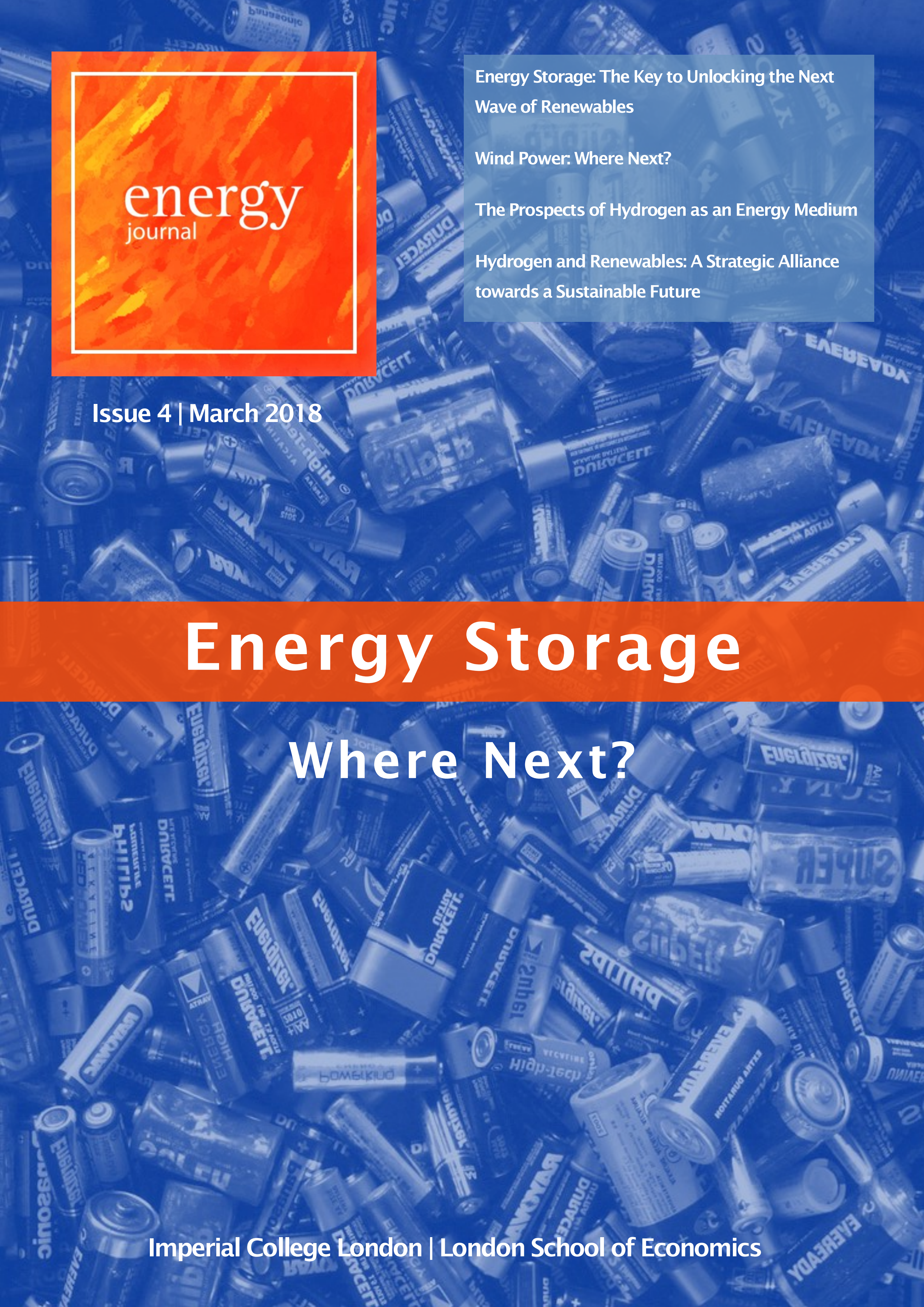

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Issue 4 | March 2018

Energy Storage

Where Next?

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From the Editor

Dear reader,

The energy industry is undergoing tremendous change. This edition of the *Energy Journal* explores the single most important transformation in energy: the shift towards solar energy and towards battery storage. The articles explore technological, financial and political affairs that are disrupting energy.

The revolution towards low-carbon and renewable sources of energy is tearing down the incumbent fossil fuel monopolies. Energy is being electrified as demand for electricity, notably from electric vehicles, rises. Technological advances, changing consumer preferences, and new policies are pushing de-centralisation of power away from top-down, one-way centralised grids. They are being replaced by decentralised and dispersed grids that offer more control for customers to generate and store their own energy. This future energy system is being powered by solar power and made possible by battery storage.

Both have witnessed huge falls in prices as well as technological breakthroughs. Both are becoming economically feasible as well as cost competitive with fossil fuels. Whereas solar energy generates long-term financial benefits, battery storage offers energy independence and reliability. When combined, smart solar-plus-storage leverage the digital transformation to provide clean, lean and green electricity. The ability for households, businesses and communities to generate and store their own electricity is re-defining energy. Decentralised solar-plus-storage is compatible with social equality, pluralism and liberty.

Energy constitutes 10% of global GDP. The transition towards the future is a unique opportunity for you to discover, understand and seize.

It is my pleasure to present you with the fourth issue of the *Energy Journal*. I would like to personally thank all the writers for the time they've dedicated. Their enthusiasm to write for you meant that not all articles were selected, although the effort invested did not go unnoticed. I would also like to thank my team. We worked tirelessly to deliver to you this overhauled edition.

In its second year, the *Energy Journal* has been rebranded and redesigned. We've also welcomed the Imperial College London Energy Society. Merging the two pre-eminent universities' different backgrounds offers complementary and inter-disciplinary diversity to our publication. We have introduced several additions to encourage you to learn more about the opportunities in energy.

Last but not least, I want to thank you – the reader – on behalf of the entire team for your interest in the *Energy Journal*.

Your chief editor,

Egor Nevsky

Raison d'Être of the Energy Journal

The Energy Journal is a biannual magazine focused on current energy affairs, published by the LSE and ICL Energy Societies. The Energy Journal exists to raise awareness of the opportunities in energy. Although it has always existed, the energy landscape is currently being up-ended by technological innovation, climate action and market forces. Editions are accessible to all students to discover the future of energy. Pro-active and ambitious students are given the opportunity to join the energy community to define that future.

Politics

The **UK's** Eggborough **coal power** station is to close this autumn, leaving just eight coal-burning generators in the country. 130 jobs may be lost. The Yorkshire plant usually supplies 2 gigawatts of electricity but failed to secure contracts for next winter. It began operation in 1967.

The **United States** through its International Trade Commission has implemented a 30% tariff on all foreign imports of **solar cells and modules**. The decision results in a 10 cents/W increase in the price of solar modules and could lead to a 11% curtailment of US solar installations by 2022.

The **United States** has passed a **carbon capture tax credit** (called "45Q") that would fund $50 per ton of CO2 that is buried into the ground. The credit is expected to support development and implementation of Carbon Capture and Sequestration technology

What's the news in Britain? A report commissioned by the All-Party Parliamentary Group on **Energy Storage** found that 12GW of energy storage could be installed in the **UK** by 2021 (REA, 2017). Among the options is London startup ArenkoGroup, which in February announced a partnership with GE to supply a subsidy-free 41MW energy storage facility near the Midlands in 2018 (Arenko, 2018).

Scientists at the **US Department of Energy** have found an efficient way to turn **waste carbon dioxide captured** from CCS processes into syngas – a mixture of carbon monoxide and hydrogen that can be used as fuel, though conventional carbon storage is still needed in combating global warming.

The **Abu Dhabi National Oil Company** plans to expand its **carbon capture programme** six-fold to cope with the increase in the use of CO2 in maturing oilfields. CO2 has been extensively used to boost oil recovery rates, the process of which is known as Enhanced Oil Recovery (EOR).

UK investments in wind, solar and other **renewable** sources dropped by 56% to $10.3bn (£7.5bn) in 2017. This was the steepest decline of any country, far out-stripping the decrease of 26% for Europe as a whole. Keegan Kruger, wind analyst for BNEF, said to The Guardian in January 2018 that investors and developers need more transparency from the government.

Donald **Trump** has controversially suggested funding to the **Office of Energy Efficiency and Renewable Energy**, will be cut by 72%. Stated in the President's draft budget for the 2019 fiscal year, the proposed changes will reduce the budget from $2.04bn to just $575.5m; however, this will have to pass congress.

In 2018, **Iceland** looks set to expend more energy mining virtual currencies than powering its homes. The process involves enormous amounts of energy to power the computers involved in the mining process, and due to Iceland's bounty of renewable energy sources, the country has boomed as an international **cryptocurrency** hub.

The **UK's power consumption** fell by about 2% in 2017. It became the only country to see a fall in the EU, who saw an overall rise by 0.7%. The decline is one the largest in several years and could be attributed to a decrease in industrial activity and users choosing more energy-saving appliances.

Polar bears are losing weight in the Arctic. Scientists conducted a study on 9 female white giants over 10 days in April and found that 5 of them lost weight, with one of them losing 51 pounds in 9 days. **Climate change** is a cause as the reduced ice cover makes it harder for them to hunt for seals.

As of December 2017, the £16bn **International Thermonuclear Experimental Reactor** (ITER) being built in France is now 50% complete. The scientists are on course to begin generating plasma in the machine's core in December 2025. If this nuclear fusion technology is proven, it could generate **clean energy** in just over 20 years.

Markets

EDF is planning to accelerate **renewable energy deployment** having witnessed its UK nuclear revenues collapse in 2017. EDF's wind and solar generation capacity now stands at 8.8 GW across the group. The company in 2017 installed an additional 1.8 GW of this type of generating capacity, representing a 23% increase in its overall wind and solar capacity.

Dyson has announced its intention to enter the **electric vehicle market**. The company is investing £2 billion, half of which is earmarked for battery research. It intends to start selling the first of three models in 2021. Dyson specialises in appliance manufacture; this is its first automotive venture.

Blockchain technology will soon be implemented in **Germany** in a "first of its kind" pilot project to provide decentralized solutions to bottleneck problems in the power grid. Storage systems will be used for "re-dispatching" excess of energy. **IBM** blockchain platform will be used to record the transactions automatically and in a secure way.

Indian electricity company **Tata Power** reported a four-fold increase in profits from their **renewable energy** business. The company has proposed to 'draw up to 40% of its generation capacity' using renewables by 2025; this ambition is nationwide as India looks to move away from coal-based plants.

BP has declared it is looking to acquire more **green energy firms**, as the British oil giant pledged to set carbon targets for its operations. BP recently bought a $200m stake in Europe's biggest solar developer, returning to solar power six years after it quit the sector.

A 15-hour flight between LA and Melbourne on 29th January 2018 was the first flight powered by **biofuels**. Mustard seeds were used as part of a blended fuel on the **Qantas** flight, and this helped reduced carbon emissions by 7% as compared to the usual flight.

Boeing 787-9; Photo: Qantas

FOCUS

Energy Storage

Energy Storage

Energy Storage: The Key to Unlocking the Next Wave of Renewables

Nathan Murray – ICL

A clichéd criticism of low-cost renewable energy such as wind and solar goes something like this: "What will we do when the sun doesn't shine, and the wind doesn't blow?" In response, many energy enthusiasts argue that large-scale energy storage is necessary to transition the world to a low-emission (and low-cost) energy system. The benefits of such technology may be more widespread than they first seem.

Solar power has a problem both when the sun doesn't shine - and when it does. Take a look at a country like Germany, which can supply half of its domestic demand during a sunny day in the summer (Fraunhofer, 2018). When solar panels were first installed at scale in Germany during the end of the 2000s, solar power enjoyed the benefit of supplying electricity when demand was highest and at its most expensive. The electricity price is set by the marginal generator. The plant is considered 'marginal' because it the most expensive generator operating on the network. The *merit order effect* (Figure 1) describes how generators can be ranked by their capacity and cost. For a given electricity demand, the most expensive generator sets the price to meet its costs. The rest of the plants on the system are paid the same price and receive a margin of profit. For solar, the fuel cost is zero. As sufficient solar power comes on-line (or demand is reduced), the marginal plant shuts down and the next most expensive plant running lowers the price.

As German solar energy reached higher levels of market penetration, an interesting effect occurred: electricity became less valuable (Hirth, 2015). From 2006-2013, as solar market share increased to 5%, its market value fell by 35% due to excess supply and lower market prices during the mid-day hours. However, as soon as the sun sets, the electricity price snaps back, sometimes over the long-run average. The same trend, with a more modest effect, can be seen with wind generators. Renewables are cannibalizing their own market!

Electricity is valuable when it is scarce. It is even more valuable when it can be supplied under unexpected circumstances. The UK National Grid employs a set of ancillary services in order to prevent emergencies in the electricity system. Frequency Response helps maintain the frequency, or 'clock', of the UK grid at 50 Hertz (plus or minus 1%). Reserve Services ensure that energy is balanced between supply and demand points. Demand Response allows the National Grid to drop off loads that stress its wires. Typically, these lucrative services are met with low capital-cost, high operational-cost machines such as 'peaking' oil or gas generators, which operate when national electric power demand is at its highest. However, an old technology strengthened by the new electric vehicle revolution is changing the paradigm.

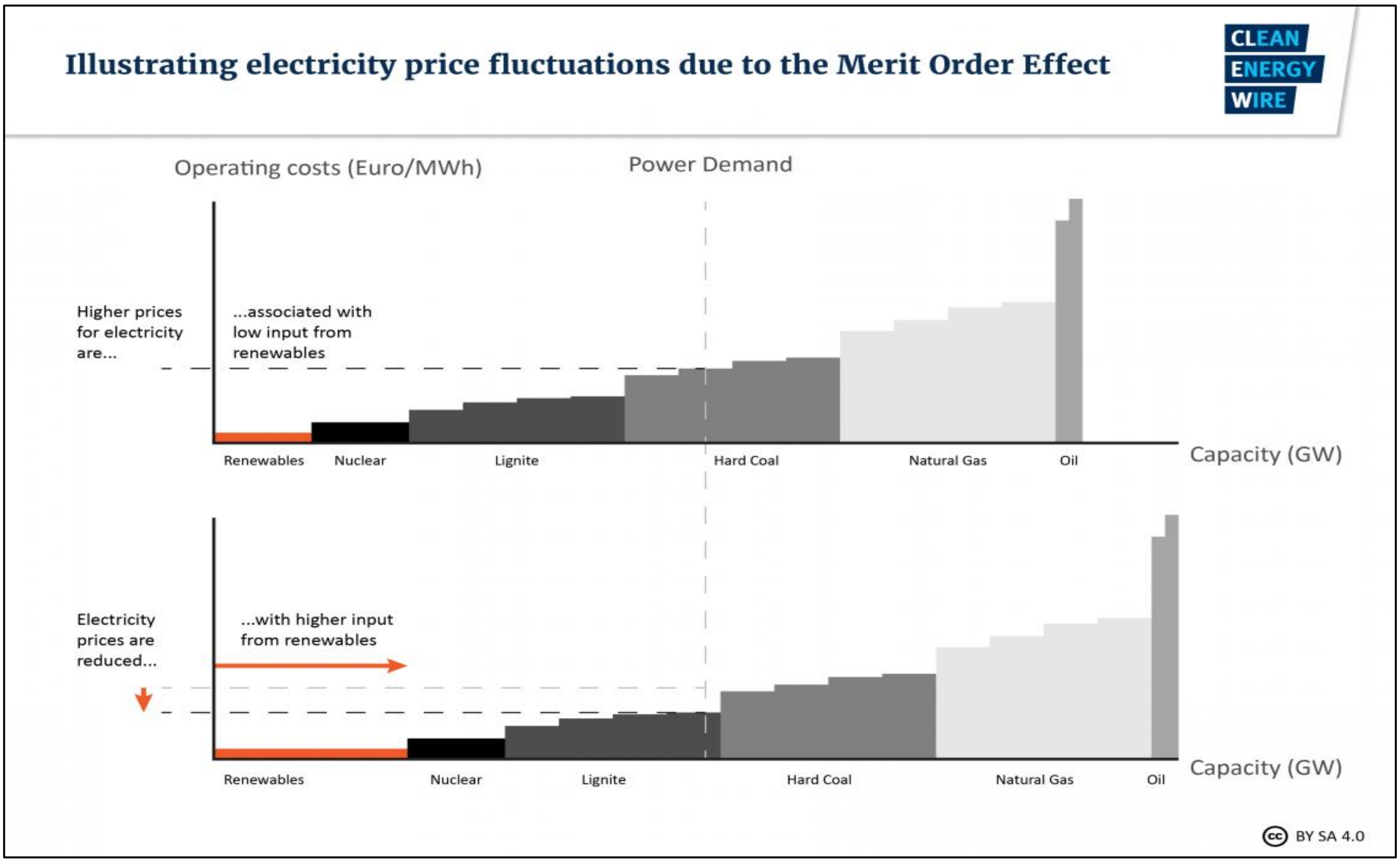

Figure 1: The Merit Order Effect. Source: (CLEW, 2015)

Not Your Father's Battery

Energy Storage is not a new technology. North Wales proposed the UK's first pumped hydroelectric storage facility at Ffestiniog in 1953 (Roseveare, 1964) . After charging its reservoir with low-cost electricity at night, Ffestiniog can throttle to 360MW of power in 5 minutes. Its capabilities were useful in the pre-Netflix era, as it was touted for its support during 'television load' which could see grid demand spike by 1000MW in 10 minutes after a popular programme as toilets were flushed and kettles switched on synchronously.

Could we buffer the entire UK grid with hydroelectric storage? In his book, 'Sustainable Energy - Without The Hot Air', David McKay estimated that the complete exploitation of highland territory in Scotland and Wales would provide only a third of the energy necessary to buffer a renewables-led electricity grid (MacKay, 2008). Other technologies will need to fill in the gap.

One candidate for the next generation of energy storage is advanced low-cost lithium-ion batteries. A case-study in the powers of scale in manufacturing, batteries for energy storage have become a convenient by-product of the electric vehicle industry. Tesla recently made headlines by commissioning the world's largest lithium-ion battery in South Australia. The 100MW facility was notoriously offered by Elon Musk in a bet after the local grid faced stability issues after a storm caused a blackout in the state in 2016(Morton, 2017). It was switched on in December 2017. After a large 560MW coal plant unexpectedly tripped offline later in the month, the battery was able to respond in less than a second to support the grid (Parkinson, 2017).

Virtual Power Plants and Beyond

Building off the success of the 100MW battery in South Australia, state Premier Jay Weatherill has announced further plans with Tesla to provide 250MW of distributed solar and storage capacity in a trial of a "Virtual Power Plant" (Bloomberg, 2018). The scheme would offer 5kW solar panels and 13.5kWh Tesla Powerwall 2s to consumers at no fee. As the solar panels charge the batteries in the Powerwall during the day, the grid operator would be able to coordinate the storage resources to provide as much power as a single coal or gas power station. The system savings from the project could be passed onto consumers in the form of a 30% rate cut(Harmsen, 2018).

Can energy storage solve the problem of renewables' self-cannibalization? While no technology can change when the sun shines or when the wind blows, batteries can help shift when renewable energy is sold. Other regions with high solar generation such as California, are starting to witness the effect of excess renewable generation during the day in what is referred to as the 'duck-curve' (Jones-Albertus, 2017). The immediate challenge faced by system operators is to flatten the curve in order to provide electric system stability (Figure 2).

A study conducted by the Massachusetts Institute of Technology recently concluded that, at the right price, energy storage can profitably arbitrage electricity markets (Braff, Mueller & Trancik, 2016). The 'duck curve' will flatten as energy shifts to periods of high demand. Energy storage may be just the key to help renewables make a greater impact in the energy transition.

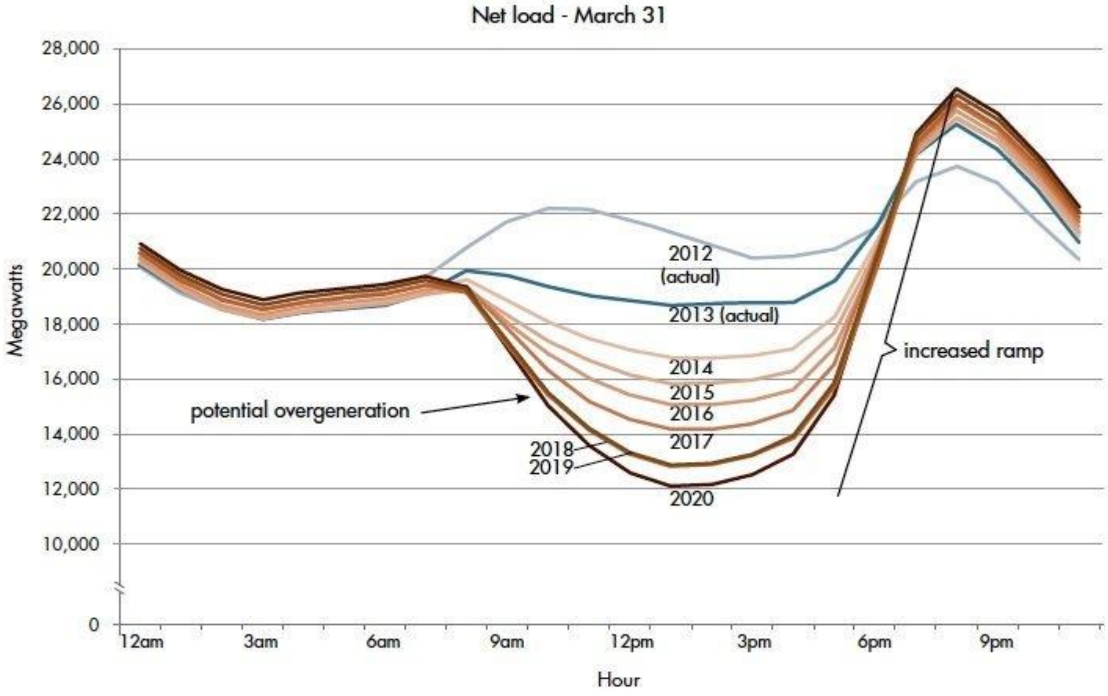

Figure 2 – The California 'duck-curve' Source: (Jones-Albertus, 2017)

Wind Power

Where Next for Wind?

Paul Curtis – ICL

Wind power is nothing new. For hundreds of years humanity has harnessed its power to transform the Earth, travel to faraway lands and to drive huge machines (DK Books, 2009). Now in the 21st century, it is a multi-billion-pound market which is being used to generate more of our electricity. Wind, therefore, is essential in the shift towards using cleaner, more renewable energy sources.

Wind turbines were first used to generate electricity at the end of the 19th century. The first was built in 1887 by Professor James Blyth from Anderson's College, Glasgow, Scotland, to power his home in Marykirk (Nixon, 2008). This was pioneering at the time, and although the technology has advanced a long way since then, the basic concept still remains the same. The typical three-bladed wind turbine design we see today has been utilised since the 1930s, mostly on account of its optimised build cost - output efficiency ratio. In essence, wind turbines covert the wind's kinetic energy into electricity. The blades of a wind turbine spin, causing a connected shaft to spin, this in turn spins a generator and thus electricity is produced.

Figure 1: Blyth's 1887 turbine (left) compared to a modern-day Siemens SWT-6.0-154 (right). With a rotor diameter of 154 metres, the Siemens turbine is around 50 times bigger than Blyth's. (Siemens, 2015; Wikipedia).

So why wind power? Wind turbines are more efficient than most of their counterparts; with current technology, photovoltaic cells (solar panels) have a maximum efficiency of around 20%, whereas a wind farm can peak at 50% efficiency. This makes them just as efficient as greenhouse gas-emitting coal-fired and gas-powered stations (NSW Governement - Environment, Climate Change & Water, 2010). Hydroelectric power has a peak efficiency of 90%, however, for countries such as the UK, limitations in geography mean they aren't always cost-effective (EDF Energy, 2018). Furthermore, they can cause adverse damage to eco-systems.

What's the catch? Clearly, if there is no wind, then wind turbines won't spin and electricity will not be generated. This 'on-off' nature has led to scepticism about the value of wind turbines, often claiming they aren't worth their production costs. To overcome electricity production fluctuations, a large number of wind turbines in the UK are in offshore wind farms; almost half of the wind power generated in the UK comes from offshore wind farms (World Energy Council, 2016), such as the London Array, Greater Gabbard and Dudgeon. Wind speeds offshore are generally higher than those onshore, and the wind is more consistent (Anderson, 2013), so we should expect the cost efficiency to be higher. However, the costs involved with building offshore wind farms are considerably higher, leading to the cost of their energy being around 2.6 times more expensive than their onshore counterparts (Institute for Energy Research, n.d.). The three aforementioned wind farms had production costs of £1.8bn (London Array Ltd), £1.5bn (SSE) and £1.25bn (Statoil, 2017) respectively; this is mostly down to problems of constructing in dangerous seas.

Although wind power has a long history, is it important to the current energy landscape? Simply put, very. In Europe alone, 2016 saw 300TWh generated from wind power, providing over 10% of the energy demand in the EU. Furthermore, wind power has the second-largest power generation capacity in Europe. This is largely due to increases in funding for wind farms, with the EU investing €27.5bn in 2016, 5% more than the previous year (Wind Europe, 2017), so clearly the value of the market is escalating.

Wind power is hugely important in Europe. During 2015, Spain produced almost 20% of its total energy from wind power (REE, 2016) and 2016 saw Denmark generate 61.6% of its electricity from renewable sources, of which nearly 72% was produced by wind power (ENERGINET, 2017). Furthermore, with China planning to invest an enormous $360bn in renewables by 2020 (Jiang & Jonathan, 2017), it is hardly surprising that they have the highest wind power capacity of any country in the world. From the statistics, it is clear that the influence of wind power is large.

And for the future? One analysis suggests that the global wind capacity will more than definitely double, potentially trebling or even quadrupling between the years 2015 and 2030. A safe estimate of the 2030 capacity would be 977GW, however this could certainly be in the 2TW range (World Energy Council, 2016). This is to be expected when you consider the sheer size of the Chinese investment in clean energy, further bolstered by a clean energy revolution in India and funding in the EU set to continue increasing.

However, we all know government funding for renewable energy in the UK has taken a big hit over the last two years. Investment in wind and solar has fallen 56% over a single year; this is as a result of the governments' ban on onshore wind subsidies and cuts to solar power. This is the second year in a row that investment has declined on this scale in the UK (Merrick, 2018). With Brexit set to reduce

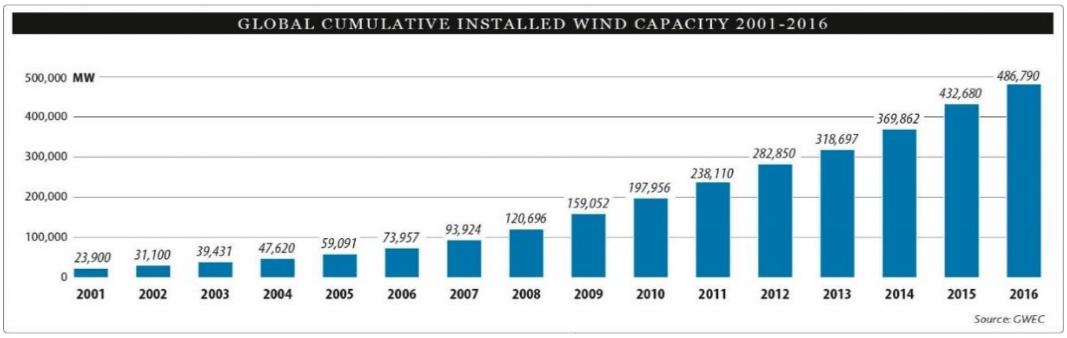

Figure 2: Evolution of the global wind power capacity (Global World Energy Council, 2017)

international investment in British industry, it is perfectly reasonable to question whether the UK will continue to be a global player in this industry. For example, the uncertainty around Brexit has already caused a slump in manufacturing investment (Monaghan, 2017), which will have direct ramifications on building sources of renewable energy. Furthermore, by leaving the European Union, the government is likely to have 'more freedom' for phasing out renewable energy support schemes (Norton Rose Fulbright, 2016). Perhaps all we can do is hope this decline isn't set to continue, and the impending effects of Brexit are minimised. Over the pond, the Trump administration look set to cut funding for the Energy Efficiency and Renewable Energy office 'by nearly three-quarters' (Shugerman, 2018), so the situation in the States is perhaps even worse.

However, it's not all doom and gloom. With regards to future wind turbine design, the future looks promising. One company in Spain, Vortex Bladeless, has designed revolutionary, 'bladeless' wind turbines. These contraptions have no moving parts; subsequently, this makes them 'noiseless' and more 'respectful of nature'. The technology works because the wind causes tall, carbon fibre pillars to oscillate in the wind; this mechanical energy is then converted into electricity. One idea is that these pillars will be built on top of houses to power them. Vortex Bladeless state the manufacturing and operating costs will be reduced by 50% (Vortex Bladeless, 2015). The reduced production costs mean the relative cost of energy produced by them is reduced, a major problem with current wind turbines.

Meanwhile, here in the UK, KPS are using kites to generate electricity. This neat way of producing electricity is achieved by flying two kites, both connected to a generator, and continually unreeling them and reeling them in. Each kite is connected by a cable to a generator such that when they are unreeled, the cable is 'spooled out rapidly', consequently generating electricity (KPS). When each kite is reeled in, they are manipulated to consume a minimal amount of energy, therefore, over one cycle there is a net energy gain. Furthermore, to keep the energy supply constant, the two kites are run at a half-cycle phase, i.e. when one is generating, the other is being reeled in. KPS claim that one of these devices could power 380 homes per year (KPS). Reflecting on this factor, for locations such as Wales or Scotland where villages and towns are more sparsely distributed, this technology could be a game-changer.

Perhaps one issue with the preceding concepts is that they require space at ground level to operate. However, researchers at the Massachusetts Institute of Technology (MIT) may have found a solution through their spin-off company Altaeros Energies (Harris, 2017). Their design uses an aerial platform called an 'aerostat' to host a wind turbine at an elevation of 600m. It is claimed that at this height, the turbine will generate 'over twice the energy output of similarly rated wind turbines'; this makes sense because wind speeds at higher altitude are both higher and more consistent (Altaeros). Makani are using a similar concept with their 'energy kite'; again, this uses an airborne device to generate electricity which is transported back to earth through a long cable. Rated at 600kW (Makani, 2017), this is, however, lower than conventional wind turbines which generate power on a MW scale. Nonetheless, with continued research and development, it is highly possible future wind kites will be on par with current wind turbines. For large cities such as London and New York, using cables to connect these devices may not be feasible or safe; furthermore, their elevation could interfere with a cities' airspace. However, when you take into consideration their portability and speed of assembly, they may have uses when immediate power is needed in a natural disaster, or when powering remote communities.

Wind power really has the potential to change the energy production landscape, even if its future, and the future of all renewables in the UK and USA is unclear. Innovations in technology and continued global financial support mean that wind power, in conjunction with the other renewables will one day dominate, and overthrow the current main sources of energy.

Figure 3: An Altaeros Aerostat (Matheson, 2014).

Hydrogen

The prospects of hydrogen as an energy medium

Catherine Hayes – ICL

Hydrogen could be incredibly important to our energy system in the future. Why is it so promising? Burning hydrogen releases zero air pollution, so it has fewer health impacts than conventional fuels. There is no noise, no risk of carbon monoxide poisoning, and no direct climate impact (Lucia, 2014).

While hydrogen can be burned, fuel cells are a better option. Like electric cars, these are a 19th century invention that have seen a burst of research in the past few decades. A group of technologies that use hydrogen fuel cells as a medium – for instance, central heating and cars - are just reaching the public. They take in a fuel, like combustion engines, but use electrochemistry to produce heat and electricity. The only waste product is pure water.

Fuel cells are incredibly efficient, turning up to 95% of the fuel energy into electricity and heating (ene.field, 2018). They can be built at almost any scale imaginable, from portable cells to systems for whole city districts, but most research efforts are for car-sized or domestic boiler-sized systems (Lucia, 2014). In a CHP arrangement, one hydrogen fuel cell unit can provide electricity, heating and cooling. Fuel cells are one of the best future tools for distributed energy, in which people and communities generate their electricity locally.

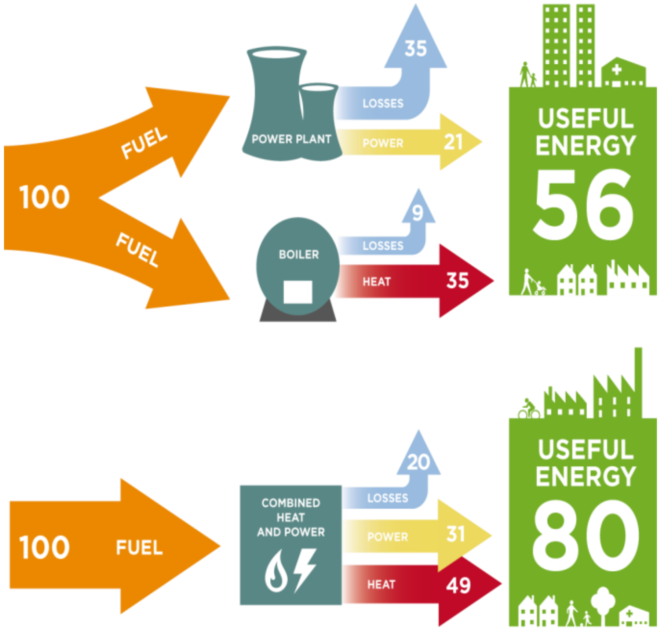

Figure 1: Energy efficiency of CHP compared to conventional power generation (P3P Partners, 2018).

CHP stands for 'combined heat and power'. A CHP unit is an electrical generator that also makes hot water or steam. This is much more efficient than generating the same amount of heat and electricity in separate processes. CHP units are often used as power sources for large businesses and institutions, including ICL's South Kensington campus (Czyzewski, 2016). Micro-CHP units for single homes also exist.

Transport and mobility

Fuel cell cars also exist, but how do they compare to rival designs? They operate at twice the efficiency of conventional cars. They don't have the range problems of electric vehicles: they can travel more than 500 km on one tank and refuel as quickly as a petrol car (ICCT, 2017). They can even be designed to act as electricity generators in an emergency (Toyota, 2016).

Figure 2: Toyota Mirai fuel cell car (Toyota, 2018).

Fuel cell cars are commercially available, but the lack of charging infrastructure is a massive issue. There is no hydrogen network, and only a handful of filling stations in the UK sell H_2 gas. To distribute hydrogen easily, it must be liquefied, which can wipe out most of the environmental benefits (ICCT, 2017). Electric cars have charging points that can be installed wherever the electrical grid is present. Until recently, charging an electric car could take hours, but the advent of rapid chargers has shortened the waiting time to minutes (Zap Map, 2017).

There are 4500 fuel cell vehicles in the world according to the latest figures, up from under 500 two years ago, so despite exponential growth, the industry has a long way to go before it can make any sort of impact (ICCT, 2017). The cars have garnered investment from multiple manufacturers, including Honda, Hyundai and Toyota, and are made in tiny quantities.

Some cause for optimism remains – according to projections, the costs of manufacturing a fuel cell car may fall as low as $5000 by 2030 (ICCT, 2017). There is active research into heavier vehicles. The US army is developing a Chevrolet hydrogen truck for rough terrain (Army Times, 2017). Proof of concept exists for hydrogen buses and

HGVs, and some models are already running in London, thanks to TfL.

Hydrogen at home

Heating and distributed energy is a larger market for fuel cells. Single household systems (micro-CHP) are on the brink of commercialisation. Japan's EneFarm has installed more than 150,000 units (Crolius 2017). But Japan is unique – the fast uptake of fuel cells has been linked to problems of electricity supply following the 2011 Fukushima incident. The backlash against nuclear power led to a change in Japan's energy policy, pushing hydrogen to the top of the agenda (Akiba, 2017).

Elsewhere, fuel cells are further behind. The ene.field EU demonstration trial published its results last October: it established that fuel cell microCHP technology is ready to scale up in Europe, but that they will need to be fuelled by natural gas instead of hydrogen. The goal of the project was to overcome the practical barriers to the fuel cell industry, such as the immature supply chain and the lack of standardisation and maintenance experience (enefield, 2017a). Usually, these micro-CHP units can be fuelled by natural gas as well as hydrogen, so they can be installed before hydrogen is commercially available in homes (ene.field, 2017b). Because it uses fuel more efficiently than the electrical grid, a gas-powered fuel cell still reduces CO_2 emissions, though not as much as a hydrogen-powered fuel cell.

Given all the advantages of fuel cells, why don't we use them already? Until recently, fuel cells were still technically limited, with significantly shorter operating lifetimes than the engines and boilers they replace. This is now less of an issue (Elmer et al, 2015). Currently, fuel cell CHP is too expensive for most consumers to buy, but estimates predict that given sufficient economies of scale, the price could be comparable to a gas combustion boiler. A manufacturing run of 5,000-10,000 units would be enough, but this target is more than the current total number of fuel cells in Europe. In the long term, by generating valuable electricity from cheap gas at home, fuel cells can save money (ene.field, 2017a).

City-scale plans

There have also been studies on the feasibility of converting the whole natural gas system in the UK to carry hydrogen instead. Gas is used for more than 80% of UK heating, and finding a replacement is tough. Domestic heating accounts for almost 15% of the UK's carbon dioxide emissions each year; reducing these emissions is necessary to meet the UK government's targets for mitigating climate change (BEIS, 2018). And the UK has taken notice. In 2016, the city of Leeds commissioned a detailed report on how it could switch to hydrogen (Northern Gas Networks, 2016).

This conversion is less difficult that it seems. By coincidence, the gas network is already being upgraded to polyethylene pipes that can handle hydrogen, through the Iron Mains Replacement Programme (Northern Gas Networks, 2016). Until the 1970s, the UK gas supply was around 50% hydrogen – in a way, this would be reversing a historic conversion.

According to the Leeds study, the project is feasible, cheap even though it is an infrastructure project and possible at no added cost to the consumer. However, it is still a huge undertaking. A serious barrier is the difficulty of replacing gas appliances. Their estimates place this cost at £3078 per household, a serious investment. Yet the technical capacity is there. The scheme's biggest weakness is where the hydrogen comes from.

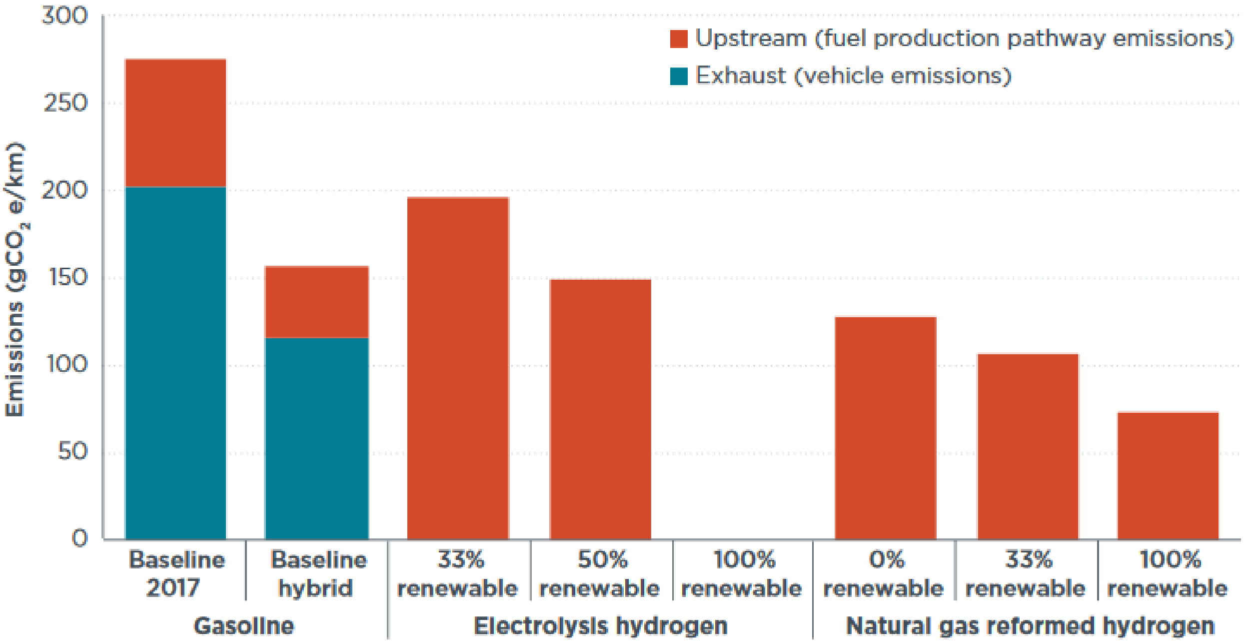

Figure 3. Hydrogen fuel cell vehicle CO_2e versus conventional and hybrid gasoline vehicles.

Credits: ICCT, 2017

Sources of hydrogen

The main commercial use for hydrogen is in industry, so the technology for its production is well-established. Natural gas is treated at high temperatures and pressures to produce CO_2 and H_2 in a process called steam methane reformation (SMR). This way of producing hydrogen is terrible for the environment. There are two main problems with SMR: its feedstock is a fossil fuel, and it releases greenhouse gases to the atmosphere. The fact that natural gas is a fossil fuel is a minor problem. The world's natural gas supply is expected to grow for at least the next three decades, and peak gas is not on the horizon (World Energy Council, 2017). The greenhouse gas issue could theoretically be solved by carbon capture and storage (CCS), but that is expensive. CCS adoption has been hampered by years of slow progress (d'Aprile, 2016). Then again, the hydrogen plan is ambitious, and the Leeds results are encouraging: 59% lower CO_2 emissions with SMR and CCS technology.

While adopting CCS is one way to solve the problem of producing clean hydrogen, it is not the only option. There's plenty of interesting research into how to scale up renewable hydrogen instead. In the long term, it should be possible to make hydrogen from water instead of natural gas.

One big idea is using intermittent renewables like wind energy to power a water electrolysis plant. This makes oxygen and hydrogen, which are stored until the energy is needed. The hydrogen is valuable and can be kept like gas for weeks or months, whereas most storage technologies work on a seconds-to-hours timescale. However, the business model is only valid if the electricity is cheap and abundant: producing hydrogen with standard grid electricity is prohibitively expensive. In Germany, there have already been times when the amount of renewable energy exceeded demand (Cox, 2017). In these cases, the extra revenue and electricity grid stabilisation are a gift to utility companies and help to make the business case for renewable energy much stronger.

Solar fuels are in still in R&D but may be the best solution for hydrogen production in the long term. These are produced by a cross between a solar panel and an electrolytic cell. The technology uses photocatalytic semiconductors to split water into hydrogen and oxygen. In contrast to electrolysis, all the necessary power comes from sunlight. Similar chemistry can be used to turn carbon dioxide back into oil and gas. Costs are currently still too high for commercial operations, and solar fuels are an area of active research.

Conclusions

Will hydrogen become a successful renewable energy source? In the long term, yes. Fuel cell micro-CHP is very promising, as it offers a way to heat and power our homes sustainably. Hydrogen vehicles, however, are losing ground in comparison to electric vehicles. The prospects for a renewable hydrogen system look good, but true sustainability is a long way off.

Figure 4: Toyota Sora fuel cell bus, 2017 Tokyo Motor Show front
Source: Wikimedia Commons

Hydrogens and Renewables

A Strategic Alliance towards a Sustainable Future

Filippo Colagrande – ICL

After roughly a decade since the launch of the world's first production fuel-cell vehicle, a hydrogen economy still looks far away. However, we are currently witnessing what is being described as the "Hydrogen Comeback". Years of persistence and technical improvements, along with recent changes in the politics of energy and environment, make hydrogen an appealing solution for some of the biggest challenges of decarbonisation. While producing hydrogen from renewables is not a new idea, today we have stronger incentives for doing that than in the past.

The renewed interested around hydrogen is quite different from what propelled the initial hype in the early 2000s. Now the attention is much less focused on transportation (Nathan, 2017). We look at other possible arenas in the energy sector, from the traditional (heating) to the revolutionary (storage). In the end, versatility could make hydrogen the "wild card".

This is the broad view that emerged during my talk with Dr. Zeynep Kurban, from Imperial Energy Futures Lab. Kurban is the manager of H2FC Supergen Hub, a program funded by the UK government to address the key challenges in the hydrogen fuel-cell sector. "In the last couple of years", she explains, "especially since COP21[1], governments are under pressure to provide solutions to decarbonize and change the energy system as a whole. Hydrogen is very versatile: it has many different applications, and so it makes sense, based on our modelling, to use hydrogen across the economy, where it can be more cost effective". Looking at possible competing technologies, Kurban doesn't believe in a sole winner: "It is not like there would be only one or another technology in the different sectors that we have: what we are trying to see is which mix of solutions works. So, going forward, probably we won't have just a hydrogen economy as we talked in the past, but we see that hydrogen will be part of the solution rather than the only solution" (Brandon, 2017).

The role of hydrogen

The rapid transformation of the energy sector to move towards a zero-carbon society might give rise to attractive synergies. As the plunging costs of wind and solar energy push ahead their rapid deployment, a rising amount of green power is being curtailed. As experienced in different countries, and recently also in UK, electricity prices may go negative: a serious problem for generators and system operators as well (Clark, 2016). Renewables will keep putting pressure on the network as the problem of fluctuating and unpredictable generation is yet to be addressed. Potentially, hydrogen could address this problem. Clean hydrogen is an exceptional energy carrier: produced with zero carbon emissions, using electricity from wind and solar, it can provide the storage capacity required by renewable generation, and enable integrated solutions to address the energy needs of a future sustainable society.

Curtailment: defined as the "reduction in the output of a generator from what it could otherwise produce given available resources", curtailment is typically due to transmission congestion or to excess generation during low demand period (Bird, 2014).

We are still far from having hydrogen batteries in every home. Nevertheless, visionary companies are developing breakthrough technologies to enable a world of distributed hydrogen generation. HyperSolar, located in Santa Barbara (CA), is working on a novel technology, based on photoelectrochemical (PEC) water splitting (Rothschild**,** 2017), for competitive, low-cost hydrogen production directly from sunlight. The company aims to be the solution for the "hydrogen at the point of distribution."

Its proprietary generator consists of nano-size PEC systems that can ensure optimal energy utilization, and therefore achieve a higher solar-to-hydrogen efficiency. The expensive platinum in the catalyst has been replaced by earth-abundant elements, primarily ruthenium, resulting in lower initial capital costs compared to conventional methods of production, such as electrochemical water splitting or methane steam reforming (in which natural gas reacts with steam at high temperature producing hydrogen and carbon monoxide). In the words of Tim Young, CEO of HyperSolar, this technology "immerses billions of autonomous nanoscale solar cells in water to split the molecules into oxygen and hydrogen. Ultimately this process will prove to be much more economical and with better fault tolerance".

While this technology is still in the prototype stage, modern electrolysers already allow the development of an attractive business case for green hydrogen production. "In large scale electrolysis systems, the cost of electricity is between 75% and 85% the cost of hydrogen", says Bjørn Simonsen, "and with a levelized cost of the electricity (LCOE) down to

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[1] *The 2015 United Nations Climate Change Conference, during which the Paris Agreement was negotiated.*

$0.03/kWh[2] hydrogen could be produced at $1.50 at the pump, and therefore be competitive with the gasoline at the pump".

The **levelized cost of electricity** represents the per-kWh cost (in discounted real dollars) of building and operating a generating plant over an assumed financial life. It can also be regarded as the average minimum cost at which electricity must be sold in order to break-even over the lifetime of the project (EIA, 2017).

Simonsen is responsible for market development at Nel ASA, one of the world's largest electrolyser producers. In June 2017, Nel announced a multimillion contract agreement with French company H2V PRODUCT for a "first of its kind", large power-to-gas project: a 100 MW hydrogen production plant powered with electricity from both solar and wind installations (Nel ASA, 2016). As reported on the company website, the installation will be developed in France, within the transport infrastructures network linking the liquefied natural gas (LNG) terminals of the Atlantic.

The hurdle of transportation

The previous case represents an exception rather than the rule, as transportation remains on a global scale probably the greatest barrier towards a wide, integrated hydrogen market. With cryogenic liquefaction and high-pressure compression being expensive and inefficient, and considering the prohibitive capital investment required to build pipelines, alternative solutions need to be adopted for the early stage of the transition. Perhaps another energy carrier: ammonia. With a hydrogen content of 17.6 wt.% once stored in liquid form (at 20°C, 7.5 bars are adequate), ammonia volumetric hydrogen density is about 45% higher than that of liquid hydrogen itself (Thomas, 2006). This means that ammonia can be stored in a simple, inexpensive way, while achieving high energy density, and therefore make the transportation of hydrogen in large volumes more feasible.

Although the role of ammonia has been long investigated, the stringent requirement of proton-exchange membrane (PEM) fuel cells, in terms of hydrogen purity, and the need for an optimized, low-cost technology make the decomposition and purification of ammonia still an engineering challenge, but we may have reached a tipping point.

"With a well-established infrastructure and safety standards, ammonia can reduce the techno-economic risk of the transition [to hydrogen]", as Dr. Michael Dolan says. Dolan joined Australia's national research agency, the Commonwealth Scientific and Industrial Research Organization (CSIRO), in 2004 and has since led the development of advanced membranes for hydrogen production processes. Scientists at CSIRO have recently developed a vanadium-based membrane that can separate high purity hydrogen from ammonia: the metal is 90% cheaper but 25 times more permeable than commonly-employed palladium (Hla, 2018).

As Dolan explains, the membrane technology has a number of advantages over traditional purification systems, and it is particularly suited for small scale, distributed applications. The project, supported by various companies (Hyundai and Toyota among others) has also received funding from the Australian government, which now sees the opportunity to turn the nation's immense solar and wind potential into "green fuel" exports for hydrogen-hungry economies, such as those of Korea and Japan (Parkinson, 2017). Since 2015, the Japanese government has incentivized the production of CO_2-free hydrogen and plans to demonstrate at the 2020 Tokyo Olympic and Paralympic Games a combination of hydrogen solutions for the future low-carbon communities (JFS, 2016).

With new technologies becoming more mature and making the transportation of hydrogen over long distances finally feasible, we may be witnessing, in the opinion of some experts, the rise of hydrogen export as the new LNG industry.

Implications from a European perspective

Some of the major economies are increasingly looking at hydrogen to gain independence from fossil fuels: particularly, the UK is considering hydrogen as a potential solution in its long-term strategy to decarbonize the heating system, provide fuel to vehicles, and power the industry. As in the case of Australia and its Asian partners, the creation of a market for hydrogen is likely to involve the cooperation between industrial economies, hydrogen importers, and energy-producing countries. Those countries could be represented, in the case of Europe, by developing African nations. The continent is blessed with large amounts of solar energy, and the installed capacity of renewable energy is expected to grow by 70% in the next 5 years. Once renewables become widespread and the local demand is met, African countries could start producing and exporting hydrogen for the future European market.

Considering that the energy product imports (mainly crude oil) from Africa amounted to €61.6 billion in 2015, around

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[2] [2]*In August 2016, Spanish solar PV company SolarPack won an electricity auction in Chile submitting a record-low bid at $29.1/MWh*

47% of total EU imports from Africa that year (Eurostat, 2016), the establishment of such market won't only provide Europe with "green fuel" but will fundamentally contribute to rebalance the trading relationship between the two continents once Europe decides to phase out oil and gas.

Conclusion

In a world committed to keep global warming below 2°C, energy supply and demand need to radically change. The transition towards a zero-carbon economy poses serious challenges, not only for our dependence from fossil fuels, but also for the hurdles to install significant capacity of fluctuating renewable energy and integrate it into the system.

In this scenario, the role of hydrogen is still uncertain and subject to opposite views. However, as we strive to cope with the pace and the effects of the green transformation, the potential of hydrogen as enabler of this transition become increasingly more evident. Thanks to its unique properties of high energy density and versatility, hydrogen can be used in different sectors of the energy system and enable integrated solutions for decarbonization.

While continuous progress in cost and performance of technologies is increasing hydrogen competitiveness, the long-term horizon of the investments and the lack of a clear political commitment become the major barriers to the efforts for large-scale commercialization: a stable policy framework and coordination between public and private sector are therefore essential to create a future "hydrogen society".

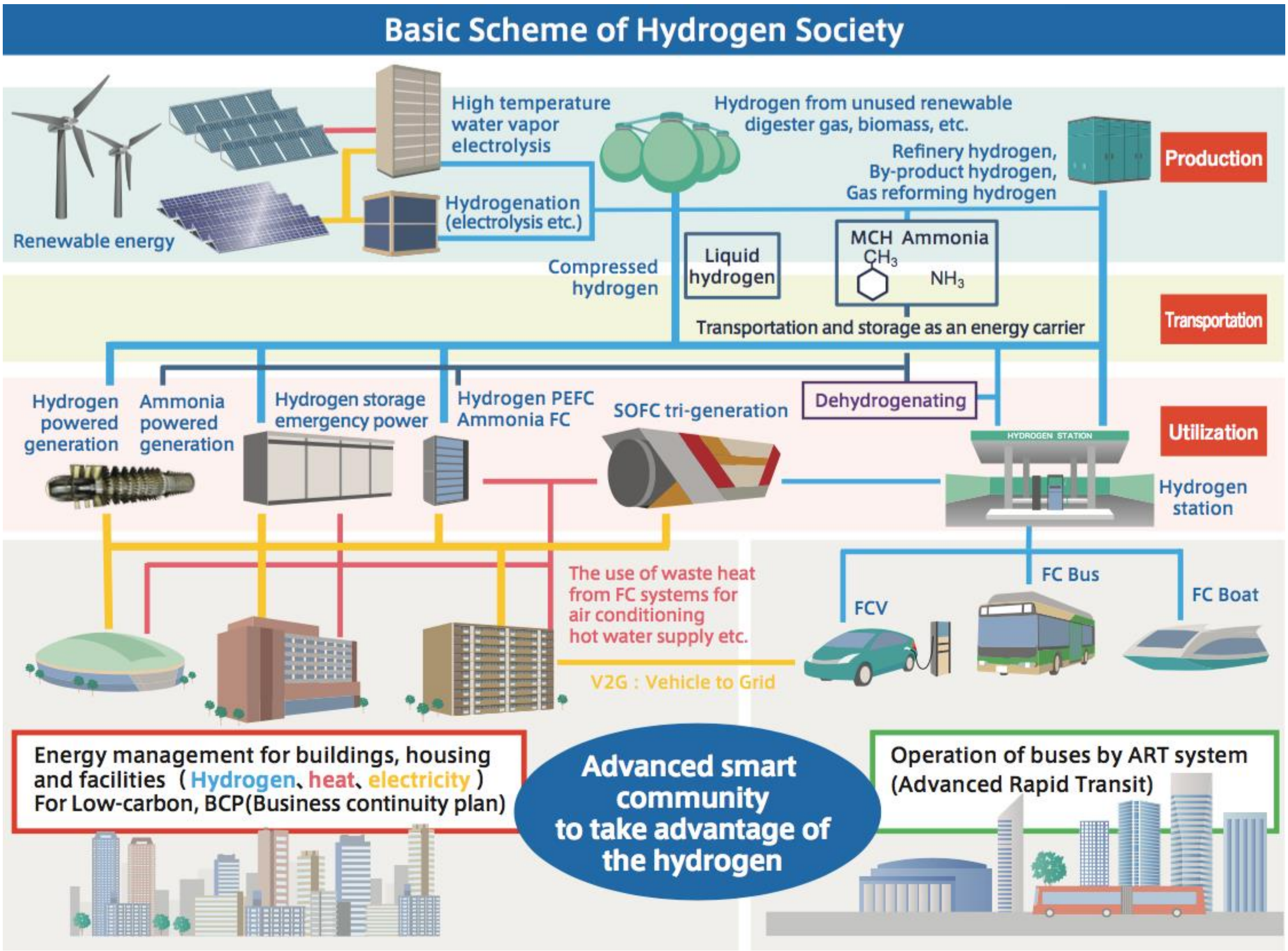


Figure 1: "The Hydrogen Society", SIP Energy Carriers 2015, Japan Science and Technology Agency & Cabinet Office

Electric Vehicles

The Age of Electric Cars is closer than You Think

Muhammad Waabis – ICL

Electric cars offer us a glimpse into the future but what most people don't know is that the concept of a battery-powered vehicle can be traced back to the 1800s [1]. Pioneers in the Netherlands and the United States developed some of the first small-scale electric cars. By 1900, electric vehicles dominated the roads [2] beating steam and gasoline powered cars. No car could compare to the ease of driving and the quietness of the electric car. It was the Henry Ford's mass-produced Model T that dealt a blow to the electric car [3]. It not only lowered the price of gasoline cars but also greatly improved the driving quality.

Cheap, abundant gasoline and continued development of the internal combustion engine (ICE) has hampered the mainstream adoption of the electric vehicle-until now. Surging oil prices at the start of the 21st century and strict emissions regulations have paved the way for the rebirth of the electric car.

Range Anxiety

Most electric vehicles on the market today have a range of 120-180 miles [4]. Looking at average daily driving distances, this should be more than enough for an average consumer. Research by ING, however, shows that 61% of the people want a range greater than 370 miles [5]. Tesla's Model S gets close to this at 315 miles [6] while other manufacturers fall far behind. Tesla offers the highest lithium-ion (Li-ion) cell density of 170Wh/kg [7] but to achieve the 370-mile range we may have to switch to a different battery technology altogether. Tesla's battery supplier, Panasonic, is working on solid-state technology which could extend the energy density of Li-ion batteries by up to 30% [8]. Finding a solid material that is conductive enough is challenging and companies like Toyota are trying to solve this problem. As Panasonic's President Kazuhiro Tsuga said, "There is a trade-off between energy density and safety. So, if you look for even more density, you have to think about additional safety technology as well." [9]

Solid-state batteries replace the liquid electrolyte found in current Li-ion batteries with a solid.

Until we can prove the feasibility of solid-state batteries and achieve the same safety standards as Li-ion batteries, we must focus on developing the current Li-ion technology.

One of the biggest issues with today's battery packs is the cost. The United States Advanced Battery Consortium has set a cost target of $250 per kWh [11] for electric cars to become mainstream. According to Figure 1, this target will likely be achieved by 2020. Currently, Li-ion batteries cost about $1100 per kWh at low volumes [12] and to lower this cost, the production must be scaled up significantly. One example of this is Tesla's Gigafactory in Nevada, which has a planned annual production capacity equal to the entire world's battery production combined [13]. This economy of scale will allow Tesla to lower their cost of battery cells while significantly ramping up production to meet the current demand.

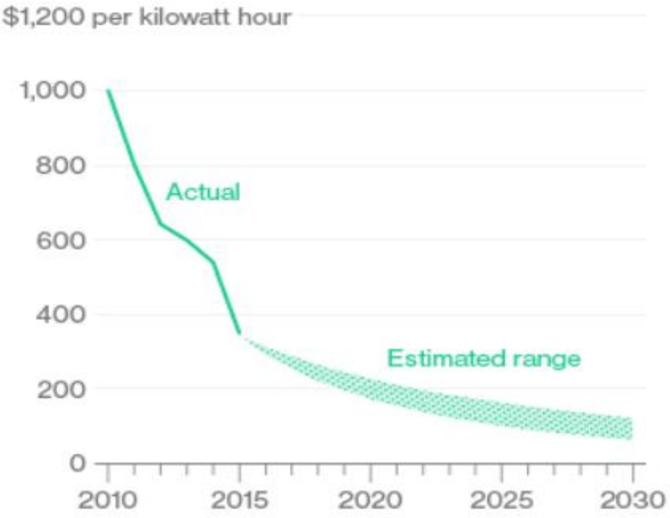


Figure 1 – Cost of Li-ion battery packs [10]

Charging Infrastructure

The number of charging points is now almost equal to the number of gas stations in Europe [14]. Part of this explosive growth could be attributed to national and local government subsidies for charging infrastructure. So, if there are enough charging points, what seems to be the problem? Charging speed. As shown in Figure 2, the maximum charging time people find acceptable is 30 minutes [15]. To put that into perspective, a typical electric car such as the Nissan Leaf takes 4 hours to charge from empty [16].

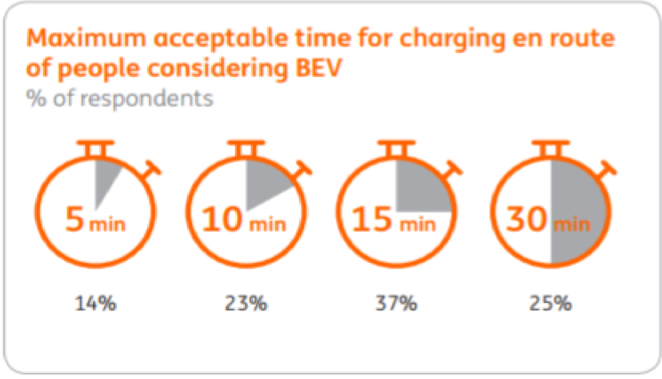


Figure 2- Maximum acceptable charging time [17]

Charging standards are required to maintain high levels of service and help meet customer expectations. Fast-charging systems such as Tesla's 'Supercharger' network can charge 80% of a battery in 40 minutes [18], but this technology isn't standardised across the industry. Companies like BP are moving in the right direction by planning to add rapid-charging points at its petrol stations [19]. Until the charging network is standardised like the fuel used by ICE vehicles, it will continue to be a fragmented market for the customers, thus hampering the adoption of electric cars.

Cost of electric car ownership

One major aspect people consider when buying a car is the total cost of ownership (TCO). Electricity is cheaper than fuel costs and therefore electric cars are cheaper to run over the ownership period. They also have much simpler powertrains and therefore require less maintenance and repair compared to an ICE. The one aspect which consumers can't digest is the initial cost of purchase for an electric car. Even with government grants and subsidies, electric cars tend to be more expensive than similar ICE counterparts [20], mainly due to the high cost of battery packs. The fall in battery pack prices is inevitable, thanks to increased production and improved manufacturing processes [21]. By 2040, 35% of new car sales are expected to be electric, compared to a measly 1.9% currently [22].

The **powertrain** in a vehicle is composed of everything that makes the vehicle move. This includes everything from the engine to the transmission to all the parts that allow the power from the engine to get to the wheels.

The future

History repeats itself and electric vehicles are about to take their once-hefty market share back from ICE vehicles. Electric cars have a promising future once they undercut ICE vehicles on ownership costs and offer a better range and driving quality. Now it's only a matter of time before we reach the new electric age.

Figure 3: Electric Car recharging; Source: Wikimedia Commons

Carbon Capture and Storage

A Technological Overview

Humera Ansari – ICL

Climate change is a factor that is influencing most energy policy decisions. The Intergovernmental Panel on Climate Change (IPCC) has continuously stressed that without urgent action, climate change will have an irreversible impact on the world. The Paris Agreement, which came into force in November 2016 and calls for a limit in global temperature rise of less than 2°C (UN, 2015), was a strong win for the cause and has guaranteed the cooperation of many countries to combat the global temperature rise with strong measures. However, in the IPCC Fifth Assessment Report (2014), many climate models predict that atmospheric levels of 450 ppm of CO_2-equivalent, which corresponds to the 2°C temperature rise, are unattainable without Carbon Capture and Storage (CCS). In addition, the US just recently approved a new policy, the '45Q law', which is a tax credit for CO_2 storage (Global CCS Institute, 2018c). This move will stimulate growth in the sector and encourage energy companies to investigate options to benefit from this policy. To appreciate the impact of widespread deployment of CCS projects, it is key to understand the technologies involved.

What is CCS?

Carbon Capture and Storage/Sequestration (CCS) is a means to reduce the carbon dioxide (CO_2) we release into the atmosphere. The process essentially involves the capture of CO_2 from point sources in industry, compression of it for transport and injection of it in storage sites suitable for permanent retention of the fluid. Figure 1 shows an overview of the process.

CCS allows the continued use of our existing carbon-based systems (albeit at more controlled levels) and simultaneously helps reduce the impact of our industries on global greenhouse gas (GHG) emissions (Pires et al., 2011). The following sections delve deeper into each distinct stage of the CCS process.

Capture

CO_2 capture technologies depend on how the CO_2 is generated, and several processes such as pre-combustion, post-combustion and oxy-fuel combustion capture exist for this purpose. It is applicable to various industries from natural gas processing to cement manufacture.

The energy from fossil fuels is achieved by burning them, which gives off CO_2 as a by-product. Pre-combustion capture involves converting the fuel to a mixture of hydrogen and CO_2. The two gases are then separated. The major advantage of this process is that hydrogen can be used as a fuel for various purposes. Post-combustion capture allows the capture of CO_2 from the flue gas mixture from fossil fuel combustion, through processes like absorption. This method can easily be retrofitted onto existing plants making it the easiest to implement. Oxy-fuel combustion capture is the process of burning the fuel in pure oxygen (rather than air), which produces a mixture of CO_2 and water vapour. This mixture is much easier to separate and allows for high purity CO_2 capture (Global CCS Institute, 2018a, UKCCSRC, 2018).

Transport

Transport of CO_2 is a well-understood process and is considered the most technologically mature step of the CCS process. Once the fluid is captured, it needs to be transported to the storage site. Pipelines are used for large-scale transport, and this is similar to the transportation of oil and gas. Ships and truck and rail can be used for small-scale transport (CCSA, 2018b, Global CCS Institute, 2018b)

Storage

Geological storage of gases is a natural process; it is how natural gas that we extract for fuel is stored. CO_2 storage involves injecting CO_2 into suitable storage sites (large, deep, porous reservoirs) where it is basically in a liquid-like state (supercritical phase). These sites can potentially be saline formations, non-mineable coal seams or depleted fields (for enhanced recovery processes). So, what stops the CO_2 from escaping? Once the CO_2 is injected at high-pressure into these deep formations, it migrates upwards until it hits a layer

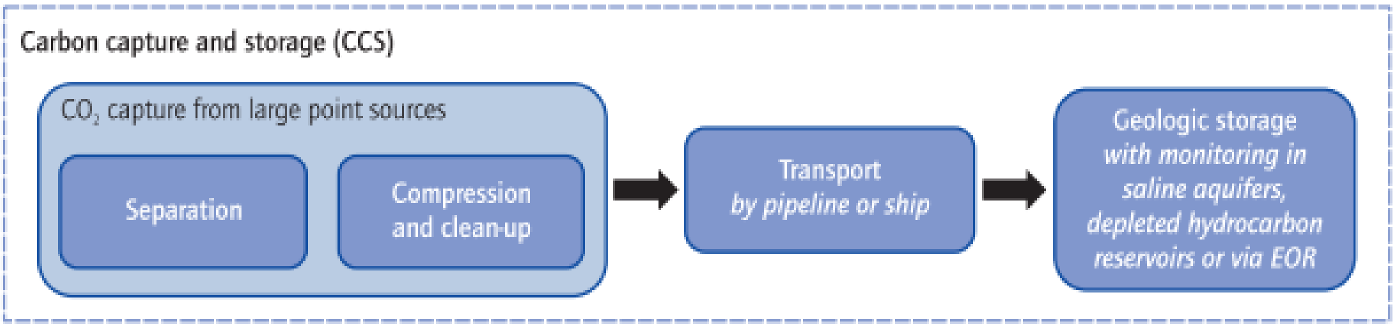


Figure 1: Overview of Carbon Capture and Storage (International Energy Agency, 2013)

of impermeable rock (cap rock). This is called structural storage. During migration, some CO_2 can get left behind and get trapped in the very small pores of the rock, which is called residual storage. Over time, the CO_2 dissolves into surrounding water, causing it to sink (dissolution storage). It can also bond chemically with the rock (mineral storage). Cumulatively these processes ensure that as time goes on, the chance of CO_2 leakage becomes smaller (CCSA, 2018a). Once stored, it is also important to monitor the stored CO_2 (International Energy Agency, 2013).

Outlook

According to the International Energy Agency (2015b), CO_2 from fossil fuel combustion accounts for nearly 90% of all energy-related GHG emissions. Carbon Capture and Storage/Sequestration is regarded as the most credible way to reduce the impact of fossil fuel emissions. Fortunately, this technology has seen some success in the industry. 15 large-scale projects exist around the world, including the Sleipner project in Norway, which has a 20-year history of storing 1 million tonnes of CO_2 per year from a natural gas processing plant (International Energy Agency, 2015a). CCS has experienced rigorous research and undergone extensive monitoring, and with the new tax credit system in the US for CO_2 storage, CCS can potentially be impactful on our climate change goals as a true climate change mitigation technology.

Credits: Eric Kayne

Carbon Capture and Storage

Potential, Costs, and Outlook

Mingchuan Zheng – ICL

A spectre is haunting the world – the spectre of carbon dioxide (CO_2). Ever since the world entered the industrial age, the amount of CO_2 emitted has been continuously rising. In recent decades, with the economic rise of the developing world, such increase has only been accelerating.

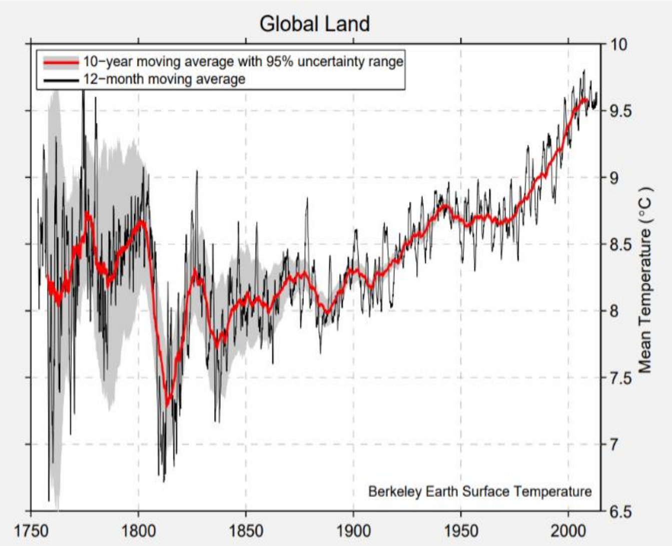


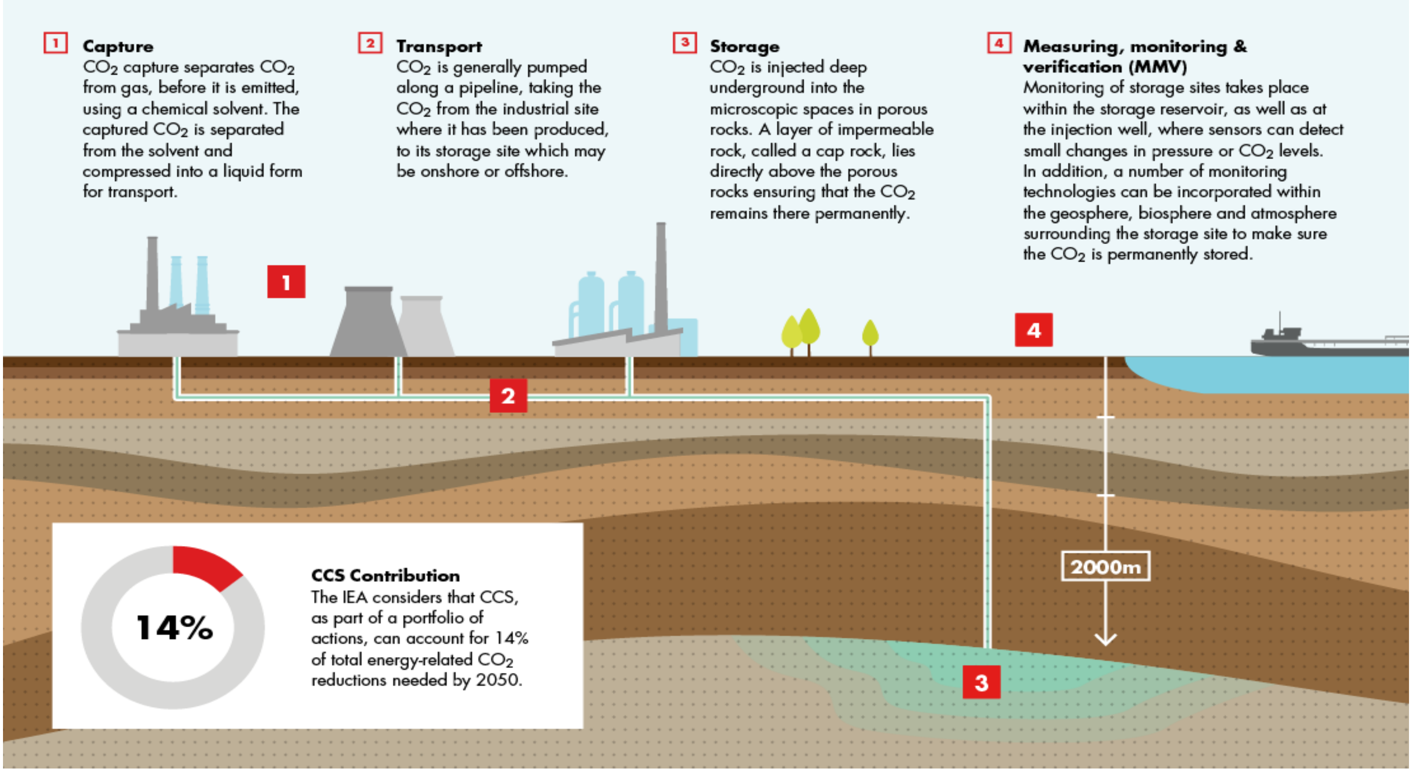
Figure 1 - Global average land temperature from 1750 (Rohde, et al., 2013)

Due to its special spectroscopic properties (such as being infrared active), CO_2 is believed to be a greenhouse gas (GHG) capable of increasing the global average surface temperature and changing the climate (Kazarian, 2016; Shah, 2016).

Two essential points result from these facts:
I. The increasing trend of the average global surface temperature over the past hundreds of years is believed to have been associated with the increasing anthropogenic atmospheric emission of CO_2.
II. It is high time that humankind should, in the face of its challenge, come together and put the best endeavours to exorcise this spectre.

To this end, scientists and engineers around the world have been developing viable, effective, and energy-efficient Carbon Capture and Storage (CCS) technology to help meet this global challenge. One of the main objectives is that humans can continue to use fossil fuels as energy sources while not inducing significant amounts of carbon emissions (Boot-Handford, et al., 2014).

The basic idea of **Carbon Capture and Storage** is to capture CO_2, especially those from industrial emissions, and store it while preventing it from being released onto the Earth's atmosphere. An example of this is the decarbonisation of fossil fuel power generation processes, where the CO_2 in the post-combustion waste stream is captured and stored (House of Commons ECCC, 2016).



1 Capture
CO_2 capture separates CO_2 from gas, before it is emitted, using a chemical solvent. The captured CO_2 is separated from the solvent and compressed into a liquid form for transport.

2 Transport
CO_2 is generally pumped along a pipeline, taking the CO_2 from the industrial site where it has been produced, to its storage site which may be onshore or offshore.

3 Storage
CO_2 is injected deep underground into the microscopic spaces in porous rocks. A layer of impermeable rock, called a cap rock, lies directly above the porous rocks ensuring that the CO_2 remains there permanently.

4 Measuring, monitoring & verification (MMV)
Monitoring of storage sites takes place within the storage reservoir, as well as at the injection well, where sensors can detect small changes in pressure or CO_2 levels. In addition, a number of monitoring technologies can be incorporated within the geosphere, biosphere and atmosphere surrounding the storage site to make sure the CO_2 is permanently stored.

CCS Contribution
The IEA considers that CCS, as part of a portfolio of actions, can account for 14% of total energy-related CO_2 reductions needed by 2050.

Figure 2 – A schematic of CCS (Shell, 2016)

Carbon Capture and Storage

A Brief History of CCS

CO_2 capture technology has been put to commercial use since the 1920s for separating CO_2 found in natural gas extracts (IEA, 2017). In the early 1970s, many gas processing facilities in Texas started to CO_2 into the oil field to boost oil recovery rate; this process is known as Enhanced Oil Recovery (EOR). It was then an engineering success and has seen wide implementation elsewhere in the world.

In the late 1980s, MIT initiated the Carbon Capture and Sequestration Technologies Program (CC&ST) (MIT CC&ST, 1989), which marked the beginning of the development of CCS technology. Then there came Sleipner in Norway in the late 1990s, which was the first CO_2 storage project in the world. In 2000, eight of the world's leading energy companies including BP, Encana, Chevron, etc. and initiated the Carbon Capture Program (CCP) together with the U.S. Department of Energy, Norges Forskningsråd, and the European Union. Nowadays, there are CCS and EOR projects all over the world, the exact number of which is hard to estimate, but as of 2016, there were 15 large-scale projects globally.

In 2001, the United Nations Framework Convention on Climate Change (UNFCCC) invited the Intergovernmental Panel on Climate Change (IPCC) to prepare a special report on carbon capture and storage technologies; IPCC, in turn, decided to hold a workshop to do a literature of CCS in 2002, which at last, resulted in the famous IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005). Since then, the amount of literature on CCS has increased significantly, with academic journals created, theses, papers, and books written, and educational programs designed. The CCS Pilot Plant situated in the Department of Chemical Engineering, Imperial College London is an excellent example of one that serves both educational and academic purposes (Hale, 2017).

Potential

The most widely implemented method of carbon capture is chemical absorption-desorption. To use the example of the CCS Pilot Plant at Imperial College London, in its best performance, it can remove up to 99% of the CO_2 content of the CO_2-rich feed stream (Hale, 2017). Many other processes such as the Fluor Econamine FG Plus Process (Fluor, 2018) and the Kerr-McGee/ABB Lummus Crest Process (Barchas & Davis, 1992) are also proven to be highly effective in chemically capturing CO_2, also removing up to 99% of CO_2 in a single cycle.

Studies by IPCC predict that CCS will be contributing 17% of the necessary global emissions reductions by 2050 (from coal, gas, and heavy industry) and delivering 14% of the cumulative emissions reductions needed between 2018 and 2050 (IPCC, 2005). A more recent study by the International Energy Agency remarks that without CCS, the cost of meeting a target of reducing 50% global CO_2 emission by 2050 would increase by 40% (IEA, 2016).

Costs

Unfortunately, the cost of CCS technology still poses a huge barrier to its widespread use as a GHG control strategy. The total cost of CCS consists of the cost of CO_2 capture and compression, the cost of CO_2 transport (typically via a pipeline), and the cost of CO_2 storage (limited to geological sequestration). The typical costs associated with CCS of various industrial processes are tabulated in Table 1 (Rubin, Chen & Rao, 2007).

It is also argued that the lower the desired final CO_2 concentration is, the higher the operating costs are, and the lower the economic reliability becomes (Alie, 2004). The challenge of this is that it is necessary for CCS facilities to make trade-offs between high effectiveness (characterised by high amount of CO_2 removed per cycle) and low economic costs.

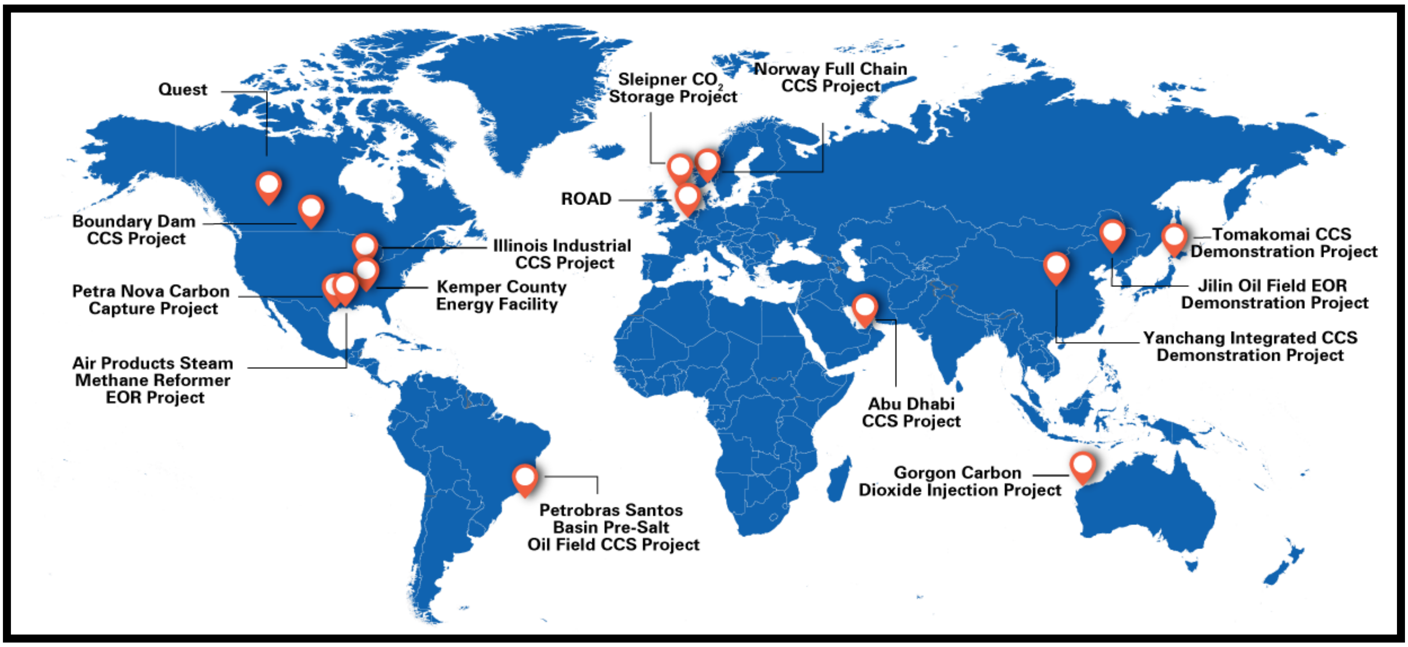


Figure 3 - The Global Status of CCS (Global CCS Institute, 2016)

Another great cost associated with CCS is its potential of acidifying the ocean (Albert II, 2018). CO_2 is a weakly-acidic gas which, under normal atmospheric conditions, is not very soluble in water; however, in underground storage sites especially under the sea, the pressure is typically high, so CO_2 can dissolve in water and form an acidic solution. Careful consideration must be made on the choice of storage site for the captured CO_2, so that it is far enough from the ocean and will not damage the subtle ecology therein (Haslam, Ravipati, Galindo & Jackson, 2018).

Outlook

Since the cost of CCS is a great obstacle to its large-scale application, to reduce the cost, there are several fields of research that can be explored:

1. The choice of solvent (Aronu, 2009). The most popular choice as of the time this article is written is aqueous MEA. However, MEA has a high energy penalty for CO_2 absorption, meaning that using it as the solvent induces an enormous amount of energy consumption in desorbing CO_2. A lot of studies are being carried out on better solvents, among which potassium carbonate is a plausible replacement (Kothandaraman, 2010).

2. The engineering of CCS processes. Typically carried out on existing CCS facilities and hence by researchers from the business sector, studies can be done on what operating conditions are the most optimum for a best performance of the plant, e.g., what flowrate of solvent to use, what composition of the CO_2-rich feed stream should be, what temperature to maintain in the separator units, etc. (Yeh & Pennline, 2001).

3. The implementation of membranes, packing materials and types, and catalysts (Rochelle, 2009). There have been numerous studies done on, for instance, the potential of employing metal-organic framework (MOF) structures in CCS processes to boost the performance (Simmons, Wu, Zhou, & Yildirim, 2011).

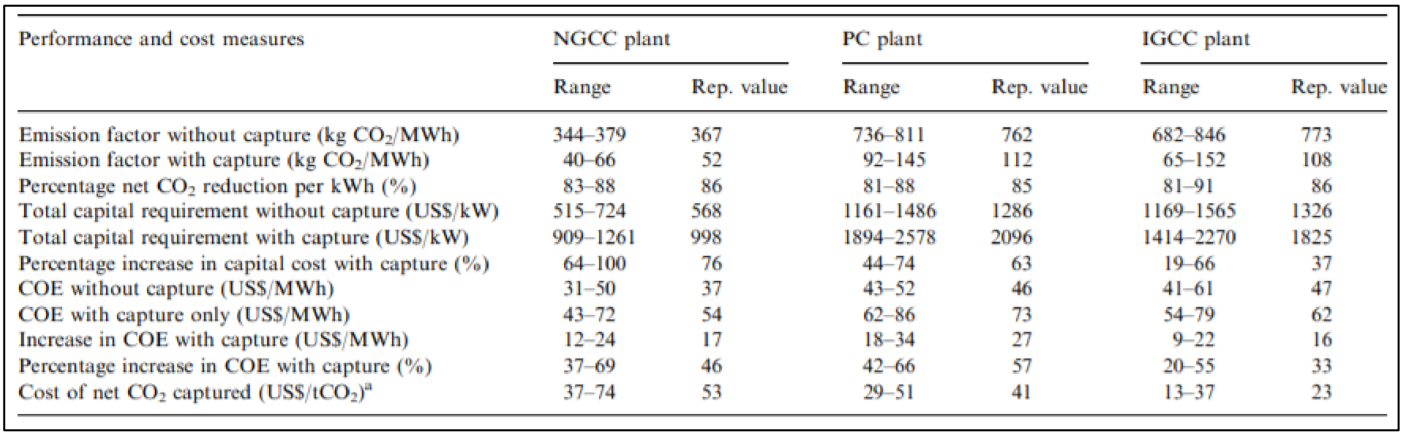
Other than these, several other potential fields for study on CCS include:

1. The storage of captured CO_2. For example, there has been plenty of research on what geological formations can trap the CO_2 and the phase behaviours, electrochemical properties, and surface interactions with the storage wall (Haslam, Ravipati, Galindo & Jackson, 2018).

2. Carbon capture and utilisation (CCU). Among this, EOR is the most excellent example, since boosting oil recovery is very important the petroleum industry and the amount of CO_2 used is large. Other than that, there are also studies on the potential of turning CO_2 into energy sources such as gasoline (Wei, et al., 2017) and synthesising plastic materials like polypropylene carbonate (PPC) using CO_2 (Styring, 2011). Utilising CO_2 in plant-cultivation and producing biofuels is also an attractive choice.

3. The economics of CCS. It is important to know how expensive a CCS operation is and how it is going to be funded. This field of research is known as technoeconomic analysis (Leeson, et al., 2017).

There surely exist many others that can be studied. In conclusion, though CCS is still at its infancy, as argued by Obama (2017), its development is part of the "irresistible momentum of clean energy". For the UK, it will be challenging if CCS is not widely applied to new gas-fired power stations and energy intensive industries (House of Commons ECCC, 2016).



Performance and cost measures	NGCC plant		PC plant		IGCC plant	
	Range	Rep. value	Range	Rep. value	Range	Rep. value
Emission factor without capture (kg CO_2/MWh)	344–379	367	736–811	762	682–846	773
Emission factor with capture (kg CO_2/MWh)	40–66	52	92–145	112	65–152	108
Percentage net CO_2 reduction per kWh (%)	83–88	86	81–88	85	81–91	86
Total capital requirement without capture (US$/kW)	515–724	568	1161–1486	1286	1169–1565	1326
Total capital requirement with capture (US$/kW)	909–1261	998	1894–2578	2096	1414–2270	1825
Percentage increase in capital cost with capture (%)	64–100	76	44–74	63	19–66	37
COE without capture (US$/MWh)	31–50	37	43–52	46	41–61	47
COE with capture only (US$/MWh)	43–72	54	62–86	73	54–79	62
Increase in COE with capture (US$/MWh)	12–24	17	18–34	27	9–22	16
Percentage increase in COE with capture (%)	37–69	46	42–66	57	20–55	33
Cost of net CO_2 captured (US$/t$CO_2$)[a]	37–74	53	29–51	41	13–37	23

Table 1 - Summary of reported CO_2 emissions and costs for a new electric power plant with and without CO_2 capture based on current technology (excluding CO_2 transport and storage costs) (Rubin, Chen & Rao, 2007)

1. *All costs in constant US$2002.*
2. *NGCC=natural gas combined cycle; PC=pulverized coal; IGCC=integrated gasification combined cycle. Rep. Value=representative value based on the average of values in the different studies; COE=cost of electricity production; MWh=megawatt-hours. All PC and IGCC data are for bituminous coals only at costs of 1.0–1.5US$/GJ (LHV); All PC plants are supercritical units; NGCC data based on natural gas prices of 2.8–4.4US$/GJ (LHV basis); Power plant sizes range from approximately 400–800 MW without capture and 300–700 MW with capture; Capacity factors vary from 65% to 85% for coal plants and 50–95% for gas plants (average for each=80%); Fixed charge factors vary from 11% to 16%.*
3. *Cost of net CO_2 captured is equivalent to cost of CO_2 avoided for zero transport and storage cost based on the given plant type with and without capture.*

The New Natural Gas Export Market Dynamic

Impact on Canada in Relation to The United States

Max Tang – LSE

Natural gas is the most affordable form of energy in terms of the capital cost of its power plants. It is also more reliable than renewable technologies due to its abundance (Sakmar, 2013). The latest International Energy Outlook conducted by the U.S. Energy Information Administration assessed that the worldwide consumption of natural gas was at 120Tcf in 2012 and will increase to 203Tcf in 2040. This accounts for the largest increase in worldwide primary energy consumption. The world supply of natural gas growth has been coming mainly from an increase in shale resources. The U.S., Russia, and China, with increase supplies of 11.3Tcf, 10Tcf and 15.5Tcf respectively, accounts for nearly 44% of the overall increase (EIA, 2016). In terms of liquid natural gas (LNG), the EIA projected world trade would increase from 12Tcf in 2012 to 29Tcf in 2040 (2016). Based on the BP Statistical Review of World Energy, in 2014 LNG accounted for 10% of the world consumption of natural gas, and 31% of all natural gas trade, increasing by an average of 6% on a yearly basis (2016). Three-fourths of all LNG trade is occurring in the Asia Pacific region, with Japan, South Korea, India, and China being its main importers (EIA, 2016). In terms of suppliers, Qatar is currently the largest LNG exporter, with Malaysia ranking second and Canada ranking fourth. However, the United States and Australia are not far behind, with 93% of new liquefaction capacity worldwide between 2015 and 2019 (EIA, 2016).

The United States has become a new major exporter of LNG, benefits largely due to the shale revolution. The general consensus could be described by the claim of John Dutch, a former professor of MIT, published in the Wall Street Journal: “the US natural-gas boom will transform the world” (2012). More precisely, unconventional natural gas activities are bringing significant benefits to the U.S. economy in terms of jobs, government revenues and its GDP (IHS, 2012). It was estimated that the shale boom increased the total U.S. consumer and producer surplus by $48bn in 2013 (Huntington, 2015). FIDs taken between 2009 and 2015 were projected to increase U.S. LNG trade significantly between 2016 and 2020, representing 40% of the global increase (Corbeau *et al.*, 2016). Furthermore, the U.S. completed its first natural gas overseas export terminal in the beginning of 2016 at the Sabine Pass. The same year in August, the first shipment of LNG from the lower 48 U.S. states arrived in China. As of Feburary 2018, four other terminals are under construction: Freeport LNG, Cameron LNG, Cove Point, and Corpus Christi; Eleven other projects are waiting of FERC orders (Carson & Laursen, 2016). Since the U.S. has been importing LNG for decades, these brownfield projects to convert existing import terminals into export terminals are much easier than greenfield projects (Cheniere, 2013).

On the other hand, according to the National Energy Board of Canada, Canada well known for its wealth of natural resources is the fifth largest producer of natural gas and the fourth largest natural gas exporter in the world (2016). In 2015, the natural gas sector generated over $25.3bn of annual revenue for Canadians (IBISWorld, 2016), while natural gas exports to the U.S amounted to $9.8bn (NEB, 2016). However, recent technological innovations in shale gas have made the United States the country’s only customer of its natural gas exports, its number one competitor. As a result, the total export of Canadian natural gas declined by nearly one-third between 2007 and 2014 (figure 1) (CAPP, 2015). This trend will likely continue since the U.S. became a natural gas net exporter in the beginning of 2018. Without an alternative consumer of its product, Canada could face severe economic repercussions.

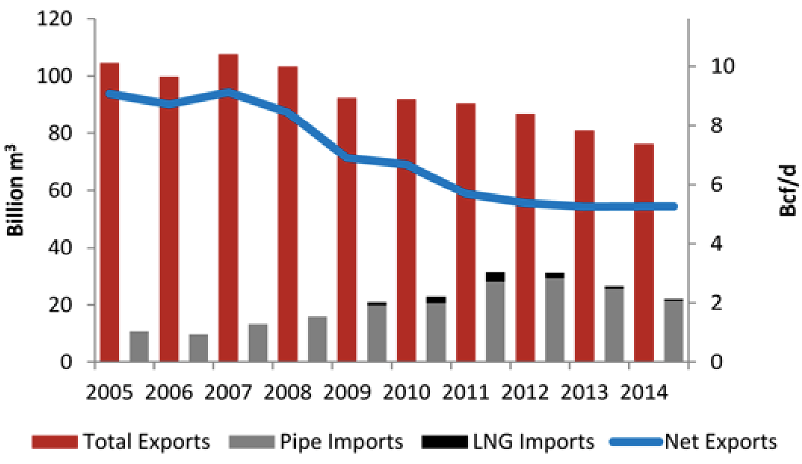


Figure 1: Canadian Natural Gas Export 2007-2014
Source: Canadian Association of Petroleum Producers, 2016

As the U.S. is slowly becoming a net natural gas exporter, Canadian natural gas exports are slowly disappearing due to the lack of export facilities, regulatory and cost uncertainty, coupled with unfavourable market conditions and economics (Blyschak, 2016). Given that LNG boom failed to materialize in Canada, major gas companies are giving up on it. On October 21, 2016, Royal Dutch Shell announced it would scale back its oil and gas operations in Canada by selling $1.3bn worth of properties in Western Canada. Today, Canada currently does not have any operating export facilities. Until 2025, the future of the Canadian LNG industry will consist entirely of three hypothetical projects that could potentially come into service in 2022 at the earliest (Robins *et al.*, 2016). These three projects consist of Kitimat LNG, LNG Canada, and Pacific Northwest; none of the three have yet received a Final Investment Decision as of February 2018.

Due to the rapid decline in Canadian natural gas exports, stakeholders especially in the oil & gas industries are welcoming the idea of exporting oversea. Tim McMillan, president and CEO of the Canadian Association of Petroleum Producers, stated: "the economic benefits of selling Canadian energy overseas are significant" due to potential increase in government revenue, economic growth and the creation of permanent jobs in British Columbia (2016). The federal government also supports the idea. In September 2016, Petronas received a conditional government approval on the proposed $27bn liquefied natural gas plant to be constructed on Canada's Pacific Coast (Karstens-Smith, 2016).

However, strong opposition led by the First Nations is the main reason that the country cannot proceed with the construction of these liquefaction facilities. Since natural gas is a form of fossil fuel, any activity remotely related would most likely to be reviewed under severe scrutiny due to the social stigma associated with its pollution potentials. These risk assessments could be extremely time consuming because researches on how these facilities affect health, safety, security, and the environment, as well as technical, commercial, legal, contractual and economic matters are often difficult to assess (Maniruzzaman, 2008).

In addition, these risk analyses are expected to be provided by the Canadian federal government staffs to avoid bias (Streigler, 2016). After the research is delivered, communicating results and convincing the opposition party that liquefaction facilities do not have significant long-term impacts are also very difficult. This is because the liquefaction process of LNG is not intuitive scientifically. Thus, many proposed Canadian liquefaction facilities have been cancelled due to timeline uncertainty. This is the reason that the earliest facilities in operation would have to wait until 2022 if FID could be made in the near future.

Without an alternative consumer of its product, Canadian natural gas exports are likely to disappear, and the country could face economic repercussions. Although in Canada the specific number of workers employed in natural gas export is not available, yet to estimate the potential impact on Canadian jobs, we can use the median salary of an employee in natural gas and the total wages in the industry to estimate the employment impact. In 2015, 40% of all revenue from natural gas resulted from U.S. exports; total wages paid in the natural gas sector was $1.466bn (IBISWorld, 2016) and the median salary in Canada for an employee with 5-9 years of working experience in the natural gas sector was $76,948 (Payscale, 2014). If we take 40% of the total wage paid in 2015, then divide it by the median salary, Canada would lose approximatively 7620 high paying jobs when the U.S. becomes a natural gas net exporter. Therefore, finding an alternative natural gas customer despite of current difficulties is crucial for the Canadian economy.

Picture 1: Vancouver's Port; Source: Wikimedia Commons

Decreasing Price of Solar

The Drivers and the Limits

Elyas Helmke – LSE

According to a study conducted last year by GTM Research, the price of solar is expected to decrease by a further 27% by 2022. Assuming no further advancements than the standard predicted rate of 4.4% cost decrease per watt of produced electricity that is – a modest assumption given constant technological changes and advancements. Nonetheless this paints a rosy picture for the future of solar. Having gone from a fringe renewable capable of around 10% energy conversion under lab conditions, and huge expenses, no 25 years ago, solar generation costs have reached parity with traditional sources, and begun rapidly undercutting them.

Nowhere else has this perhaps been more apparent than India and China. India is now producing solar panels at a levelised cost of $0.65/watt. Indeed, the drop in the cost of solar production has been so marked that in May 2017 alone India decided to scrap plans for the construction of around 14GW in coal-fired energy production, largely replacing it with solar. The implications for global energy markets and climate change abound. A report by the Institute for Energy Economics and Financial Analysis shows India's coal demand peaking by 2027, much earlier than previously predicted, while at the same time producing 27% of its energy demand from renewables by then. Not only does this afford India a chance to meet its Paris commitment to 1.5°C temperature increase, but it also shifts global and domestic markets in favour of renewables. The question remains what countries like India will do with stranded assets, billions still being invested into coal mines, particularly in Australia and China.

It's the cost-reductions, as well as global cooperation on climate change reduction, that are pushing the bounds in solar installation. Even more marked than India's developments has been China's energy revolution. One of the largest polluter and consumer of coal in the world last year cancelled 104 new coal plants, instead opting for renewable projects, many of them solar. The simultaneous construction of two 150MW plants, providing electricity to almost 150,000 people, are spear-heading a £360b state investment into clean energy projects, creating over 13m jobs by 2020. Compounded with the efforts in Europe and South America, with countries like Germany, Sweden and Nicaragua rapidly encroaching on 100% renewable generation capacity, the tide seems set to have turned in solar energy's favour.

So where are these drastic reductions in price coming from? By-and-large the increasing globalisation of supply chains, improved production techniques and bigger funding from banks. As solar has established itself as a viable and cost-effective energy source, corporate lending, government subsidies and R&D investments have led to tremendous economies of scale with expanded operations. From 2014-16, installed capacity almost doubled from 40 to almost 80GW of installed capacity. This is by far the most profound increase in capacity of any current energy source.

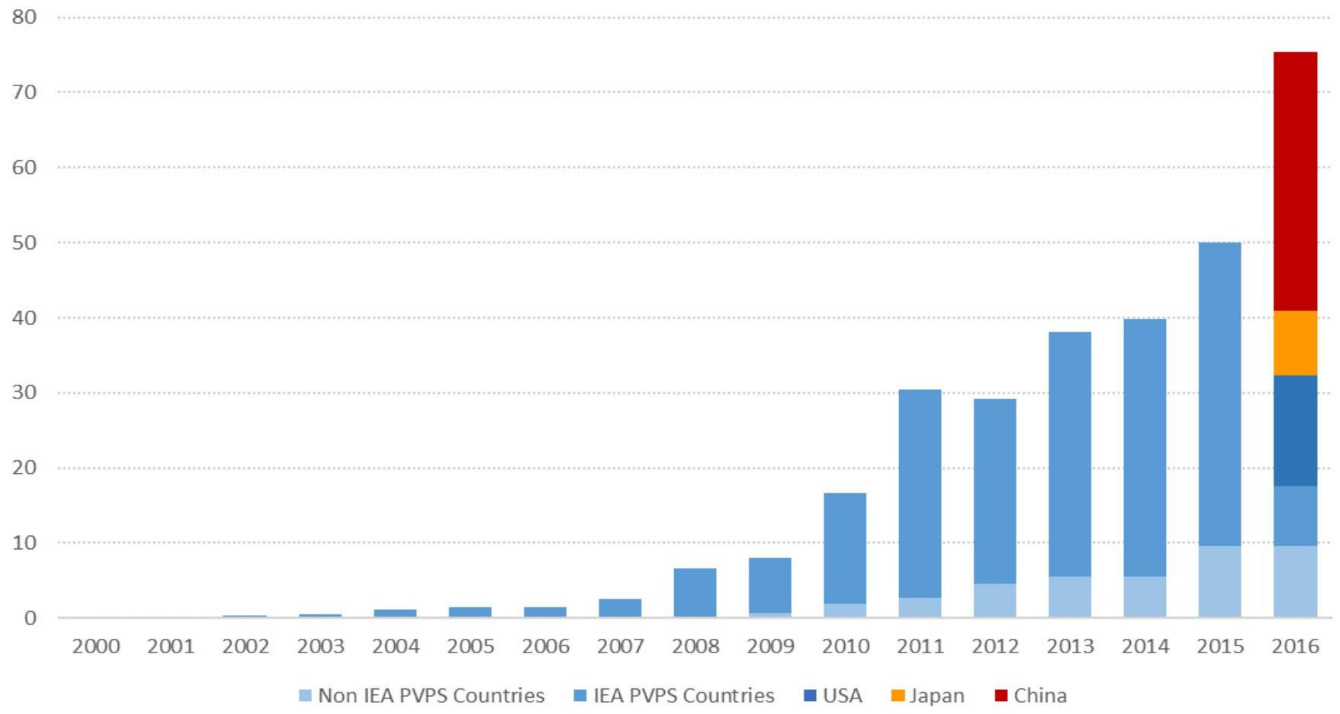


Figure 1: Evolution of Annual PV Installations (GW – DC); Source: GreenTech Media

These economies of scale are best captured by Swansons' Law. Richard Swanson, founder of SunPower Corporation, noted that solar prices have decreased roughly 20% for every doubling of volume shipped. Continuing at contemporary rates, this means costs have been halving roughly every 10 years.

Outsourcing of production-lines and the globalisation of supply-chains have also been key, with cheaper access to labour, capital and raw materials like silica, cadmium and aluminium.

The cost of solar doesn't seem set to level-out any time soon, so are the question remains, where are the boundaries on growth and cost-effectiveness? Or else, surely by now, the whole world would've gone solar.

In short, while the hard costs of solar have decreased so drastically, the portion shared by the soft costs, i.e. installation, operation & maintenance, and residential system costs, remains relatively high. Furthermore, the issue is exacerbated by project-developers underquoting projects in developing regions. This has become a major problem in India, after the defaulting of several developers due to understated cost-declarations which they failed to deliver on[1]. In America, large-scale photovoltaic manufacturers and plant-installers are now having to deal with Trump-administration incentives for reviving the coal-industry, decreased subsidies for renewables, and decreasing demand in the residential-solar market. This has again been driven by relatively high soft costs, and decreased federal and state incentives since Obama-era pushes. Competition from China, which now produces two-thirds of the world's solar panels, has led to the Trump-administration to impose protectionist tariffs, likely to further raise the cost of solar in America and create the potential for domestic inefficiencies. Finally, the growth of solar in most European countries has led to a nigh-elimination of government subsidies, which are often based on installed capacity quotas that have now been reached or are close to. This is leaving solar to compete against coal, gas and oil on its own two feet for the first time, and testing these waters will provide some challenges.

So, while the global solar revolution spurs on, driven by price-parity and undercutting, billion-dollar incentives from developing nations, and installation subsidies from developed ones, the focus in the western hemisphere will shift to the market conditions created by American protectionism. The rolling-back of state subsidies, combined with America's return to coal, however, fortunately don't look set to impact the global development of solar energy, with the key drivers of production and installation coming from the East, China and India leading the way. Finally, price-parity and climate change commitments in Europe underpin the global demand and production chains which are fuelling the ever-decreasing costs and feasibility of solar.

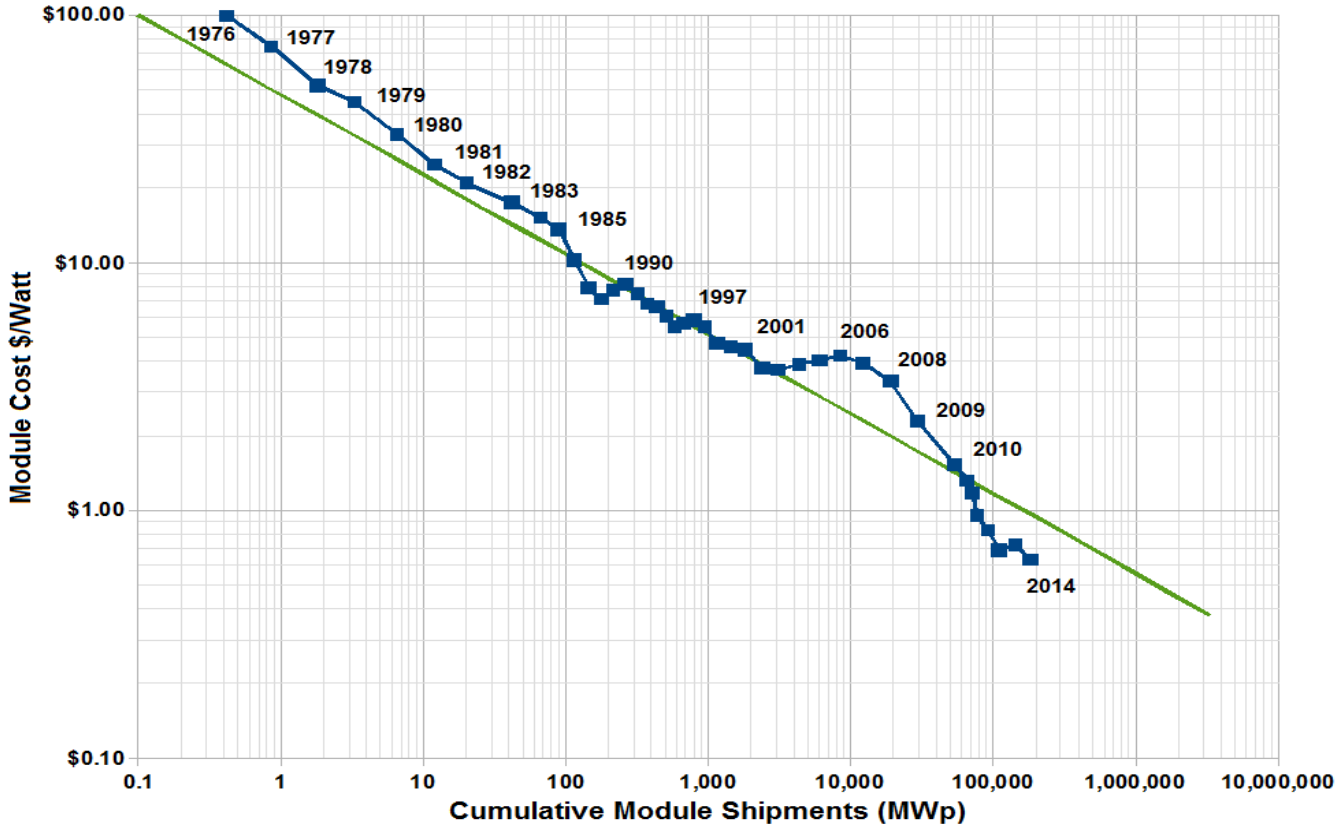


Figure 2: Swanson's Law

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[1] *India to hit peak coal demand faster than expected, says report,* Kiran Stacey, Financial Times, 21/11/2017

Guest Articles

Guest Article : Business Model Innovation at Statoil

Statoil

Disrupted or Disruptor: Business Model Innovation at Statoil

By Christina Khayat – Corporate Innovation

The world is indubitably witnessing accelerated rhythms of change. Whilst the seasoned generation that came before us were steadily waltzing along, we today are engaged in a high-tempo salsa, trying to keep up with its unrelenting cadence. Yesterday's industry front-runners are effortlessly swatted out of the contest by an influx of indefatigable newcomers. We have all observed that the world's largest taxi company possesses no vehicles and the world's largest accommodation provider owns no real estates and so on – the list is getting more exhaustive. Above all, the traditional view of business does not capture the way great companies think their way to success.

Are oil and gas companies far away from this, complacently enjoying the predictable 1-2-3 rise and fall of the waltz? The answer is no. For starters, technological advancements are redefining the economics of energy. For example, blockchain may enable new players to disrupt the way energy is traded. Utility companies are already feeling heat from start-ups who are developing smart homes solutions, made possible by recent advances in Internet of Things and digital assistant technology.

Climate change also contributes significantly to this context of uncertainty. Even in Statoil's most encouraging of futuristic scenarios, "Renewal" (that includes coordinated rapid policy changes and accelerated energy efficiency improvements), we predict a probability below 66% of limiting the average global temperature increase to 2°C (Figure 1). This challenge is exacerbated by geopolitical disagreements, aggravated through the resurgent trends of nationalism, protectionism, sanctions, and even threats of exiting international agreements. The oil & gas majors are nevertheless undergoing an evolutionary phase, as the global energy mix steadily shifts towards low carbon sources (Figure 2).

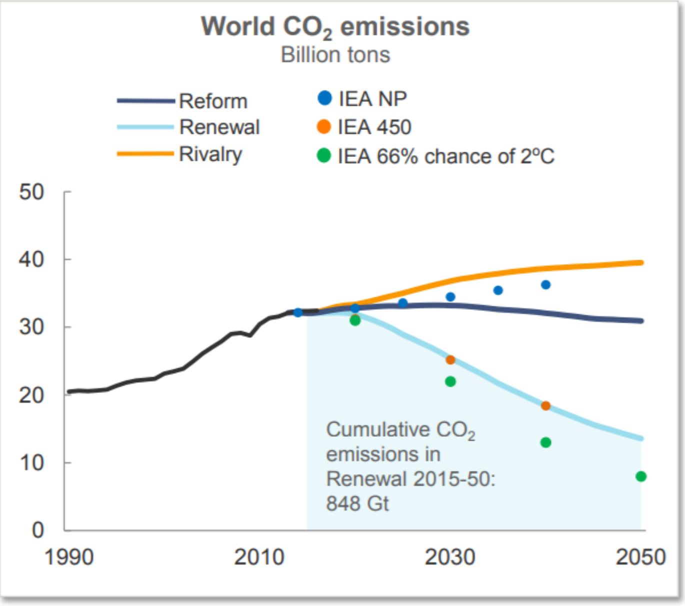


Figure 1: Historical and projected World CO$_2$ emissions given Statoil's three scenarios, benchmarked against IEA emissions for different temperature scenarios.

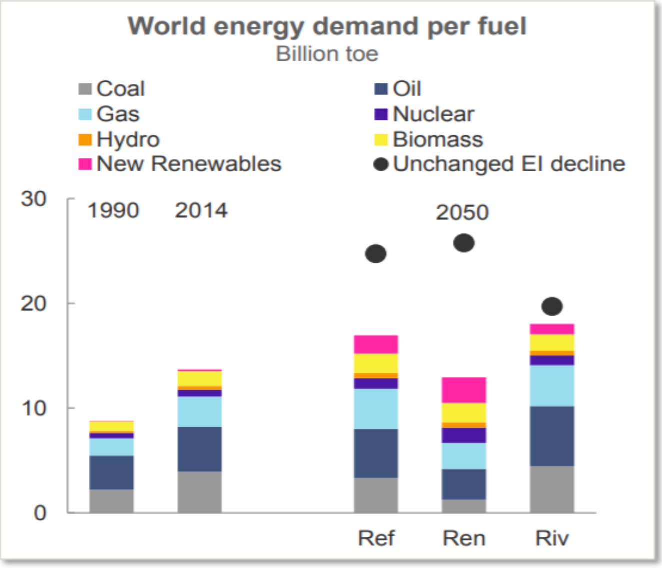


Figure 2: Historical and projected world energy demand per fuel in the three scenarios: Reform, Renewal and Rivalry .

In this rapidly changing competitive environment, Statoil has refused to adopt an attitude of complacency. Our vision is to shape the future of energy, by actively navigating around these challenges; re-posturing ourselves by treating them as opportunities.

Statoil has a notable track-record in innovation: We have proven that it is possible to develop an offshore oilfield without any rigs visible on the surface, while our subsea wells are changing the concept of offshore production. We have also taken pride in launching the world's first floating windfarm, off the coast of Scotland. However, this is just the beginning: Technological improvements must be complemented with business model innovation for us to remain competitive, and achieve our environmental goals. Our CEO recently expressed our ambition to move from an oil and gas company to a broad energy major. What strategic moves will get us there? One way is through exploring and creating options through business model innovation. In a nutshell, business model innovations (BMIs) answer one of two questions: how can you create value in improving what you already do, or how can you come up with completely new ways of doing so? The elements of a business model that are already being tinkered with are the value proposition, profit formula, resources and processes. BMIs can draw on the company's assets, leverage something the company does well in a new space, or even call on unfamiliar assets to serve new markets or customer needs.

Guest Article : Business Model Innovation at Statoil

To come up with BMIs, businesses rely both on their employees and their external stakeholders, along with customers, business partners, and academics. Unlocking every touchpoint delivers diverse knowledge and expertise from larger ecosystems; creating a synergistic market of ideas. Students, in particular, bring the hugely desired tray of fresh ideas to the business. A recent undertaking of Statoil's innovation team includes working closely with students who have created and investigated BMIs that could stem from Blockchain technology and generate value by exploiting Statoil's inherent advantage as a responsible energy producer.

The preferred business case is now being piloted at Statoil, with prospective adoption by our Midstream, Marketing and Processing businesses. This is but one of the many examples, where students have been given the mandate to challenge how things work at Statoil, and design integrated, value-adding solutions to achieve Statoil's mission and fulfil its overall responsibility.

To learn more about your career opportunities at Statoil, check our career page at Statoil.com

Student presenting their 'Blockchain shaping the future of energy' findings; Photo: The Innovation Effect

The Corporate Graduate Programme at Statoil

For students in their final year, or recent Masters/Ph.D. graduates, we offer the opportunity to contribute to shaping the future of energy through our Corporate Graduate Programme.

The programme consists of an introduction to Statoil and the energy industry, including physical and virtual learning sessions focusing on network building, individual development and an understanding of the business we work in. We offer challenging and meaningful tasks, and an opportunity to work with your own goals and interests.

For Bachelors students, please check out our summer internship programme at statoil.com

Waste Heat Recovery

A Critical Step for an Energy Efficient Future

Imperial College London

Kai Wang and Christos N. Markides | Clean Energy Processes (CEP) Laboratory, Imperial College London

Energy efficiency is considered one of the key pathways for satisfying the growing global demand for energy while restraining resource use and emissions. However, current energy efficiency measures are still at a level far from satisfactory. Only 28% of the global primary energy supply is utilized for useful energy services (electricity generation, transportation, industrial, residential and commercial applications), while up to 52% of the total supply is released to the environment as waste heat[1] (see Figure 1). For example, in internal combustion engines, about 20-45% of the fuel energy released by combustion is typically converted into motive power, while the rest is mostly wasted as heat from the radiators and in the form of exhaust gases[2]. In the cement, steel, glass, oil and gas industries, a massive amount of waste heat is available at temperatures around 250-500 °C, corresponding to about 30% of the total energy input[1,3]. In addition, thermal energy is also widely available from renewable energy sources such as geothermal and solar heat, the temperature of which can vary from 100 to 600 °C. Of the total rejected waste heat globally, the majority is at low (≤ 100 °C, 63%) and medium (100-300 °C, 16%) temperatures. If recovered appropriately, this "waste" heat can be turned into a significant energy resource in its own right, which would act as an important substitute of primary fuels or energy.

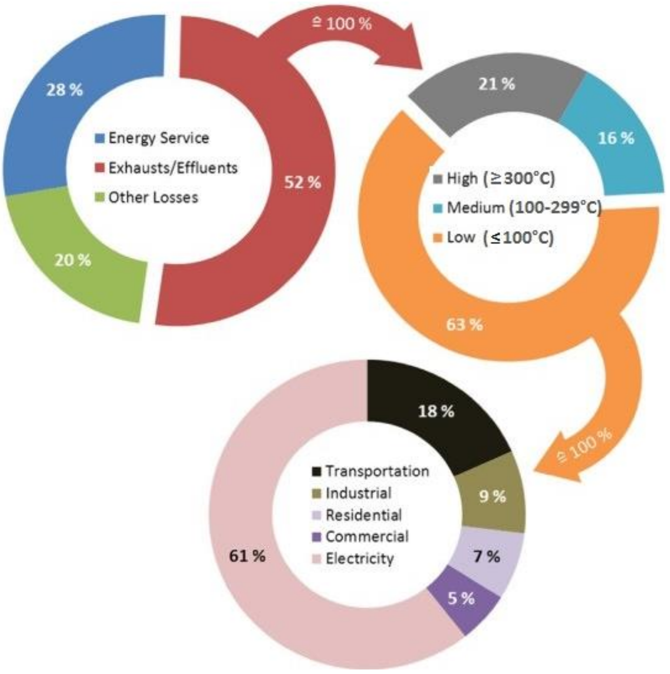


Figure 1. *Shares of world energy flows by sector[1].*

Numerous solutions are now available for delivering a useful end-product from recovered waste heat. Relevant technologies can be categorized into direct and indirect, depending on whether the waste heat is reused directly without conversion or whether it is transformed into another form of energy (e.g. mechanical or electrical power) or upgraded to higher/lower temperature levels for heating/cooling provision to end users.

In direct utilization approaches, waste heat is recycled or reused through heat exchangers for preheating in other industrial processes (e.g. combustion air preheating or boiler feedwater preheating) or for district heating in residential/commercial buildings[4]. Although the recovery and direct reuse of heat without conversion appears to be a straightforward solution, it is associated with non-trivial challenges which have limited the wider adoption of this practice. Firstly, heat is a low-value energy vector that can be easily generated with low carbon intensity, e.g. with highly responsive biomass/gas boilers. Secondly, it pre-supposes that a sufficient demand exists for the heat, with sinks that match not only the time-varying quantity but also the temperature and location of each heat source; significant thermal energy storage is otherwise necessary over a large range of temperatures and scales, which adds complexity and cost. A continuous and reliable servicing of heat sinks is difficult to guarantee in practice, in some cases leading to problematic scenarios and elevated risk levels for the end-user, whether this is another on-site process or an 'over-the-fence' heat supply. Thirdly, a lack of a suitable regulatory framework and culture to deal with 'over-the-fence' sharing, as well as a lack of industrial thermal 'symbiosis' mechanisms or of a suitable district-heating network to connect to have appeared as barriers in some regions, which has acted to impede this type of solution from making tangible inroads even in cases that have otherwise appeared financially attractive in the short term.

In combination with direct reuse, e.g. in district-heating networks, conversion to heating, cooling or electricity[5], introduces promising alternatives that bypass or mitigate the problems associated with direct usage of waste heat. Generally, absorption, adsorption and thermoelectric devices are the main refrigeration options typically considered in the context of waste-heat recovery for providing cooling; however, the absorption refrigeration cycle is the most readily available cycle for low-temperature waste heat recovery in industry. Beyond cooling, waste heat can also be upgraded to higher-temperature heat, mainly by mechanical vapour compression, absorption or adsorption heat pumps. Compared to mechanically driven refrigeration or heat pump systems, the electrical energy requirements when using absorption cycles are minimal as these machines can utilize waste heat (75-200 °C) as the driving energy source, which make them of particular interest in some cases. The water-lithium bromide (H_2O-LiBr) and ammonia-water (NH_3-H_2O) absorption cycles are the most commonly used such cycles[6]. Commercially available absorption systems typically have a cooling coefficient of performance (COP) that varies from 0.7 for a single effect system to 1.2 for a double effect system with a cooling power ranging from 10 kW to several MW[7]. Triple effect absorption chillers are also available.

Generating electricity represents another important avenue for transforming waste heat into a much higher quality energy vector. The potential technologies for converting waste heat into electrical power mainly include, amongst others: Organic Rankine cycle (ORC), Kalina cycle, Stirling cycle or thermoacoustic (TA) engines, and thermoelectric generators (TEGs). Of these technologies that can be considered for waste-heat recovery and conversion to power, the ORC is one of the most promising candidates, and is suitable for converting low- and medium-grade waste heat, typically at temperatures between 80 °C and 500 °C, into electricity[8]. In this temperature range, ORC systems significantly outperform the other competing options: TEGs[9], Stirling[10] and TA engines[11] (see Figure 2). Efficiencies up to 25%, and in some cases even higher, are achievable at the higher temperatures. In addition, ORC systems have a much better scalability in industrial applications with plant sizes up to tens of megawatts while the sizes of competing technologies are generally limited to hundreds of kilowatts. Therefore, an extensive research effort is now being devoted to ORC systems, and more than 600 plants have been deployed worldwide with a cumulative capacity in excess of 2 GW.

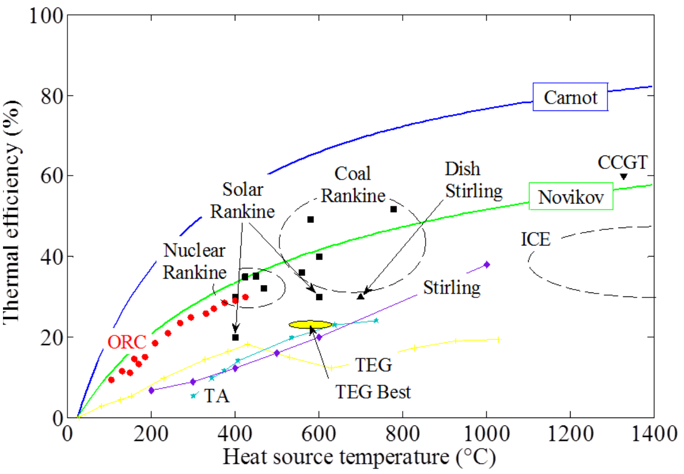
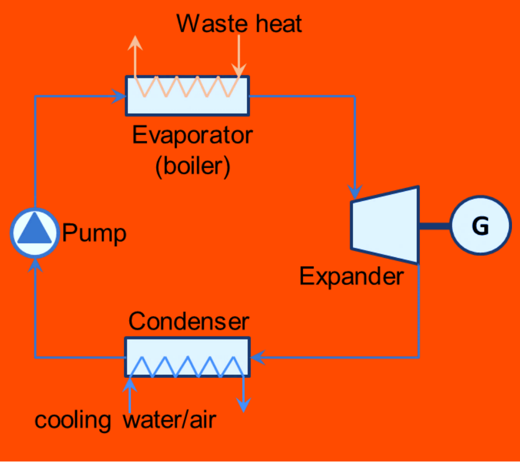


Figure 2. *Conversion efficiency of different power conversion technologies; reproduced from Ref. 12.*

An **ORC system** comprises an evaporator (boiler), an expander, a condenser and a pump. Instead of water, as used in steam Rankine cycle power plants, ORC systems use organic working fluids in order to convert heat more effectively from lower temperature heat sources. The organic working fluid absorbs heat from the heat source in the boiler and evaporates. The resulting high-pressure vapour stream then enters the expander and imparts mechanical work onto this component. The expanded steam flows into the condenser at low pressure and low temperature, where it is cooled and condensed into a liquid. The pump then lifts up the pressure of the condensed liquid and sends it back into the evaporator for the next cycle.



An exciting research activity that focuses on the development of advanced technical solutions and modelling tools for waste heat recovery, which can have a transformative role in key energy sectors in the decades to come, is being undertaken at the Clean Energy Processes (CEP) Laboratory at Imperial College London. The project, which is one of three major projects funded by the UK Engineering and Physical Sciences Research Council (EPSRC) in the strategic area of "Reducing Industrial Energy Demand", aims at minimizing primary-energy use in UK industry through the development of next-generation energy-conversion technologies specifically by considering advancements to and the integration of ORC power generation and absorption refrigeration technologies in target industrial sectors and plants[13]. This research and development effort focuses specifically on selected 'bottleneck' aspects of these two technologies, including working-fluid selection, highly efficient heat exchangers, low-loss expansion machines, advanced system architectures, and optimized system design, operation and control, based on an advanced molecules-components-technologies-systems development strategy.

In particular, novel computer-aided molecular design (CAMD) techniques based on the advanced Statistical Associating Fluid Theory (SAFT) are being explored for identifying novel next-generation tailored working fluids and for developing optimized ORC and absorption systems for waste heat recovery applications[14]. This holistic approach circumvents the limitations of conventional working fluid selection methods, which are typically based on screening known fluids with predefined criteria through parametric optimizations and have difficulties in exploring new fluids with no or limited available experimental data. In addition, proposals such as advanced heat exchangers with coatings or structured surfaces, working fluids with nanoparticle additives and novel thermal-energy-storage materials in integrated components are being tested to enhance two-phase heat transfer from the waste heat sources to/from the working fluids and to address the challenge of the effective and efficient use of unsteady and distributed heat-sources by stabilizing the input energy source[15]. ORC and absorption systems with thermal inputs in the range of 100 kW - 1 MW are targeted in this project for integration with CHP engines and/or waste-heat recovery and conversion, with significantly improved performance, reduced capital cost and payback times, as well as in-built modularity and flexible transferability to a range of industrial applications and settings.

A recent DECC-commissioned study identified a total of 48 TWh/yr of recoverable waste heat in UK (17% of all industrial energy-use), of which 58% or 28 TWh/yr (corresponding to 5.6 $MtCO_2$/yr) could be recovered and supplied at 100 °C or higher at a cost below £90/MWh[16]. This potential represents 10% of total UK industrial energy-use. However, of the 28 TWh/yr, only 17% had an economic or commercial potential with current technologies. If the identified 28 TWh/yr of total wasted heat from suitable (non-solid) sources and suitable temperatures is converted to useful power through the aforementioned technologies, an estimated 4-7 TWh/yr or 2-3% of all UK power demand (300 TWh/yr) could be generated, replacing 1 average UK coal-fired power station (~1 GW) or 3 new CCGT (Combined Cycle Gas Turbine) power plants (~400 MW).

Clearly, waste heat recovery systems have a huge potential to increase resource efficiency and reduce emissions if these were made economically viable. Projects such as the one at Imperial College, but also many others, are crucial in delivering the solutions with which to realise this widely desired energy-efficient future.

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