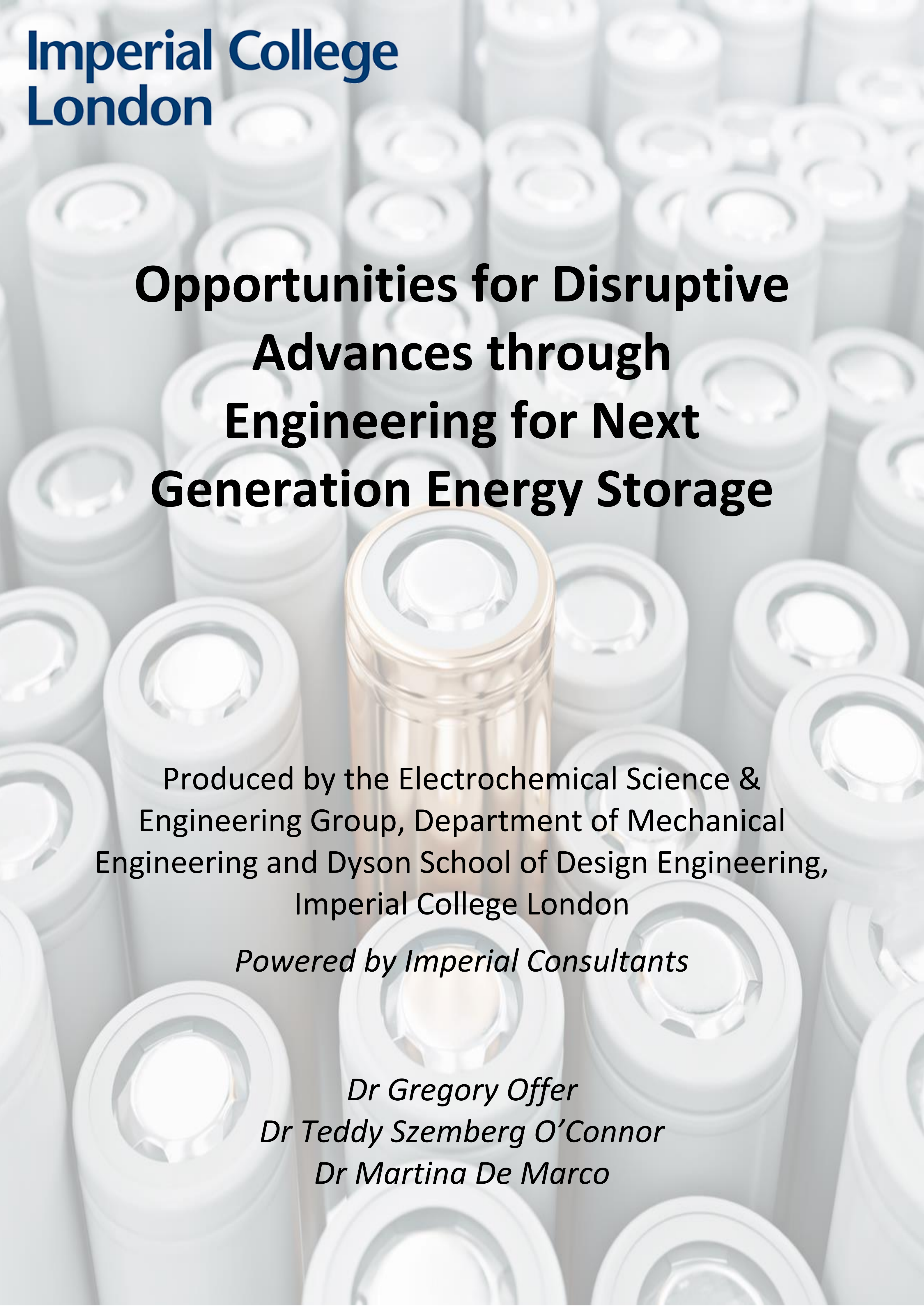

Imperial College
London

Opportunities for Disruptive Advances through Engineering for Next Generation Energy Storage

Produced by the Electrochemical Science &
Engineering Group, Department of Mechanical
Engineering and Dyson School of Design Engineering,
Imperial College London

Powered by Imperial Consultants

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Executive Summary

- Throughout human history, major economic disruption has been due to technological breakthroughs.
- Since 1990 the energy density of lithium-ion cells has increased by a factor of four and the cost has dropped by a factor of 10.
- This has caused disruption to the energy industry, but advances are slowing.
- The manufacturing and supply chain complexity means that the next big technology will take 15 years to dominate.
- The academic literature charts this process of development and can be used to show what is in the pipeline.
- Three candidates that have had a large increase in publication count are: lithium sulphur, solid-state, and sodium-ion technology.
- From the level of investments in start-ups and academic publication counts, solid-state cells are closest to maturity.
- To identify disruption potential, look at uncertainty in performance. Cell lifetime in lithium-ion cells indicates room for improvement.
- Define a new disruption metric: $Lifetime\ cost\ [\$/(kWh * Wh)] = cell\ cost\ [\$]/(cell\ energy\ [kWh]\ *\ Wh)$. Look for areas of industry that lower this metric.
- Thermal management is a lucrative area for improvement. Cooling the cell tabs of a 5Ah cell reduces the lifetime cost by 66%, compared to 8%/pa for 13 years relying on cost reduction.
- Second life applications lower the lifetime cost by using the remaining 75% of energy throughput available in a cell after use in an electric vehicle.
- Drop-in changes to standard manufacturing processes enable huge disruption. Electrolyte additives can increase cell life by 10 times, lowering lifetime cost by 90% in a simple manufacturing intervention.

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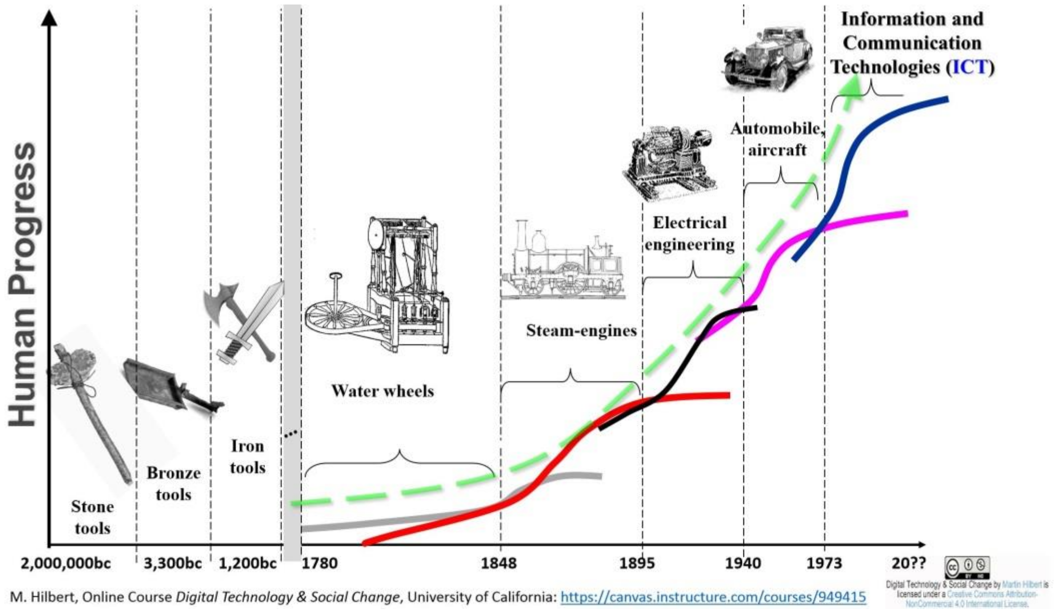
DOI: 10.5281/zenodo.3931338

1. Introduction

Disruption, in the context of technical progress, has many definitions. It conveys a sense of significant change that overturns the current way of doing things; manufacturing, communicating, transporting, etc. This is usually triggered by a technical breakthrough that increases the performance of a process by a ‘large’ amount; outperforming the incumbent at a lower cost and even enabling new tasks to be completed.
Figure 1 shows historical examples that have fundamentally changed the ability of humankind to perform new tasks which were previously impossible, and existing tasks more easily [1]. Records of technological change are available from the industrial revolution and allow human technological progress to be charted in detail. Each technology has a period of development, during which its impact on the world is small, a deployment and use period during which its contribution is greatest, and a period of decline during which an alternative offers a better solution; often built on technology that had been through a period of refinement for many years. The key questions we aim to answer in this white paper are: how can you tell what is a disruptive technology? And which of the viable alternatives is likely to dominate?



M. Hilbert, Online Course *Digital Technology & Social Change*, University of California: https://canvas.instructure.com/courses/949415

Figure 1 Human progress through the ages led by technical disruption. Image from M. Hilbert, Online Course: Digital Technology & Social Change, University of California.

To answer the first question, a definition is useful. A simple illustrative model of human progress can be expressed as:

$$\text{Economic activity } = k * \text{human effort.}$$

We define disruption to be when $k > 2$, and a technological revolution to be when $k > 10$. We are interested in identifying either case in the energy storage industry. Lithium-ion technology is currently the dominant chemistry for electrochemical storage devices, which has been driven by technological improvements in energy density and a reduction in the cost per unit of energy stored in the cell. The latter factor has been more dramatic and is a result of investment in mass-manufacturing processes, which reduce the per-unit cost due to economies of scale.

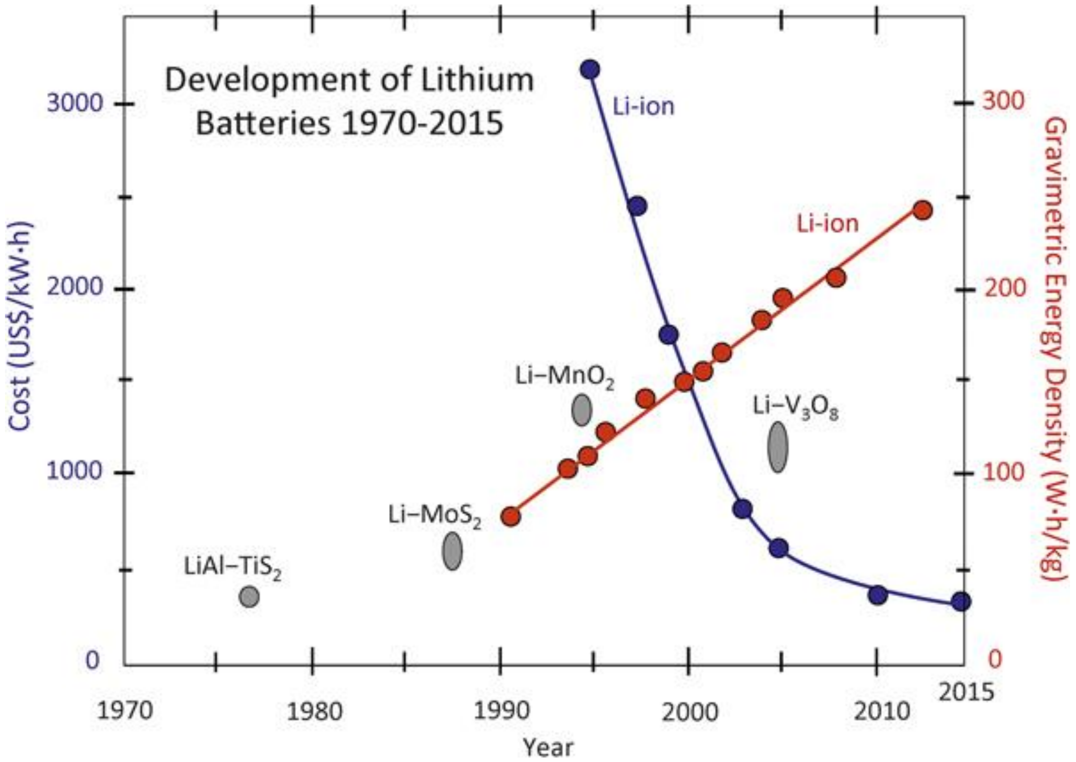


Figure 2 Two core metrics that lead to a disruptive technology: cost and performance [2]. Reproduced with permission and acknowledgment of Cambridge University Press.

Figure 2 demonstrates why lithium-ion technology has become so popular [2]. Since 1990, its performance at the cell level (here represented by energy per kilogram of cell) has increased by roughly a factor of four, whilst the cost per unit energy has reduced by a factor of ten. The flattening of the cost curve from about 2005 onwards suggests that the current manufacturing techniques are maturing to the point where the likelihood of a major disruption in cost is unlikely, although incremental improvements and increases in volume are still driving the cost down year on year. There is also a general consensus that the current generation of lithium-ion cells are unlikely to deliver more than approximately 350 Wh/kg [2]. The trend of cost reduction and technological improvement is also clear in electric vehicle battery pack cost (Figure 3)[3]. Not only have manufacturing costs reported by industry leaders, academia, and the media converged, but costs are approaching a floor of lowest-possible cost, set by the price of raw materials, refining processes, manufacturing and transportation. Once the cell cost benefits from the economies of scale at large manufacturing volumes, there won't be much room left for improvement. We conclude that for a true disruption in unit cost (i.e. halving in a short period of time), a new technology is needed and we cannot see one in the pipeline yet.

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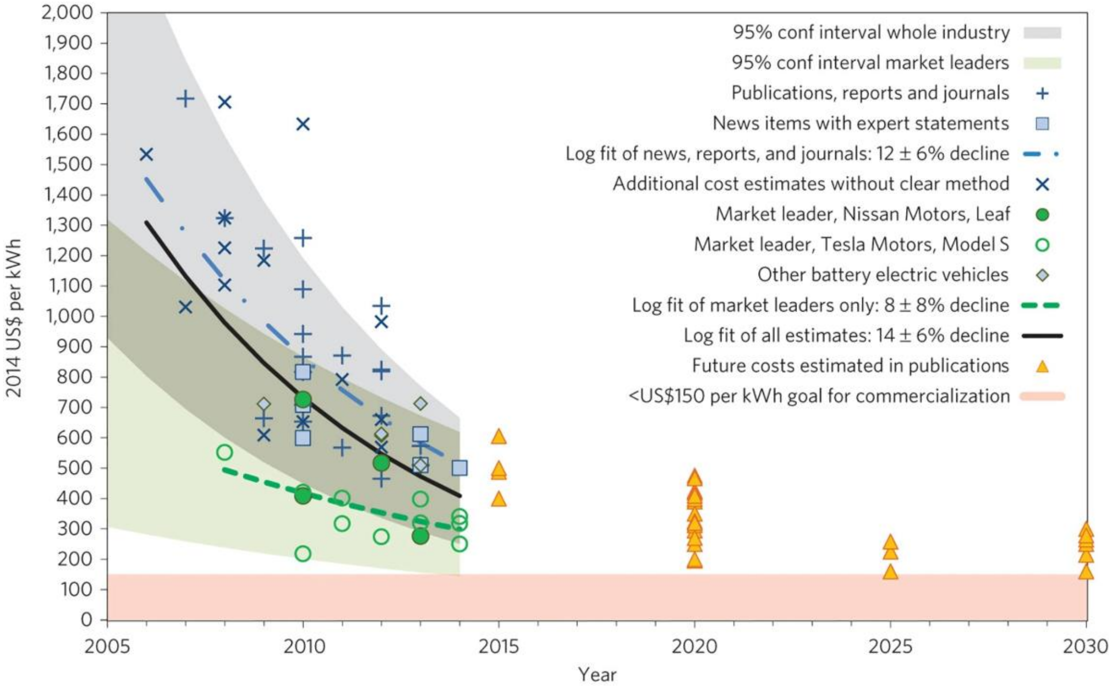

Figure 3 Historical cost trends of lithium-ion battery packs in battery electric vehicles [3]. Reproduced with permission and acknowledgment of Springer Nature.

2. The next big technology

Many industries are currently affected by the promise of electrification, and batteries offer a way to shift the point of generation to the point of demand, usually by periods of less than a day. The automotive industry is perhaps going through the largest change in its 120-year history, pushed by both legislation and technical competitiveness of lithium-ion technology. It can be hard to evaluate the maturity of new technologies from the frequent reports claiming to have cracked the problems of new generation batteries. However, we can look to the academic literature for a strong indicator of how close to readiness each technology is. Take, for example, the use of silicon in the negative electrode as a replacement or complement for graphite. Media announcements, such as Fortune Tech in 2016, hailed this is a breakthrough when its use was announced in the Tesla Model 3 battery pack. However, the use of silicon in negative electrodes was first published 17 years earlier in the academic literature, in 1999 (see for example [4]). This was followed by a year-on-year exponential increase in publications developing silicon anodes, and the establishment of a number of spin-out companies a few years later, such as Nexeon in 2006. Following a similar trajectory, NMC cathodes, which were invented at Argonne National Labs in 1997, became the dominant cathode material within 20 years. Although NMC is the fastest example we could find of scaling up a new material, it is only a drop-in replacement for just one component, and not a whole new type of battery. We have not found any examples of entirely new types of batteries which have been scaled up in fewer than 30 years. To see which technology is moving through the pipeline, evidence of an exponential growth in publications, multiple spin-outs, significant investment, and prototype trials are needed. However, projecting forward their benefits, these technologies are nearly always included in the “glide path” of cost, energy and power improvements predicted by the incumbents.

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The reason that this industry can be predicted with a higher level of confidence than say, the software industry, is because of the time taken to scale the manufacturing processes and supply chains. Factories, mining, parts suppliers, process control, and quality assurance, all take time to develop and bed into place. This is well illustrated by the historical trend of energy technology deployment worldwide, shown in Figure 4 (note the log scale of the vertical axis). Each of the technologies required a large investment in a complex network of supply chains and infrastructure to enable it to deliver a significant change to the energy mix [5]. The same is true for most new battery technologies. However, there could still be opportunities where this constraint will not apply.

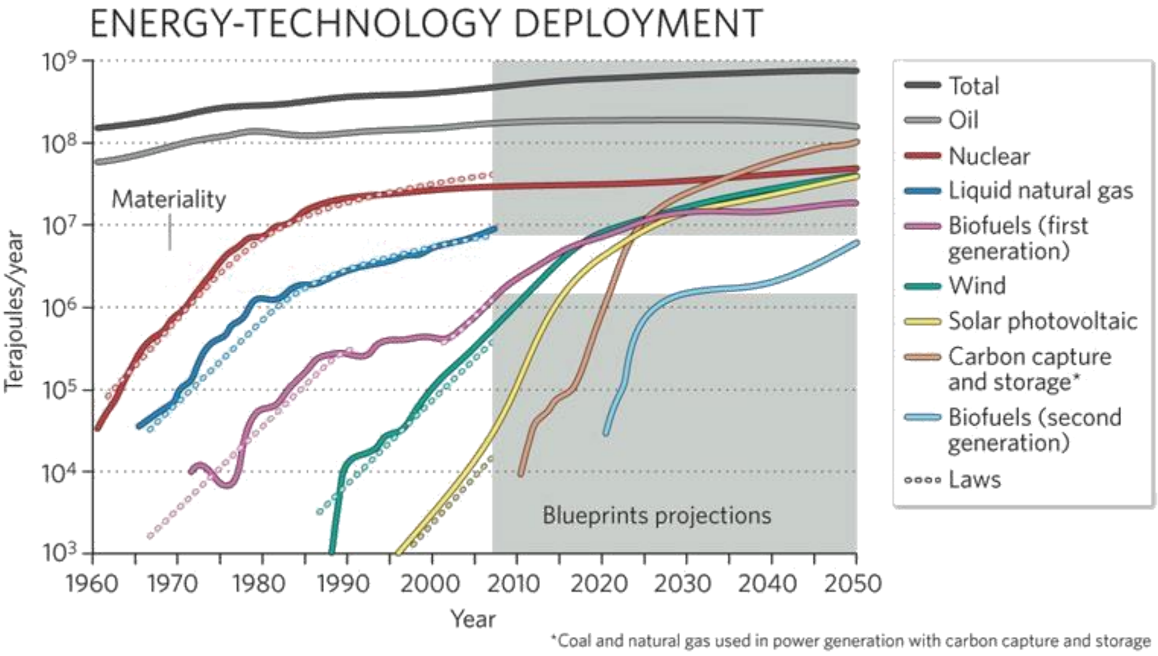

Figure 4 The time needed to scale up new technologies [5]. Reproduced with permission and acknowledgment of Springer Nature.

Given these constraints and time scales, what are the likely candidates for future replacements of lithium-ion based cells? There are three examples that have potentially disruptive benefits: lithium sulphur cells, which are made from a cheap and readily available precursor (sulphur) and have high energy density at approximately 500 Wh/kg; sodium-ion based cells, which benefit from the lower cost of sodium compared to lithium; solid state cells, which promise improved safety by removing the flammable petroleum-based electrolyte.

Figure 5 illustrates the growth of lithium-ion technology and the performance improvement of potential replacements [6].

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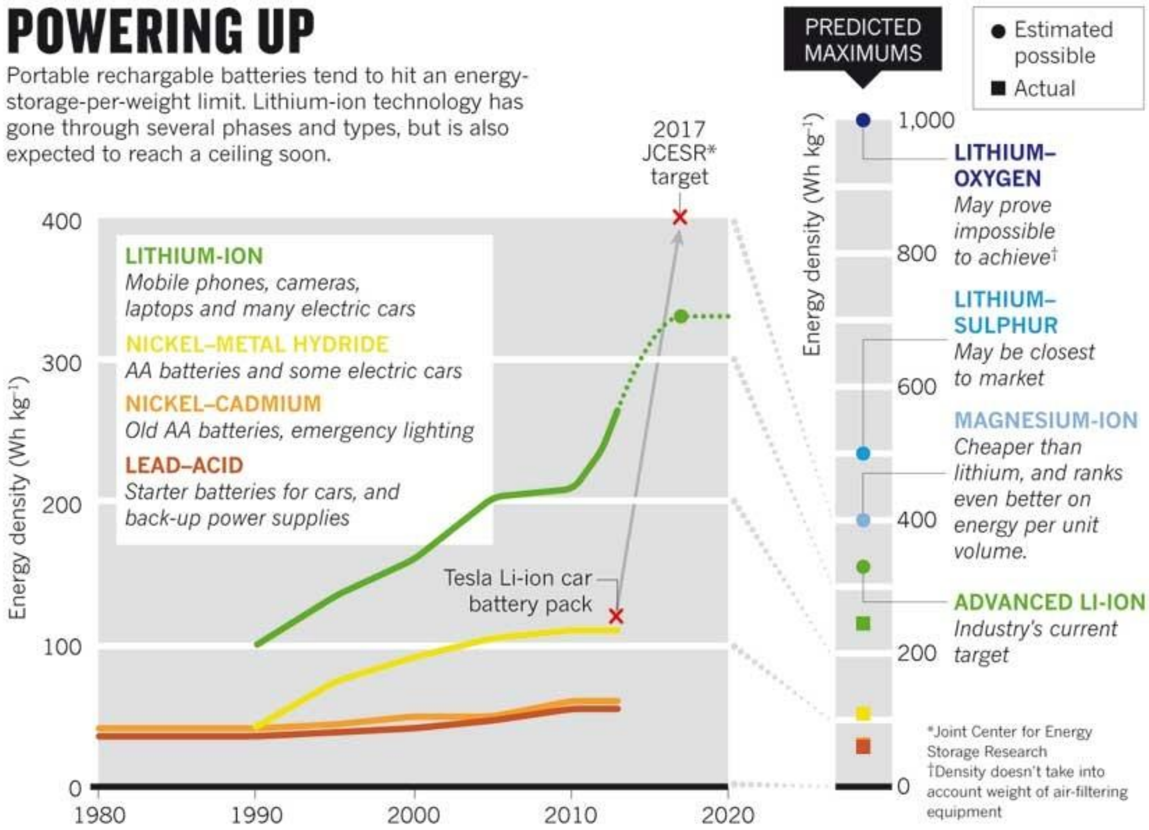

Figure 5 The rise of lithium-ion battery chemistry and the potential of alternatives [6]. Reproduced with permission and acknowledgment of Springer Nature.

The academic literature provides an indication of the effort being invested in improving each of these technologies, see Figure 6 for the increase in publication count. Lithium sulphur has had the largest percentage increase, by a factor of ten over the last decade or so, but in 2019 still has the fewest papers of these three technologies considered. In contrast, there are over twice as many publications with the keywords "sodium-ion battery" and 4.7 times as many with the keywords "solid state battery". In addition, we could find over 75 companies or institutions commercialising solid state batteries, about 8 in sodium ion, but just 3 in lithium sulphur (also significant, this used to be 4, but Sion Power switched to focus on solid state batteries instead). If we were to 'follow the money' in the words of William Goldman's character Deep Throat, then we would assume that solid state batteries are the most likely to be the next generation of battery technology. However, each has their own unique USP, and so sodium ion and lithium sulphur could still represent markets worth $10-100 billion in the future. However, predictions of future performance, which consider the rate at which technical development is happening in academia, are based upon the implicit assumption that they will succeed! The more research being done, the more likely this assumption will be correct.

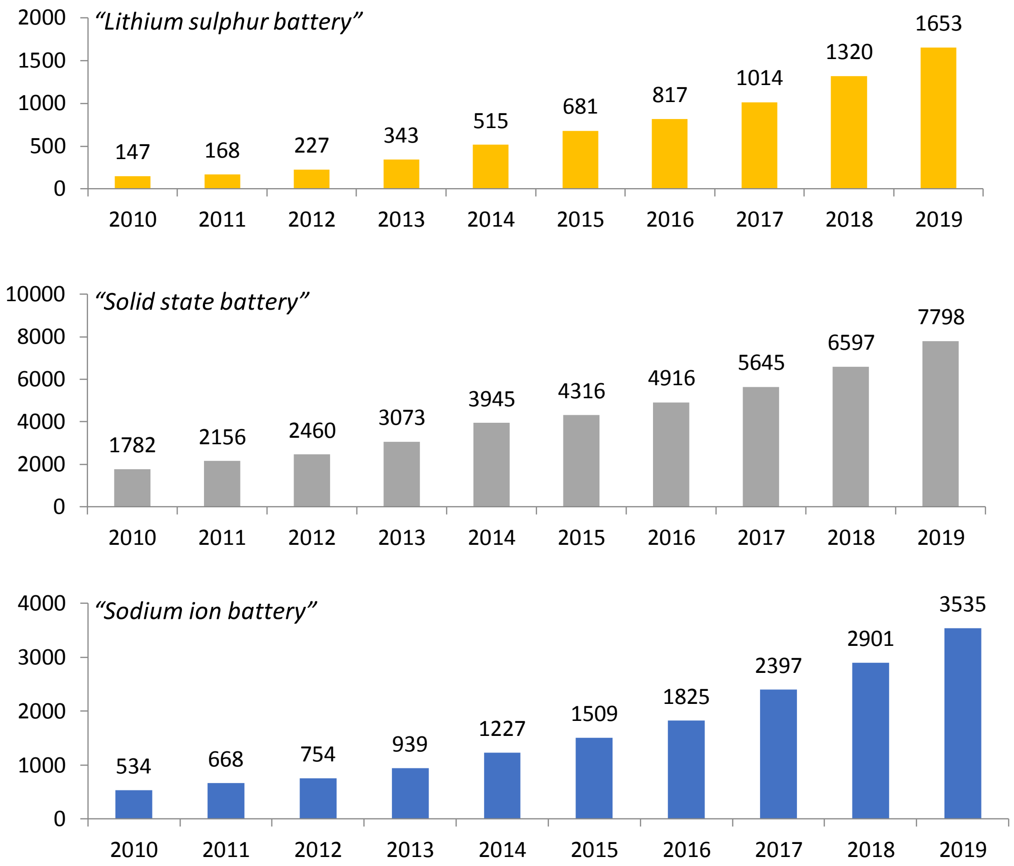

Figure 6 Academic publication count on Science Direct when searching for "lithium sulphur battery" (top) on 20th April 2020; (middle) "solid state battery" on 20th April 2020; (bottom) "sodium ion battery" on 20th April 2020.

3. How to predict disruption

We have argued that the literature is a good predictor for what technological advancements can be expected over the next 10-15 years, but to narrow this range even more requires a way to quantify uncertainty. Battery lifetime is one of the strongest metrics for this: an accurate lifetime for a cell model (given the same operating conditions) is crucial to build trust for the engineers who must design products with it and consumers who will ultimately use it. More consistent values of battery life indicate how much of the systematic error has been removed from a manufacturing process and overall quality of the product. Figure 7 shows the variation in capacity of 24 pouch cells, taken from Harris et al. [7], when subjected to the same tests under the same conditions. It demonstrates the large variability in cell performance that is not conveyed on a spec sheet or marketing material. In fact, to collect this quantity of data takes a large dedicated experimental campaign that has not been the norm in battery research. Increasingly, customers are demanding such data, indicating the increase in maturity of lithium-ion technology. The more statistically consistent the performance of a new chemistry under different conditions over many cycles, the closer to market readiness it is.

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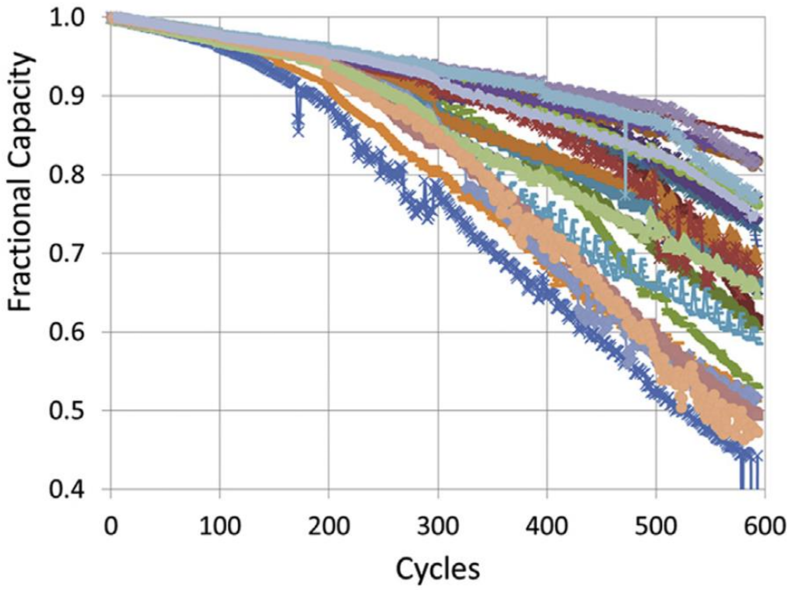

Figure 7 Variation in lifetime of 24 pouch cells shows room for improvement [7]. Reproduced with permission and acknowledgment of Elsevier.

Although the above argument is true, it misses a crucial component: cost. To truly measure the market readiness, we need to capture the cost to store a given amount of energy:

$$Energy\ cost\ [\$/kWh] = \frac{cell\ cost\ [\$]}{cell\ energy\ [kWh]}$$

However, to capture the uncertainty in lifetime caused by significant variations in the rate of degradation, we need to modify this equation to include the lifetime component (our "disruptiveness" metric) to give us an *energy storage cost for a given lifetime,* or

$$Lifetime\ cost\ [\$/(kWh * Wh)] = \frac{cell\ cost\ [\$]}{cell\ energy\ [kWh]\ *\ Wh}$$

Armed with this metric we can scan through the media, literature, and manufacturing claims looking for major disruptive potential that significantly reduces the *lifetime cost*. This metric is already common in the flow battery community, where the business model is most sensitive to the total cost of ownership over decades. However, in the lithium ion battery community, articles claiming a breakthrough technology may have improved one of the three terms on the right-hand side of the equation, but to the detriment of the other two. Cracking all three is tough. Indeed, we can see from Figure 7 that the *cycles to end of life* is still an issue for mature lithium ion technology.

Encouragingly, we can find numerous examples in the academic literature of approaches which can significantly improve the *lifetime cost*. For example, cells can be improved by optimising those factors that help control *cycles to end of life*. A major factor being the thermal management. Hunt et. al [8] showed that the lifetime cost could be reduced by 66% by cooling the electrical tabs of a 5Ah pouch cell, compared to cooling the surfaces (see Figure 8). To achieve this just through reducing cell upfront cost would take 13 years with an annual reduction in cost of 8%. Clearly achieving this in a few years through re-engineering would be

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disruptive. A good example of this conducted by our research group at Imperial College is to look at the effect of simple changes to cell geometry and component thickness through thermally-coupled electrochemical models of cells. Taking the LG Chem E63 cell (used on the Renault Zoe) and increasing the tab thickness from 0.1 mm to 1.5 mm reduces the maximum cell temperature by 8 °C (from 42 °C to 36 °C, see Figure 9[9]), a change that may seem small except that the kinetics that cause degradation increase exponentially in temperature (among other variables). The improvement in lifetime due to better cell cooling is significant while the reduction in energy density, due to a larger proportion of the cell volume allocated to tab material, is less than 5%.

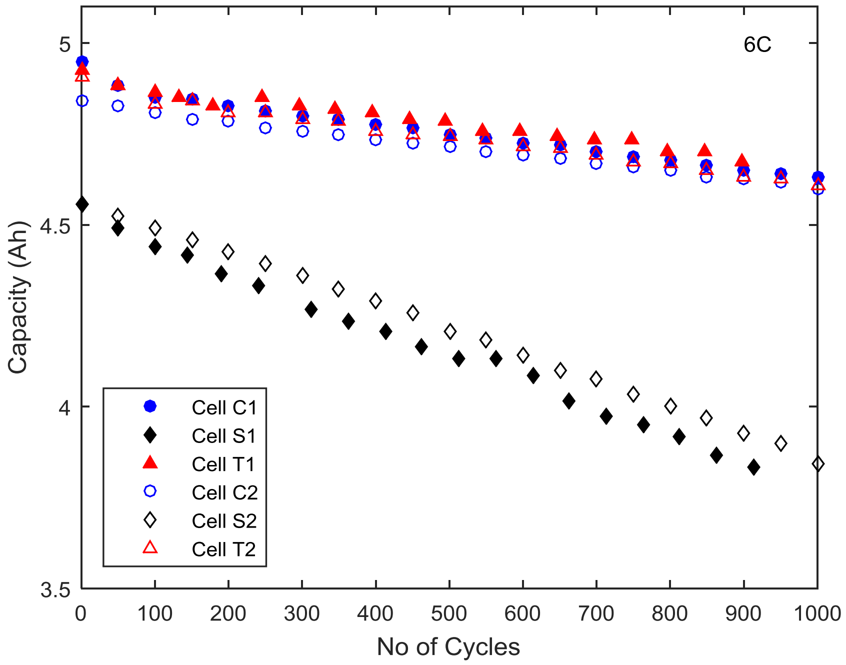

Figure 8 The benefit of cooling the electrical tabs instead of the plastic cell surfaces [8]. Reproduced with permission and acknowledgment of Cambridge University Press..

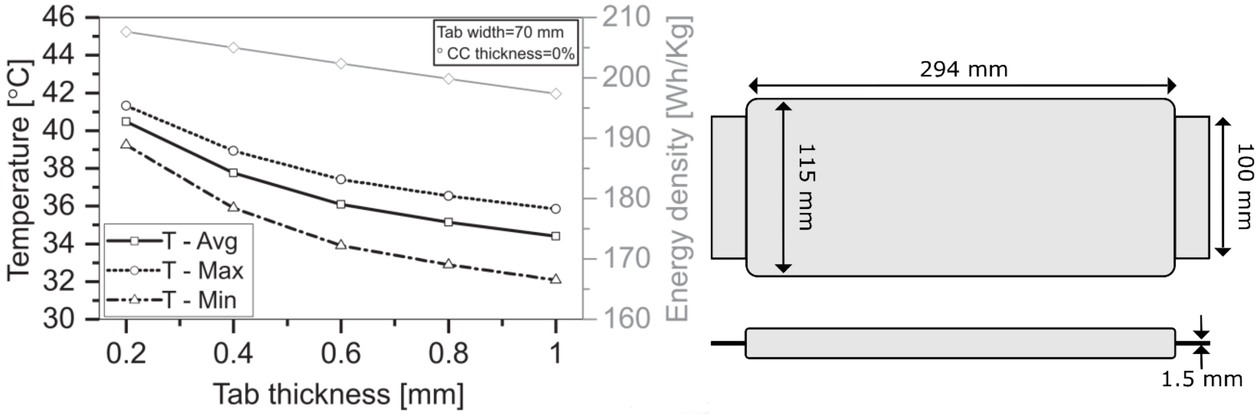

Figure 9 Increasing tab thickness reduces temperature of cell during operation [9].

An alternative way to reduce the lifetime cost metric is to increase the total number of cycles that the battery undergoes before it is retired. One approach is to look at *second-life*

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applications. As the number of electric vehicle battery packs increases and reach the end of their *first life* (defined as the point when the capacity reaches 80% of its beginning-of-life value), the opportunity for disruption is still present. Take a simple model of a state-of-the-art NMC chemistry and apply a 0.01% reduction in capacity per charge-discharge cycle. Figure 10 indicates that only 25% of the lifetime energy throughput has been used. By adopting a new business model to use the cells down to 20% capacity, we could reduce the $\$ \cdot kWh^{-1}cycle^{-1}$ by 75%.

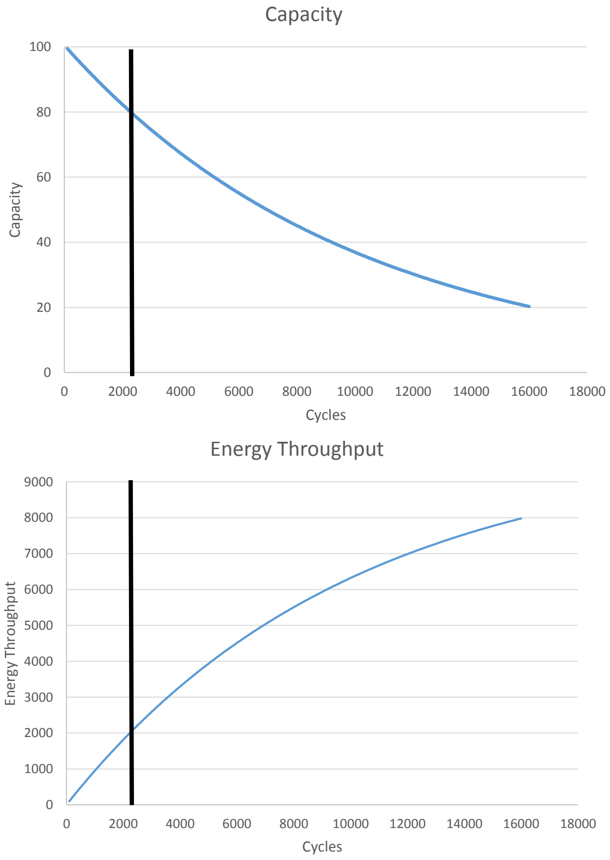

Figure 10 A model battery with 0.01% degradation per cycle. There is 75% of the total energy available for second life applications.

Even larger disruption is possible when fundamental scientific advances can be deployed quickly in existing products without major interventions. In the battery manufacturing world, this can be partly achieved through "drop in" replacement chemicals. A large amount of capital and time is needed to build a mass production battery line, leaving few economic ways to make significant changes to cell performance once it has started operation. Alternative electrolyte additives or active material mixtures that are compatible with the existing production techniques and processes bypass this restriction. The replacements are usually straightforward to protect by intellectual property rights and can have a significant effect on cell performance. For example, ten-fold increases in cell lifetime have been reported with a new electrolyte additive (see Figure 11 [10]), which would reduce the $\$ \cdot kWh^{-1}cycle^{-1}$ by 90%, an order of magnitude, which qualifies as a technology revolution by our definition.

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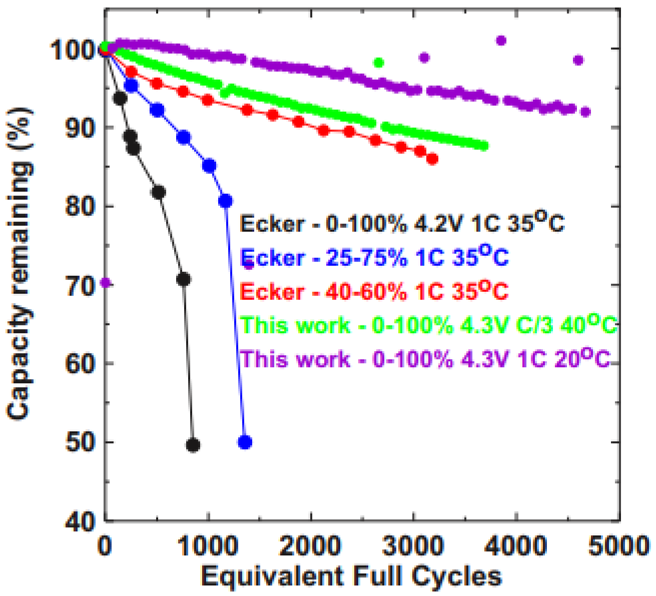

Figure 11 Additives can increase battery lifetime by ten times [10].

4. Conclusions

In this report, we have covered a brief history of technological disruption and how to identify new candidates in the energy storage industry. We define disruption to be when a key performance indicator increases by a factor of 2, and a technology revolution to be when it increases by a factor of 10. Following the scientific literature and investments in start-up companies is a good indicator for the pace of development in lithium-ion batteries. It is possible to predict with reasonable confidence what will be coming to market for the next 15 years. It typically takes at least 20-30 years to scale up new discoveries for mass production with increasingly expensive trials along the way. In this way, the battery material discovery industry is very much like the pharmaceutical industry.

Many “breakthroughs” are only incremental improvements once they have made it to mass production 20-30 years later. We do not see any technologies in the pipeline that will disrupt unit cost ($\$\cdot kWh^{-1}$), energy/power density ($Wh\cdot kg^{-1}$ or $Wh\cdot L^{-1}$) or specific energy/power ($W\cdot kg^{-1}$, $W\cdot L^{-1}$) in the near future. However, just like big pharma, a few materials will make it big and will dominate what is projected to become a trillion-dollar industry in the next 2-3 decades. The prize is very large, but it will be a long hard slog.

Existing lithium-ion battery materials are approaching limits in improvements for cost, energy and power. There are multiple candidates for replacement, all viable but at various stages along the pipeline. If you ‘follow the money’, the most likely successor to lithium ion technology is solid state batteries. However, extrapolating forward when they will achieve mass production, we contend they will not actually be disruptive breakthroughs but are instead now essential to maintain the rates of incremental improvement in 10 years’ time and beyond. We believe the industry has already costed them into the glide paths for cost, energy and power.

High uncertainty in a specific key metric is the best indicator for disruption, as it suggests a lack of scientific understanding. Understanding degradation is one of the biggest areas of uncertainty in the scientific literature. The metric of lifetime cost ($\$\cdot kWh^{-1}\cdot Wh^{-1}$ where the Wh^{-1} is energy throughput over the lifetime) incorporates degradation. The evidence suggests this metric can be changed for many applications by at least a factor of 2, and perhaps even a factor of 10, through a better understanding of degradation. This creates opportunities for truly disruptive ‘breakthroughs’ and potentially even a ‘revolution’ now.

DOI: 10.5281/zenodo.3931338

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