environmental monitoring are among the sectors where the impact is going to be most immediate and visible.

As a new universal connecting infrastructure, the IoT will potentially influence every existing domain of human endeavour, while at the same time cataylsing the emergence of new ones:

- **In health care**, for example, IoT is already improving efficiency in treating patients with chronic conditions, as wearable sensors alert medical staff about emerging problems. An increasingly widespread example is the incorporation of sensors into cardiac pacemakers to create 'smart hearts', which generate and share information about patients' conditions, enabling better clinical decision making and even automated actions such as recalibrating pacing rhythms in real-time. In developing countries, the IoT is used to ensure that health clinics are always fully stocked with vaccines and anti-malarial medication.[141]
- **In manufacturing**, sensors can be used to track machinery and provide real-time updates on equipment status, decreasing downtime; as well as tracking trucks and pallets to improve supply chain management, reducing inventory levels and optimising the flow of materials.
- **In energy,** smart electrical grids are improving energy demand management and reducing costly peak usage. Grid sensors can monitor and actively diagnose network problems to prevent outages and reduce maintenance costs.

A technician from M-KOPA, a Kenyan based company specialising in low-cost solar lighting, installing and activating a solar lighting system in a rural property. This works thanks to mobile money and sensors connected to the Internet of things. Photo credit: Sven Torfinn – Panos.

- **In agriculture,** sensors measure soil moisture, temperature and stress in plants, and gather information about how water moves through a field to optimise irrigation schedules and fertiliser use.[142]
- **In water delivery systems**, sensors are used to monitor the availability and safety of drinking water. Furthermore, sensors are being used in developing countries to monitor the performance and structural integrity of water pumps.

These technologies will continue to benefit developing countries in driving social and economic advancement by improving services and economic activities. However, the special conditions and limitations that pervade developing countries will shape the extent and scale at which the IoT develops.

Lack of connectivity, limited technological literacy and economic capacity, and the lack of basic infrastructure favour smaller-scale, simpler and more cost-effective solutions. In developing countries, for example, deployments are more likely to be made in isolation and independent of supporting infrastructure, using widespread available technologies such as mobile phones and SMS (text messaging). Much experimentation in developing countries is in the areas of health care, water, agriculture, natural resource management, resilience to climate change, and energy.

A number of promising initiatives are being developed. For example:

- **Health care** – Across sub-Saharan Africa SMS-enabled thermometers help to preserve the freshness of vaccines throughout delivery to remote and rural areas through real-time monitoring of temperatures in cold storage units.[143]
- **Water delivery** – detect usage patterns and failures of village water pumps, helping to reduce their downtime and plan future infrastructure investments.[144]
- **Agriculture** – Low-cost greenhouses equipped with sensors use SMS to send alerts and receive irrigation commands from farmers.[145] IoT apps are also used to track and manage smart multi-functional shareable micro-tractors, available for farmers on demand as a collaborative consumption tool.[146]
- **Resilience** – Mobile phone activity is increasingly used to understand emerging crisis trends such as the sudden mass population movements, and to improve disaster management; for example, by synthesising and providing real-time information gathered from communities during floods.[147]
- **Energy** – Firms such as M-KOPA Solar use IoT-supported financing schemes to provide rent-to-own solar energy products to hundreds of thousands of off-grid households.[148]

Potential benefits for development

The IoT holds significant promise in delivering social and economic benefits to emerging and developing economies. Awareness is growing in the international development sector of the game-changing role that the IoT – in conjunction with other digital and frontier technologies – could potentially play in development.

Experience clearly shows that these technologies can be successfully adapted to developing countries to improve research, public policy, basic service delivery and evaluation of programmes across a range of sectors. Innovators all over the developing world are creating sustainable and successful IoT-based business models that generate enormous value for economically disadvantaged people.

It is not surprising that NGOs, academia and social enterprises drive most frontier innovation, through small-scale, exploratory interventions. The IoT is composed of nascent technologies with a number of unresolved issues (see below) that become especially prevalent in developing countries with precarious infrastructure, sparse network accessibility and uneven purchasing capacity. To reach the untapped potential that the IoT offers to these countries, it is necessary to transition from small-scale experimentation to more systematic, scaled-up use of the technology. Successful pilots will need to find pathways to evolve into sustainable businesses, where corporate or individual customers are willing to pay; or into successful public or civil programmes, where governments and the third sector pay for services because of the social value they generate.

M-KOPA Solar has empowered off-grid households that lack purchasing capacity to directly leapfrog into leasing and financial services, and has also created an emerging IoT network that could lead to further applications and benefits.

With appropriate levels of experimentation, it is entirely feasible for developing countries to use the IoT to leapfrog to new levels of social and economic development. M-Pesa, for example, has allowed 19 million people in Kenya to access banking services via mobile technology, leapfrogging traditional banking networks. It has transformed economic interactions in that country, facilitated the creation of thousands of small businesses, promoted rural development and poverty reduction, and indeed set down an infrastructure for IoT applications.[149] Building on this, M-KOPA Solar has empowered off-grid households that lack purchasing capacity to directly leapfrog into leasing and financial services, and has also created an emerging IoT network that could lead to further applications and benefits.[150]

Local and national governments, and public service providers in general, need to get involved and take the lead in progressively introducing better, IoT-powered public services. This cannot happen immediately because few countries have the necessary capacity – either on the government side or among commercial providers – to implement reliable, cost-effective, off-the-shelf solutions that can be deployed at scale. But the learning processes leading in that direction should begin, supported and facilitated by international organisations.

Enablers and barriers

The IoT offers great promise, but to deliver on its potential certain conditions need to be in place and obstacles need to be overcome. Some of these issues are technical, some relate to regulation, and others are structural and behavioural, or are questions of trust and habit. Certain challenges have been identified as the most pressing for the IoT.[151, 152]

Technology

For widespread adoption of the IoT, the cost of basic hardware – such as sensors, tags, batteries and storage – must continue to fall. For example, the cost of MEMS (microelectromechanical systems) sensors dropped by 35 per cent between 2010 and 2013 and is expected to continue to drop.[153] This is especially relevant for developing countries, where the cost of solutions can be an important deterrent to experimentation. Further development is also needed in analytical and visualisation software, and IoT software development tools that are suited to developing countries and available technologies.

Security

The security of IoT products and services is fundamental. Users need to be able to trust that IoT devices and related data services are secure from vulnerabilities, as this technology becomes more pervasive and integrated into our daily lives. Poorly secured IoT devices and services can serve as potential entry points for cyberattack and expose user data to theft by leaving data streams inadequately protected. When the IoT is used to control physical assets, such as water treatment plants or vehicles, the consequences associated with a breach in security extend beyond unauthorised release of information to potentially causing physical harm.

Privacy

The IoT is dramatically changing how personal data is collected, analysed, used and protected. Concerns about privacy and potential harms might well hold back wholesale adoption of the IoT. IoT providers need to be transparent about what data is used and how, and ensure that users are appropriately protected. This is especially important for groups in developing countries that are already marginalised and subject to abuses of human and other rights.

Interoperability and standards

Greater collaboration and coordination is needed to address the fragmented environment of proprietary IoT technical implementation. Without concerted efforts, fragmentation is likely to inhibit the anticipated value for users and businesses. Purchasers will remain hesitant to buy IoT products and services at scale if there is lack of integration, high product complexity or lock-in to specific vendors. ITU has estimated that there currently over '115 different protocols used by IoT devices to connect to the cloud today'.[154] Without interoperability, the majority of potential IoT benefits will not be achieved. The use of generic, open, and widely available standards as technical building blocks for IoT devices and services will support greater user benefits, innovation, and economic opportunity. Private and state-led approaches have been proposed in the discussion about how to effectively and safely move towards greater interoperability[155] There are potential risks (e.g. security and privacy) if interoperability is implemented poorly.

Legal, regulatory and rights issues

The use of IoT devices raises regulatory and legal questions, as many IoT applications cannot proceed without regulatory approval. This has implications across the areas of licensing, spectrum management, standards, competition, security and privacy. The rapid rate of change in IoT technology frequently outpaces the ability of associated policy, legal and regulatory structures to adapt. For example, there are issues about tensions between law enforcement-related surveillance and civil rights; data retention, sharing and destruction policies; and legal liability for unintended uses, security breaches or privacy lapses.

> It is important to nurture pro-poor innovation which develops IoT goods and services for those at the bottom of the income pyramid in the sectors that matter most to these target groups, such as health, education and small-scale agriculture.

Organisational skills and capacities

The IoT combines the physical and digital worlds, and thereby challenges conventional notions of organisational responsibility. To achieve the vision expounded by champions of IoT, many different functions and departments in government, development organisations and private companies will need to radically increase their awareness of and knowledge about how IoT systems could be put to use in their areas of work. They need the capacity and mindset to use the IoT to guide data-driven decision making; and the trust and willingness to adapt to new processes and business models.

Emerging economy and development issues

Developing countries have to cope with additional difficulties to achieve the IoT's potential, as they typically lack infrastructure readiness, market and investment incentives, and required technical skills and policy resources. In these settings it is important to nurture pro-poor innovation which develops goods and services for those at the bottom of the income pyramid in the sectors that matter most to these target groups, such as health, education and small-scale agriculture.[156] However, given the ubiquity of mobile phones in many developing countries, IoT platforms that leverage mobile phone coverage – for example, using SMS-enabled sensors to monitor water pumps – provide exciting opportunities to overcome major infrastructure constraints such as connectivity. Other infrastructural constraints and the difficulties mentioned above must also be overcome for such applications to reach scale.

What next for development sector actors?

The next 3–5 are going to be critical for actors in the IoT field to define the exact nature and scale of its long-term impacts. IoT constitutes new territory, even for those with a high degree of technical expertise; much evolution and continuing development is expected. We are clearly in the very early days of IoT4D, and it is perhaps unsurprising that development sector actors are still unsure about how to approach it.

In such an incipient stage of technological development, it is just as important to trigger learning processes within and across development organisations as to launch new IoT initiatives. Currently, even if a successful IoT project managed to gather significant flows of data for a specific development challenge or area, it is doubtful that there would be sufficient institutional capacity to properly analyse the data and act on it. Moreover, IoT components and infrastructure are still expensive and lack interoperability, leading to higher risk of failed investments.

The best IoT projects do not have a narrow technological focus; instead, they focus on development problems and consider the wider social, economic and cultural contexts.

Therefore, an immediate priority is to continue working to improve enabling factors for the IoT in developing countries, especially in relation to improving connectivity and regulation. At the same time, investment is needed in capacity building to be able to better assess projects, understand the potential of IoT4D, and provide strategic guidance to in-country partners.

Development actors working with the IoT might consider actions in the following specific areas:

- **Increase awareness and knowledge about the IoT in the field** – Development actors need to increase their capacity to integrate IoT technologies into their processes and programmes. This means investing in internal resources, but also fostering cooperation with experts, advisers and researchers, and establishing partnerships with private companies. If the IoT and other digital and frontier technologies are going to be game changers in the development field, people who work in the development sector will need a critical understanding of IoT technology and the skills to use it, across different sectors and departments.
- **Convene a variety of actors to strengthen networking and collaboration** – Networks are of vital importance and should include partners in national civil society and government from the outset. Loose networks, sector-specific communities of practice and more formal cooperation mechanisms all have a role to play. The capacity of IT companies to provide technical training and certify competencies could be leveraged and tailored for the international development sector as a way to disseminate IoT knowledge and foster cooperation in development projects.
- **Incentivise new IoT4D solutions to address outstanding challenges** – A lot of innovation and experimentation are already happening in the field of IoT4D. Challenges and seed innovation funds can provide good instruments to catalyse new ideas and support initial field-testing. Equipped with their knowledge of development contexts and the appropriateness of particular technologies, development organisations could collect evidence and evaluate projects' results and impact potential, as a way to keep replicating and disseminating the best examples. IoT4D projects should have sound business models that promote their sustainability and provide inclusive pro-poor innovation that benefits the most excluded sectors. Moreover, the best IoT4D projects do not have a narrow technological focus; instead, they focus on problems and consider the wider context and alternatives. For example, what makes M-KOPA Solar successful is not that it provides electricity to off-grid households, but its innovative approach to providing them with financial services, using IoT technologies to turn off devices when payments are interrupted. This has led to some of the lowest drop-out rates of any loan programme, while providing a platform to develop more sophisticated products and services in the future.
- **Fund and support the best technologies and innovations** – Development organisations should provide financial and technical assistance to the most promising examples. This cooperation would not only benefit the recipients of support, but it would also allow development organisations to keep learning and improving their knowledge of the IoT. If the technology proves to be useful, pre-commercial procurement could also be used to give the technology a final push on its way to becoming self-sustaining.

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Transportation and Logistics
Technology Reviews

- Unmanned aerial vehicles/drones
- Airships

Philippines, Mabalacat, Luzon
Microlite aircraft fly above a rift in the meters-thick layer of lahar ash that covers this area. The ash came from the Mt Pinatubo volcanic explosion two years earlier.

Credit: Chris Stowers – Panos

Unmanned aerial vehicles/Drones

What is the challenge or opportunity?

The proliferation of unmanned aerial vehicles (UAVs) – commonly known as drones – that are easy to use and low cost is leading to their widespread deployment in aerial inspection tasks, mapping physical and social phenomena, providing unmanned cargo deliveries, and taking aerial photography and video. There is a clear opportunity to transform the way development organisations collect and deliver data and physical objects, enabling these tasks to be undertaken faster, safer, cheaper, more efficiently and more accurately than ever before.

Over the coming decade, low-cost, commercially available drones could be used for a range of applications, disrupting industry landscapes as varied as agriculture, infrastructure management, policing, and transportation & logistics.

Drones as a frontier technology

The idea of computer-controlled or enabled flight is not new. The military has used unmanned aircraft since the 1970s to perform intelligence, surveillance and reconnaissance missions considered to be too dangerous, dull or dirty for human pilots. Since the mid-1980s, computers have been able to take over most aspects of flying commercial aircraft, including navigation, take-off and landing. Thanks to recent developments in a cluster of technologies including machine vision, sensors, actuators and batteries, UAVs have come into widespread commercial and personal use.

Over the coming decade, low-cost, commercially available drones could be used for a range of applications, disrupting industry landscapes as varied as agriculture – where drone-assisted monitoring could boost crop yields – infrastructure management, policing, and transportation and logistics. Sales of drones are booming in the consumer and commercial sectors; whose sales in the United states (US) they are expected to rise from 2.5m units in 2016 to 7m in 2020.[157]

The growing availability of these automated flying vehicles, which can operate over large spaces, with the capacity to gather and transmit high-quality data and carry lightweight cargo, is expected to have a huge impact on business. According to a projection by professional services firm PwC, by 2020 UAVs could replace business services and labour with a current value of $127bn, across a range of sectors from delivery and logistics to construction, agriculture, and assessing assets and insurance claims.[158]

Definition

A UAV is simply an aircraft without a human pilot on board. UAVs operate with various degrees of autonomy: either under remote control by a human operator using radio frequency or satellite remote network connections; or intermittently or fully controlled by on-board computers. UAVs emerged from military applications, but their use is now expanding in commercial, scientific, recreational and a whole host of other applications. In fact, civilian and commercial drones now vastly outnumber military drones, with estimates of over 4.3m sold globally in 2015. Civilian UAVs can be classified according to their size – ranging from mini-drones through to people-carrying drones – the altitude they can reach, and their range or autonomy.[159]

AfricanskyCAM uses multirotor UAVs to get high resolution video and imagery of news stories in real time as they unfold. Photo credit: AfricanskyCAM, www.africanskycam.com

UAVs can be divided into three main categories based on their flight mechanisms:[160]

- **Multirotor UAVs** – These may have four, six or eight rotors. They are capable of hovering in a fixed position and flying in any direction, carrying out manoeuvres quickly and efficiently. They can get airborne without a runway, but have slower maximum speeds, and shorter flight times, than fixed-wing drones.[161]

Zipline uses low-cost fixed-wing drones to deliver medicine, vaccines, blood and small medical supplies in Rwanda.
Photo credit: Zipline, http://flyzipline.com/product

- **Fixed-wing UAVs** – These have a simpler structure than other UAVs, similar to an aeroplane. They can fly for longer, and at higher speeds, and thus can be used to survey cover larger areas. They are able to carry heavier payloads over longer distances by using less fuel and energy. As a result, they can carry bigger and better sensors and cameras. Fixed-wing UAVs need a runway or launcher to take off and land, and must stay in constant forward motion.[162] Zipline is a delivery company working across a number of African countries, most prominently in Rwanda, that uses low-cost fixed-wing drones to deliver medicine, vaccines, blood and small medical supplies.[163]

- **Hybrid model (tilt-wing)** – These drones are able to hover but can also transition to faster and more efficient fixed-wing flight.[164] They offer some of the best features of the other two types. The number of tilt-wing drones on the market is low at the moment, but companies including Amazon are working on new models, particularly for delivery applications.[165]

Potential for acceleration

Civilian UAVs have come a long way since unmanned helicopters were used for the first time in Japan at the beginning of the 1980s, and proved to be an efficient way to spray pesticides on rice fields. Drone technology can now be considered a mature, if fast-evolving, technology. Developments in UAVs' underlying technologies are helping to drive improvements in their performance and capacities; these include image processing, chips, artificial intelligence, improved control and communications, battery capacity, and drone detection and avoidance technologies. The overall market is booming, and further price falls are likely to accelerate the trend towards ever-greater capabilities.

> Shipments of consumer drones will more than quadruple over the next five years, fuelled by increasing price competition and new technologies.

While the military sector is expected to continue to lead the way in drone-related spending in the coming 5–10 years, this is due to military drones' high cost and the growing number of countries willing to acquire them for military purposes. According to PwC, shipments of consumer drones will more than quadruple over the next five years, fuelled by increasing price competition and new technologies.[166] Regarding commercial use of drones, the main challenge has been regulatory issues, which limit the use of commercial drones to a select few industries and applications, and to specific geographies. However, the accelerating pace of drone adoption is pushing governments to create new regulations and find new ways of balancing safety and innovation. As a result of these legal developments, growth in shipments and revenues in the enterprise sector are expected to outpace the consumer sector.[167]

Drone technologies are most likely to be used in and transform sectors that require mobility and high-quality data. Businesses that manage assets dispersed over wide regions (such as large-scale capital projects), infrastructure maintenance and agriculture, could benefit greatly from the integration of drones into day-to-day business. Insurance and mining will find potential process improvements as they gain new levels of data quality and accessibility; and the entire transportation industry could evolve its approach to last-mile delivery through the use of networks of drones.

Potential value generation and impacts

UAVs are expected to generate immense value among many industries and public services. A non-exhaustive list of sectors where drones generate considerable value and impacts includes:

- **Infrastructure** – For example, in inspection of power lines and pipelines;
- **Transport** – AfroTech plans to use drones to deliver blood transplants/samples and medical supplies;[168]
- **Insurance** – Over US 100 firms have received regulatory approval for using drones in inspections and surveys, enabling improvements in risk assessment, risk management, loss control and surety;[169]
- **Media and entertainment** – African SkyCAM uses drones to get aerial footage for journalists in hard-to-reach areas, replacing the need to use expensive helicopters;[170]
- **Agriculture** – For crop and land surveying; SenseFly supplies drones for precision agriculture;[171]
- **Security** – For reconnaissance missions, border patrols, surveillance, crowd monitoring; the TIRAMISU project uses drones to spot landmines;[172]
- **Wildlife and environmental monitoring** – Including poacher tracking, pollution monitoring (e.g. illegal landfill detection);
- **Mining** – For example, RocketMine provides mining companies in South Africa with low-cost survey and mapping services;[173] and
- **Disaster management** – Including forest fire detection, landslide measurement, post-disaster surveys and targeted disaster response.

Compelling UAVs innovations have focused on humanitarian efforts. After the 2015 earthquake, Kathmandu Flying Labs brought together Nepali UAV experts and a global network of crisis-mapping specialists to generate and analyse images of earthquake affected areas.

UAVs could clearly become an important tool for international development, as many of the above applications have considerable potential. In developing countries, for example, drones can provide value for actors who are constrained by a lack of proper transportation infrastructure and under-developed basic services. The improved data collection capacity that drones provide and their agile payload delivery functions are useful, and could lead to rapid and dramatic gains in efficiency and productivity in key areas of public service delivery.

In Africa, Ghana, Rwanda and South Africa and Ghana have taken a lead and shown a clear commitment towards establishing ICT infrastructure and commercial drone use, for example by implementing new regulatory frameworks.

In Africa, Ghana, Rwanda and South Africa and Ghana have taken a lead and shown a clear commitment towards establishing ICT infrastructure and commercial drone use.[174] They have implemented, for example, modern regulatory frameworks for commercial UAV's, something especially noteworthy when compared with the relative regulatory hesitancy in the US and most European countries.[175] Thanks to this movement, these countries are increasingly becoming testbeds for commercial drone services and new UAV delivery businesses. For example, RocketMine provides miners, farmers, civil engineers, and water and forestry companies in South Africa with low-cost survey and mapping services.[176] Flying Donkey and RedLine seek to create a cargo delivery network in Africa to overcome logistical constraints in humanitarian aid and health.[177]

UAVs also have considerable potential in disaster relief, in everything from mapping disaster-affected areas to delivering of emergency supplies. Some compelling innovations in the field of international cooperation on UAVs have focused on humanitarian efforts, such as the Kathmandu Flying Labs, which following the 2015 earthquake brought together Nepali UAV experts and a global network of crisis-mapping specialists to generate and analyse images of earthquake-affected areas.

Drone delivery of urgently needed medical supplies, such as medicine or blood, to inaccessible places makes it possible to avoid logistical problems related to road transport conditions altogether.

Potential benefits for development

UAVs offer opportunities to improve tasks that development organisations have historically performed, by doing them faster, cheaper, more safely, more efficiently or more accurately than before. But drones also increasingly offer the possibility to rethink how things are done, and provide new types of dynamic and adaptive processes for the delivery of public services.

Medical payload delivery services in emergencies provide a clear example. Drone delivery of urgently needed medical supplies, such as medicine or blood, to inaccessible places makes it possible to avoid logistical problems related to road transport conditions altogether. But to achieve real change, the whole system should be rethought; for example, by training community health workers who visit small villages and determine local demand for basic needs such as vaccines, nutritional supplements and antibiotics. They could communicate the demand to regional distribution centres via SMS (text message) and arrange for their delivery to remote points of care.[178] This is a model that Zipline provides in Rwanda, in cooperation with the government.[179]

A great deal of drone-based experimentation has been taking place in various sectors that have a focus on developing countries. While most of these projects have operated at small scale, and have had varying levels of success, they provide a useful indication of the potential of the technology. UAVs have been used in:

- Transporting medical supplies (medicines, samples, blood);[180]
- Spotting landmines;[181]
- Search and rescue operations for migrants in the Mediterranean;[182]
- Drone journalism;[183]
- Crisis mapping and disaster preparedness;[184]
- Conservation and poaching prevention;[185]
- Supporting UN peace-keeping missions;[186] and
- Agricultural analysis.[187]

Enablers and barriers

Despite the growth in the commercial and personal use of drones, several enablers and barriers that might serve to either facilitate or slow down the wider adoption of the technology. Some of these issues and drivers are technical in nature; others relate more to regulatory frameworks.[188]

Regulatory frameworks

Regulatory frameworks are the key factor affecting the pace of adoption of UAVs by businesses and government units. National and international aviation authorities have started developing frameworks to guarantee safe drone operation, while allowing innovation to continue. Once regulatory frameworks have been established, many more companies may decide to adopt drone-based solutions.

Companies have been using satellites, planes and helicopters to gather photogrammetry and geospatial data for many years. However, drones are much more cost effective and guarantee higher data quality.

Growing demand for high-quality data

Companies have been using satellites, planes and helicopters to gather photogrammetry and geospatial data for many years. These kind of images are very expensive and do not provide the best level of detail and quality. Drones are much more cost effective and guarantee higher data quality. Growing demand for data will increase the use of drones for commercial purposes, displacing manned aviation and satellites.

Enhancing data processing and accessibility

Data acquired during drone operations has to be processed to deliver substantial benefits for businesses. Data accessibility is going to be one of the key drivers that fuels adoption of drone technologies in business processes. This is also connected with the trend of simplifying and automating the use of drones. Another example may be the development of autonomous flight control systems, enabling businesses to automatically operate whole fleets of drones on various kinds of missions.

New technological opportunities

Drones are composed of many technologically advanced parts that determine their efficiency, safety and reliability. Constant improvements in hardware solutions and decreasing prices will contribute to the rising number of possible drone applications. Technological breakthroughs – especially in the areas of hardware, software and data processing – will drive the growth of drone applications. The development of new types of power sources, engines and structural materials will affect the drone market's potential. Drone manufacturers are working to implement autonomous avoidance, to stop them crashing into other flying objects, and automatic take-off and landing systems.

Constant improvements in hardware solutions and decreasing prices will contribute to the rising number of possible drone applications.

Safety of drone operations

The most urgent challenge that national aviation authorities and the private sector have to face is ensuring secure supervision of recreational and commercial drone operations. One part of a secure supervision system will be mandatory drone registration, allowing authorities to identify drone pilots who break the law. Additionally, there is a need for air traffic management systems for UAVs to prevent collisions with other flying objects. Technologies such as collision avoidance will make flying drones safer and give regulators the confidence to allow larger numbers of drones taking to the skies.[189]

Privacy and trust issues

When UAVs fly over certain types of sites, they can collect large amounts of data, potentially including confidential or sensitive information about private property or behaviour. Given the very broad definition of personal data, it is not clear how companies should store this data, what types of data should not be collected, or how individuals and companies can defend their privacy rights. Market growth increases the pressure to regulate this area, although it will take time to prepare and pass legislation. In some developing countries drones have been used for military operations, including surveillance and to attack military targets including people and infrastructure; it has been widely reported that many civilians have also been injured or killed in such attacks. In these contexts, much more resistance and mistrust to programmes using drones should be expected.

Insurance coverage availability

In most countries, regulators oblige aircraft users to have insurance to meet their liabilities in case of accidents. The laws governing UAV operators are still evolving, and insurance will need to become part of the regulatory framework, to provide coverage in case of physical losses or liabilities during and after drone operations. Drone manufacturers and insurers are starting to offer these services, enabling customers to overcome one of the barriers to commercial use.

What next for development sector actors?

Civilian attitudes and perspectives on drones vary widely and it is vital for development and humanitarian applications to be grounded in – and to build on – national and local interests and needs.

- **Regulatory and procedural frameworks** – Such frameworks are necessary for the use of drones in situations that are neither commercial nor personal, but instead relate to delivery of public services or other forms of socio-economic support. At present, such regulatory aspects are ambiguous or non-existent in relation to issues such as accidents, security and privacy. Where guidelines or codes exist – such as the UAViators Code of Conduct – they are not always applied 'with teeth', but are instead voluntary in nature.

- **Better assessment and evaluation of drone pilot programmes** – Evidence of UAV efficacy and effectiveness is limited at present. Most initiatives have focused on what drones can offer, without assessing whether this has a positive impact or not.

- **More systematic learning** – It is important to have a better sense of the costs and benefits in different settings and in relation to different challenges.

- **Strengthening national and local capacity to test, learn, use and maintain drone technology** – Building on existing networks and initiatives, such capacities could be further strengthened through training, knowledge exchange, and mentoring of national and local actors. As well as capacity development, a concerted effort is needed to educate the general public about the pros and cons of drone technology use.

Airships

Airships require little or no infrastructure to land making them ideal for delivering goods and supplies to remote areas developing countries or areas inaccessible via conventional transport after natural disasters. Photo credit: VariaLift Airships, www.varialift.com

Modern airships have the potential to transport fully assembled goods, supplies, and even large structures from the point of manufacture directly to their point of use without the need to build any of the usual transportation infrastructure such as roads, railways, runways or airports.

What is the challenge or opportunity?

Some of the most remote areas in the world have long been unreachable using conventional transport. According to the World Bank Rural Access Index, over one billion people in rural areas lacked access to adequate transport systems and infrastructure in 2010.[190] Moreover, due to increasing numbers of disasters and crises, it is not possible to reach growing numbers of people on a temporary basis. A lack of, or heavy damage to, infrastructure makes it difficult to deliver essential goods, and supplies.

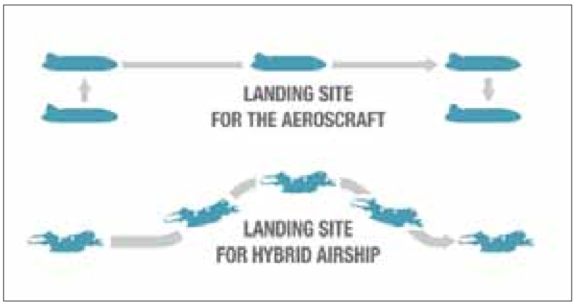
Airships as a frontier technology

A new generation of airships and hybrid aircraft are emerging that require little to no infrastructure, and which thereby hold the potential to meet the needs of people living in such settings and conditions. Conventional means of transport are limited in their ability to carry large quantities of cargo to these areas. Aeroplanes require too much infrastructure (e.g. roads and runways) that is often unavailable or inaccessible in these areas; and helicopters are limited in terms of range – not much more than 500 nautical miles even in extreme cases when they are not carrying much cargo – and their load carrying is also limited – the maximum amount is around 10 tons.

Definition

Airships, also often referred to as 'lighter than air' vehicles, are aircraft that are wholly or partially held aloft by a body of gas that is lighter than air (typically non-flammable helium). Hybrid aircraft are heavier than air, but get an advantage from combining buoyant lift from the gas with aerodynamic lift – the aerodynamic (or wing-shape) lift countering the weight of the aircraft. Airships have been around since the late nineteenth century, but newer versions of the technology have been developed that overcome many of the constraints that previously restricted their widespread adoption. Modern airships have the potential to transport fully assembled goods, supplies, and even large structures from the point of manufacture directly to their point of use without the need to build any of the usual transportation infrastructure such as roads, railways, runways or airports. Airships could be a game changer for communities living in areas that are permanently or temporarily inaccessible by more conventional means due to geographic remoteness or temporary factors, such as disasters or weather conditions.

Figure 9 Landing sites for conventional airships (Aeroscraft) and hybrid airships



Source: Aeros (2016)[192]

There are two main types of airships: conventional and hybrid (see Figure 9). 'Conventional airships control heaviness by changing aerostatic (buoyant) lift and ballast' meaning they take off vertically. Hybrid airships combine characteristics of airships, helicopters and aeroplanes: 'Hybrid airships combine aerostatic (buoyant) lift with aerodynamic lift (wing-borne) and direct (propulsive) lift.'[191] Hybrid airships often have a vertical take-off capability, but normally use a more efficient standard horizontal rolling take-off. They can do this from a variety of flat(ish) surfaces, typically taking off within a body length or two.

Potential for acceleration

Airships have been around since the late 1800s,[193] and were the first air vehicles capable of controlled flight. They saw their heyday in the early twentieth century as the quickest form of long-haul travel. In the 1920s, airships were regarded as the first reliable form of intercontinental travel and the Graf Zeppelin model had circumnavigated the world by 1929. However, by the 1930s and 1940s, other modes of transport had overtaken airships: they were not capable of transporting as many passengers as quickly as airplanes; and could not carry as much cargo or freight as trains or ships. They were also susceptible to weather, difficult to manoeuvre, and required large operational teams on hand to assist during take-off and landing.[194] The decline of airships was accelerated by the high-profile crash of the Hindenburg in 1937, attributable to the flammable hydrogen gas that the first generation of airships used. The advent of jet aircraft confirmed airships literal and figurative decline from grace.[195]

> Researchers at the Smith School of Enterprise and Environment project that airships will be able to carry up to nine times as much cargo as a Boeing 747.

Several companies seem to have overcome these structural hurdles and have found potential paths for future acceleration of the technology. Among them are Worldwide Aeros Corporation, Lockheed Martin and Hybrid Air Vehicles. Moreover, issues of safety have now been overcome with the use of non-flammable helium rather than hydrogen. Ballasts are no longer needed – at least in most scenarios – and take-off and landing is controlled by in effect gently sinking the aircraft to the ground because they are heavier than air so very few or no personnel are needed on the ground. Modern airships are getting to the stage now of being capable of loading and unloading cargo with far fewer personnel than other means of cargo transport. Although it has not yet demonstrated this capability, Aeros claims its Aeroscraft only requires one person – the pilot – to load and unload a payload.[196]

Airships provide the capability to move fully functional machinery and structures directly from where the machinery is made to where it will be used, decreasing the need to assemble it on site and thereby saving time and money for businesses and operations in in remote areas.

Moreover, modern airships are able to offer cargo bays that are far larger than the cargo space in other aircraft and are therefore capable of shipping bigger and heavier cargoes.[197] Additionally, given their lower speeds, airships and hybrids should be better able to carry outsize and underslung loads than other aircraft. Researchers at the Smith School of Enterprise and Environment project that airships will be able to carry up to nine times as much cargo as a Boeing 747. [198] The Aeroscraft ML868 is projected to be able to carry up to 250 tons of cargo, while the ML86x could carry up to 500 tons of cargo.[199] Hybrid Air Vehicles' Airlander 10 is now the largest flying aircraft in the world and can carry up to 10 tons of cargo; and the company already has plans to build the Airlander 50, which will be much larger and carry up to 50 tons of cargo, with designs also underway for a hybrid airship that will be able to carry up to 200 tons.[200]

Potential value generation and impacts

If successfully commercialised, airships could 'open trade and supply routes to regions lacking surface transportation infrastructure' and for industries and sectors including mining, oil exploration, energy installations and logging.[201]

In extractive industries such as mining and oil, airships provide the capacity to transport fully assembled heavy machinery such as tractors directly from the factory to mining sites and oil fields and other remote areas. A lot of large industrial infrastructure is required in remote areas, such as bridges, pipelines, power-line masts and mobile phone base stations, and airships could be invaluable in transporting these to their destinations and bringing in replacements when needed.

Airships could transport entire wind turbines directly to wind farms, a transportation process that typically requires up to eight stages using multiple transportation modes under current practices.[202] This is also good in environmental terms, because large swathes of forest or other areas can need levelling to create roads to get the wind turbines to their remote locations. More generally, airships provide the capability to move fully functional machinery and structures directly from where the machinery is made to where it will be used, decreasing the need to assemble it on site and thereby saving time and money for businesses and operations in in remote areas. They can also move raw materials out of remote areas after they have been extracted.

Airships require little infrastructure of even the most basic kind – paved ground or concrete are not always necessary – which allows them to take off from unconventional places. This is in marked contrast to planes, automobiles and trains that are largely reliant on airports, roads, and railways. As well as enabling physical delivery of materials, goods, supplies and infrastructure it also means airships are less likely to disrupt or affect the environment around take-off and landing sites. More widespread haulage of cargo via airships could help to decrease airport, road, and railway congestion, and because they fly at lower altitudes than airplanes, their widespread use is also anticipated to reduce air traffic congestion and related conflicts.[203]

Airships require little infrastructure of even the most basic kind – paved ground or concrete are not always necessary – which allows them to take off from unconventional places.

The Airlander 10 takes off for its maiden flight in Cardington Airfield in Bedfordshire, UK in 2016.
Photo credit: Hybrid Air Vehicles, www.hybridairvehicles.com

After delivering necessary supplies, airships can be used to evacuate injured or vulnerable people on outbound/return legs. Airships could also 'open trade and supply routes to regions lacking surface transportation infrastructure' including remote areas in Africa, Asia and polar regions.

Having been one of the biggest supporters and promoters of innovation in the sector, militaries are expected to be among the most prominent airship clients. For example, the US military funded the DARPA Walrus HULA (Hybrid Ultra Large Aircraft) project between 2008 and 2010 in hopes of building an aircraft with the capacity to carry up to 1,000 tons of cargo over distances up to 22,000km.[204] Aeros anticipates that its Aeroscraft models will be extensively used by militaries for resupply, humanitarian, medical and fire containment missions. Airships can reduce dependence on foreign airbases and ports, and provide the capability to transport entire tanks and other heavy weaponry directly to combat arenas.[205]

Aeros also claims that the Aeroscraft can be used as an air-deployed mobile hospital, fully equipped with operating rooms and emergency equipment, which could quickly enter and exit hostile environments. Hybrid Air Vehicles won a contract with the US Army to develop an unmanned (drone) airship for military surveillance that could stay in the air for 21 days at a time. This ultimately led to the creation of the Airlander 10, which is being developed under civil regulation and for manned operations.[206] Because airships can carry many tons of water and have the ability to fly at low speeds and hover, they are also seen as ideal for fighting forest fires.

Because airships can take off and land without the need for a runway, there is great potential for their use in responding to emergencies.

Airships also hold promising applications for leisure and tourism. Hybrid Air Vehicle's hopes that the windowed lounge viewing deck of its Airlander 10 could be used for safaris, and other luxury tourism and sky-based cruises.[207] Aeros has proposed that its airships could soon be converted into sky cruisers and luxurious sky-yachts to directly compete with sea-based cruises. Potentially airships could also be used as an alternative mode of transport for customers travelling short distances.[208]

Airships could also relay WiFi and broadband signals to focused areas. Although similar in some ways to the technologies covered in the technology review on alternative internet delivery in this report, airship manufacturers have suggested that airships would be best suited to the localised provision of temporary internet and wireless services in specific geographic areas; for example, for large gatherings of people at big sports events or festivals, where existing network capacities may be overstretched. There would seem to be less scope for airships to be organised into wide-scale, permanent installations with the aim of reaching the digitally disconnected.

Leapfrogging infrastructure

Because airships can take off and land without the need for a runway, there is great potential for their use in responding to emergencies; for example, after tsunamis, earthquakes and other natural disasters when infrastructure has been destroyed and it is difficult to transport supplies by other means (see figure 10 for how airships might be positioned relative to other transportation types). Although not all airships take off vertically, the ones that do not are still generally able to take off from almost anywhere, given enough open space: while they take off at an angle, they do not require a road to get airborne. Emergency response missions are plagued by logistical challenges involved in transporting large quantities of goods using roads, ports, airports and railway systems that have typically been damaged and are under heavy strain due to excessive use. Increased demand places severe strain on local skills and capacities, escalating freight costs, and in the worst cases leading to logistical shutdowns; for example, as happened at Port-au-Prince Airport after the January 2010 earthquake in Haiti.[209]

Because they can transport goods, equipment and people directly from point of origin to point of delivery, airships can overcome these bottlenecks in emergency response. Some airships will be able to carry hundreds of tons of cargo, which might include basic relief supplies such as fuel, medicine, water, or anything else affected communities and disaster responders need.[210] Moreover, after delivering necessary supplies, airships can be used to evacuate injured or vulnerable people on outbound/return legs.[211]

Airships could also ‘open trade and supply routes to regions lacking surface transportation infrastructure’ including remote areas in Africa, Asia and polar regions. This could be especially useful for transportation to the poorest rural areas of developing countries, where there is a lack of adequate infrastructure and where there is low likelihood of this being addressed with short-to-medium term investments.[212] Airships also overcome the challenges of maintenance that often limit the sustainability and development impact of infrastructure investments in remote areas. Carey, Inderwildi, and King believe that:

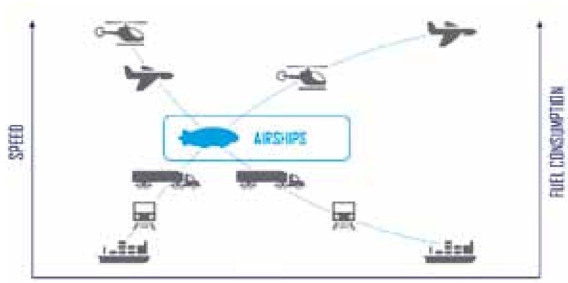
> in less developed parts of the world, the need for expensive and carbon heavy infrastructure projects could be removed by fleets of

NASA has noted that airships could feasibly be entirely powered by renewable energy.

> “lorries in the sky” providing multi-drop capability, and connecting distant communities with international markets. This lack of infrastructure also appeals to aid agencies, which see airships as a possible method of delivering significant levels of supplies… quickly, and at much lower cost, than current multimodal methods.[213]

The potential is not limited to developing countries. NASA analysis suggests that Alaska and northern Canada may be among the best initial markets for airships.[214] Around 82 per cent of Alaskan communities are not currently served by a road network, while the whole of

Figure 10 Positioning of airships



Source: Lockheed Martin (2016) [222]

northern Canada has very sparse transportation networks. The ability for airships to take off and land just about anywhere makes them an attractive alternative to building infrastructure in these areas to meet the needs of remote communities.[215] Montreal-based company LTA (Lighter Than Air) Aerostructures plans to build airships capable of transporting pre-fabricated houses to solve the indigenous population’s housing crisis in the north.[216] This is part of a broader interest across Canada, with the national House of Commons calling in 2016 for airships to be trialled in service delivery to remote indigenous communities.[217] Because of the similar bottlenecks and opportunities that exist for communities in developing countries, companies that perform successfully in tests could have a large number of potentially lucrative markets to tap into globally.

Airships are less physically damaging to the environment than conventional aircraft because they do not require the construction of runways and their engines make much less noise.

Greener transportation

Although most airships in operation today are partially powered by diesel engines, they are much less polluting that conventional means of transportation. Researchers at the Smith School of Enterprise and Environment estimate that that the transport of a load of cargo of 220 tons would emit only 4.2 tons of carbon dioxide (CO_2) emissions compared to 42 tons over the same distance by a typical jet plane.[218] They are also more fuel efficient, requiring one-third of the fuel of cargo planes and one-tenth of the fuel of helicopters to haul the same amount of cargo over the same distance.[219] This enhances their environmental credentials and also offers potential operational cost savings.[220] Beyond fuel costs, Aeros claims its aircrafts require one-third of the acquisition and maintenance costs of other air-based cargo transport methods.[221]

Because of the lack of constraints in terms of the size and shape of the payload module, airships and hybrids are likely to be early adopters of electric engines – they will be able to carry the weight and size of batteries to make them workable. Hybrid Air Vehicles is part of a UK government programme looking into 'More Electric Aircraft', which proposes an airship design with two electric engines at the front and two diesel ones at the back. This will make it easier to negotiate regulatory hurdles and ensures there is sufficient power on take-off, when the four engines are needed.

Governments have played an active 'entrepreneurial state' role in the development and advancement of airship technologies to their current position.

This is seen as a first step to an all-electric aircraft, which could ultimately be powered by a thin film of solar panels that would cover the entire upper side of the hull. A technical memorandum by NASA has noted that airships could feasibly be entirely powered by renewable energy. Solar- and wireless microwave-powered airships have already shown promising results in prototyping efforts, and more pilots are under way to test other sources of renewable energy.[223] Moreover, as mentioned above airships are less physically damaging to the environment because they do not require the construction of runways and their engines make much less noise.

Such factors have led NASA to declare airships to be 'the most environmentally responsible transport technology',[224] with the wider dissemination of airships having the potential to make the global logistics and freight sector far more environmentally friendly.

Enablers and barriers

Thanks to determined efforts made to overcome the technological and safety issues of previous generations of airships, a number of obvious markets have emerged for airships in hard-to-reach areas with little – or damaged – infrastructure. Where airships can be more economical than conventional shipping and transport methods it is expected that early adopters such as the military will start to use them in growing numbers.[225] As already noted, airships can potentially leapfrog the need to build airport and other infrastructure to transport goods.[226]

Airships are becoming increasingly flexible in terms of when, where and how they are deployed. Some airships, such as the Airlander 10, can land on or hover over land, water and ice. Others do not need to land to make deliveries, and can operate at low speed, hovering in the air while picking up and dropping off goods, equipment and personnel.

The airship market has been estimated by industry experts to grow to $50bn over the next 20 years, with more than 500 airships expected to be in operation by 2036.[227] Lockheed Martin signed a non-legally binding letter of intent with Sraightline Aviation in early 2016 to deliver 12 airships at an order value of $480m. Straightline Aviation plans to use them to deliver cargo to remote and hard-to-reach areas that lack adequate infrastructure.[228]

Governments have played an active 'entrepreneurial state' role in the development and advancement of airship technologies to their current position. The US military committed $300m to Hybrid Air Vehicles in 2001, with a further $90m for intellectual property rights, but the investments have been plagued by slow development and spending cuts. After a successful test flight in 2012, Hybrid Air Vehicles was able to buy back its patents.[229]

Although the US military has not continued to fund the venture, past backing for over a decade as well as grants from the UK government have played a role in Hybrid Air Vehicles' being able to claim that its technology is years ahead of its competitors.[230] Further use of airships by militaries after the new generation of airships is commercialised is likely to spur more research and development investments, with strong potential for the development of airships that cross over into the consumer and international development spheres.

However, although airships have been proposed for passenger flights, they are too slow to compete with fixed-wing aircraft across continents or large distances. For example, the fastest model currently in development is the Airlander 10, which travels at about at a speed of 148 km per hour.[231] They would most likely be best suited for flights over relatively short distances where infrastructure constraints do not allow faster transportation methods. More generally, they should not be viewed as alternatives/replacements for existing modes of transport, but as a means of extending existing infrastructure into remote and inaccessible areas. One industry expert notes that the most probable market for short-haul flights may be sightseeing trips and experience flights.[232]

> Airships should not be viewed as alternatives or replacements for existing modes of transport, but as a means of extending existing infrastructure into remote and inaccessible areas.

The emerging reliance of airships on helium comes in the context of growing demand for helium for a wide range of medical,[233] high-tech, military, and space applications, resulting in increased prices for the gas. Although there have been concerns over a potential shortage of helium,[234, 235] these fears may prove to be misplaced. As with fossil fuels, helium is a finite resource. However, the current supply is expected to continue as long as natural gas is being drilled. There have been a number of reports of helium shortages in the near term, but most helium – captured in natural gas wells – is simply released into the atmosphere. As the supply–demand curve balances, more helium will be captured. In 2014 the US government estimated that there were sufficient helium reserves for 177 years. Moreover, in June 2016, using methods similar to oil exploration, scientists discovered a rich helium reserve in Tanzania, which they estimated contains approximately seven times the annual global helium demand.[236]

Hybrid Air Vehicles Head of Partnerships Chris Daniels estimates that there are currently 20 true airships flying and only about 12 are in service at any time. Moreover, the airships currently in commission are mostly older-generation airships (blimps) used for advertising, research and surveillance.[237] Most of the new-generation airships mentioned above are merely prototypes and not yet fully operational or commercial, and there have been some issues with testing of new models. If demand increases, it is unclear how prepared manufacturers will be to scale up production.

No airships exist that are devoted to emergency response, nor have any been deployed for such missions. It is unclear if current models of airships would meet the needs of humanitarian organisations or emergency response missions. Such an airship could require a tailored design that could be costly and take a long time to design and build. Little dialogue has taken place between airship manufacturers and humanitarian aid organisations, although there is no reason this could not change.[238]

The Canadian government's support for airships to address very similar challenges to those found in developing countries is good news for development organisations. Rather than starting from scratch, development organisations could collaborate with the Canadian government to learn from its experience and share findings.

The airship has been seen as 'the technology of the future' since the nineteenth century, but has never quite managed to achieve its potential. Many ventures have tried to revive the industry since its high-profile decline but have resulted in failure. The most recent example was Cargolifter AG, based in Germany, which went bankrupt in 2002 after attracting hundreds of millions of dollars from investors.[239] Time will tell if today's technologies and ventures will be able to turn the current interest – and hype – into commercially viable businesses. A good number of investors seem to think so; an example of the public interest was the Airlander 10 crowdfunding campaign in 2016, which raised more than £3.5m over two rounds.[240]

What next for development sector actors?

- **Demonstration projects and pilots** – Airship manufacturers could undertake tests in areas and under conditions similar to those encountered during emergency response missions, which could be very useful to help test their merit in such contexts. These could be incentivised and brokered through challenge funds and other mechanisms. The Canadian government's support for airships to address very similar challenges to those found in developing countries is good news for development organisations. Rather than starting from scratch, development organisations could collaborate with the Canadian government to learn from its experience and share findings.
- **Cross-organisational engagement** – Along with engagement with the private sector, this could help determine whether current airship models are appropriate to address challenges in development and humanitarian settings. Test runs may be worth exploring, as well as identification of specific development and humanitarian opportunities where existing infrastructure does not meet organisational or community needs.
- **Funding for airship initiatives** – Projects that seek to use airships to reach remote communities are likely to require public or donor support. Even more than the other technologies covered in this report, the use of airship technology has not yet been proved and governments may be hesitant to put scarce taxpayer money into it just yet. Development organisations and innovation funds could invest in small-scale exploratory research projects, and a compelling case could be made for funding research to better understand the challenges and opportunities for airships in development.

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Fresh Water
Technology Reviews

- Solar Desalination
- Atmospheric Water Condensers

India, Raj Nagar, New Delhi
People using a water ATM in the suburb of Dwarka. The solar-powered machines installed by a for-profit social enterprise called Piramal dispense clean drinking water via a pre-paid smartcard to residents who have no access to water on tap in their homes.

Credit: Stuart Freedman – Panos


दिल्ली जल बोर्ड
R.K.

Solar desalination

What is the challenge or opportunity?

Water stress occurs when there is insufficient quantity or quality of water supply to meet diverse needs and demands[241] in a specific area or region,[242] It is rising globally because of changes in living patterns and food production, high levels of pollution, and the rising cost of treating and distributing water. Globally, this means that billions of people need to mitigate, overcome or in some other way manage high levels of water stress.[243] In developing countries this translates into large numbers of poor and vulnerable people who do not have access to affordable, safe, sufficient, sustainable and environmentally safe water.[244]

Solar desalination as a frontier technology

Historically, people have tried to increase water availability to meet demands by exploiting unutilised fresh water sources, such as rainwater, groundwater and atmospheric water, or through improved water management practices, including demand management, water recycling, river flow regulation and so on.[245] While these practices are widespread today, their potential mitigating impact on escalating levels of water stress is somewhat limited because fresh water only accounts for around 3% of global water volumes.

As a result, increasing attempts have been made to harness the remaining 97% of saline water, comprising seawater and brackish water.[246] Experts argue that methods to turn saline into fresh water are likely to play an important role, especially in developing countries. Some go as far as to suggest that 'desalination [could] make a revolution in water supply globally.'[247]

Technological advances have led to considerable improvements in these processes, ranging from the use of new energy-efficient means of heating water to evaporation point to the invention of more effective membranes and materials for filtration.

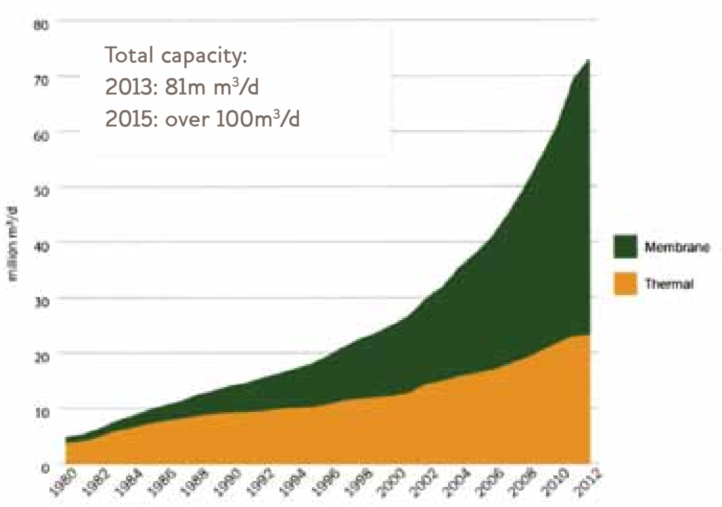
Definition

Desalination has been practised for centuries through one of two methods: *distillation*, through the evaporation of saline water into steam, and then condensing it into a pure non-saline form; and second, through the application of intensive *filtration* processes to extract salt from the water.[248]

The effectiveness of new desalination technologies has led to rapid diffusion of facilities. There are more than 16,000 desalination plants worldwide, with a total global output capacity of 100m cubic metres per day in 2015.[249] Private sector consortia typically set up and run the plants, with a mix of public and corporate clients.

A Sundrop farms seawater greenhouse, which uses solar desalination technology to grow vegetables in the South Australian desert.
Photo credit: Seawater Greenhouse, www.seawatergreenhouse.com/australia.html

Figure 11 Installed water desalination capacity



Source: Ghaffour *et al.* (2015)[251]

Global capacity has grown considerably over the past decade and is anticipated to continue growing exponentially as more countries and regions seek out new ways to combat water stress (see Figure 11).[250]

Plants tend to use one of three main processes:

- **Thermal distillation:** this involves the distillation of saline water into steam, which is then condensed into pure fresh water;
- Extraction processes:
  - **Electro-dialysis:** whereby salts are separated from water by means of applying an electric load; and
  - **Reverse osmosis:** whereby a pressurised flow of water passes through a semipermeable membrane that prevents the salts from passing, with higher saline water requiring higher pressures.

Globally, 68 per cent of all desalinated water is produced using filtration or membrane processes, and 30 per cent using thermal distillation (with the remaining 2 per cent coming from other processes).[252] Membrane technology has become dominant since the 1990s, with reverse osmosis being the most widely used approach. Desalination water is split, with 59 per cent coming from seawater and 22 per cent from brackish groundwater sources; the remainder comes from surface water and saline wastewater. These figures tend to change frequently because of the rapid growth and evolution of the desalination market.

The high energy costs of filtration and distillation contribute to high financial and environmental costs. These are especially pronounced because the majority of desalination facilities are powered by fossil fuels. Desalinating water is estimated to use at least 75.2 TWh/year, which amounts to approximately 0.4% of global electricity consumption.[253] Significant capital investments and maintenance costs are also involved in setting up and running desalination plants.[254] According to researchers from the International Water Management Institute (IWMI), this poses a significant constraint on the wider adoption of desalination technologies in developing countries: 'The major present hindrance in using desalination to help alleviate global water scarcity is the cost of this technology, which, in turn is due to energy cost involved.'[255]

In recent decades efforts to develop renewable energy-based desalination technologies have grown, with various ways of incorporating renewable energies into the desalination process being tested. The most frequent application is the combination of solar energy and reverse osmosis,[256] which is seen as having considerable potential because of the abundance of solar energy in those areas and countries that face the greatest levels of water stress, its permanence and minimal environmental impacts.

Growing numbers of initiatives and studies have shown that a number of solar-based desalination processes have considerable scope for widespread application in developing countries and with reduced costs compared to conventional desalination approaches and the cost of centralised infrastructure investments. Box 2 shows four of the more prominent examples.

A Seawater Greenhouse in Somaliland aims to transform the hostile local environment into 'micro oases' to efficiently and effectively grow crops using solar desalination technology. Photo credit: Seawater Greenhouse, www.seawatergreenhouse.com/downloads/Somaliland%20Seawater%20Greenhouse%20Flyer.pdf

Box 2 Types of solar desalination

Solar-powered reverse osmosis

Also known as photovoltaic powered reverse osmosis (PVRO). The process uses solar power to pressurise water and push it through a membrane where salts are intensively filtered out.[257] Such systems are generally used to meet clean water needs for small remote communities in low- and middle-income countries. Although such systems have technical, cost and operational challenges, technology reviews show that effective community engagement in the design, implementation, operation and maintenance of the systems can resolve them.[258]

Membrane distillation

A thermally driven distillation process that uses a porous membrane, either side of which is maintained at a different temperature.[259] The feed water is heated and brought into contact with the membrane, which allows only vapour to go through the dry pores, which condenses on the other side. A temperature difference of 7–10°C between the warm and cold sides is sufficient to produce fresh water. The process works at relatively low temperatures, and so can use low-grade water and renewable energy including solar and geothermal. High feed salinity does not greatly affect performance, as has been proved in benchmarking and pilot studies.[260]

Adsorption desalination

A form of distillation that uses a low-temperature heat source to power the desalination process, producing cooling and high-grade potable water. Brackish water or seawater is fed into an evaporator at an ambient temperature. An adsorbent material such as silica gel is used to draw out vapour at very low pressure and temperature. This process is energy efficient and low maintenance because of the lack of major moving components. It is also between five and 12 times less polluting in terms of CO_2 emissions when compared with conventional desalination processes.

Greenhouse desalination

Greenhouse desalination processes use sunlight, seawater or brackish water, and the atmosphere to produce fresh water and cool air, creating suitable conditions for crop cultivation.[261] The process recreates the natural hydrological cycle in a controlled environment, using humidifiers to keep the greenhouse cool while allowing crops to grow in strong sunlight. Saturated air leaves an evaporator and passes over a condenser. The fresh water condensing from the humid air has zero salinity, and this is then piped to storage tanks for irrigation. The system has several benefits such as flexible capacity; moderate installation and operating costs; simplicity of design and operation; and the possibility of using low temperatures and numerous renewable energy sources, including solar, wind and geothermal. Pilots have been developed and tested in the Canary Islands, United Arab Emirates, Oman and Australia.[262]

A Seawater Greenhouse (left) uses solar energy to desalinate water for crop production (right). Photo credit: Seawater Greenhouse, http://www.seawatergreenhouse.com/projects.html

Potential for acceleration

Current installed desalination capacity powered by renewable energy is relatively small compared with the world's total desalination capacity. The Prodes Group of Experts suggested in 2009 that the target for the use of solar energy should be a 3–5% share of new installations in the global desalination market by 2016. According to the International Renewable Energy Agency, by 2012 this had reached 1%.[263]

Mass production and diffusion of solar energy systems has led to significant cost reductions in many related applications and this trend is expected to continue for solar desalination also. Growing demand is starting to facilitate commercialisation opportunities. Combined with the growing cost of fossil fuels, these factors are serving to increase the competitiveness of solar desalination. However, a number of issues need to be addressed relating to the production and operation of the solar desalination technology and improvements in efficiency and output levels.[264]

In terms of production most solar desalination systems are not developed as a single coherent system, but instead are the result of localised efforts to identify a workable solution, using a number of components that are usually made by various suppliers. This poses a particular challenge to production costs and reliability. An added complication is that solar desalination systems are not based on a single technology but on the effective coupling of water desalination and solar technologies. Work needs to be done if all combinations of these technologies are to integrate in a smooth and efficient fashion. However, some approaches that have been developed and tested are more advanced than others, such as the greenhouse desalination described in Box 2.

As well as these technological and commercial aspects, the scope for acceleration in solar desalination in different settings is influenced by a number of context-specific local factors. These include:

- **Plant location** - Solar energy is abundant in many coastal areas of arid and semi-arid regions where a large proportion of the developing world population lives.
- **Self-Sufficiency** - It is possible to increase energy diversification by including solar energy in the energy source mix; increased use of solar energy further reduces dependence on energy imports if no national fossil fuel resources are available, and this can lead to a virtuous circle for solar desalination systems.[265]

Small-scale solar membrane systems can provide a viable treatment option for rural areas in many developing countries because they are able to reliably treat many feedwater types to meet drinking water standards, and work in settings where there is low infrastructure for water and electricity.

- **Economics -** Solar desalination is an ideal solution for remote areas and inland cities, which otherwise often depend on fresh water transport over long distances, which leads to high costs and potential microbial contamination due to poor hygiene.
- **Operation and maintenance -** Solar energy systems can generally be operated and maintained more easily than conventional energy systems and are therefore a more suitable option for remote areas because they are self-contained.[266]

Potential value generation and impacts

Evidence shows that the viability and value of solar desalination is greatest in areas undergoing the highest levels of water stress, where the cost of fossil fuels is high, where infrastructure for water supply to arid areas is limited, and where national or international financing mechanisms subsidise or offset investment costs in solar desalination.

Relatively small-scale solar membrane systems can provide a viable treatment option for rural areas in many developing countries because they are able to reliably treat many feedwater types to meet drinking water standards, and work in settings where there is low infrastructure for water and electricity. Compared to the costs of infrastructure and untreated water, the cost of the system may not be as big a barrier as is often assumed. Solar desalination systems have been described as having strong leapfrogging potential.

However, for it to achieve its potential in a variety of settings will require in-depth consideration of many parameters - a one-size-fits all solution not likely.

In commercial terms, a recent review by Mahmoudi and Ghaffour[267] noted that while solar-assisted desalination has proved to be technically feasible, the processes have not yet been successfully commercialised.[268] A more critical assessment suggests that a range of technological and economic factors come into consideration that limit the commercialisation of solar desalination including the cost of photovoltaic (PV) cells, water collectors and related plant equipment such as membranes and pumps. Until these individual technologies can be mass-produced, and issues of interoperability considered at the design stages, overall costs are unlikely to drop significantly, and the opportunity may seem unattractive to potential innovators and investors.

Potential benefits for development

The successful application of renewable energy for solar desalination can help achieve three sets of goals: social, economic and environmental. These goals are not always compatible and trade-offs are typically required. The potential benefit of solar desalination systems is that they present an investment 'sweet spot', whereby it is possible to meet goals in all three areas simultaneously.

The majority of applications in developing countries have been in remote and arid areas, and where national and local investment or external financing through development assistance meet the costs of plant set-up, operation and maintenance.[269]

For example, research has been undertaken on German-built solar-powered desalination systems in northern Namibia, near the Etosha salt pan, which receives an annual average rainfall of 470mm and an annual average daily solar irradiance of 46 kWh/square metre. The CuveWaters project involved four different solar desalination pilot plants in the villages of Amarika and Akutsima in the Omusati region in July 2010. The plants are important because roads are poor and there are no electricity, mobile phone network or piped water connections. In Amarika, the chosen technologies were PV-powered reverse osmosis (with battery back-up) and solar thermal membrane distillation; in Akutsima, two non-membrane evaporation-based solar thermal systems were installed.

Over the pilot period and subsequently, the CuveWaters project showed that it is possible to install and operate small solar-powered desalination plants in a remote area of sub-Saharan Africa. According to the project evaluation, 'the first step on the path to the realization of a financially, environmentally, and socially sustainable provision of clean drinking water in developing countries using solar-power has been demonstrated.' The Namibian Ministry of Agriculture, Water and Forestry has since taken over operation of the plants and is looking to use the technology in other similar settings.

DFID is currently in the process of setting up a new programme of solar desalination systems in Bangladesh, and a critical consideration has been how to find the right business model for sustainable operation. Achieving long-term benefits requires ways of designing and implementing collaborative arrangements between communities, industry, government and innovators.

Enablers and barriers

Enablers

To reach greater scale, solar desalination needs to be perceived as a viable or at the very least a promising way of meeting the growing demand for fresh water. Context-specific conditions such as extreme water stress, high water costs, and natural characteristics that are favourable for desalination can contribute to its viability.

The wider growth in the use of solar-generated electricity, especially from PV sources, is likely to lead to growing scope for experiments in solar desalination. The potential for the electricity generated to also be used for other purposes is likely to strengthen arguments for investments.[270] Many installed plants could connect to an alternative grid to serve households, for example.

A key driver of solar power has been positive public support and opinion. There is also a strong environmental impact argument that could lead to greater levels of solar take-up across desalination investments more generally.

Although solar is still less efficient than fossil fuels in solar desalination by direct cost comparison,[271] numerous studies of these new approaches suggest that the feasibility of desalination systems based on renewable energy becomes more justified if environmental degradation costs associated with fossil fuel-based desalination are taken into account.[272]

Where solar desalination plants have been installed in developing countries, it is because their costs are not assessed relative to fossil fuel-powered desalination, but rather as an alternative to centralised infrastructure investments and related operation and maintenance costs. A key enabler is therefore the extent to which solar desalination is framed as a leapfrogging technology.

Barriers

Although capital investments are important, as with many different forms of water and sanitation investments in remote and rural settings, the challenge relates to the need for sustainable use. This demands skilled operators, infrastructure for operation and maintenance, robust technology service networks, availability of spare parts and, perhaps most importantly, the adaptive capacity of communities to adopt and develop solutions specifically suited to local conditions.[273]

Other barriers that need to be overcome for the typical sites where solar desalination could be applied include a general lack of infrastructure; limited accessibility, especially during rainy seasons; and lack of suitably skilled staff who are permanently on site to deal with set-up challenges.

The need for greater efficiency in the technology is also a sticking point that will need to be addressed. At present, solar desalination is not a viable option for large-scale applications, either technically – due to fluctuation in energy supply leading to operation at different loads – or economically. In addition, solar energy is only available during daytime and its intensity changes from morning to evening, with peak intensity in the afternoon, whereas the energy requirement of conventional desalination processes is constant and continuous. In general, system efficiencies tend to be low if operated at variable loads and operating conditions. These limitations may pose a challenge to attracting investments in the technology, which in turn limits the rate of improvements in small-scale applications.

The potential for the electricity generated to also be used for other purposes is likely to strengthen arguments for investments. Many installed plants could connect to an alternative grid to serve households.

Currently, the cost of solar desalination exceeds those of conventional desalination by at least a factor of four. While solar energy is available free of charge, capturing it is far from free. More efforts is needed globally, which will serve to drive down the cost of solar for desalination applications. These activities should be undertaken by solar and water experts working in collaboration.

Risks

In general, the risks are the same as those that desalination efforts face generally. Intensive efforts can create new kinds of water and environmental stresses, especially due to by-product saline brines being discharged back into water sources, with brine disposal proving more challenging inland than in coastal areas. Other risks include the growing use and impact of chemical additives in various desalination processes. No specific standards for impact assessments exist, only guidelines drawn up by the United Nations Environment Programme (UNEP), and environmental impact assessments have not played a central role in solar desalination set-up and management policies.[274]

The optimal size and location of facilities should be assessed, as well as the potential uses of water, including by households, communities, agriculture and small and medium enterprises.

What next for development sector actors?

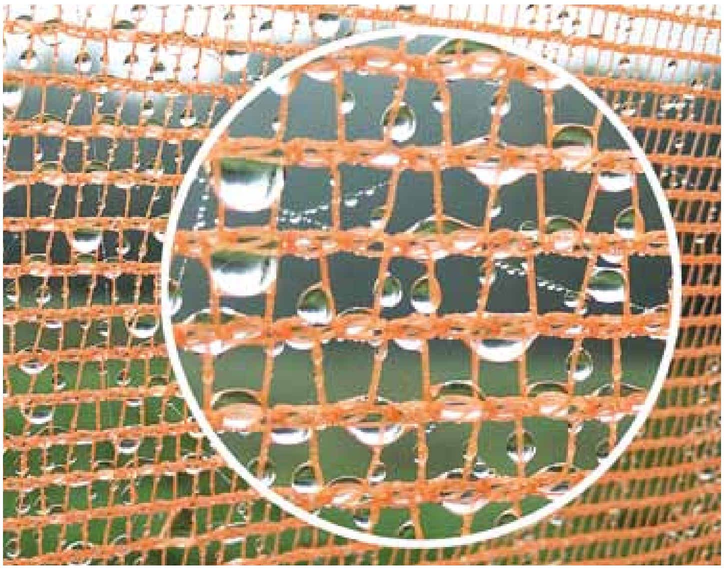
- **Local engagement** – Development actors should seek to build on research already undertaken to assess and evaluate in a comprehensive fashion where solar desalination might fit local and regional needs and opportunities. Such assessments should involve the engagement of communities to determine the interest in and capacity for solar desalination initiatives.[275] The optimal size and location of facilities should be assessed, as well as the potential uses of water, including by households, communities, agriculture and small and medium enterprises.[276]

- **Pilot programmes and cross-organisational engagement** – Efforts should also be made to develop and pilot test programmes, as has already happened with the USAID Desal Prize for acceleration of solar desalination.[277] Such efforts should look at partnerships between international organisations providing initial outlays; NGOs and civil society organisations with good knowledge and understanding of community capacities and needs; private sector organisations bringing technological knowhow and skills; and government bodies providing policy frameworks and, where possible, investment and maintenance guarantees. As well as testing the technology for further applications, efforts need to be made in testing out different kinds of contractual and institutional arrangements, both for the operation of plants and facilities, and for the distribution of water.

- **Regulatory and legal frameworks** – Ultimately, solar desalination programmes need to be considered as part of overall water resource management strategies and a potential alterative to other forms of water generation and access technologies. Better regulation and legislation is needed for solar desalination to fulfil its potential as a viable alternative approach to dealing with water stress.[278]

- **Donor support** – Donor bodies in particular have a role to play in expanding the understanding of solar desalination and finding ways to subsidise and kickstart new pilot programmes, and assess viability and cost benefits in a rigorous fashion.[279]

Atmospheric water condensers



The mesh materials of fog collectors often mimic properties found in nature (from insects and plants) to maximise the amount of water collected.
Photo credit: Warka Water http://www.warkawater.org/

What is the challenge or opportunity?

Access to safe drinking water remains out of reach for 663 million people. Diarrhoea, often caused by unsafe drinking water, is the leading cause of malnutrition and second leading cause death of children under five years of age globally.[280] Furthermore, climate change threatens to increase water insecurity and many have predicted inter- and intra-state conflict as nations find it increasingly difficult to acquire the scarce resources needed to grow food for human consumption.

Atmospheric water condensers as a frontier technology

Atmospheric water collectors are most effective as a source of drinking water in places where drinking water sources are sparse, ground water is unsustainable or expensive, and there is an abundance of fog, dew or rain. Because of the aforementioned criteria, these systems have been mainly deployed in arid/semi-arid and tropical/subtropical climates, often in mountainous regions near coasts.[281]

A review of fog collection initiatives around the world showed that in almost all cases the water produced from the technology meets World Health Organization (WHO) standards for safe drinking water.[282] It has been put to a variety of uses including reforestation efforts, fighting and preventing forest fires, combating desertification, supporting agricultural activities, gardening, and providing safe drinking water to church visitors, schools, and entire communities,[283] as well as for business and recreational purposes such as making beer.

Definition

Fog collectors use atmospheric water condensing processes to extract water from the atmosphere – whether in the form of dew, fog or rain – and collect it for human use.[284]

Many of these technologies draw on the emerging field of 'biomimicry' or 'bio-inspiration', which seeks to develop innovations based on observations of naturally occurring processes such as how desert beetles' carapaces or rain forest systems collect and use water.[285]

Naturally occurring wind currents push fog through a meshed material, on which it condenses and drips down into storage tanks.[286] Because the process of evaporation by the sun naturally desalinates fog water, fog collectors typically provide a fresh source of water for irrigation and consumption. The most famous example of fog collection systems is in northern Chile, where the Chungungo community was able to produce considerable volumes of water for use by villagers. The initiative led to the creation of international NGO FogQuest, which works to disseminate the technology worldwide.[287]

Fog collectors are not the only technologies capable of capturing safe drinking water from the air. Other examples include passive and active dew collectors, which work by providing some form of engineered funnel or surface to collect moisture from the atmosphere. The difference between active and passive dew collectors is that active dew collectors require additional energy inputs – such as fossil fuels or solar energy – whereas passive dew collectors do not. Dew collectors have not been included in this report but could be a potentially exciting area for further research.

Fog collectors have provided Chilean villages in the Atacama Desert with safe drinking water since 1992. Photo credit: Nicole Saffie,

Potential value generation and development benefits

Because water collection may be possible all year round in some regions, it can potentially free up time for household members – often women – who are in charge of getting water for other productive activities, especially if the fog collector is nearer and easier to access than previously used sources.[288] Studies suggest that poor communities are the usual beneficiaries of fog collection because it allows homes in areas that are not currently linked to water sources to gain access to clean water.

Atmospheric water condensers have been around since the 1960s.[289] In 1987, a fog water collection project was implemented in a north Chilean fishing village consisting of 100 fog collectors serving 300 people in one village. The fog collectors yielded a daily average of 331 litres of clean water per person.[290] Apart from providing drinking water, the water generated from this project also allowed the village to undertake small agricultural projects, thus diversifying people's diets, attracted tourism, and led to reverse migration. Its success led to many more projects being implemented across the world.

One particular mesh material – the Raschel mesh, made in Chile – has been used in fog collectors in 35 countries on five continents. Other meshes are also available that are specifically geared towards contexts with extreme or no winds.[291] Newer bio-inspired materials have also begun to show promising results. The ability of certain insects, animals and plants to survive in very dry conditions thanks to microstructures and textures on their skins and surfaces that allow them to collect water from the air has long been noted.[292, 293] In an effort to replicate this capability, scientists have turned to biomimicry, using designs based on techniques found in nature. Park et al. (2016) found that a combination of elements inspired by the surfaces of Namib desert beetles, cacti, and Nepenthes pitcher plants produced mesh materials that are up to six times more efficient than current materials. With this novel bio-inspired surface, 'droplets rapidly grow and start to shed much earlier than on other state of the art surfaces'.[294]

The amount of water that a fog collector can collect depends on many factors including its size, how high it is off the ground, the mesh material used, the thickness of the fog, the speed of the wind, and seasonality, among other things. Tojuia village in Guatemala is located 3,300m above sea level and harvests approximately 6,300 litres of water per day using 35 fog collectors during the dry season, which lasts up to six months.[295] Outside the dry season, fog collectors' yields can be even higher due to their ability to capture rain. Typical water production rates from fog collectors range from 150 to 750 litres per day, but some schemes produce between 2,000 and 5,000 litres per day.[296]

According to the International Development Research Centre, in addition to Chile, Peru, and Ecuador, the areas with the most potential to benefit from fog collectors include Angola, Cape Verde, China, Kenya, Oman, Mexico, Namibia, Sri Lanka and eastern Yemen.

Apart from fog collectors in the form of meshes and nets, and dew collectors in the form of cones or other concave surfaces, a number of other structures have also been tested to collect fog and dew.[297] One of the most widely publicised has been the prototype Warka Water Tower, which is being piloted in northern Ethiopia (see figure 12). Rather than just relying on one source, the tower collects water from dew, fog and rain. It also collects water from all angles rather than having to face an optimal direction, as with conventional fog collectors. Many of the tower's components are sourced from the surrounding areas, including bamboo and Warka tree leaves. It is estimated to have taken ten community members ten days to build the component parts of the tower using simple tools and two hours to assemble them. The cost of a single tower is estimated to be about $1,000; and one tower is projected to collect 50–100 litres of water on an average day.[298]

Enablers and barriers

Enablers

Fog and dew collectors have mainly been tested in arid/semi-arid tropical/subtropical mountainous regions – usually 500+ metres above sea level – near coastlines, with positive results.[299] They are a feasible technology for many developing countries. In fact, fog collectors have been almost exclusively deployed and tested in developing countries that lack 'the means to extend a conventional water supply system to all parts of the country… located in arid and semi-arid regions of the world where there is a shortage of potable water'.[300]

Previous studies have shown that community involvement and ownership often make or break atmospheric water collection projects. It is important that the community is made aware of the project and involved in the installation process, and that the project is socially accepted to ensure its sustainability. It is especially important to involve women, because they are typically the 'primary users and direct beneficiaries of collected water'.[301]

Furthermore, although most upfront funding come from outside actors, the operation of collectors is ideally funded from within the community. Community members should be selected at the outset of the project to serve as technicians, who should be compensated by the community in exchange for water consumption. How and by whom this is done is likely to vary from context to context, but generally speaking the community must charge its members for water to fund the collectors' operation, minor repairs and maintenance.[302]

The International Development Research Centre (IDRC) review suggests that smaller communities are more likely to take ownership of projects. However, it also argues that because of the heavy workload in putting the project together and maintaining it, at least 80 people should be involved in an implementing village including at least 20–30 adults. Moreover, when villages grow in population size, the amount of water that a limited number of fog collectors can produce may be insufficient. This has led villages in the past to opt for other sources of water.

Figure 12 Warka Water tower

WarkaWater towers collect fog, rain, and dew and convert it into safe drinking water for isolated rural villages in the North East region of Ethiopia. Photo credit: Warka Water, http://www.warkawater.org

Other factors recommend the use of fog collectors:

- They been widely tried and tested in suitable contexts;
- Their simplicity and high potential to deliver water to targeted communities;
- When there is fog, it tends to be abundant and fog collection projects are only limited by the number of fog collectors installed;
- It is a passive technology that does not require energy inputs to run;
- Fog collectors are durable, typically lasting for ten years if maintained and operated effectively;
- They are easy to maintain and maintenance costs are low;
- The technology is cost effective and usually cheaper than transporting clean water from far away.

Barriers

- High upfront costs – 100 fog collectors cost an estimated $40,000, but this can vary according to context;
- Systems are difficult to install and require expertise to find potential areas for installation, meaning communities must hire expensive external experts at the beginning of the project;
- Finding the best place to mount a fog catcher can be time consuming and expensive. However, innovations in easy-to-use probes capable of identifying these locations is promising. When linked to laptops the probes allow installers to 'measure the moisture content and velocity of the fog in hopes of inferring its prevailing direction';[303]
- Fog collectors are heavy and need to be transported to hard-to-reach high mountainous regions, which is expensive;
- The collectors are also difficult to assemble, creating even more reliance on external experts to install them. This has led to calls for collectors that could be flat-packed and assembled like IKEA furniture, but these do not yet exist;
- Although the water from fog collectors is clean in most cases, it can be prone to emissions and pollution if the collectors are located near power and industrial plants, leading to the need to for expensive evaluations to assess water quality before implementing a project;
- Collectors are susceptible to heavy winds and most models are inefficient at collecting fogs in conditions with little or no wind; and
- Collectors require regular maintenance and supervision, which can lead to their deterioration if communities do not take ownership of the project.[304]

Previous studies have shown that community involvement and ownership often make or break atmospheric water collection projects.

What next for development sector actors?

- **Participate in networks** – An international conference bringing together scientists and practitioners working on fog and dew collection takes place every three years, with the most recent one occurring during the writing of this report in July 2016. [305] Development actors could also benefit from attending to learn from experts with knowledge in implementing fog-collectors around the world and users about what has worked where and why. This could also provide a good networking and partnership-building opportunity.
- **Ensure funding is paired with evidence** – Given the large upfront costs, international aid organisations have mainly financed fog collectors and their installation. Unless the high costs incurred at the beginning of fog collection projects are significantly reduced, they will probably have to continue to be funded this way. However, more research and evidence is needed to highlight the costs and benefits of such investments.
- **Engage communities** – The literature suggests that identifying villages that are suitable and can potentially benefit from fog collectors and towers is only half the battle. Development actors also have to find ways to involve communities in the identification and implementation process to ensure community ownership and sustainability of projects. The real potential of atmospheric water collectors will be achieved when they are used in conjunction with other strategies and approaches to addressing water needs in poor and rural areas.

[241] Uses of water range from direct human consumption in drinking, washing and cleaning, to food production and farming, industrial production and development, a variety of environmental efforts, and a wide range of other applications such as in leisure and relaxation.

[242] www.eea.europa.eu/themes/water/wise-help-centre/glossary-definitions/water-stress

[243] www.wri.org/blog/2015/08/ranking-world%E2%80%99s-most-water-stressed-countries-2040

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[246] Brackish water is salt water and fresh water mixed together. It results from natural mixing of seawater with fresh water, such as in estuaries, or it may occur in brackish aquifers.

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[263] www.irena.org/DocumentDownloads/Publications/IRENAETSAP%20Tech%20Brief%20I12%20Water-Desalination.pdf

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Clean Energy and Air

Technology Reviews

- Household-scale batteries
- Smog-reducing technologies

India, Kanyakumari District, Tamil Nadu
Men rides their bicycle past wind turbines at Muppandal wind farm. Muppandal is one of the largest wind farms in Asia.

Credit: Qilai Shen – Panos

Household-scale batteries

What is the challenge or opportunity?

Globally, 1.3 billion people do not have access to electricity and 2.7 billion are still cooking on harmful and inefficient stoves.[306] Many of these people live in rural communities and urgently need energy services to achieve development progress and improvements in their quality of life. Off-grid solar systems are seen as the key to addressing household and community-level energy needs, especially in sub-Saharan African and South Asian countries. These systems rely heavily on batteries to mediate the intermittent generation of solar energy and match it to use patterns.

Household-scale batteries as a frontier technology

Thanks to growing efforts in developing and implementing decentralised renewable energy systems, it is becoming apparent that small-scale, off-grid solar power systems built around household-scale batteries have great potential to leapfrog the need for large-scale capital investments in energy infrastructure.[307] It is estimated by Pike Research estimates that 'micro-grids' will account for 4.7GW of electricity and US$17.13bn of global revenue by 2017 as they are increasingly used in developed countries also.[308] Bloomberg predicts that by 2020 battery storage will become commonly deployed alongside rooftop solar systems and that over 10 per cent of global generating capacity will be from small-scale photovoltaic (PV) cells/units by 2040, although in some countries this share will be significantly higher.[309] Although the use cases for household batteries on the grid and in off-grid situations differ, market recognition is growing that energy storage is the key issue in allowing greater use of intermittent renewables, and that consumers do not have to wait for the grid to deliver it. Advances in better and cheaper batteries in developed countries – including for electric cars and phones – can also open up new possibilities in off-grid areas of developing countries.

BBOXX Home Solar system comes with a 50W roof-mounted solar panel, a battery (seen in the picture) and can be financed using a pay-as-you-go financing scheme over three years. It has 2 USB slots and can be monitored and controlled remotely via SMS. Photo credit: Solar BBOXX, www.bboxx.co.uk

Definition

Batteries and power packs for household use are a very rapidly evolving technology. The launch in April 2015 of Tesla's Powerwall – an innovative home battery system that recharges using electricity generated from solar panels, or when utility rates are low – at a price that undercuts the current cost of lithium-ion energy storage providers, considerably raised the profile of battery technology.[310]

There are three main types of rechargeable battery technologies:

- **Lead-acid** – Invented in 1859, these are the most commonly used globally, thanks to lower costs, the maturity of the technology and their availability. They are widely used in starting automobiles, lighting, various forms of ignition, battery-powered vehicles and back-up power supplies in the event of disasters. Lead-acid battery lifespans can be shortened if the battery is not fully discharged before recharging. Moreover, the average life of 6–15 years does – under ideal conditions – not match solar panel lifespans. Moreover, high atmospheric temperatures – very common in developing countries – can severely cut the lifespan of lead-acid batteries. The lifespan of a lead-acid battery is generally halved for every 8.3°C above 25°C.[311]
- **Flow** – First used in the 1880s to power airships, flow batteries were revived thanks in part to NASA in the 1970s. Although relatively new, the technology is in principle well-suited to utility-scale storage; for example, to store energy from large-scale renewable plants in California where they are to be used to offset peak demand.[312] Flow batteries have the advantages of ease of scaling, reliability and long life, making them likely candidates for long-term adoption as the technology and its application mature.[313] However, although some specialised manufacturers use them, uptake by generic original equipment manufacturers has been limited, which has kept their cost high on a per kWh basis compared to other types of batteries.[314]
- **Lithium-ion (Li-ion)** – Developed in the 1970s and made commercially available in the 1990s. Although lithium-ion batteries are widely used in home and personal electronics – notably in mobile phones and computers because of the batteries' additional power and small size – they are less widely deployed than lead-acid batteries because the cost structure is prohibitively high for large-scale deployment for home storage. However, at-scale manufacturing is anticipated to bring down costs over the medium term, and there is also the potential to sustainably recycle lithium-ion batteries for reuse.[315] Tesla's Powerwall uses lithium-ion batteries for storage within home solar systems. Battery research by Gamos, funded by DFID (see Box 3), indicated that this field 'remains developmental, with continuing changes in battery chemistry (the actual energy materials in individual cells) and in the design of battery packs (groups of cells assembled and engineered with a view to particular applications)'.[316] The study highlighted other battery technologies that use lithium sulphur (Li/S), 'lithium-air' (actually Li/O_2) and sodium-ion as exciting interest.

Box 3 DFID-funded research on solar electric cooking

To meet the demands of the electrical grid, the batteries that solar systems use must have high charge and discharge rates, as well as the ability to withstand multiple charge cycles. Research by Gamos into the viability of solar-derived electrical power for cooking[317] suggests that in urban areas in most developing countries, operating PV-based cooking systems (electric stoves) would use much less energy and cost less than the basic stoves typically used in developing countries. Gamos suggests that storing energy in batteries would increase the cost of cooking with electric stoves by $0.25 per kWh.

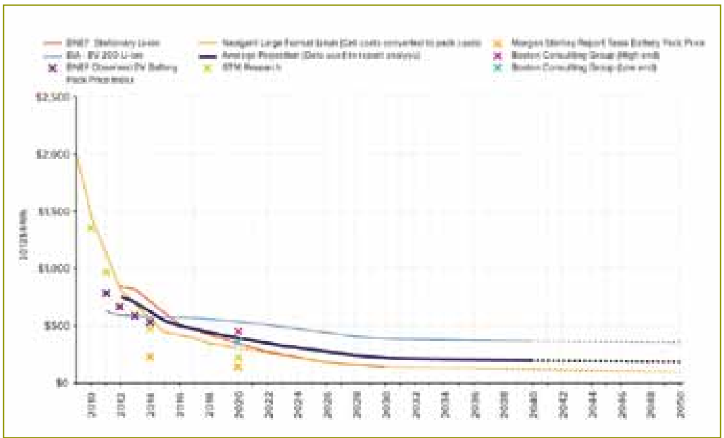
However, households off the grid would also have to purchase a solar panel, stove and battery, which would cost an estimated $500. Gamos research suggests that by 2020 – as prices continue to drop and the technologies advance – a pay-as-you go model for a bundle including a solar panel, battery and installation of the product could cost about $10 per month, making it affordable for poor households.

Potential for acceleration

Many analysts predict a rapid expansion of zero-emission solar power, which is only possible using energy storage to enable continued power delivery at night. Although other electricity storage technologies exist – such as pumped hydro-storage, flywheels, and loads with inherent storage (e.g. ice production) – batteries are a core electricity storage solution, particularly at household scale. Any decreases in the price of batteries will in turn reduce the price per kWh of energy. Some estimates forecast 200GW of battery-backed solar power by 2025, which is a fourfold increase on 2015 figures, and a fortyfold increase on 2005. Between 2010 and 2015 the price of a lithium-ion battery dropped from $1,000/kWh to $300–400/kWh.[318] Tesla's 2015 entry into the household battery market has triggered new entrants and incentivised existing players to revamp their offerings.

Tesla's Gigafactory will produce stationary batteries as well as for electric cars, and this large-scale manufacturing will lower costs and speed up production.[319] Deutsche Bank's energy analytics team describes batteries that are commercially available at an economically competitive price as the 'holy grail of solar penetration'. The expectation is that battery deployment will occur primarily where there is a clear economic rationale. Figure 13 below shows the forecast drop in lithium-ion battery pack prices from 2010 to 2050.

Figure 13 Lithium-ion battery pack prices: historical and forecast



Source: Rocky Mountain Institute (2015)[320]

Potential value generation and impacts

As a frontier technology, batteries have considerable potential in developed and developing countries. For example, in the United States (US) the grid model of central thermal generation and one-way electricity distribution to end-user customers on the edge of the grid's distribution is changing rapidly.[321] The Rocky Mountain Institute suggests that residential and commercial consumers will find it increasingly easier to leave existing utility providers and the electricity grid and, supply themselves with power from solar plus-battery systems,[322] leading to greater levels of energy independence and lower costs.

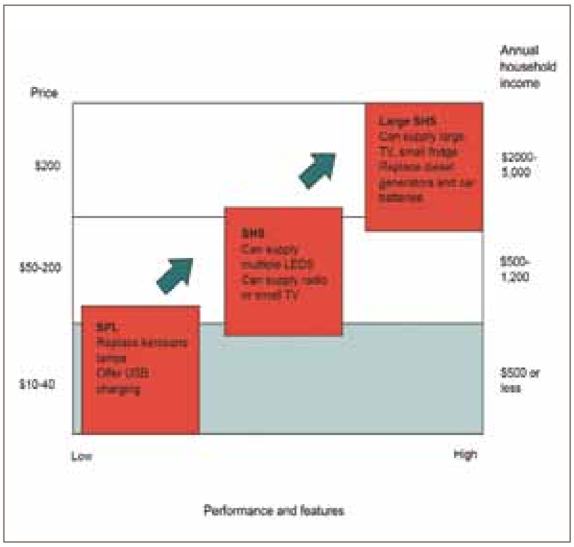
Between 2010 and 2015 the price of a lithium-ion battery dropped from $1,000/kWh to $300–400/kWh.

This potential has led to intensive commercial investments aimed at markets in the US and Western Europe. Overall the value generation potential is extremely large: Deutsche Bank expects the solar industry to increase tenfold over the next 20 years and to generate $5tn in cumulative revenue.[323] This rate of investment and resulting innovation has led to considerable potential for knock-on benefits for users in developing countries, both in terms of the cost and effectiveness of the technology, and also related business and financial models by which these technologies can be brought to market.

In developing countries, a number of systems have emerged built around batteries of different kinds, initially powered by renewable energy and pay-as-you-go models, which initially lease batteries and related equipment, followed by full ownership after making payments over a number of years. In contrast to the benefits of energy independence and cost reduction seen in developed countries, much of the value of battery-enabled household energy systems are at a more basic level of energy access for the first time, at costs lower than electricity from the grid. AT Kearney's solar product energy ladder (see Figure 14 opposite) highlights the different kinds of energy access that solar products offer households according to their income.

One of the most prominent success stories is M-KOPA Solar, an asset-financing company founded in Kenya in 2011 that sells battery-based solar household systems to off-grid households. M-KOPA was created in response to the finding that the average off-grid Kenyan household living

Figure 14 Solar product energy ladder



Source: AT Kearney (2012)

on $2 per day spent up to $200 on kerosene and other energy sources each year. Customers buy the system on a pay-as-you-go basis, using the M-Pesa mobile payment system, with an initial deposit followed by daily payments for up to one year, after which they own the system outright. The systems comprise either 4W or 5W panels with options for LED lights, mobile phone chargers, a radio and – as of 2016 – televisions. Because the daily payment was fixed at lower than the daily cost of kerosene, switching decisions were made as easy as possible, and the use of M-Pesa, widely employed in Kenya, made the payment process familiar and simple.[324] M-KOPA Solar has now expanded across a number of East African countries and more companies have entered the market, with differing system and payment configurations.

In India, Simpa Networks' 'Progressive Purchase' model offers a similar solution, promising an affordable initial purchase price and ownership cost, and in flexibility of ongoing expenditure.[325] Its system costs between 180 and 950 rupees ($2.70 and $14.25) a month. The company has grown to employ 300 full-time staff and around 500 technicians and 'solar entrepreneurs'.[326]

Customers buy the system on a pay-as-you-go basis, using the M-Pesa mobile payment system, with an initial deposit followed by daily payments for up to one year, after which they own the system outright.

Potential benefits for development

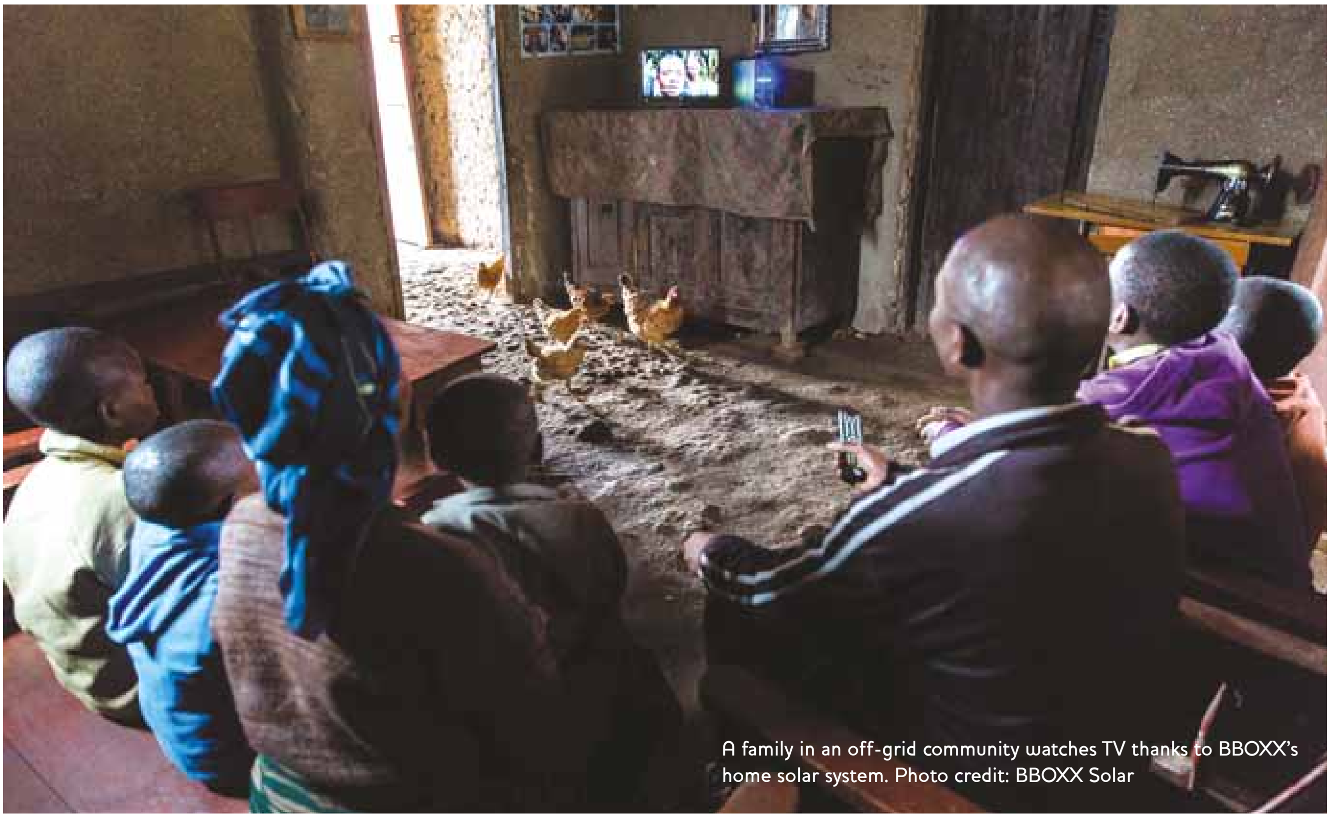
There is a strong correlation between access to energy and a wide range of social goods: indicators such as the percentage of people below the poverty line and childhood mortality decline as access to energy increases.[327] The *Africa Progress Report* found that energy sector bottlenecks and power shortages cost sub-Saharan Africa 2–4 per cent of gross domestic product (GDP) annually, undermining sustainable economic growth, jobs and investment. Halving costs of inefficient lighting sources would save $50bn for the poorest communities at the 'bottom of the pyramid' that live on less than $2.50 per day.[328]

As noted above, batteries play a vital role in driving accessible, affordable, renewable energy systems because they can leapfrog the need to roll out electrical grid infrastructure to remote areas. These systems can have positive knock-on effects on other development outcomes such as sustainable livelihoods, sanitation and education. For example, the Eco Green Livelihoods project in Rural India provides livelihoods for rural women;[329] they manufacture small-scale solar lighting systems from lead-acid batteries and solar panels with a minimal amount of training.[330] Having household lighting means that children can study in the evening and outside lighting makes sanitation safer. The motorcycle batteries used in this system currently cost in the region of $10 per unit. A reduction in battery cost of just 10 per cent would have an enormous impact on the margin of profit for this project, which would generate additional income for the participating women.

Research across a number of developing countries indicates that 'there is increasing evidence that solar household systems are contributing towards several development goals, including income poverty reduction, better education and improved health'.[331] Batteries could also be significant in developing countries in the deployment of localised energy generation to reduce power fluctuations and stabilise telecommunications systems such as mobile phone networks.[332]

Enablers and barriers

The World Economic Forum (WEF) has identified several key factors that have enabled technological and volume improvements in electric car batteries, which apply to equally batteries in general. These include regulations, subsidies and incentives for success factors.



A family in an off-grid community watches TV thanks to BBOXX's home solar system. Photo credit: BBOXX Solar

Stable policy frameworks are a major factor that affects the success of transformations in the energy landscape. For example, it has been shown that carbon dioxide (CO_2) emission targets in the European Union could mobilise and incentivise the emerging electrified vehicle industry.

Policy structures also need to reduce the risks for the private sector and promote investment in future solutions. The United Kingdom-led Energy Africa Initiative for example is working to ensure that regulatory environments support off-grid options through Energy Africa.[333] 'Compacts' with partner governments, which also seek to better co-ordinate donor support to the sector. The key argument is that market growth hinges on the public sector providing transparent regulatory and policies that provide clear, predictable rules for project development, investment and operation.[334] A good example of a policy structure that reduces risks for the private sector while promoting investment in future solutions is Rwanda's rural electrification strategy, which aims to provide all of the population with electricity by 2020, up from 24 per cent in 2016, and has a built-in mechanism to establish 'a risk mitigation facility that will support the private sector'.[335]

In terms of market interventions, the availability of consumer finance at a large scale is a potential game changer in the off-grid solar market, as this will broaden the user base.[336] Working capital to finance inventory and distributors, corporate new entrants in the markets and increased consumer awareness are also fundamental. The *2016 Off-Grid Solar Market Trends Report*, produced by Bloomberg New Energy Finance and World Bank's Lighting Global[337] suggests that these variables are more likely to have a higher impact than battery costs, which are relatively low compared to distribution and finance costs and barriers. This does not mean that it would be wise to veer away from efforts to reduce the costs of batteries altogether. A combination of the variables mentioned by the *Off-Grid Solar Market Trends Report 2016* and a reduction in maintenance and upfront costs – using better and cheaper batteries – would lower costs further.

As has been noted time and again, at the global level, political will is a key inhibitor when it comes to transforming energy systems. Without appropriate financial and regulatory incentives, it will not be possible to develop cost-effective household-scale energy storage solutions and build a dependable business case for them. In general, markets cannot by themselves provide the necessary incentives for companies to invest in the development of new technologies in the short term.[338] Many energy ministries in developing countries may still be unaware of the potential benefits and impacts of energy storage, both on and off the grid. A high-level learning programme on energy storage may be needed to bring energy ministries up to date and on board with the potential of household-scale solar batteries.[339]

The potential costs of universal energy access are significant. The International Energy Agency has forecast a tab upwards of $756bn to achieve universal energy access by 2030 using a mix of grid, micro-grid and off-grid sources.[340]

Risks

Economic

The WEF warned in 2013 that grid-wide energy storage solutions face several crucial problems, including their early stage of development, economic feasibility and the rapidly evolving nature of the market.[341] These challenges have underpinned a number of failures among battery makers,[342] one of the most high-profile cases being US company Xtreme Power, which filed for bankruptcy in 2014.[343] The story has been described as a common tale for clean power startups: the company grew too fast, had a business model based on another company's technology, and could not sustain itself.

Market growth hinges on the public sector providing transparent regulatory and policies that provide clear, predictable rules for project development, investment and operation.

There is also a risk of hyperbole from companies looking to maximise their value in a competitive market. Tom Milnes, energy storage expert and CEO of Open Water Power, suggests that Tesla is overpromising on the potential of its system: 'Lithium-ion batteries just won't store the amount of energy required to be as useful as [Tesla CEO Elon] Musk promises'.[344]

Environmental

The rapid growth of lithium-ion batteries has resulted in increased demand for lithium and cobalt (which is used in the cathode). This means that effective recycling of batteries will be required, not only to ease pressure on demand for these resources, but also to limit the polluting effects of their disposal.[345] The US Environmental Protection Agency has suggested ways to improve the environmental profile of lithium-ion batteries, including reducing cobalt and nickel material, incorporating recovered material in battery production and focusing future design changes on increasing battery lifetime.[346] Global lithium-ion battery recycling capacity is currently only 30 per cent of global production. Investments will also be needed in battery recycling facilities across the developing and developed world. For example, there are no recycling facilities for lithium-based batteries in Africa.[347]

What next for development sector actors?

- **Improved analysis of global opportunities and local needs** – There is considerable value in assessing the overall market potential for household-scale batteries in developing countries, including assessments of country-specific opportunities. Collecting and sharing typical use and performance data would be a good starting point. This would help battery manufacturers test and design their batteries against context-specific charge and discharge profiles.[348] This would be complemented by a better understanding of the nature and scope of local needs for off-grid populations, ongoing lifecycle-based comparison of different energy storage options; and a better watching brief on new future battery technology developments.[349] Together, these information investments would comprise important public goods that donors could underwrite, to benefit the overall effort to increase energy access using improved household-scale batteries.
- **Work with international and national financial expertise to develop appropriate business models** – Efforts in a number of countries have seen accelerating adoption of solar energy by working with local banks to provide financing and servicing arrangements for solar panels that are appropriate for the rural poor. As described above, a promising sector-wide approach has been applied in Rwanda. This kind of approach could be usefully rolled out more widely.

In terms of market interventions, the availability of consumer finance at a large scale is a potential game changer in the off-grid solar market, as this will broaden the user base.

Effective recycling of batteries will be required, not only to ease pressure on demand for these resources, but also to limit the polluting effects of their disposal.

- **Incentivising investment in technological advances that benefit the poor** – Establishing structured global and national challenge funds that focus on meeting the needs of the poor off-grid population is of primary importance. It could involve working with new research and development initiatives such as the Breakthrough Energy Coalition, convened by the Bill & Melinda Gates Foundation, which seeks to:

> Accelerate the change to the advanced energy future our planet needs. Success requires a partnership of increased government research, with a transparent and workable structure to objectively evaluate those projects, and committed private sector investors willing to support the innovative ideas that come out of the public research pipeline.[350]

There is also a need for such accelerators to work at national level in different settings to incentivise national innovators.

- **Support to networks and coalitions** – A good example is Power For All, a new coalition of off-grid renewable energy providers and advocacy groups, which argues that 'business-as-usual energy delivery will not achieve global goals to end energy poverty by (or before) 2030'.[351] The coalition goes as far as to suggest that current trajectories and approaches will lead to more people being energy poor in 2030 than are today. Power For All is focusing its efforts on pushing for renewable, distributed, democratised power. As well as making the case, such networks play a central role in driving innovation. The WEF has called for more and better collaborative innovation to successfully transform the energy landscape, and meet future challenges of sustainability and the surging demand to develop the best solutions fast, and link idea creation and evaluation.[352] This type of innovation requires two or more players – for example, industry, government, academia, research institutes, customers, regulators and/or non-profit organisations – to be partners in developing new products, processes, services or even business models.

Current trajectories and approaches will lead to more people being energy poor in 2030 than are today.

Smog-reducing technologies

The Italian Pavilion in Milan has a facade that improves air quality by 'eating' smog when exposed to sunlight.
Photo credit: Aumod on Pixabay, https://pixabay.com/en/milan-exhibition-architecture-1272520

What is the challenge or opportunity?

Rapid urbanisation and motorisation have led to the deterioration of air quality in many big cities around the world. Research suggests that outdoor and indoor pollution is responsible for 5.5m deaths annually across the globe, with half of those deaths occurring in just two countries: India and China. This global total accounts for more deaths annually than HIV/AIDS and malaria combined. Air pollution is also a cause of multiple illnesses that lead to premature death, including heart disease and stroke (80%), chronic constructive pulmonary disease and acute lower respiratory infections (14%), and lung cancer (6%).

Moreover, there are direct links between air pollution and cancer – not just lung cancer but also urinary tract/bladder. The World Health Organization (WHO) estimates that in 2012 there were 3.7m premature deaths due to outdoor air pollution, 88 per cent of which (around 3.26m) occurred in low- and middle-income countries. In northern China alone, smog contributed to a reduction in life expectancy of 5.5 years for 500 million people, leading to a total loss of 2.5bn years of aggregate human life expectancy.[353]

The World Health Organization (WHO) estimates that in 2012 there were 3.7m premature deaths due to outdoor air pollution, 88 per cent of which (around 3.26m) occurred in low- and middle-income countries.

Developing countries with trends of economic growth, urbanisation, motorisation and lax environmental laws are particularly susceptible to air pollution and the respiratory illnesses it causes. Furthermore, the problem is likely to get worse in coming years: to take just one example, it is estimated that there will be at least 2bn cars on the road by 2030 worldwide, double the number from 2010.[354]

Definition

'Smog' refers to visible air pollution resulting from a mixture of high concentrations of moisture (fog) and smoke that stagnate over a specific area, creating respiratory health hazards.[355] The smog-reducing technologies covered in this Technology Review come in a number of different forms, but all share a common focus on treating air pollution after it has been created or cleaning air after it has been polluted rather than finding alternative non-polluting technologies, or promoting non-polluting actions or behaviours. The three technologies covered in this report are catalytic converters, photocatalytic oxidation materials, and smog-reducing towers, all of which are at different stages of maturity and perform different functions in relation to reducing smog.

Catalytic converters as a frontier technology

A catalytic converter is a component in a vehicle's exhaust system that eliminates harmful emissions.[356] Catalytic converters were first introduced in the 1940s to combat air pollution in major cities in the US. They typically contain precious metals (e.g. platinum and chromuim), which makes them expensive to manufacture.

These metals make up between 60 and 70 per cent of the composition of catalytic converters, and coat a ceramic structure that is placed between the engine and the vehicle tail pipe. Catalytic converters are typically positioned so as to maximise the precious metal surface area that is exposed to the exhaust stream, while minimising the amount of precious metal that is actually used, to keep down costs.

As gases from the engine pass over the converter, they break apart a proportion of the pollutant gases and convert them into water vapour and gases that are less harmful in the atmosphere.[357] Over the past few decades, catalytic converters have been widely installed in new vehicles, especially in countries where environmental regulations require all fossil fuel-based vehicles to have them. However, they are frontier in two senses: first, advanced new catalytic converters are entering the marketplace that promise to significantly improve emissions-reducing performance; and second, standard catalytic converters are still not used in many vehicles destined for developing countries.

Photocatalytic oxidation or 'catalytic paints' as a frontier technology

Photocatalytic oxidation is a process by which specific nanoparticles – usually titanium dioxide (TiO_2) and calcium carbonate particles that are 30 nanometres wide – are mixed into building or decorative materials. The base of the materials, which is usually some form of silicon-based polymer, is porous enough to let noxious gases through, which bond to and react with the nanoparticles, converting them into less harmful forms. One common example is the use of catalytic paints, in which the (TiO_2) absorbs sunlight and nitrogen oxide (NOx), and uses the energy from ultraviolet (UV) radiation in light to convert the gases into significantly less harmful nitrates such as nitric acid. The alkaline calcium carbonate particles neutralise the acid, and rain washes away the residues.[358]

Photocatalytic oxidation technologies could work in tandem with catalytic converters to clean the NOx that catalytic converters have not converted into less harmful gas themselves, or that are emitted by dirty cars in countries and regions where catalytic converters are not mandatory. There are also numerous examples of buildings whose exteriors are coated with catalytic paints, along with novel designs and materials to maximise the surface area that is exposed to the air, and therefore the amount of gases that can be absorbed and cleaned. Examples of such buildings include the Italian Pavilion in Milan and the Torre de Especialidades hospital in Mexico City.[359]

Smog-reducing towers as a frontier technology

Smog-reducing towers suck in dirty air – much like a vacuum cleaner – and turn them into 'bubbles' of smog-free air. They work by using ionisation processes. Smog particles that are smaller than 10 micrometres in diameter are easily inhaled and cause damage to the heart and lungs. The towers incorporate a ventilation system at the top, powered by wind energy, which draws in smog and uses electrically charged surfaces to give a positive electric charge to any particles smaller than 15 micrometres. These particles are then attracted to an electrode in the chamber and trapped in the tower; clear air is expelled through vents in the lower half of the

Roosegarde's Smog-Free tower creates bubbles of clean air. In heavily polluted cities, this juxtaposition could potentially raise awareness and/or be a catalyst for collective action. Photo credit: www.studioroosegaarde.net

tower, creating a bubble of clean air around the structure. It is claimed that smog-reducing towers only use as much electricity as a kettle, and so the technology is environmentally sustainable in its own right.

Smog-reducing towers have been successfully piloted in Rotterdam, in the Netherlands, and have gone on tour to China, with plans to install them in Mexico City, Paris and Los Angeles. Artist and designer Dan Roosegaarde launched a Kickstarter campaign in 2015 to take his 7m-tall Smog Free Tower on a world tour as part of his Smog Free Project; the campaign received more than double its goal of €50,000.[360, 361]

Potential for acceleration

Catalytic converters, photocatalytic oxidation-enabled materials, and smog-reducing towers differ from one another in the kinds of smog-reducing processes they use, and their forms. They are also at very different stages from one another in terms of development, acceleration and diffusion, which affects the opportunities they present for value generation in and outside of international development. This section briefly summarises the potential for acceleration for these technologies as a whole, and then looks at their individual potential.

In general, such technologies usually accelerate not because of commercial ambitions, with the exception of environmentally friendly vehicle designs, but because of emissions regulations, which vary considerably across jurisdictions. Catalytic converters have been fitted to most cars used in Europe, North America and Japan since the 1970s and 1980s, thanks to high levels of legislation. Although some governments (e.g. China and India) are beginning to make emissions regulations a priority, in most of Asia and Africa these regulations are still weak or non-existent.

It is claimed that smog-reducing towers only use as much electricity as a kettle, and so the technology is environmentally sustainable in its own right.

Catalytic converters

The design of catalytic converters has not changed fundamentally since they were first introduced in the 1940s,[362] and their widespread use in developed countries today is thanks to effective legislation of car manufacturing and clean fuel. Although the uptake of greener cars is increasing – including of hybrid vehicles that run on electricity and fuel, and fully electric vehicles – most of the cars on the road in 2030 are still expected to use an internal combustion engine, particularly in poorer and power-constrained countries. Moreover, because hybrid vehicles still need to burn fuel, they will continue to need catalytic converters to reduce emissions. As a result, demand for new and improved catalytic converters is likely to continue.

In recent years, innovations have enhanced the efficiency and effectiveness of converters. For example, a prototype by scientists at Imperial College London uses 80 per cent less rare earth materials while improving its performance by increasing the surface area of the converter using microscopic channels on its ceramic surface. This has the potential to decrease the costs of producing catalytic converters significantly, and enhance emissionsreducing efficiency. The new design also makes the exhaust more efficient and decreases the use of fuel by reducing back pressure, which is a build up of exhaust gases that makes engines work harder and reduces performance levels.[363] It is important to note, however, that despite the proliferation of legislation requiring automobile manufacturers to equip cars with parts that burn fossil fuels more efficiently, and innovations that enhance the efficiency of such parts, it is still possible for automobile manufacturers to find ways to circumvent these requirements, as seen in the 2015 Volkswagen scandal over cheating emissions standards.[364]

Materials that use photocatalytic oxidation have been successfully incorporated into buildings and construction – in asphalt, pavement, walls, buildings – and are seen as 'a promising technology for mitigation of urban air pollution'.

Photocatalytic oxidation-enabled materials

As already noted, materials that use photocatalytic oxidation have been successfully incorporated into buildings and construction – in asphalt, pavement, walls, buildings – and are seen as 'a promising technology for mitigation of urban air pollution', based on a number of small-scale pilots.[365]

In an experiment carried out in Hangelo, in the Netherlands, roads coated with anatase TiO_2 reduced harmful NOx concentrations by 19 per cent over the course of a whole day and 28 per cent during afternoons , on average, and showed the potential to decrease NOx by up to 55 per cent under favourable weather conditions.[366] Moreover, a company that applies TiO_2 to roofing tiles claims that its tiles turn NOx into calcium nitrate, which then washes off roofs and can be used as a garden fertiliser.[367]

As mentioned above, TiO_2-coated tiles have been used on buildings in Mexico City and Milan, and around the world to clean the surrounding air.[368] Italian firm ItalCementi has has been applying its TXActive[369] cement mixed with TiO_2 in Segrate, a town near Milan, and claims that when applied on the road surface of a busy street it can reduced nitric oxides in the area by as much as 60 per cent. As a result of this and other applications, TXActive smog-eating cement was named one of the best 50 inventions of 2008 *by TIME Magazine*.[370] These experiments continue to slowly grow and some are happening in developing countries, including India, China and the Philippines.

Smog-reducing towers

Roosegaarde's Smog-free towers can clean up to 30.000m3 of air per hour while collecting over 75% of PM2.5 and PM10 airborne smog particle and releases air around the tower with a 360-degree coverage creating an almost circular zone of clean air in its surrounding'

It has been tested mostly in parks and other public settings, but does not appear to be at the stage of production where it might directly solve the smog problem at scale. However, it can serve to raise awareness of how bad the pollution situation is through, for example, installations in public parks that allow people to experience the difference between a localised bubble of clean air and the rest of the city, and serve to open up the possibilities for novel technological solutions that might follow. Smog-reducing towers also have a built-in 'circular' financing mechanism. Once dirty air is sucked into the tower, it is collected, compressed into solid form and used to create

Cleaning up the air, potentially via these and other similar technologies, could 'reduce the burden of disease from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma' and help combat climate change.

high-end jewellery items, the sale of which will finance the building and deployment of more smog-reducing towers. Every ring represents 1,000 cubic metres of clean air.[371]

Potential value generation and impacts

Cleaning up the air, potentially via these and other similar technologies, could 'reduce the burden of disease from stroke, heart disease, lung cancer, and chronic and acute respiratory diseases, including asthma, and help combat climate change.[372]

Potential benefits for development

Due to rapid urbanisation, increasing numbers of people are likely to be exposed to dirty air in cities if no action is taken to reduce air pollutants. In 1950 only 30 per cent of the world's population (746 million people) resided in urban areas; in 2014 the percentage of people living in urban areas was 54 per cent (3.9 billion), and the United Nations (UN) Department of Economic and Social Affairs projects that the number of people living in urban areas will increase to roughly two-thirds (66%) of the world's population by 2050, with 90 per cent of the growth expected to occur in Africa and Asia.[373] The UN projects that 'sustainable development challenges will be increasingly concentrated in cities, particularly in the lower-and-middle-income countries.'[374]

The presence or absence of air pollution can make a significant difference to quality of life. Studies show that children growing up in areas with cleaner air tend to have bigger and stronger lungs during childhood, and enjoy health benefits that remain until much later in life.[375] Moreover, given that air pollution leads to deteriorating health and that a healthy population has long been recognised as a factor that stimulates economic growth, countries and cities, in particular, potentially have a great deal to gain from cleaning up their air.[376]

Research on Beijing, Shanghai, Guangzhou and Xi'an highlighted that PM2.5 air pollution, which is caused by particles smaller than 2.5 micrometres, exceeds WHO air quality guidelines in all four cities.[377] The same research found that had the four cities effectively controlled PM2.5 levels and met the WHO guidelines in 2012, 'the number of premature deaths would have decreased by at least 81%, while the economic benefits of reducing these premature deaths in the four cities would amount to $875m'. There are obviously wider human, social, cultural and lifestyle benefits from clean air, many of which can be harder to quantify.[378]

Enablers and barriers

Advances in solar energy, batteries, and electric vehicles may help to progress clean transportation, which will drive further improvements in the underlying technologies. Five years ago it was hard to imagine a car that ran completely on electricity, let alone one that is commercially viable and affordable.

Moreover, electric vehicles must be charged, and unless the energy used to generate the electricity to charge them is cleaner than the fossil fuels that conventional cars run on, a shift towards electric cars will not lead to cleaner air. Thus, further investments that increase the concentration of renewable and clean energy in the energy mix may be required to ensure the sustainability gains from electric vehicles.

The number of cars on the road is expected to double by 2030. Developing countries are expected to continue implementing green policies that including requirements for all new cars to have catalytic converters. At first glance it may seem that countries with rich reserves of the precious metals that are used to manufacturingcatalytic converters are well positioned to benefit from an increase in demand. This has been the case in South Africa, which contains over 70 per cent of the world's chromium and 80 per cent of its platinum metal group reserves, both of which are widely used in converters.[379]

However, expiration of favourable policies for automobile component exports, along with high logistical costs and long distances to automobile markets have led the industry increasingly to operate well below its capacity, and catalytic manufactures leaving South Africa have fallen in recent years despite previous annual compound growth of 14 per cent from 1995 to 2011. Having precious metal reserves does not in itself guarantee that a country will be an attractive sourcing destination for catalytic converters. Moreover, the advent of new designs that require a fraction of the amount of precious metals to manufacture make production near precious metal reserves even less attractive, they make up a smaller portion of the production cost.

As noted earlier, these technologies simply reduce emissions rather than eliminating the generation of pollutants altogether. In general, such technologies mainly treat the effects of air pollution rather than tackling air pollution at its source. A longer-term solution to reducing smog may require finding ways that avoid creating it in the first place by switching to renewable energy sources. The degradation of air quality and the environment is the epitome of the tragedy of the commons, where individuals – and corporations – act out of self-interest and pollute the air rather than taking care of it, despite the overall societal gains from good air quality being maintained.[380]

If all cars are manufactured to burn fuel more cleanly, but the number of cars on the road increases substantially, the reduction in air pollution from switching to cleaner cars is likely to be at least partially offset. Moreover, given that unwanted cars from rich countries often end up in poorer ones as second-hand cars, and that older cars are less likely to be equipped with catalytic converters, developing countries may not benefit from requirements for manufacturers to make new cars with catalytic converters.

Smog-reducing technologies mainly treat the effects of air pollution rather than tackling air pollution at its source.

The sale of second-hand vehicles from developed to developing countries is very profitable, with some vehicles selling for about three times their resale value in countries with less stringent environmental regulations. The number of second-hand vehicles exported from developed to developing countries grew by 284 per cent between 1997 and 2007.

Many of the cars exported are no longer allowed on the road in developed countries that have adopted tighter environmental regulations on fuel efficiency and safety.[381] In Mexico for example, second-hand vehicle imports from the US tripled from 1996 to 2006, and 68 per cent of the second-hand vehicles sold were SUVs (sport utility vehicles), vans and light trucks. In contrast, 65 per cent of new vehicles purchased were compact cars, which were much lighter emitters.

Thus, if all countries do not adopt tighter vehicle emission regulations, dirty cars are likely to find a home somewhere. To overcome these issues, regulations on the sale of second-hand vehicles that require emissions testing will be necessary. This situation becomes even more challenging when new vehicles are fitted with older engines but sold as having new ones.[382]

When it comes to photocatalytic materials, many factors that can hinder their performance including weather conditions (temperature, precipitation, humidity, wind speed and direction, air pressure), UV radiance intensity, dust and time since the last coating. Given that the effectiveness of coatings decreases over time, materials have to be periodically re-coated with photocatalytic materials to ensure that they continuously clean the air.[383] Another factor that may limit the uptake of photocatalytic materials is their cost. Cement equipped with photocatalytic materials has been estimated to cost 50 per cent more than regular cement, and coating tiles with photocatalytic materials is estimated to increase their cost by $600–1,000 for an average 22,000 square feet roof in the US.[384]

None of these three technologies alone is likely to solve urban air quality issues. Although catalytic converters and photocatalytic oxidation-enabled materials convert some harmful gases into less harmful ones, and the technologies tend to be more efficient at converting certain gases than others. Catalytic converters and photocatalytic oxidation-enabled materials working in tandem is likely to lead to a greater reduction in harmful gases in urban areas than either technology on its own. Smog-reducing towers, although not necessarily a scalable technology in their own right, can be part of demonstration projects that raise the awareness necessary for widespread investment in and installation of the other technologies.

Smog-reducing towers, although not necessarily a scalable technology in their own right, can be part of demonstration projects that raise the awareness necessary for widespread investment in and installation of the other technologies.

Technologies such as the smog-reducing tower provide a great opportunity to expose ordinary citizens to processes of green transformation by allowing them to experience the difference of clean air first-hand in parks and other popular locations of interest.

Last but not least, these technologies all focus on cleaning outdoor air pollution. Indoor air pollution is also a serious concern that is overlooked. It is especially prominent for around 3 billion people who use solid fuels – for example, wood, charcoal, coal, dung, crop wastes – to cook and heat their homes. In poorly ventilated homes these fuel sources can produce smoke that exceeds acceptable levels of pollutants many times over. WHO estimates that indoor air pollution was responsible for 4.3m premature deaths in 2012, with most of those deaths occurring in low- and middle-income countries.[385] This report has focused mainly on outdoor air pollution, but (frontier) technologies also aim to tackle indoor pollution.[386]

What next for development sector actors?

- **Exploratory research** – Many of these technologies have mainly been deployed and tested in developed countries. Research is needed to find potential applications and the best areas to implement the technologies in developing countries.
- **Support and engagement** – Development actors should work with initiatives that raise awareness about smog in developing country cities. This needs to go beyond writing reports and policy briefs for policymakers and academics. Technologies such as the smog-reducing tower provide a great opportunity to expose ordinary citizens to processes of green transformation by allowing them to experience the difference of clean air first-hand in parks and other popular locations of interest. This could empower citizens to self-organise and demand change from their governments, rather than having to depend on international pressure to bring about environmental regulation.
- **International advocacy** – A concerted effort is necessary to move forward legislation on critical issues such as vehicular emissions and the use of catalytic converters. This will need to be balanced with national-level efforts to drive and shape new regulatory frameworks.
- **Driving down costs** – Finding a way to bring the price of these technologies to or near parity with conventional materials and products will also be required for them to be more widely adopted. Currently, catalytic converters are an added cost to exhaust systems that is ultimately passed on to the consumer, and photocatalytic oxidation materials cost more than competing construction materials that do not have smog-reducing features.

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