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.

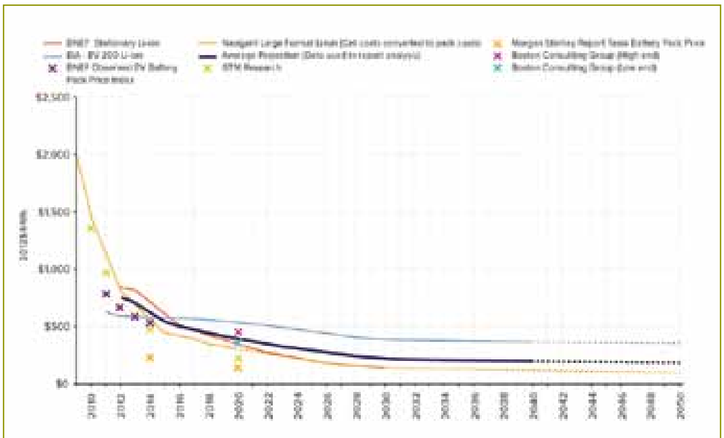
However, households off the grid would also have to purchase a solar panel, stove and battery, which would cost an estimated $500. Gamos research suggests that by 2020 – as prices continue to drop and the technologies advance – a pay-as-you go model for a bundle including a solar panel, battery and installation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

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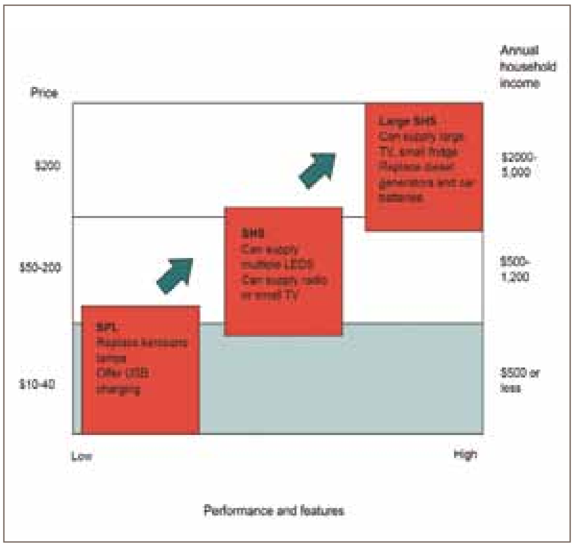
This potential has led to intensive commercial investments aimed at markets in the US and Western Europe. Overall the value generation potential is extremely large: Deutsche Bank expects the solar industry to increase tenfold over the next 20 years and to generate $5tn in cumulative revenue.[323] This 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

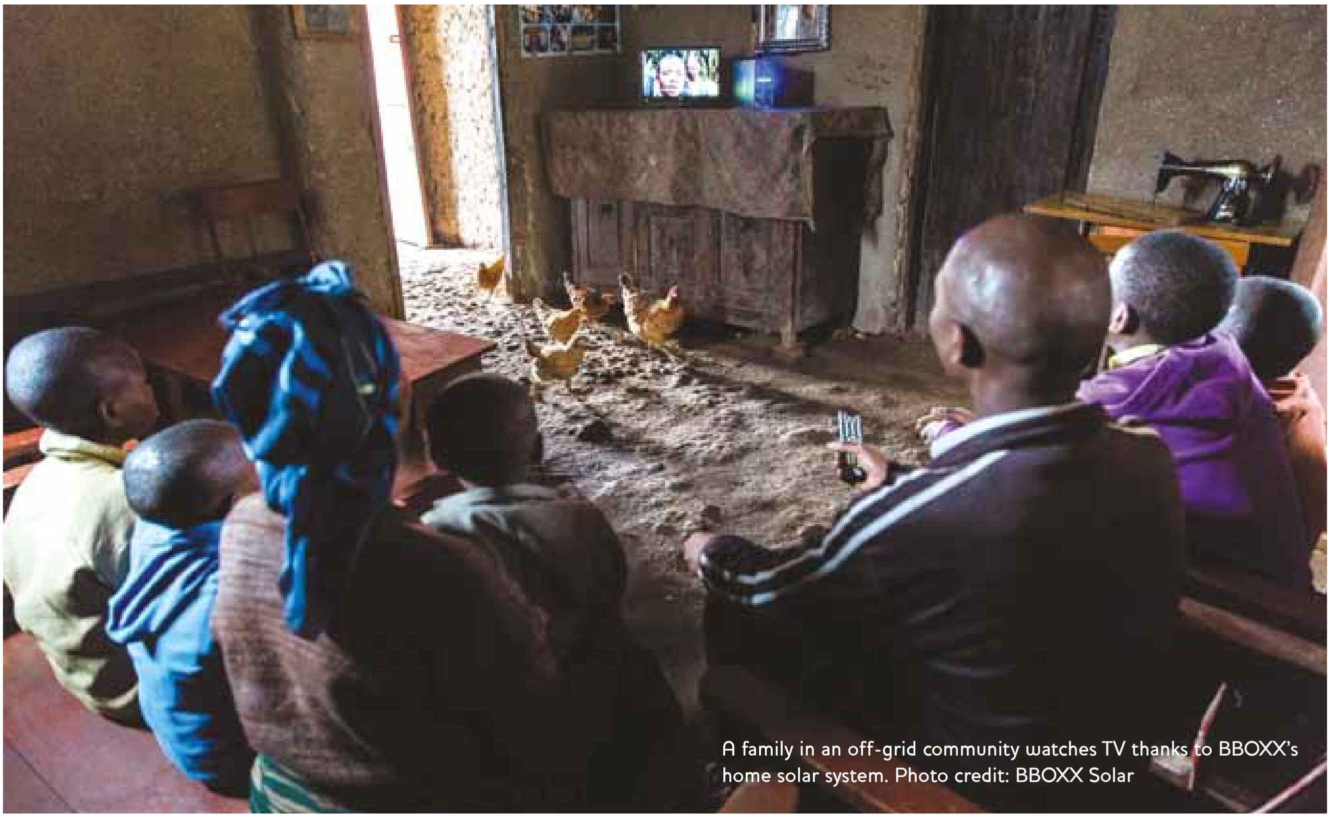
There is a strong correlation between access to energy and a wide range of social goods: indicators such as the percentage of people below the poverty line and childhood mortality decline as access to energy increases.[327] The *Africa Progress Report* found that energy sector bottlenecks and power shortages 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.

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- **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]

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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.

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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.

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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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