Energy and Economic Growth
Applied Research Programme

How disruptive electricity technology could be revolutionary

State of knowledge paper

Jonathan Walters

February 2020

Oxford Policy Management

UK aid from the British people

Abstract

The present paper discusses the possible impact on power sectors in developing countries, particularly those of South Asia and sub-Saharan Africa, of 'disruptive technologies' – that is, technologies which pass tipping points at which they become so cheap they spread very rapidly. Such tipping points are analysed, their relation to energy transitions discussed, and some principal disruptive technologies are described and related to prospective tipping points. The paper then discusses some implications for policies and institutions. Finally, some suggestions for further research are outlined, given how rapidly the situation is evolving. As the paper notes, at this stage of the technology cycle, there are more questions than answers.

Acknowledgements

Drafts of this paper have benefited from valuable comments by Carla Benauges, Chrysostomos Makrakis, Nigel Taylor, Frank Wouters, and anonymous peer reviewers. All responsibility for the final version is, of course, mine alone.

Introduction

The global power sector is changing very rapidly and disruptively, and becoming much more complex and interrelated. There are a lot more options than there used to be, and it is very hard to develop a comprehensive overview. Many people working in the sector, making policy about the sector, or simply observing it, are struggling to keep up – both knowing and understanding what is happening. In reality, everyone is trying to understand where the revolution is leading, while actually being right in the middle of it – or, more accurately, being right in the middle of their own piece of the revolution, but trying to see the whole revolution. And all the while, trying to maintain their professional credibility and to do the right thing. It's a tough position to be in.

This paper about disruptive technology in the power sector endeavours to provide signposts to give some sense of where the revolution might be going. The paper utilises the concept of 'tipping points' to explain what happens when specific technologies, or combinations of technologies, suddenly become cheaper than the previously dominant technologies. It discusses how that relates to energy transitions, outlines various scenarios for those transitions, describes the potential disruptiveness of a number of technologies and how they interrelate to each other, and concludes with a discussion of some of the institutional and political economy dimensions of disruption.

Context – the pace of change accelerates

For a very long time, technology in the electricity sector changed only gradually. As a result, policymakers, consumers, investors, and workers in the sector generally expected only gradual change in the future. One could say they became pretty conservative, and were quite ready to make decisions whose consequences would be with them for a very long time. And when they had made those decisions, they didn't generally expect any major threat to their strategies or interests as a consequence.

Then things started to change very fast, very unpredictably, and very disruptively. People often say this was because of rapid technological change, but it might be more accurate to say it was because the economics of some technologies were changing much faster, and more unpredictably, than the economics of others. When did this step-change happen in the power sector, when things got very fast? It's hard to say precisely, but it wasn't like that a decade ago, while it is very much like that now. Sometime in between, there was a major paradigm shift in the economics of power sector technologies.

In parallel, the future of power sector technology became increasingly linked to the future of other technologies – in transport, in industrial heat or cooling, in power-to-gas, in building management, in information technology, water desalination, and so on. This phenomenon of growing 'sector coupling' or 'sector integration' meant that the prospective economics of any given technology became much more complicated.

Sometimes this concept is expressed, rather loosely, as the 'electrification of everything' – for electric vehicles, for electric cooking, heating and cooling, in electric desalination of water, in digitalisation-driven demand for electricity, the Internet of Things, etc. For example, the scale of demand for electric vehicles could greatly impact the achievement of economies of scale in disruptive electricity generation technologies, and hence the achievement of tipping points in those technologies.

A similar concept of coupling or integration started to apply more and more within the power sector itself – for example, it became difficult to think about a variable power technology (like wind power, available only when the wind is blowing) as it got cheaper, without also simultaneously thinking about flexible power technologies (like combined-cycle gas turbines (CCGT) or long-duration energy storage) that could always be available when the variable technologies were not. Or it became difficult to think about main grids, without thinking about how mini-grids might eventually be nested in them, as the economics of mini-grids improved compared to the extension of main grids.

All these developments meant that if people wanted to keep abreast of what was happening in the power sector, they needed to know a lot more about a lot more technologies (and about how different technologies interact with each other in systems) than they had needed to know in the past, and they needed to update their knowledge a lot more often. Some people kept up with this rapid change much more effectively than others.

This growing disparity in knowledge between people or between different groups was in itself disruptive. People's expectations about the sector started to diverge greatly. Some people saw that situation as ripe with opportunities, and other people mostly saw growing threats, and became defensive of their interests. Large divergences in expectations were sometimes legitimate and objective in the face of growing complexity, and were sometimes, instead, more reflective of divergences in interests – and it was often not easy to tell the difference.

The political economy of those divergences also became very important. Planning, policy, and investment decisions in the face of such technology uncertainty became much more contentious and complex. Decision-making institutions were in effect being disrupted by disruptive technology.

Debates about developing countries 'catching up' with developed country technologies, or instead leapfrogging them, became prevalent. Technology debates about decarbonisation versus evolving economics began to abound, and developing countries increasingly needed to determine the practical differences between these approaches – should they adopt clean energy primarily to save the planet, or primarily to save money? Different stakeholders had very different views.

Long-established ideological and geopolitical divides therefore also faced disruption, particularly about how climate change should be addressed and by whom. Should developing countries – particularly poor ones – leave the responsibility for addressing climate change mitigation to richer countries or instead address it as a co-benefit of their own economic development?

All the above considerations now frame the discussion of technology disruption in the global power sector, and particularly how that will affect the countries of sub-Saharan Africa and South Asia. Countries in these regions are realising that they are participating in a global energy revolution. A revolution that could have enormous benefits for them, if they seize the opportunities in time, and while their rapidly-growing power sectors are still open to the leapfrog scenario.

Disruption and tipping points

We can define 'disruptive' technology in the power sector as a technology that becomes so cheap that it tends to dominate new investments, and may eventually even displace existing assets (those assets becoming 'stranded').

We can call the point at which that happens a 'tipping point'. For example, a new photovoltaic (PV) solar power plant may become cheaper than a new CCGT power plant, and new investments in PV power plants might perhaps then become much more common than new investments in CCGT plants. This can be considered the 'first' tipping point.

As the relative costs change even more in favour of PV, it might become cheaper to invest in a new PV plant than it is even to continue to run an existing CCGT plant, and then another tipping point would occur in which new PV plants are displacing even existing CCGT plants. Let's call that the 'second' tipping point.

In essence, when a technology becomes cheap enough to pass either the first or the second tipping point, we can say it is ‘disruptive’. In our example, PV is disruptive because it becomes much more widespread. However, the examples used in regard to PV and CCGT underline some of the power system complexities of determining when a particular technology has actually become truly disruptive.

CCGT can be operated continuously whenever that is needed – making it a ‘flexible’ or ‘dispatchable’ energy source; PV can be operated only when the sun is shining, and in fact only when it is shining above some minimum level of irradiation. Since any power system generally needs to provide some electricity all the time (at least ideally, abstracting from the possibility of involuntary blackouts), a PV-only system would not be feasible.

That means that any power system dominated by PV needs something other than PV on the system to provide power when the sun is not shining at all, or even just not shining enough. As we can see, the cost of that something else, to ‘back up’ PV, needs to be included in any complete analysis of whether PV has passed a tipping point. That is, to determine that, we can’t just examine the cost of PV itself.

That points to the fact that tipping points in variable renewable energy, such as PV, has generated a certain tipping point at a conceptual level as regards how power systems are planned and operated. In power systems that preceded the advent of variable renewables, planners thought in terms of ‘baseload’ power that could operate continuously to provide electricity at the minimum level of demand, and ‘peak-load’ power to provide electricity for peaks in demand above that minimum level (e.g. when demand peaked in the middle of the day, driven by air-conditioning, or when lighting needs made demand peak in early evening).

With significant penetration rates of variable renewables on power systems, planners have started thinking in terms of ‘variable’ power (that usually has low or zero marginal cost because there is no fuel to pay for), which should generally be used whenever it is available, and ‘flexible’ power, which is whatever technology can be used when variable renewables are not adequately available. In consequence, baseload and peak-load are becoming outmoded concepts.

Flexibility can be provided not only by certain generation technologies, but also by energy storage, by interconnections with neighbouring power systems, and by ‘demand-responsiveness’ (namely, demand that cycles on and off depending on whether the power system is in surplus or deficit at any given time). Looking at this need for flexibility of the grid, increasing digitalisation is obviously an important enabling technology for managing demand-responsiveness.

That digitalisation has also facilitated the development of ‘prosumers’: electricity consumers who are also electricity producers – for example, consumers with solar home systems (or commercial and industrial systems) who sell surplus electricity to the power system or to neighbours (in so-called ‘peer-to-peer’ trading). This takes place within main grids, and sometimes in mini- or micro-grids. In all cases, the existence of prosumers can become an important factor in grid planning and operation. In the future, we are likely to see a lot more prosumers providing power to the grid from energy storage, such as the batteries of electric vehicles.

The need for flexible generation can profoundly affect the optimal generation technology mix on the power system, and some technologies are more capable of being flexible than others (e.g. CCGT is more flexible than coal or nuclear, or at least there are significant costs to flexing coal or nuclear up and down substantially, in terms of wear-and-tear etc.). Indeed, a power system that has a lot of inflexible power technologies may be thereby retarding the utilisation of variable renewables, which becomes particularly problematic when variable renewables become very cheap. This is becoming a major policy issue for all countries as they plan their power systems.

Another illustration of the real-life complexity of tipping points and disruption is that of mini-grids and main grids. In the past, there was a widespread planning presumption that the best way to expand electricity access economically was to extend national grids to as many customers as possible, as fast as possible. However, increasingly, reality set in, and it was seen that in many countries ‘as fast as possible’ was actually extremely slow, particularly where state-owned electricity utilities were financially-distressed, and where distances to customers were very great in areas of low-density rural populations. As a result, mini-grids multiplied, providing power only at the local level, economising on transmission investments (Energy Sector Management Assistance Program (ESMAP), 2019).

There was a widespread view that this was not economic in the long term, because the mini-grid solution did not allow the exploitation of the economies of scale of large centralised power stations, and that savings in long-distance transmission investments did not fully offset those economies of scale in generation.

However, as PV-based mini-grids have spread (often with battery or diesel back-up supply) replacing the previous dominant technology of diesel-only generation for mini-grids, it is no longer clear that connecting to large-scale centralised power stations will ultimately be more economic. There might be many cases in which small-scale PV without long-distance transmission will be cheaper than large-scale PV, or any other large-scale generation technology, with long-distance transmission. A tipping point might have been reached for mini-grids because of the tipping point being reached in PV (in terms of cost declines), combined with the way that economies of scale operate for PV (as compared to how economies of scale operate for diesel generation). Small is probably much more beautiful for PV than for diesel.

But the core observation to underline here is that, however complex the determination of exactly when a tipping point occurs, and therefore when the technology in question becomes disruptive, tipping points and disruptive technologies in the power sector used to be very rare – and now they are very common. And that in itself has huge implications.

Disruption and energy transitions

So huge have the implications of tipping points become that more and more people describe whole-system transformation in countries as an ‘energy transition’. Increasingly often, the connotation is that an energy transition will not only transform countries’ environmental impacts (in terms of both global and local pollution), but will have major impacts on its economic competitiveness in global markets, through reduced costs of energy. This could obviously have major implications for economic growth, employment, and poverty reduction.

Managing energy transitions effectively has therefore risen up the development agenda, particularly for low-income countries with relatively few step-change development options, and for whom the cost of missed development opportunities can be very large.

A very interesting paper by Michael Leifman, commissioned by the World Bank, constructed three scenarios of technology deployment relevant to energy transitions (Leifman, 2019). The scenarios describe the extent to which disruptive technologies are deployed, based on whether government policies help or hinder that deployment.

The most optimistic of the scenarios is ‘leapfrog’, in which countries have deployed disruptive technologies rapidly and are well on their way to universal deployment in the sector. The least optimistic scenario is ‘locked-in’, in which technologies have advanced globally, but locally the barriers to adoption are so great that countries are sticking with older technologies. The in-between scenario is called ‘lopsided’, in which disruptive technologies may have diffused in some areas and in some segments of the population (e.g. the wealthier sections of society), but are blocked in others by adverse policies, conservative institutions, decision paralysis, traditional habits, vested interests, etc. We will use these scenarios to contextualise the policy and institutional factors which affect the deployment of disruptive technologies in the power sector, and hence the pace and nature of a country's energy transition.

It is also worth noting that the nature of some of the technologies underpinning electricity transitions might be making such transitions intrinsically more regional in scope than was the case with power sectors dominated by conventional, fossil fuel-based technologies. In general, oil, natural gas, or coal can be transformed into electricity where the oil, gas, and coal are found (and the electricity then transported to where the market for that electricity is), or, instead, the oil, gas, and coal can be transported to where the market for electricity is located and then transformed into electricity at that location. In short, there is a choice between transporting electrons or transporting molecules. And molecules can often be shipped very long distances and still remain economic.

For renewable energy, that choice does not usually exist – sunshine or wind cannot be transported as such, but they can be transported once they have been transformed into electricity.[1] This is important particularly because of two factors. First, the sun shines and the wind blows at different places at different times, so that variability can be managed to some extent by drawing on a larger geographical space than simply a national one. Secondly, the global distribution of solar and wind resources is highly unequal – some countries have much greater resources than others, so the advantages of cross-border trade are very pronounced.

The growing importance of renewable electricity therefore means that regional cooperation and integration become more important than they were for conventional electricity (although transmission losses for electrons are a greater constraint to the economics of distance than is the cost of transporting molecules; simply put, you can ship oil, gas, or coal to the other side of the world; you can't yet do that economically with electricity – even if it is very cheap electricity – but you can nonetheless transport it across borders.). This regional dimension of the transition to renewable energy therefore has the potential to become highly disruptive of how national power systems are planned and managed.

Some of the principal disruptive technologies

In this section, we briefly discuss some of the principal disruptive technologies that are frequently mentioned in power sector debates. These examples are not intended to be an exhaustive list, nor do we cover the examples in detail – they are intended to illustrate where the sector seems to be heading. But be warned: the very concept of disruptiveness implies a degree of unpredictability – the equivalent illustrative examples in a couple of years' time might look a bit different, just as they would have done a couple of years ago.

It is also worth noting that various broader technologies are developing quite fast and are enabling the development of disruptive technologies in the power sector, even if they are not strictly disruptive technologies themselves (by reference to our definition about tipping points). Examples of 'enabling technologies' in the power sector include artificial intelligence and machine-learning, industrial Internet of Things, sensors, the spread of batteries for mobility and communications, digital transformers and static compensators, high-voltage direct current transmission and dynamic cables, 5G communications technology, lighting from light-emitting diodes (LEDS), drones, compressor-less air-conditioning and electro-chromic windows, and so on[2]. The development of such enabling technologies is helping the disruptive technologies reach their tipping points, and power system planners need to be increasingly aware of such developments. The deployment of these enabling technologies are likely to strongly influence whether countries achieve the leapfrog scenario.

[1] Biomass is an exception to this generalisation, since it can be transported as molecules or as electrons.

[2] Some of these enabling technologies involve innovations in energy efficiency allowing substantially more services to be provided for the same amount of power, thereby improving the economics of potentially disruptive power technologies.

Now we briefly discuss the disruptive potential of various illustrative examples of power sector technologies (International Energy Agency (IEA), 2019a; International Renewable Energy Agency, 2019), that will be core to any leapfrog scenario.

What is the disruptive potential of solar PV?

The cost of solar PV has been plummeting for some years now, and there is probably still some way to go in terms of cost reductions. For some period of time, these cost declines were driven by government subsidies in various countries, with Germany and China playing important roles, but nowadays subsidies have become much less important in determining the cost of PV. PV has benefited from economies of scale in its manufacturing as its deployment has risen astronomically. In some countries, rooftop and small-scale ground-mounted PV has predominated, but in others we have seen a growing number of large, centralised PV power plants, with sometimes hundreds of megawatts in capacity. There are clearly some economies of scale in plant size, particularly where land is readily available and relatively cheap (e.g. in desert countries).

PV is powered by diffuse and direct sunlight ('global horizontal irradiation' – GHI). It can be deployed almost anywhere in the world, but its effectiveness does vary by location, depending on the quality and extent of GHI, the hours of daylight, and to some extent the ambient temperature (the performance of PV declines somewhat as the temperature rises). We can expect to see more cross-border trade in PV electricity developing, based on GHI differences, at least where there are no policy barriers to the development of such trade.

We have also recently begun see the development of floating PV, which could expand rapidly. Floating PV can utilise available water bodies (such as hydropower reservoirs, water treatment reservoirs, lakes, etc.), and might develop into offshore areas. The opportunity cost of using water bodies is usually significantly less than that of land, and is particularly advantageous in densely-populated areas (such as South Asia). Where floating PV is developed on hydropower reservoirs, the possibility could exist of co-managing the PV and the hydropower such that the hydropower acts like energy storage – namely, that the hydropower is operated disproportionately when the sun is not shining (Solar Energy Research Institute of Singapore, 2018).

More broadly, the principal enabler of the spread of PV, as power systems achieve high penetration rates of variable renewables, will be the availability of adequate flexibility solutions. In high-penetration systems with high decarbonisation targets, the development and deployment of low-cost energy storage, with the possibility of long duration and even seasonal storage, will ultimately be an important enabler. Other non-carbon flexibility solutions will also play a role in such systems (e.g. cross-border interconnections, demand-responsiveness measures), where these are feasible. Overall, the spread of PV, as its cost and that of complementary flexibility solutions falls, will enable more ambitious decarbonisation of power systems. It could also enable the spread of renewable gases produced from renewable electricity, such as green hydrogen, to compete with natural gas, grey or blue hydrogen, and other fuels (see below for explanations of these terms 'green', 'grey', and 'blue' hydrogen).

It is particularly worth noting that PV projects can be implemented very fast (sometimes even with a few months), and that they can often be implemented incrementally. This is quite unlike, for example, a CCGT plant, which takes much longer and is typically a large, lumpy investment. In a period of disruptive technology in which the relative costs of technology are changing rapidly, the benefits of not committing too much capital upfront to any particular technology can be considerable. PV (and similar modular technologies) may sometimes be preferred for that reason (particularly in low-income countries that can least afford investment mistakes). Power system planning processes may therefore need to adapt to a more exploratory and modular approach than was traditional when technology change was much more gradual and predictable. Traditional long-term least-cost power system planning, based on stable assumptions about costs, has become outmoded.

However, to give some context to the ongoing global scale-up of PV, the IEA pointed out in 2019, 'The big open question for Africa remains the speed at which solar PV will grow. To date, a continent with the richest solar resources in the world has installed … less than 1% of the global total. Solar PV would provide the cheapest source of electricity for many of the 600 million people across Africa without electricity access today' (IEA, 2019a). In short, solar PV could become much more disruptive of energy access than it has been so far, if governments enable leapfrog scenarios

What is the disruptive potential of wind power?

Much that has just been said of solar PV can also be said of wind power. It has spread fast as its cost has declined dramatically (enabled in part by industrial-scale manufacturing of wind towers and turbines, and in part by the maximum size of wind turbines having increased substantially). In many places, wind power no longer receives subsidies due to the cost decline. Wind power plants can be established on a large scale or a small scale, and usually can be implemented quite quickly.

In most places wind power is rather variable because the windiness is not continuous or even predictable, although there are some locations that are exceptions to this (in general, solar PV availability is more predictable than wind availability – daytime sunshine is relatively predictable and night-time sunshine is totally predictable!). Wind power is increasingly being developed offshore, where winds tend to be better than on land, and this is likely to continue to expand (obviously offshore development economises on land where land is scarce). In some places, it is particularly windy at night, which provides a useful complement to solar PV.

Overall, the comments above on the importance of flexibility solutions to enable the spread of PV apply also to the spread of wind power. As with PV, we can expect energy storage with various technologies to be an important enabler of wind power.

What is the disruptive potential of biomass?

Biomass refers to the use of plant or animal material for energy production, including electricity generation. This can include wood or forest residues, waste from food crops or food processing, human or animal waste, or cultivated energy crops. It can also include the intermediate conversion of certain types of biomass to biogas before combustion. Combustion of plant-based biomass has been classified in UN and EU legal frameworks as renewable, even though it emits carbon dioxide, because photosynthesis absorbs carbon dioxide into new plants, replacing those which are burnt. The extent to which the carbon dioxide absorption is greater or less than the carbon dioxide released does of course vary case-by-case, and can therefore be environmentally controversial. It should also be noted that the supply chain for biomass can create income-earning opportunities for large numbers of people, particularly in the rural/agricultural sector, and therefore can have significant distributional and poverty-reduction potential compared to most other sources of primary energy.

The disruptiveness of biomass may depend mostly on its potential to co-fire fossil fuels, and thereby partly replace them. For example, cofiring of biomass with coal has been increasing, which can reduce the carbon dioxide emissions per kilowatt hour generated.

What is the disruptive potential of concentrated solar power (CSP)?

Direct sunshine can be concentrated to generate heat, the heat can be transformed into steam, and the steam can generate electricity through a conventional turbine. This is the essence of concentrated solar power (or concentrated solar thermal), abbreviated to CSP, which utilises direct normal irradiation (DNI) from the sun (which is one component of the GHI used by PV – see above). CSP thus depends on direct sunshine from largely cloudless skies, preferably without much dust or humidity in the air to impede the sunshine. Most types of CSP concentrate (or focus) DNI with mirrors on to a line or small area, from which the high temperature heat is collected and transformed into steam.

The most widely spread CSP technologies are the parabolic trough and the solar tower. Almost all recent CSP investments have included thermal storage (usually in molten salts[3] – see below), so that CSP can be available at times when DNI is not sufficient during the day and at night. Very recent plants have included storage of up to 15 hours; the temperature of the stored heat can be maintained for days or weeks with only slight declines.

Molten salts storage typically exhibit considerable economies of scale at the plant level – the more hours of storage the lower the unit cost per megawatt hour of energy released from storage. This is partly because the fixed costs of the power block (turbine etc.) can be spread over more hours of operation (i.e. the capacity factor of the power block increases), and partly because the materials used in a storage tank increase at a slower rate than the rate at which the tank's volume (and hence storage capacity) increases (this is simply because the volume of a solid increases faster than its surface area)[4].

Of course, the hours of storage actually required will depend on the demand profile for power in that system, and of expectations that this profile will change over the lifetime of a power plant. If, for example, a power system planner envisages only a short evening peak in demand, that planner may reward only a few hours of storage, which will be relatively expensive because of a lack of the plant-level economies of scale described above. Typically, countries that are more industrialised, or anticipate extended hours of demand for air-conditioning as per capita incomes rise, will see a need for extended storage hours.

The global installed capacity of CSP generation has increased substantially in recent years, which has resulted in cost decreases. However, this capacity increase has been from a very small base, and almost certainly more cost reductions can be expected as global scale increases. None of the materials in CSP plants are intrinsically expensive or scarce, and few components are protected by any intellectual property rights, so the potential for cost reductions is in principle substantial. Some countries have plans for significant new investments in CSP capacity – for example, China, Spain, Saudi Arabia, and the United Arab Emirates.

If this new investment spurs cost reductions, then a global scale-up of CSP could be expected (at least in areas with adequate DNI). It is to be noted that DNI varies between countries much more than GHI does, so many countries cannot by themselves utilise CSP effectively due to insufficient DNI, although some of those countries could import CSP energy from better-endowed countries. Some observers compare CSP primarily to PV, although in terms of its operational behaviour it would actually be better to compare it to CCGT – particularly because of CSP's flexibility, enabled by its storage. This means that a high penetration rate of variable renewables on a power system could be an important enabler of viable CSP investment.

What is the disruptive potential of electrochemical batteries?

Much power sector commentary in recent years has been focused on the potential for electrochemical batteries – particularly lithium ion batteries – to be a very disruptive technology, and to eventually allow variable renewable electricity technologies to become dispatchable, i.e. available continuously. If that happens at a competitive cost, then renewables plus storage could in principle strand a large proportion of conventional power.

---

[3] Molten salts used for thermal storage are usually a blend of potassium nitrate and sodium nitrate, which are readily available commercially.

[4] To illustrate, compare two hollow cubes (analogous to storage tanks): one cube of dimensions 1 x 1 x 1, and the other of dimensions 2 x 2 x 2. Their volumes are in the ratio 1:8; their surface areas (which determines the amount of materials used to make each cube) are in the ratio of only 6:24, i.e. 1:4. The volume (i.e. capacity) therefore increases faster than the materials used increase (in this case twice as fast), so the cost per unit stored falls as the capacity increases.

Although lithium ion batteries dominate in small devices such as smartphones, and have become a very cheap source of energy storage on that scale, it is not clear what the next phase of development will look like. It is indeed quite likely that lithium ion batteries will enable a massive scale-up of the deployment of electric vehicles, and will allow a considerable range of travel between charging sessions.

However, it is not yet clear whether lithium ion will become a major source of storage for large stationary applications in power sectors, enabling more than a few hours of storage on an economic basis. In fact, it is possible that the very scale-up of lithium ion batteries in transport and communications applications, combined with global supply bottlenecks for lithium, will make the development of longer-duration batteries for stationary storage even more costly and challenging. Nonetheless, for short-duration storage with fast response times, lithium ion seems to be the best option for stationary applications in the power sector, and investment is accelerating. Of course, the shortness of the storage duration of batteries, if they were the only storage technology available, would limit the corresponding penetration rate of variable renewables on a given power system (Australian National University, 2019).

What is the disruptive potential of pumped storage?

However, other forms of energy storage are indeed available. By far the most common form of energy storage for the power sector globally is pumped storage (about 94% of the total capacity of energy storage for the power sector). Pumped storage works by using surplus energy to pump water up to a reservoir – for example, using solar energy when the sun is actually shining – and then releasing the stored water through hydropower turbines when the energy is needed – such as when the sun is no longer shining.

At one time, it was widely believed that there may not be enough unexploited pumped storage sites in the world. After all, pumped storage does require favourable topography and availability of water resources. However, it now appears that this may have been unduly pessimistic. A recent study by the Australian National University, using newly-developed geographic information system algorithms, identified about 530,000 potential pumped storage sites globally, only a small fraction of which would be needed to support very high penetration rates of variable renewables.

Of course, in practice, given power systems would need to identify pumped storage sites with economic potential, given the circumstances of those specific power systems. Nonetheless, pumped storage appears to have enormous potential as an enabler of greatly expanded use of cheap variable renewables, and therefore could become highly disruptive.

What is the disruptive potential of molten salts thermal storage?

Molten salts storage was mentioned above in the context of enabling CSP to become a disruptive technology. However, it is now becoming clear that molten salts could become disruptive in their own right, even when used separately from CSP.

The disruptive potential of molten salts (a mature technology in itself) has arisen because PV and wind power have now become so cheap. This means that it may be becoming economic to heat molten salts with renewable electricity, and then to use the stored heat to produce steam to put through a turbine to generate electricity. This creates the possibility of retrofitting, for example, a coal-fired power plant to be fuelled instead by variable renewables, and then running it as a flexible source of power due to the storage heated by those renewables. This allows the low cost of molten salts to be utilised even where CSP is not feasible, and provides the benefit of long-duration storage where electrochemical batteries might be too expensive to firm up variable renewables to make them in effect dispatchable.

What is the disruptive potential of renewable gases?

Gases can be produced from other things, and then combusted (or passed through fuel cells) to generate electricity (and, importantly, can be stored to generate electricity later), or can be used for non-power sector applications (e.g. industrial heat). When these gases are produced with the utilisation of renewable electricity they are called 'renewable' gases. The potential disruptiveness of renewable gases derives from their ability to be a non-carbon replacement for fossil fuels (even natural gas), including their ability to be stored. And the fact that renewable gases have multiple applications means the potential of the production technologies to reach tipping points through economies of scale and technology breakthroughs is correspondingly greater.

Let's take hydrogen as an example (IEA, 2019b). Hydrogen can be a fuel for the power sector, transport sector, and industrial sector. Currently, most hydrogen produced is 'grey'– that is, it is produced based on fossil fuels. Hydrogen is called 'blue' when carbon capture (see below) is applied to its production from fossil fuels. It is 'green' when it is produced from water by electrolysis powered by renewable electricity, and no carbon dioxide is then emitted in its production or conversion.

Whether green hydrogen will eventually pass tipping points to become disruptive depends primarily on the cost of renewable electricity, the scaling up of the manufacture of electrolysers and a consequent cost reduction of that equipment, the scaling up of the deployment of fuel cell vehicles (perhaps most likely for heavy transport), the scaling up of technology in process heat-consuming industries to substitute green hydrogen for other heating fuels, the adoption of regulations to allow more blending of hydrogen in existing gas transport infrastructure and in fossil fuel-fired power plants, and ultimately the development of power plant turbines that allow a much higher proportion of hydrogen to be combusted safely (and eventually the development of pure hydrogen systems).

The core point is that the scaling up of green hydrogen and the scaling up of the other technologies mentioned here can be mutually reinforcing, and therefore can create a virtuous circle of declining costs. In short, the tipping points can help each other to tip a very long way.

What is the disruptive potential of carbon capture?

Carbon capture in the power sector is a technology that is widely discussed but not yet widely deployed. In essence, carbon capture extracts carbon dioxide before it can be emitted into the atmosphere, and either sequesters (i.e. stores it) or utilises it for other purposes.

To the extent that it is effective it could reduce the carbon dioxide emissions associated with fossil fuel-based electricity generation, and it is a technology that has been championed on that basis. Critics argue that it is not cheap, that it only removes a portion of the carbon dioxide, that the storage of carbon dioxide is not secure against leakage, and that the deployment of the technology discourages the development and deployment of alternatives to fossil fuels that emit no carbon dioxide and that ultimately can be cheaper than fossil fuels. Proponents counterargue that if the deployment of carbon capture were more widespread, it would become cheaper through economies of scale and technology breakthrough (including breakthroughs that solve the effectiveness and leakage issues), and would pass tipping points to become disruptive (and that therefore policies should be put in place that are conducive to the development and deployment of carbon capture). This conflict makes the political economy of carbon capture very complex. A full analysis of carbon capture is beyond the scope of this paper, but suffice it to note that carbon capture is a potentially disruptive technology that has not yet passed a tipping point.

What is the disruptive potential of hybridisation?

Hybridisation is not really a technology as such, but rather a combination of technologies. A new combination of technologies can become disruptive on a different timescale from the component technologies in isolation. For example, CSP might not be cheap enough yet to pass a tipping point, and hence become disruptive, but combine it with cheap PV that provides daytime power and utilise CSP stored in molten salts to provide cheaper night-time solar power than could be provided by PV with batteries and we have a potentially disruptive hybridised technology. This approach is being tried in Dubai, Chile, South Africa, and Morocco, and has the potential to spread rapidly and become highly disruptive. Other forms of hybrid – e.g. biomass with solar PV, floating PV with hydropower – could have significant disruptive potential. In a similar vein, nesting mini- or micro-grids within main grids could be seen as a form of hybridisation – it may combine the economies of scale of a main grid with the resilience and peer-to-peer trading opportunities of a mini/micro-grid. Overall, we can expect rapidly-evolving disruptive technologies to give rise to unexpected hybrid opportunities, which can magnify and accelerate the disruption.

Theoretically, almost any hybridisation at the individual project level can be implemented instead at the power system level. For example, instead of combining CSP and PV in one project, they could just both be utilised on the power system in different locations and by different project sponsors. Arguing that this approach can be equivalent in impact to a hybrid project approach involves making quite strong assumptions about the ability of power systems planners and operators to actually optimise power systems. In reality, particularly in low-income countries, it may be more efficient to delegate some optimisation to project sponsors at the individual project level, particularly where project sponsors are privately-owned and have international experience. In that way, centralised planners without actual experience in the particular technologies in question can benefit from the private sector’s experience in those technologies in other countries.

Some further observations about institutions and politics, planning, and markets

The following section is intended to give the outline of an analytical framework for thinking about the impact of disruptive technology on policies and institutions, by posing some key questions. It is difficult to generalise about these fast-evolving issues, as actual empirical experience is still rather sparse, and circumstances obviously vary a lot from country to country, or region to region. Much further research will be needed as actual experience with adapting policies and institutions to disruptive technology develops, particularly research that focuses on specific regions and countries. So far, disruptive technology is raising more questions about policies and institutions than it is yielding actual answers, yet it is already clear that institutions will shape whether countries leapfrog, become lopsided, or get locked-in.

How might disruptive technology be moving us away from centralised power system operation?

Traditional power flows were one-way – from producer to consumer. Traditional power flows were generally not stored. Traditionally, demand for power throughout the day and throughout the year was quite predictable, and the drivers of demand growth changed only gradually.

In that context, maintaining a reliable and cheap electricity system involved exploiting economies of scale (in generation and transmission) to the maximum, and instantaneously matching supply with demand by centrally dispatching from a well-planned mix of generation technologies, through transmission lines, to meet customer demand when and where it was manifested. Utilities were developed because that highly-centralised large-scale business model was well-suited to that traditional context.

Every element of that traditional context for utilities is now being disrupted by technology, as was described in detail in the sections above. Moreover, in the particular environment of South Asia and sub-Saharan Africa the utility was never all-pervasive anyway, or effective in providing reliable, let alone universal, electricity access, and it may now be desirable in some countries even to leapfrog the traditional utility stage. The rationale for the traditional utility business model is therefore no longer clear, but nor is it yet clear what business models should replace it.

Why is power system planning becoming more complex?

We can distinguish a number of ways in which disruptive technology is making power system planning more complex, and planning capacity may often not be keeping pace with the increasingly complexity.

As the use of variable renewable generation increases, the need to ensure that enough flexible resources are available also increases (this challenge did not exist before variable renewables became widespread). Variability of renewables also places demands on system operators to forecast the weather accurately, which was not a skill previously needed on the supply side of the power system. Increasing self-generation by consumers makes net demand from the power system as such more unpredictable. Increasing the use of energy storage sited in proximity to customers needs to be planned in coordination with transmission planning (if electricity is available from storage near customers, less needs to be transmitted from more distant generation) – again, this type of coordination problem did not exist in the pre-storage era.

But above all, planning is becoming more complex because technology is changing so fast and unpredictably. Planners need to know a lot more about technology options, and their possible future economics. The cost of locking into technologies too early or for too long can now be very high. Assets can become unexpectedly stranded on a scale that was hitherto unknown. On the other hand, decision paralysis in planning can be costly too. It’s an increasingly tough time to be a power system planner.

What is disruptive technology doing to wholesale power markets?

It is now becoming well-understood that the design of competitive wholesale electricity markets, in countries that have those, might need to be reconsidered in the context of increasing penetration of variable renewables. The basic problem is that variable renewables often have zero or near-zero marginal cost because they involve no fuel cost; when variable renewables are available, they tend to crowd other generation out of the market, which means that the other types of generation are not receiving a market signal that induces investment. This can lead to shortages of generation capacity, and an excessive reliance on variable generation without adequate flexibility resources being in place (Blazquez *et al*., 2019).

In South Asia and sub-Saharan Africa most countries do not actually have competitive wholesale markets, but many have been considering introducing them. They may be well-advised to observe how countries with such markets resolve the design issue described here, before moving ahead to create competitive wholesale markets.

Why are markets valuable when generation costs are changing fast?

Even though competition *in the market* might not be entirely advisable as variable renewable penetration increases, competition *for the market* is likely to be highly advisable. The relative costs of different generation technologies, different storage technologies, and different hybrid solutions are changing rapidly, and are quite specific to location, depending as they do on weather, topography, etc., as well as on country and off-taker risk.

Many countries have in effect wasted large amounts of subsidies for variable renewables beyond their tipping points when the subsidies were no longer needed, or the subsidies turned out to be simply more generous than was actually needed to induce investment. The use of competitive auctions (including minimum subsidy auctions) and tenders is strongly advised to help discover the relative costs of different options. Some degree of technology neutrality is also to be advised – for example, a country might issue a tender for 24-hour solar energy, without specifying the exact generation and storage technologies to be used. Being open to different types of hybridisation, as mentioned above, might yield very good results in terms of cost and performance.

Why does politics matter so much?

Disruptive technology disrupts political economy. There will be winners and losers in the change process, and that is the essence of politics.

When things are changing very fast, it is hard to predict how each player will perceive its own interest and the interests of others, although politics will depend heavily on those perceptions. Some players will see the future as very much theirs, as compared to the past, and they are likely to support the energy transition: for example, renewable energy generators, mini- and micro-grid operators, energy storage providers, and prosumers. Others may be just as clearly against the energy transition, fearing that their assets may become stranded: for example, fossil fuel suppliers and some conventional generators. Those in favour and those against the energy transition might each form political coalitions to advance their interests.

The role of incumbent utilities is perhaps the most ambiguous. Some incumbents will resist the deployment of disruptive technologies, considering them as a threat. Others will perceive such technologies as an opportunity, and will endeavour to transform themselves to exploit that opportunity. Either way, they are quite likely to lobby politically for their perceived interests.

The political interplay of these various interests will shape the scenario a country finds itself in: leapfrog, lopsided, or locked-in.

Possible further research

Arising from the analysis above, here are a few questions that would merit further research:

- How could institutional and policy reform in a sample of South Asia and sub-Saharan African countries be most conducive to the leapfrog scenario (and avoidance of the locked-in or lopsided scenarios)?
- For a sample of South Asian and sub-Saharan African countries, how would high penetration rates of variable renewables be most efficiently achieved by a combination of non-carbon flexibility options (e.g. interconnections, short-duration and long-duration storage of various technologies, demand-responsiveness)?
- How should tenders/auctions for disruptive technologies be best designed, including for the optimisation of hybrid solutions?
- What is the potential industrial demand for green hydrogen in South Asia and sub-Saharan Africa that could cause cost reductions for green hydrogen as a power sector fuel? Who would become net importers and who net exporters, and how would green hydrogen best be transported?
- What is the potential for CSP as a non-carbon enabler of high penetration rates of variable renewables in South Asia and sub-Saharan Africa? Are there countries with particular climatic impediments to CSP and others that are more favourable?
- What is the impact of fossil fuel subsidies and taxes in South Asia and sub-Saharan Africa on the deployment of disruptive technologies in the power sector?
- What are the political economy constraints to the reduction of fossil fuel usage in the power sector, and the deployment of disruptive technologies?

- Should mini- and micro-grids be thought of as intermediate steps towards access to the main grid, or can they be economically optimal in themselves?

Select bibliography

Australian National University (2019) 'Global Pumped Hydro Atlas', http://re100.eng.anu.edu.au/research/phes/

Blazquez, J., Fuentes-Bracamontes, R., and Manzano, B. (2019) 'A Road Map to Navigate the Energy Transition', Oxford Institute of Energy Studies.

ESMAP (2019) 'Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers'.

Friedman, J., Fan, Z., and Tang, K. (2019) 'Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today', Columbia/SIPA Center on Global Energy Policy.

IEA (2019a) *World Energy Outlook 2019.*

IEA (2019b) 'The Future of Hydrogen: Seizing Today's Opportunities, Report prepared for the G20, Japan'.

International Renewable Energy Agency (2018) 'Renewable Power Generation Costs'.

Leifman, M. (2019) 'Scenarios: Leapfrog, Lock-in, and Lopsided', World Bank. http://documents.worldbank.org/curated/en/739301550244597747/pdf/WPS8748.pdf

Solar Energy Research Institute of Singapore (2018) 'Where Sun Meets Water: Floating Solar Market Report'.

Solar Power Europe (2017) 'Digitalization and Solar: Task Force Report'.