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Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy

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ABSTRACT
Disruptive innovations are seen to have three core features: 1. They occupy a niche that expands into being a major disruption to a technological system; 2. They grow exponentially and are thus very surprising in their disruption and 3. They create stranded assets. This paper shows how renewable energy with battery storage has the three core features of a disruptive innovation, and predicts that the number of fossil fuel stranded assets are thus likely to increase with the rise of renewable energy generation. Forecasts for the share of renewable capacity in global energy demand will go beyond current estimates, due to the introduction of battery storage and decline in retail renewable electricity prices, and could account for 100% of global energy demand in a number of different scenarios by 2050. We find that renewables and storage can be characterised as disruptive innovations and have the potential to change energy systems dramatically between now and 2050.

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Stranded assets; fossil fuels; disruptive innovation; renewable energy; technological innovation

The concept of obsolescence is long standing throughout technological history. New technologies and infrastructure enter into the market place and are eventually replaced by others. In some cases, an incumbent asset has an artificially high valuation, and in others, consumers simply no longer demand it. The market wakes up to this reality due to the introduction of new, technologically superior products and as a consequence, the original product's value declines, eventually becoming obsolete or stranded.

In this paper, we focus on energy assets that have an intrinsic value and have been, or are becoming, eroded due to the advent of new competing technologies. This is different to assets that become stranded due to the formation of bubbles where a market is created for a product that has no intrinsic value (Siegel 2003). In its early phases, some in the traditional energy industry had seen the rise of renewable energy generation as something more akin to a bubble, bolstered by expensive policy (Spiegel 2013; Bryce 2014), than a sector that would sustain long-term value. The paper will look at how the second phase of renewables, coupled with and driven by battery storage, could result in more serious competition for fossil fuels.

In order to understand the nature of this transition we first examine the features of disruptive innovation in order to ascertain the potential market trajectory of renewable

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energy into the future. On this basis we develop energy forecasting curves for energy demand and renewable energy growth from today out to 2050.

1. Disruptive innovation

Disruptive innovation describes a form of technological change that leads to major system change. Before analysing how this literature can help us understand the transition in the energy system we take a brief look at the historical context.

1.1. Historical macro techno-economic theory and change

The Stone-Age, the Iron-Age and the Industrial Revolution are all periods of history that are defined by particular human processes and technologies. In 1925, the Russian economist, Nikolai Kondratieff, developed a theory to explain the evolution of technology that focused on waves of innovation, which in turn create cycles of technology. Kondratieff's waves of innovation are long economic cycles that are characterised by high sectoral growth followed by slower growth and contractions. Kondratieff held that the waves arise from the clustering together of innovations that spark technological revolutions.

Later, Austrian economist, Joseph Schumpeter, coined the term Creative Destruction (CD), also known as 'Schumpeter's Gale' in his book *Capitalism, Society & Democracy* (1942). CD is the process of 'industrial mutation that incessantly revolutionises the economic structure from within, incessantly destroying the old one, incessantly destroying the new one' (Schumpeter 1942, 83). Building upon Kondratieff's work, the theory describes new waves of industrialisation, which he believed were 50–60 years in length (Figure 1). Schumpeter subsequently referred to these waves as Kondratieff's Waves. At the time of

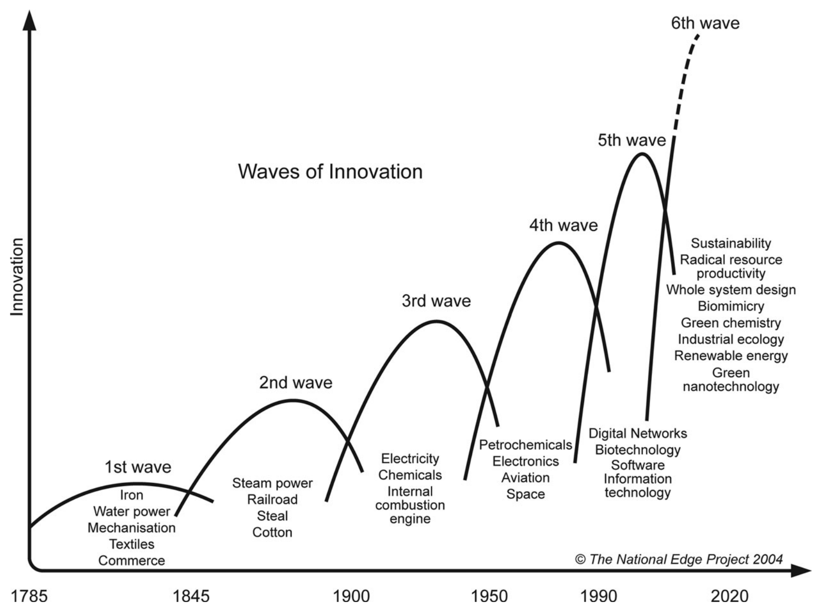

Figure 1. Waves of innovation (Hargroves and Smith 2006).

Schumpeter's death in 1950, the third of his industrial cycles had run its course. This, and the subsequent fourth and fifth cycles taking place over shorter time periods than Schumpeter had forecasted, revealed Schumpeter's long economic waves to be shortening from 50–60 years to around 25–40 years. Further research has confirmed that each new cycle is becoming shorter than its predecessor (Hargroves and Smith 2006; Smihula 2009; Adams and Mouatt 2010). The work of Karl Popper in 1945 concluded that these types of waves, or cycles of innovation, only occur in open societies where a liberal democracy, and therefore, market forces, exist. Figure 2 details the technology adoption rates measured by the market penetration of various products during the twentieth century (Cox and Alm 2008; McGrath 2013). Since the late twentieth century and into the twenty-first century, the pace of uptake of technologies is becoming faster, as highlighted by Schumpeter and affirmed by Hargroves and Smith (2006).

At the beginning of the twenty-first century, Venezuelan-British researcher Carlota Perez examined the boom and bust surges that technologies experience, further developing Schumpeter and Kondratieff's wave theory. Perez coined the term 'techno-economic paradigm shifts' that refer to the relationship between innovations, technical and institutional change, and economic development (Perez 2002, 2009, 2010, 2011).

1.2. Micro-technological theory and change in recent history

At the micro-level of technological change, the development of a new product, or an innovation around an existing product, erodes the market share of the incumbent businesses, and renders the original product defunct.

This phenomenon was termed, 'Disruptive Innovation' (DI), in 1995 by Harvard professor, Clayton Christensen. Christensen used this term to describe what he observed whilst researching industries such as communications, steel manufacturing and the health sector. DI explains how new companies create products that erode the market share of large incumbents by innovating in a market segment with a superior product at an appealing price for consumers and then cause a disruption in the incumbent technological system. One of his examples is the small memory storage disc that was not as cheap as large discs, but was cheap enough, and facilitated the lifestyles of people wanting to carry it around easily; this was the precursor to the notebook computer.

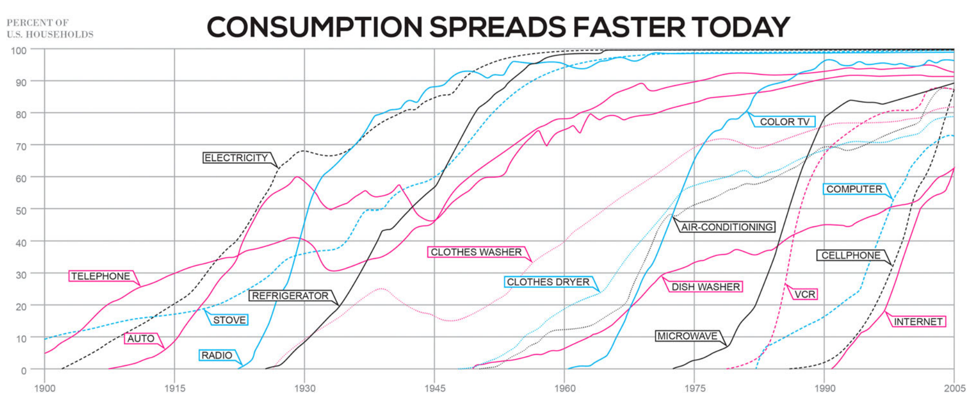

Figure 2. Technology adoption rate (Cox and Alm 2008; McGrath 2013).

Bower and Christensen (1995) describe distruptive technology as a process that has the potential to revolutionise the world. If incumbent companies do not recognise and respond to signals from their consumers for a different product or keep track of upcoming products, they are at risk of being disrupted. Christensen et al. (2006) explains that DI at its core can also bring about a change in related industries. By establishing new business models, DI presents companies with an opportunity to enter new markets. For example, technology companies are entering the energy sector in areas once only occupied by traditional utilties.

Another example of DI is technology company IBM that began its business by making mainframe computers and later began to produce more commercially successful desktop computers. However, anticipating increased competition in the retail market, IBM ceased desktop computer production to refocus on mainframe operations and embracing open source platforms such as Linux (Savage 2013). This resulted in IBM becoming the dominant supplier in the market today, capturing the niche market that exists. IBM's perception of market drivers and future trends enabled it to be well placed to take advantage of disruption within the computer market as people move to mobile computing that still requires a physical mainframe back up somewhere (Savage 2013).

Stanford University academic Tony Seba adds to Christensen's model and applies DI ideas to areas such as the energy industry (T. Seba, personal communication, 2015). He has joined other researchers (Chase 2016; Sampire 2016) in suggesting that the original DI theory is incomplete. Seba holds that DI does not explain iPhone disruption, why electric vehicles are disruptive, or what is happening with transport company Uber's disruption of the traditional taxi market, which is leading to technological system changes.

Seba expands on Christensen's definition to include all and any phenomena that result in disruption to a technological system. His book *Clean Disruption* (Seba 2014a) covers his theories around technological disruption and business model innovations, which he claims are as important as the kinds of disruptions that Christensen examined through the Information and Communication Technology sector, changing the nature of other parts of the economy (Seba 2013, 2014a). Seba discusses disruption as a micro-technological wave of innovation that is accelerating over time. Under this scenario, shortening of micro-technological waves decreases the likelihood of companies catching up to the mainstream market when they are being disrupted. According to Seba, a key characteristic of a disruptive innovation is that the product's market share grows exponentially not arithmetically.

Seba classifies Christensen's disruption theory as 'Disruption from Below', which in his opinion is just one of three modalities of disruption. The other types of disruption are 'Disruption from Above' and 'Big Bang Disruption'. Solar PV is an example of 'Disruption from Below', where the technology is initially expensive and of a lower quality and less capable at providing what the mainstream market wants, in this case 24-hour electricity, though it did begin to fit certain key niche markets. The uptake of solar was driven initially by solar subsidy, which resulted in lower production costs due to mass-market adoption. As the technology improves in quality and grows in demand, the price declines and it begins to disrupt the mainstream market. PCs, digital cameras and mobile phones are other examples that Seba gives of this type of disruption.

'Disruption from Above' refers to a superior product that is more capable than the current mainstream market offerings, but is also more expensive. As the cost of the product declines, the product disrupts the market from above as it comes down in price (Seba 2014a). The Tesla electric vehicle has been rated the best car of any kind in the world, but is currently a luxury car item at over US$100,000 (TeslaMotors 2015). However, according to Seba, as Tesla intends to release an affordable model into the market in 2017 (Hull 2016), electric vehicles will become more accessible to consumers and thus increases the likelihood of disruption to the traditional car market. Similarly, smartphones originally did not compete with traditional mobile phones due to their price, however, they have since become very affordable and 70% of the world's population is expected to have a smartphone by 2020 (Ericsson 2015).

The third type of disruption Seba refers to is called 'Big Bang Disruption'. This is where an initial product is already more capable, at a lower price, than the existing mainstream market products and, when it is introduced, immediately disrupts the current market. Driving navigation offered by Google Maps is an example of this occurring. From the beginning it was cheaper and more accessible to the market than the existing Tom-Toms. Downes and Nunes (2013) also subsequently explore Big Bang Disruption.

All the contributors to DI agree that DI phenomena results in the rapid decline of incumbent services and products. They become 'stranded assets' (detailed further below) in the mainstream technological system, both at the micro-level and the macro, or system level. DI is not limited to technology, and has a strong relationship with different contextual 'catalysts', such as governance structures, business models and behaviour change.

An example of this systemic relationship can be seen in the decline of Kodak, a photographic film company in the late twentieth century that dominated the market, but filed for bankruptcy in 2012 due to losses in the digital camera business (McCarty and Jinks 2012). Technologically, Kodak was well positioned to survive the disruption of digital camera technology as they invented it, and had hundreds of patents (Eastman Kodak 2006). They entered the market at the early stages of the deployment of digital cameras, anticipating they would participate in the market, but did not survive the disruption. This is because the business model Kodak tried to apply to digital cameras was flawed. It was an adaption of the same model used for film photography that aimed to monetise a slice of every digital photograph that was taken. This was not how the digital camera industry evolved to operate, with digital technology allowing for hundreds of photos to be taken at one time for no cost. Rather, the new business model is centred on the actual camera, camera accessories, add-on software and media platforms (Seba 2014c). Kodak's failure to innovate across their business and commercial models with the new technology demonstrates that technological developments do not occur in isolation and that systemic change within an industry must be met with new business models.

The three core features of DIs are thus: 1. They occupy a niche that expands into being a major disruption to the technological system; 2. They grow exponentially and are thus very surprising in their disruption and 3. They create stranded assets. Before applying these DI features to renewable energy, we will further expand on stranded assets.

2. Stranded asset theory

Building on the work from Krause, Bach, and Koomey (1990) who made the link between carbon budgets, fossil fuel reserves and company valuations, in 2012, Carbon Tracker, a

UK research institute evaluated the potential for fossil fuel assets to be disrupted by low-carbon energy sources (Carbon Tracker 2012), or to become 'stranded assets' (Schwab and Sala-i-Martin 2011; IPCC 2014; Kossoy et al. 2015). This disruption, in some cases, is catalysed by government policy that supports renewables and limits the consumption of fossil fuels for energy generation. According to Carbon Tracker, assets can become stranded for three main reasons: regulation, physical impacts or change in market demand, which dramatically alters the intended market course of the product (IEA 2013; Carbon Tracker Initiative 2014).

Regardless of the forces behind the change, the result is the same: the previously valued product becomes redundant and the investment required to maintain it is not covered by the benefits arising from its use, leaving owners with high costs, low revenue and a stranded asset (Seba 2014b). In the current economic and technological climate, electricity and transport generation industries that rely on carbon intensive fuels are at particular risk of becoming obsolete, as low-carbon technologies such as solar PV panels and batteries enter the market at low price points that are continuing to decline. A coalescing of factors (government policy, technological change, climate change concerns, pricing change and business models) are influencing the demand trajectory of fossil fuels, and therefore the risk of them becoming stranded. Thus the ultimate aim of this paper is to begin to develop a tool for helping in this transition.

3. The disruption of global energy markets due to solar-battery systems

Small-scale household solar has had significant uptake in recent years, mostly due to government subsidisation, and in some places, high electricty prices (IPCC 2014; Green and Newman 2016). However, there is now the potential gamechanger of relatively cost effective battery storage systems, which can operate to regulate the load of solar PV systems, as well as into other fluctuating renewable systems, like wind power (Henbest et al. 2016). This development rectifies the primary defect of solar PV technology; the inability to provide electricty at night. Battery storage has always been the holy grail for renewable energy (Arif et al. 2013; HYG 2015). Moreover, the continued innovation and mass production of these products are now pushing down their prices to make them acceptable to niche markets.

Thus the three core features of DI are applied to this emerging technology.

4. Niche in the technological system

The solar PV and battery combination occupies a niche that could expand into being a major disruption to the technological system. The key benefits in this potential disruption is the ability of battery storage to offer cost effective, fossil fuel free energy, and to give consumers a degree of energy independence as their generation systems will see them load defect, and potentially go off-grid all together (Green and Newman 2016).

Even though the uptake of household solar PV has allowed for some grid independence, the inability to provide power when the sun is not shining or the wind is not blowing has allowed households to still be at the mercy of fossil fuel energy utilities. With Tesla's 2015 announcement (Debord 2015) that they will be deploying a lithium-ion phosphate battery at a commercially viable price in 2016, along with other battery manufacturers, households now have greater control over when to use solar PV generated electricity and when to sell it back to the grid. The response to this announcement was that Tesla received a full order book in the first week, with a potential revenue value of $800 m as calculated by Bloomberg Business (Randall 2015).

In Perth, Australia, the past few years have seen Perth develop more than 550 MW of power from rooftop solar (20% of all homes (Green and Newman 2016)) with these households now adding battery systems. As batteries experience mass-market uptake their prices are set to further decline, allowing solar and battery scenarios to approach grid parity, with predictions showing that this could happen in some areas of Australia as early as 2017/2018 (Figure 3) (Green and Newman 2016).

There appears to be little doubt that battery storage along with PV is meeting a niche need and has wider applications in delivering power during peak periods, providing capacity and frequency ancillary services (Fitzgerald et al.2015) that is predicted to impact on the whole electricity system in a very short time.

5. Rapid exponential growth

Solar PV demand in the last 10 years has been fuelled by massive amounts of global investment, driving down the price by 75% (IRENA 2015) and expected to continue, further driving deployment at faster rates than seen previously (Whiteman et al. 2016).

Batteries are only set to exacerbate this growth. For example, Morgan Stanley have predicted that the incoming batteries will enter the existing Australian market of householders with solar panels, of roughly 1.5 million people, and be deployed in a further 1 million households (Koh et al. 2015). In 2016 the price of batteries went from $2000 per kwh to $500 per kwh (SolarQuotes 2016).

6. Stranded assets

The rapid adoption of renewable energy due to storage is impacting the existing electricity assets and threatening the current business models of fossil fuel companies, utilities and

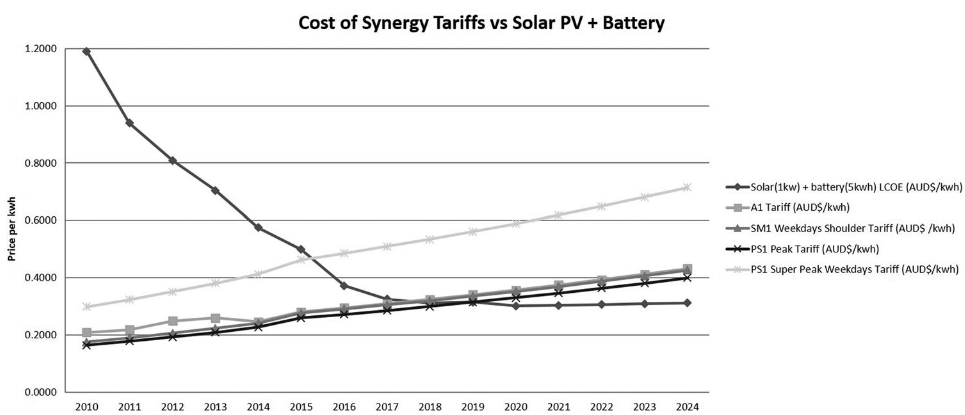

Figure 3. Solar and battery systems reaching grid parity with different tariffs (Green and Newman 2016).

related assets. The uptake of renewable energy technologies has historically been due to government subsidisation (Haas et al. 2011) but now, with generally low subsidisation, it is being driven by price as well as other demand drivers such as a desire to acquire a low-carbon lifestyle (Newton and Newman 2015). As solar PV begins to bite into the market it is predicted to disrupt the present institutional structures that have grown up around the old way of producing centralised power.

Thus the demand outlook for fossil fuels is increasingly uncertain in both the developed world and in many developing countries. Instead of their businesses being valued by volume based revenue streams, which are in decline and trending to further decline, utilities will need to innovate around technologies and business models in order to survive.

Utilities are already experiencing the beginnings of disruption. Given the rate of change that is occurring, financial analysts believe it is conceivable that as much as 80% of the global energy market will have reached grid parity for renewable energy by 2017 (Deutsche Bank 2015). Mainstream financial research has predicted that the fossil fuel industry could lose up to $28 trillion over the next two decades as a result of this and other factors (Kepler Cheuvreux 2014). If customers reduce their reliance on grid electricity further, utilities will need to either charge higher prices or change their business models to survive.

If they choose to, utilities have an opportunity to capitalise on this new technology through the provision of new products and services such as selling and leasing renewable energy and storage systems to homes and business (Alloway 2015). Outlined in Green and Newman (2016), there are three potential responses that governments and incumbent utilities can have in reacting to the disruption of energy markets: Fight, Flight or Innovate. These responses are characterised separately below, but may be displayed concurrently, that is, a company could initially lobby against battery and storage updates and also employ innovative strategies to shift their business model (see Figure 4).

6.1. Fight

Government and utilities may take a resistant position against renewables and storage, implementing protectionist policy that maintains the market share of utilities, effectively 'fighting' this new wave of technologies. In this scenario incumbent players lobby government to implement policy reform that would protect their business models, for example, setting a higher fixed tariff. Regulators could also place restrictions or limit the ability of

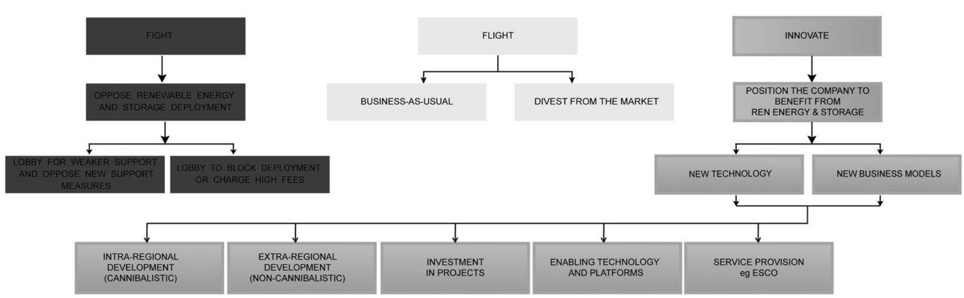

Figure 4. 'Fight', 'flight' or 'innovate' options for businesses threatened by decentralised energy business models (Green and Newman 2016).

customers to connect batteries up to a certain point, or altogether. A strong fight response may cause a negative consumer reaction, seeing households retaliate by utilising household solar PV and battery systems to dramatically reduce their dependency on offending companies. This will result in a dramatic increase in stranded assets.

6.2. Flight

The 'flight' response could see governments and utilities take one of two actions. First, they could do nothing and let solar and battery products disrupt energy markets, severely impacting their business models. Alternatively, the flight response could see companies sell their position and divest from energy markets altogether. Divestment could take the form of investors selling their shares in a utility, or a utility selling their fossil fuel-based assets. This response will also see assets stranded on a micro-level, and on a systems level will result in utilities going under as they struggle to adapt.

6.3. Innovate

Finally, utilities could adapt their business models to profit from these new products, 'innovating' through a number of different mechanisms. Likewise, regulators could implement policies that foster the uptake of renewables. Whilst the innovate response would be no guarantee of success, as some companies will offer better products and services than others, and some more quickly than others, this course of action gives companies the best chance of surviving market disruption, and to avoid becoming a stranded asset in themselves.

The three DI core features of solar PV and other renewables with batteries suggest that it is indeed a disruptive innovation. This means it is likely to dramatically impact the market, necessitating the development of tools that can help predict the point at which assets could become stranded and also the extent of the renewable energy transition.

7. Renewable forecasts

Fossil fuel companies such as Exxon Mobil and Shell have undertaken some work to examine the global energy market and developed forecasts into the future that demonstrate their businesses' immunity from potential risks such as climate change policy, or the growth of renewable energy generation (ExxonMobile 2014; Shell 2014). In April 2015, one of the world's largest coal producers, Glencore, echoed the same sentiments (Glencore 2015). These companies believe that global energy demand will continue to grow due to the industrialisation of the developing world. They therefore do not believe that renewables will have the capacity to meet global demand for energy.

A variety of organisations have created different forecasts for global energy demand out to 2050. These do not include fuel for combustion transportation. We have condensed this data in to Figure 5. These organisations are: The IEA, Shell, World Energy Council, B.P, MIT, Exxon Mobil, EIA, Bloomberg New Energy Finance, the University of Western Australia and Curtin University.

The global energy demand scenarios of the organisations evaluated range from 769 EJ (UWA) to 988 EJ (Shell). While sources aim to be as accurate as possible, it should be

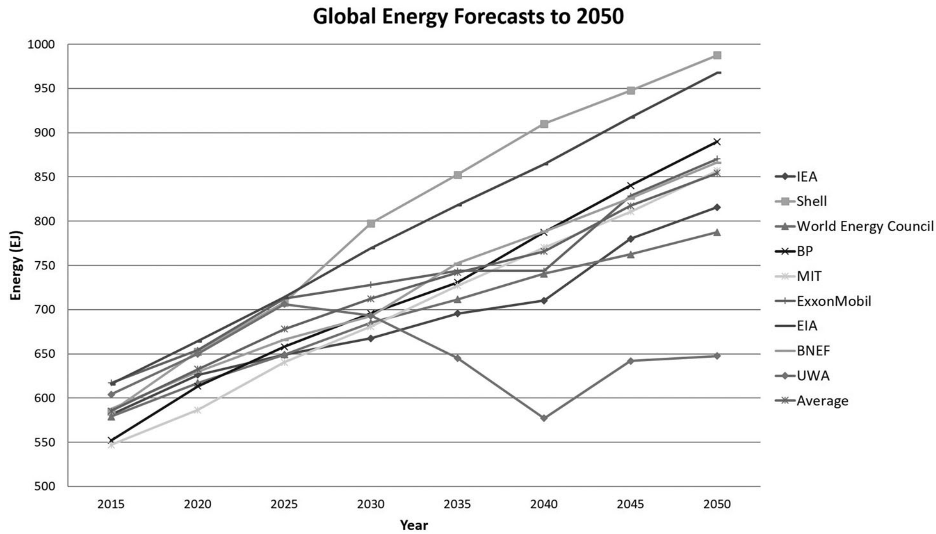

Figure 5. Energy organisation's global energy demand forecasts.

noted that the petroleum related organisations account for the figures at the higher end of the spectrum.

We also compare the renewable energy forecasts of the same set of organisations out to 2050 (Figure 6).

The range of predicted global renewable uptake forecasts are from 86.2 EJ (MIT) to 415.9 EJ (UWA). There is a large range between the forecasts and, distinct from the global energy demand forecasts, there is a diverse range of views from the petroleum related organisations. However, these graphs show that these energy companies are

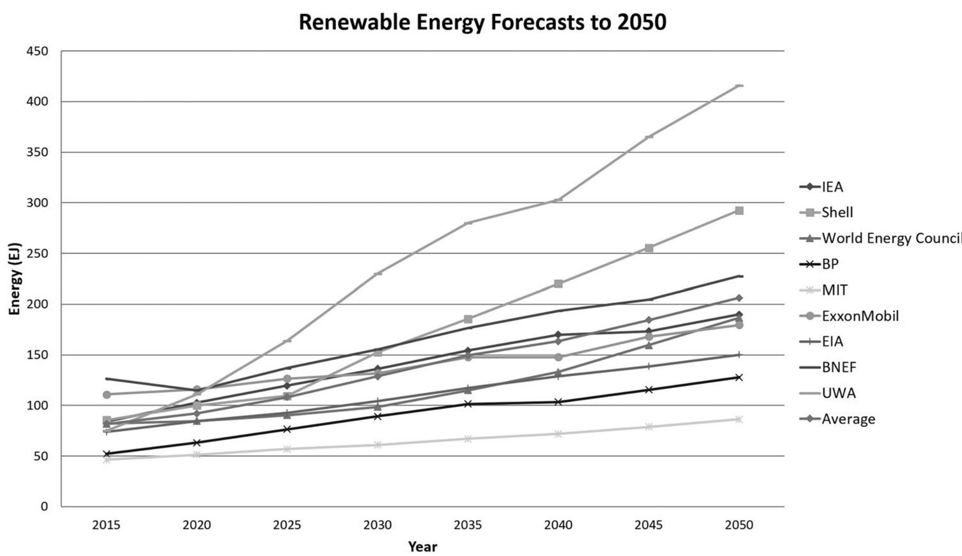

Figure 6. Energy organisation's global renewable uptake forecasts.

basing their risk analyses for their assets on assumptions that global energy demand will continue to grow, and while they acknowledge that renewables will also grow, this will not be at a rate that will allow them to meet this demand before 2050. These assumptions may or may not play out.

In October 2015, BHP Billiton released its *Climate Change: Portfolio Analysis*, that examines the impact that low-carbon technologies may have on the resources sector, as well as the effects that climate change will have on companies' asset portfolios. The report concluded that despite mitigation attempts from governments and industry alike to keep global temperature rise below two degrees, their business, which is largely predicated on fossil fuels, will grow at best, over 100%, and at worst by around 80% out to 2030. This continued growth is largely attributed to the expected growth in energy demand as developing countries industrialise, and that they have high quality and lower cost fossil fuels. On the first point, energy demand growth is true, but renewables and storage are going to compete against traditional fossil fuels. On the latter point, their resources are indeed high quality and low cost, but their analysis neglects the fact that countries may choose to source their fossil fuels domestically rather than importing them, regardless of cost and quality. India has already begun to do this. Therefore BHP Billiton's outlook for total energy and renewable energy growth are by no means certain.

In recent years, many countries are reducing their energy consumption as a function of GDP due to a number of factors including: increased energy efficiency, carbon pricing, the cost of energy etc. These trends are noticeable on a State-by-State basis in places such as the European Union, Australia, the US and even, more recently, in China (EU Commission 2013; Buckley 2014; Buckley and Sussams 2014; Stanwix, Pham, and Ball 2015). However, there is not yet a visible global trend, mostly due to the huge industrialisation push in China and India over recent decades, with China accounting for approximately 20% of global energy demand though recent data shows both China and India decoupling in both coal and oil (EIA 2015; Newman and Kenworthy 2015).

The view that large amounts of energy will be needed due to growing GDP is also being challenged by the decoupling of wealth and energy (BNEF 2015). In early 2014, BP concluded that as a result of advances made in energy efficiency and intensity, the amount per unit of GDP will decline at 1.9% p.a. between 2012 and 2035, with a total decline of 36%. The IEA also concluded in its World Energy Outlook (IEA 2014a) that primary energy demand and GDP have decoupled slowly due to structural changes in the economy and more efficient energy use. This recent global decoupling can be seen in both developed and developing countries. As an illustration, in 2015 China's GDP grew 7%, yet its energy intensity only grew 3.8% (Garnaut 2015). In the USA, the 2013 Annual Energy Outlook predicts an average decline of 2% in energy intensity, that will continue through to 2040 (U.S. Energy Information Administration 2013). There is therefore growing evidence that global fossil fuel demand and GDP are in fact already decoupling (Von Weizsäcker et al. 2014).

With this lack of consensus we undertook research on a tool that can help determine the implications and impacts of renewable energy with battery storage as a disruptive innovation. Our global energy forecasts analyse historical global energy use and forecast energy use out to 2050, including scenario analysis for the decoupling of global energy demand and GDP. We also develop scenarios for the growth of global renewable energy generation and compare this to global energy demand, identifying permutations in which renewables could account for 100% of global energy demand before 2050. The IPCC (2014) synthesised scenarios for different energy and greenhouse gas futures based on various energy mixes and economic variables. These are highly sophisticated computer models that cannot be reproduced in this research project but it is possible to add to their insights as the work summarised here simply uses more hopeful scenarios based on the rapid processes of change that are now beginning to be documented (see Green and Newman 2016) The reality of disruptive innovation enables more hopeful scenarios to be set out because the disruption is so rapid and can take over much more quickly than models that are based on past trends.

8. Estimating renewable energy disruption: global energy forecasts

Global future energy forecasts available today are typically predicated on the view that the industrialisation of the developing world will continue as the developed world did in the past. This assumes the need to rapidly supply infrastructure and energy in line with GDP growth without great consideration for energy efficiency and low-carbon energy options. However as shown above it appears that renewable energy, especially now that battery storage has become available at marketable prices, is a DI and that it is therefore likely to expand exponentially and cause major disruption to traditional markets in the fossil fuel power system. Thus instead of growth in GDP automatically causing growth in fossil fuels as has been seen for the Fourth Wave economic cycle, it is likely that fossil fuels and GDP will decouple quite dramatically.

To exemplify this we undertake the following analysis:

1. Using historical energy data from BP and the IEA from 1980 to 2014, we map historical, global energy demand and then forecast a number of scenarios in which demand decouples from GDP at a rate of 10%, 20%, 30%, 40%, 50% and 60% out to 2050.
2. Using historical energy data from the IEA from 1990 to 2010, we map the growth in renewable generation and then forecast three different scenarios in which the rate of growth of renewables increased by 10%, 20% and 30% out to 2050.
3. We then compare these scenarios, identifying which permutations will see renewable generation accounting for 100% of global energy demand by or before 2050.

For the Global Energy Forecasts we analyse data from the following institutions: the IEA, Shell, World Energy Council, BP, MIT's Joint Program on Global Change, ExxonMobil, EIA, BNEF, the University of Western Australia and Curtin University.

9. Energy scenarios to 2050: method and results

The intention of this modelling is to visualise a number of different scenarios for global energy demand, taking into account different variables such as GDP and energy efficiency. Referencing a combination of historical data from the IEA and BP from 1980 to 2014 (BP 2015; IEA 2015), we also model the growth in renewable energy generation and compare the two, highlighting which combined scenarios would see global energy demand solely produced by renewable generation.

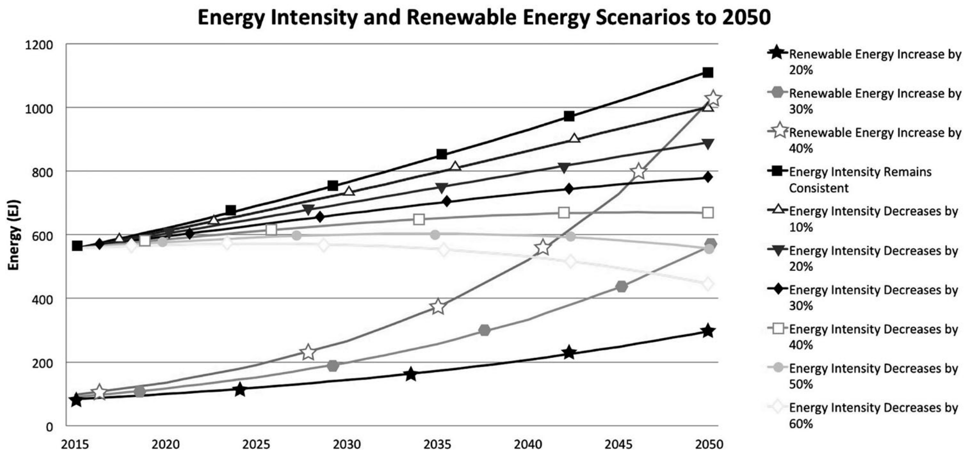

Figure 7. Energy intensity and renewable energy scenarios to 2050.

We then forecast a global energy demand scenario based on a continuing relationship between GDP growth and the growth of energy consumption, which is consistent with historical correlation from 1980. GDP is significant as the most important factor driving energy consumption, historically, is economic growth. In principle, as has been the case historically, the faster an economy grows, the greater its energy consumption (EU Commission 2005).

It is because of these emerging trends of reduced energy consumption that we have developed a number of scenarios that examine global energy demand decoupling from GDP growth rates of 10%, 20%, 30%, 40%, 50% and 60%. We have also used IEA data from 1990 to 2010, (IEA 2014b), to forecast the growth of renewables out to 2050 at a rate of 20%, 30% and 40% (Figure 7).

To compare these scenarios, we have identified eight potential permutations in different years including two options for 2050, in which 100% of global energy demand would be met by renewable generation (Table 1). For 2050, two ways of achieving this are examined to show how either a greater uptake of energy efficiency measures (as indicated by the energy and GDP relationship decoupling) or growth in renewable energy per say will impact the scenarios.

The scenario we consider most feasible sees a 40% renewable energy growth rate and the relationship between energy and GDP decoupling 20% between 2015 and 2050.

Table 1. Scenarios for renewable energy accounting for 100% of global energy demand.

Energy intensity and renewable energy scenarios to meet by 2050				
Year	Energy and GDP relationship decorrelation (%)	Renewable energy growth rate (%)	Global energy (EJ)	Renewable energy (EJ)
2041	60	40	525	562
2042	50	40	593	603
2044	40	40	669	687
2046	30	40	762	786
2047	60	30	477	485
2048	20	40	872	903
2050	10	40	1002	1020
2050	50	30	556	564

This could see renewables supply 100% of global energy demand by 2048, which would effectively render all fossil fuel assets for power generation, stranded.

10. Energy scenarios to 2050 implications

The data presented above is based on taking seriously the notion of renewable energy as a disruptive innovation that is likely to grow exponentially and cause disruption to the whole fossil fuel power system. It suggests that rapid disruption may set in and by 2050 the whole of the fossil fuel-based power system could be stranded. The majority of scenarios about the future are more of a reflection of the past; suggesting that small changes are all that could be expected. Like Kodak, fossil fuel-based power companies may be surprised. Some are beginning to support the idea that governments, utilities and industry should prepare for a more rapid transition. For example, Tony Seba's view is that technological developments and the growth rates seen in renewables will make coal, oil, nuclear, natural gas, conventional cars and electric utilities obsolete by 2030. Our view, as outlined above, is that there could be consensus around structural decline by this stage, but that the market for fossil fuels would not be stranded until around 2050.

Although some fossil fuel companies, financial analysts and investors may view energy projections from organisations such as the US Energy Information Administration (EIA) as being forecasts, the EIA has makes clear their Reference Case is a projection of current trends, not a forecast (EIA 2016). Carbon Tracker has also challenged the assumptions made in company financial reports saying that the 'distinction seems to have been lost' (Carbon Tracker 2016). Although the Energy Scenarios proposed in this paper have limitations in that they are based on speculative futures, they are not purporting to be actual futures, rather showing what disruptive conditions would need to be fulfilled for them to occur. Looking at a combination of scenarios based on a variety of assumptions is needed for robust risk management.

The major implication of these results is that fossil fuel companies need to develop a more sophisticated risk assessment approach and scenario analysis that assess different factors impacting businesses, rather than simplistic, generalised statements saying there is 'no risk'. The fossil fuel sector is mostly suggesting that future energy demand will be so great that even with significant deployment of renewable energy, fossil fuel generation will be required to meet energy demand. However, this paper has shown that due to the coalescing of a variety of factors, listed below, long-term and medium-term historical trends of global energy demand are not an adequate indication of future global energy demand. These include:

- Lowering costs of renewables;
- Lowering costs of, and as of 2017, grid-competitive energy storage due to new technology Li Ion batteries;
- Growing domestic and international policy constraints on the production of carbon dioxide and air pollution from combusting fossil fuels;
- Technology leaps in energy efficiency; and
- Trends towards knowledge-based economies along with mass transit infrastructure (Newman and Kenworthy 2015).

Not all fossil fuel companies believe the issue is immaterial. Aside from BHP's new report mentioned earlier, which stress tests their portfolio for potential liabilities, AGL Energy, one of the Australia's largest coal-fired power generation buyers of recent years, has announced it will not buy, expand or extend its current coal-fired portfolio and that it plans to close down its coal plants by 2050 (Hannam 2015). In 2014, German utility E.ON announced that it would be jettisoning its fossil fuel assets in a new company to focus on their renewable portfolio (Steitz 2014) and in September 2015 Energie Badem-Wuerttemberg, the third biggest utility in Germany announced a sale of its fossil fuel assets (3.4 Billion Asset Sale." Bloomberg Business. http://www.bloomberg.com/news/articles/2015-09-13/enbw-to-fund-green-power-makeover-with-3-4-billion-asset-sale.
Andresen 2015). These activities would suggest that renewables are already disrupting energy markets. Our analysis takes this further by showing how renewable energy could completely disrupt and displace the fossil fuel industry. These systems will need to be taken into account when forecasting the future energy mix. Forecasts are inherently subjective and we do not suggest that our energy mix forecasts are a precise depiction of the future. What this research has sought to do is look at the trends and technological shifts and consumer demand changes that are likely to play out in the short to medium term.

There are significant implications for lenders and investors that are exposed to companies tied to the fossil fuels sector. For companies that are acknowledging this energy transition, conducting robust portfolio risk analysis and hedging their exposure, investors will assume less long-term downside risk. For those companies that do not acknowledge the transition or conduct rudimentary analysis and determine there is no risk, investors are by extension more exposed to greater potential risks and financial losses. Mainstream financial *analysts* are starting to assess how prepared companies are for these changes and a number of financial products are available for investment strategies to tilt portfolios away from fossil fuels. We anticipate that companies will begin to undertake more rigorous analysis of their own portfolios. We also anticipate that financial *analysts will,* to a greater extent, incorporate these risks in informing their investment views of these companies. Those acting sooner will ultimately expose themselves less to the downside risk of falling revenues and ultimately stranded assets.

11. Conclusions

This paper suggests that solar PV with batteries is a disruptive innovation. The deployment of these technologies will rapidly grow like other disruptive innovations, now that it is near or better than cost competitive in electricity markets. It is predicted that Solar PV with battery storage systems will also impact on the businesses that are based around the centralised grid system, disrupting the whole fossil fuel-based power system. As the replacement technologies become cheaper, and as the policy settings further evolve, business models of incumbent utilities are likely to be further and further disrupted.

Companies and investors that depend on value driven by carbon intensive energy are at serious risk of being rapidly devalued. Some believe that the valuation of fossil fuel dependent companies are already showing signs of becoming stranded assets. The new urban mass-markets for solar PV with battery storage are enabling countries across the globe to introduce stronger and stronger policies that limit the emissions of carbon dioxide, thus further feeding the structural decline of fossil fuels. The G7 in 2014 committed to phasing out all fossil fuels by 2100 and the Paris Agreement in 2015 (EU Commission 2015) suggests a material step further in controls. The market strength now evident in renewables, with battery storage, provides the key disruptive innovation that has the potential to enable global forecasts to phase out fossil fuels by 2050.

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