RethinkX

Disruption, Implications, and Choices

Rethinking Energy 2020-2030

100% Solar, Wind, and Batteries is Just the Beginning

A RethinkX Sector Disruption Report

October 2020

Adam Dorr & Tony Seba

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The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

We analyze the impacts of disruption, sector by sector, across the economy. We aim to produce analyses that reflect the reality of fast-paced, technology disruption S-curves. Mainstream analysts produce linear, mechanistic, and siloed forecasts that ignore systems complexity and thus consistently underplay the speed and extent of technological disruptions – for example solar PV, electric vehicles, and mobile phone adoption. By relying on these mainstream forecasts, policymakers, investors, and businesses risk locking in inadequate or misguided policies and investments, resource misallocation and vicious cycles that lead to massive wealth, resource, and job destruction as well as increased social instability and vulnerability.

We take a systems approach to analyze the complex interplay between individuals, businesses, investors, and policymakers in driving disruption and the impact of this disruption as it ripples across the rest of society. Our methodology focuses primarily on market forces that are triggered by technology convergence, business model innovation, product innovation, and exponential improvements in both cost and capabilities.

Our aim is to inspire a global conversation about the threats and opportunities of technology-driven disruption and to focus attention on choices that can help lead to a more equitable, healthy, resilient, and stable society.

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Our thanks in no way implies agreement with all (or any) of our assumptions and findings. Any mistakes are our own.

Preface

RethinkX uses the Seba Technology Disruption Framework™ to model and forecast technology disruptions. The analysis in this report is based on detailed evaluation of data on the market, consumer, and regulatory dynamics that work together to drive disruption in the energy sector. We present an economic analysis based on existing solar photovoltaic, onshore wind power, and lithium-ion battery technologies that have well-established cost curves, and on existing business models. We extrapolate data where we have credible knowledge that these cost curves will continue in the near future. The disruption we analyze in this report could actually happen more quickly than we project if there is an acceleration of the cost curves, a breakthrough in the underlying technologies, or business model innovations that bring the disruption timeline forward.

Our findings and their implications are based on following the data and applying our knowledge of finance, economics, technology adoption, and human behavior. Our findings show the speed, scale, and implications of the disruptions that we expect to unfold in a rational context. Scenarios can only be considered in terms of probabilities. We think the limit scenario we lay out in this report to be far more probable than others currently forecast. In fact, we consider the underlying disruption of energy by solar, wind, and batteries to be inevitable. Ultimately, individual consumers, businesses, investors, and policymakers will make the decisions that determine how this disruption proceeds in any particular region. The analysis we present here marks the beginning of a series of reports about the disruption of the energy sector, and our aim is to provide insights that decision makers can then utilize to benefit society.

Disclaimer

Executive Summary

We are on the cusp of the fastest, deepest, most profound disruption of the energy sector in over a century. Like most disruptions, this one is being driven by the convergence of several key technologies whose costs and capabilities have been improving on consistent and predictable trajectories – namely, solar photovoltaic power, wind power, and lithium-ion battery energy storage. Our analysis shows that 100% clean electricity from the combination of solar, wind, and batteries (SWB) is both physically possible and economically affordable across the entire continental United States as well as the overwhelming majority of other populated regions of the world by 2030. Adoption of SWB is growing exponentially worldwide and disruption is now inevitable because by 2030 they will offer the cheapest electricity option for most regions. Coal, gas, and nuclear power assets will become stranded during the 2020s, and no new investment in these technologies is rational from this point forward. But the replacement of conventional energy technology with SWB is just the beginning. As has been the case for many other disruptions, SWB will transform our energy system in fundamental ways. The new system that emerges will be much larger than the existing one we know today and will have a completely different architecture that operates in unfamiliar ways. One of the most counterintuitive and extraordinary properties of the new system is that it will produce a much larger amount of energy overall, and that this superabundance of clean energy output – which we call *super power* – will be available at near-zero marginal cost throughout much of the year in nearly all populated locations. The SWB disruption of energy will closely parallel the digital disruption of information technology. Just as computers and the Internet slashed the marginal cost of information and opened the door to hundreds of new business models that collectively have had a transformative impact upon the global economy, so too will SWB slash the marginal cost of electricity and create a plethora of opportunities for innovation and entrepreneurship. What happened in the world of bits is now poised to happen in the world of electrons.

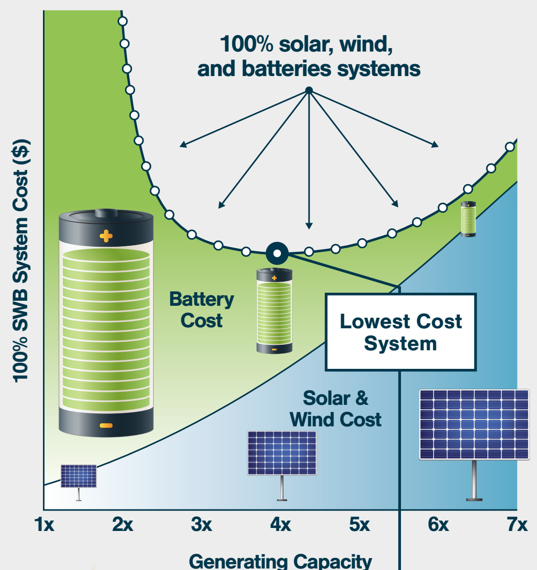
The analysis we present here marks the beginning of a series of reports that call upon decision makers at all levels of society to rethink the future of energy so that we can fully capture the benefits of the SWB disruption. In this first report, we aim to answer the question: *is it possible to generate 100% of our electricity with solar, wind, and batteries?* Our analysis shows that the answer is a clear and unequivocal yes. In subsequent reports we will explore other aspects of the SWB disruption, including its impact upon the incumbent coal, gas, petroleum, and nuclear power industries, its need for a new policy and regulatory framework that breaks up utility monopolies and supports individual energy rights, and its interactions with other disruptions that will be occurring simultaneously in the transportation and food sectors during the 2020s.

The implications of the SWB disruption of energy are profound, but in order to maximize the extraordinary benefits of the new energy system, we as individuals, communities, industries, regions, and entire nations need to make the right choices today. That process must begin with an understanding of what is possible.

Rethinking Energy 2020-2030: 100% Solar, Wind, and Batteries is Just the Beginning – Visual Summary

100% Solar, Wind, and Batteries is Possible

Thousands of combinations of SWB can deliver 100% of our electricity demand. There is a nonlinear cost tradeoff between generation and storage. To identify which combination is least expensive, we use the **Clean Energy U-Curve.**



3x-5x more generation than the existing grid

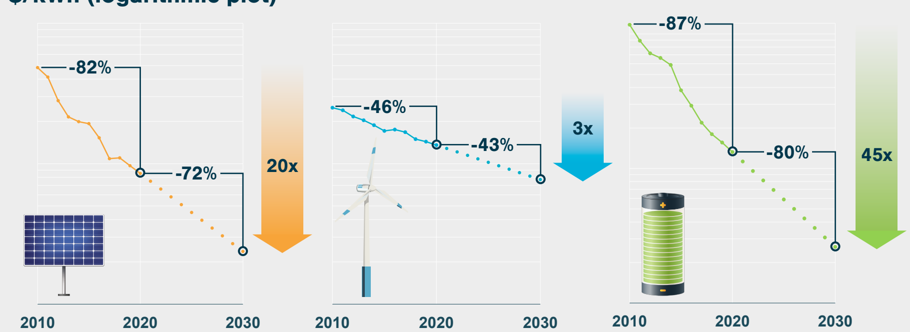
35-90 hours' worth of batteries

(varies by geography)

100% Solar, Wind, and Batteries is the Cheapest System by 2030

Falling costs drive technology disruptions. Solar and wind are already the cheapest new generation options, and cost less than existing coal, gas, and nuclear power plants in many areas. The cost of SWB systems will fall another 70% by 2030, making disruption inevitable.

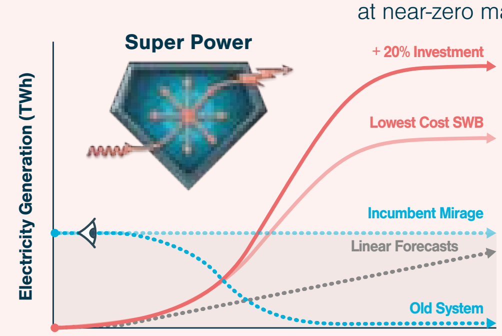
$/kWh (logarithmic plot)



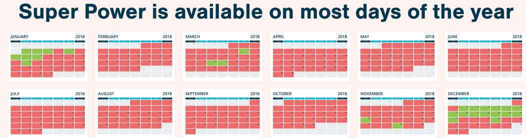
- **We are beyond the rupture point, and the bulk of disruption will unfold rapidly over the next decade.**
- **Electricity from a 100% SWB system in 2030 will cost less than 3 cents per kilowatt-hour.**
- **New investments in coal, gas, or nuclear power is financially unviable.**
- **Existing coal, gas, and nuclear assets will be stranded.**

100% Solar, Wind, and Batteries is Just the Beginning

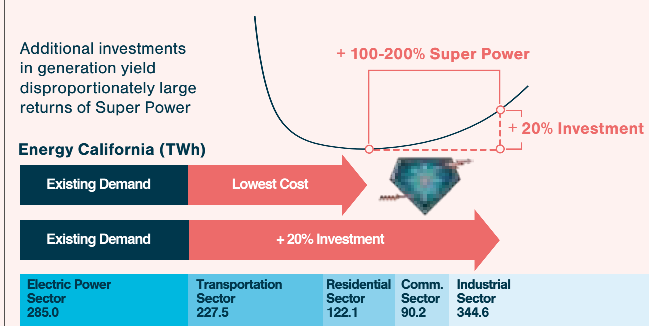
100% SWB systems naturally produce a huge surplus of clean energy at near-zero marginal cost that we call **Super Power.**



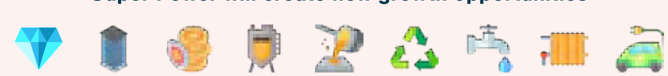
Super Power is available on most days of the year



Super Power will disrupt all existing uses of energy



Super Power will create new growth opportunities



Introduction

The disruption of the energy sector during the 2020s will be driven by the convergence of three clean energy technologies: solar photovoltaics, onshore wind power, and lithium-ion batteries (SWB). The costs and capabilities of each of these technologies have been consistently improving for several decades. Since 2010 alone, solar PV capacity costs have fallen over 80%, onshore wind capacity costs have fallen more than 45%, and lithium-ion battery capacity costs have fallen almost 90%. These technologies will continue to traverse their remarkable experience curves such that by 2030 their costs will have decreased a further 70%, 40%, and 80% respectively. The incumbent coal, gas, and nuclear power technologies are already unable to compete with new solar and wind installations for generating capacity additions, and by 2030 they will be unable to compete with battery-firmed capacity that makes electricity from solar and wind dispatchable all day, all night, all year round. This means that the disruption of the conventional technologies is now inevitable, and that no new investment in coal, gas, or nuclear power generating assets is rational from this point forward. It also means that we are not facing a slow energy transition where new solar and wind installations gradually substitute for old coal, gas, and nuclear power plants. We are instead facing a disruption that will completely transform electric power and the energy sector over the next decade.

Policymakers, investors, civic leaders, and the general public are under the false impression that it is impossible for solar photovoltaics and wind power to supply 100% of the electricity in the United States without weeks' worth of battery energy storage. This widespread misconception has been created by the failure of conventional models and forecasts to understand that future solar and wind generating capacity will greatly exceed the total electricity generating capacity installed today.

Our analysis shows that there is a fundamental tradeoff relationship between generation capacity and energy storage capacity that follows a convex cost function, which we call the *Clean Energy U-Curve*. When costs are optimized correctly according to the clean energy U-curve, it becomes clear that 100% SWB systems are not only achievable but are in fact the cheapest available option for new power generation on a timeframe to 2030 – and in many cases will be less expensive than continuing to operate existing conventional power plants as well.

Today, when solar and wind installations produce a surplus of energy, the incumbent system views this as a problem that must be addressed with curtailment. But wasting nearly-free clean energy is irrational, and such behaviors are a clear indication that the old system is failing to successfully integrate these new technologies. A 100% SWB system will not operate by the traditional rules of extractive, depletable, and polluting resources that have governed humanity's relationship with energy for over a century. It is therefore a mistake to ask how the existing grid will accommodate solar, wind, and batteries. Instead, the correct question for decision makers to ask is: *how can a new energy system based on SWB minimize costs and maximize benefits at every level of society and the economy?* It follows that regions which choose to embrace and lead the disruption will be the first to capture the extraordinary social, economic, political, and environmental benefits that 100% SWB systems have to offer.

Conventional clean energy scenarios make the common error of misunderstanding that disruptive new technologies do not simply replace old ones on a 1-to-1 basis. Instead, disruptions tend to disproportionately replace the old system with a new system that has dramatically different architecture, boundaries, and capabilities. History also shows that in most instances the new system is much larger than the old one it displaces, and the SWB disruption of the energy sector will be no exception.

As adoption of SWB grows, these technologies will produce an increasingly large surplus of energy at near-zero marginal cost that we call *Clean Energy Super Power* – or simply *super power* for short. This is because the system's capacities must be designed to fully meet electricity demand during the most challenging times of year such as the cloudy weeks of winter when the days are shortest, and as a result they are able to produce much more power throughout the rest of the year. A 100% SWB system will therefore produce a surprisingly large amount of super power – in sunny areas, more than twice total electricity demand. The resulting superabundance of clean energy will open the door to extraordinary new possibilities for society, the economy, and the environment. Super power will be plentiful enough to displace a large portion of other energy use outside of the electricity sector alone, such as in water desalination and filtration, road transportation, heating, waste management, and industrial and chemical processes – with associated reductions in greenhouse gas emissions as fossil fuels in these applications are displaced.

As with previous disruptions, entirely new business models will emerge to seize opportunities and create value within the new system architecture. Electric lighting, for example, did not simply replace candles and oil lamps on a 1-to-1 basis, but instead opened up entirely new residential, commercial, industrial, artistic, and scientific applications. Refrigeration did not just replace ice boxes on a 1-to-1 basis, but instead found new applications ranging from air conditioning and dehumidification to cryogenic industrial processing and ice skating. The smartphone did not simply replace flip phones on a 1-to-1 basis, but instead created an entirely new and much larger communication and information system that extends far beyond telephony alone to touch virtually every aspect of our lives. These disruptive technologies, like hundreds of others throughout history, wiped out their incumbent predecessors within just a few years of becoming cost competitive, and the new industries and markets were much larger than the ones they replaced. Clean energy super power from a 100% SWB system will dramatically expand the societal capability frontier of regions in the same way.

Going even further, super power returns on investment are not linear, and so regions may choose to make an additional investment in order to disproportionately increase the quantity of super power that their clean energy system produces. In sunny locations, an additional 20% investment can more than double super power output. Regions that choose to make these additional investments will further enhance the economic and social benefits that arise from energy superabundance. It also follows that the extraordinary but unexpected benefits of super power do not fully materialize in conventional clean energy scenarios that limit SWB to 90% or less of electricity supply. These scenarios explicitly – and erroneously – aim to minimize rather than maximize surplus energy production. Businesses, industries, regions, and countries that avoid this mistake and instead recognize super power as an opportunity to be seized rather than as a problem to be curtailed will stand to realize billions or even trillions of dollars in new value creation.

In this report, we present 100% SWB case studies of California, Texas, and New England. We have chosen these regions because they possess a representative range of the combined solar and wind resources in the continental United States. As such, the findings of our analysis generalize to nearly all other populated areas of the world as well.

In the last two decades we have seen similar disruptions of traditional information-based industries by the Internet, digital media, smartphones, and cloud computing that deliver products and services at near-zero marginal cost. The resulting superabundance of information and communication has created trillions of dollars of new value, dozens of new industries, and tens of millions of new jobs, which together have had a dramatic impact on the economy and society at large. These information technologies transformed the world of bits, and SWB will transform the world of electrons in a similar way.

The analysis we present here is not a forecast, but rather an illustrative "limit scenario" that makes very conservative and severely constraining assumptions:

- No electricity imports
- No distributed energy resources
- No electric vehicles
- No energy arbitrage
- No conventional reserve capacity
- No technological breakthroughs
- No geothermal or other technologies that will reduce the HVAC load of buildings
- No demand side management
- No energy efficiency or building automation technologies that reduce electricity use
- No bundling of additional services
- No subsidies or carbon taxes

We intentionally constrain the scenario this way in order to establish the upper boundary for what is possible. The actual real-world cost of achieving a 100% clean electricity system will thus be substantially lower than the upper boundary we establish here.

Extrapolating our results from California, Texas, and New England to the entire country, we find that the continental United States as a whole could achieve a 100% SWB system by 2030 for less than $2 trillion, with an average cost of electricity nationwide of under 3 cents per kilowatt-hour if 50% or more of the system's super power is utilized.

It is no longer a matter of *if* the SWB disruption of energy will happen, it is only a matter of *when*. But the timing matters, and the social, economic, political, environmental stakes could not be higher. The actual outcomes in any given locality, region, or country over the course of the 2020s depend on the choices we make today, and the benefits that accrue to those who lead the disruption rather than follow or resist it will be profound.

Extraordinary possibilities demand bold decisions. By showing what is possible in clean energy, our goal with this report is to help policymakers, investors, and other decision makers act immediately to reposition the electric power sector for the sweeping transformation that will occur worldwide during the 2020s.

Key Findings

- It is both physically possible and economically affordable to meet 100% of electricity demand with the combination of solar, wind, and batteries (SWB) by 2030 across the entire continental United States as well as the overwhelming majority of other populated regions of the world.
- The *Clean Energy U-Curve* captures the tradeoff relationship between electricity generation and energy storage, and is a valuable tool for both understanding how 100% SWB is achievable as well as identifying the optimal mix of generation and storage capacity in any given region.
- Lowest cost 100% SWB systems will typically require just 35-90 average demand hours of battery energy storage, depending on regional climate and geography.
- 100% SWB will provide the cheapest possible electricity system by 2030 – far less expensive than new conventional power plants, and in many cases less expensive than continuing to operate existing coal, gas, or nuclear power plants.
- While both solar power and wind power are necessary, these generation technologies are not equal because solar is becoming cheaper more quickly. The lowest cost 100% SWB systems will comprise up to 10x more solar than wind in most locations.
- SWB will not merely replace conventional power generation technologies as a proportional 1-to-1 substitution, but will instead create a much larger electricity system based on an entirely new architecture that operates according to a different set of rules and metrics.
- Just as the Internet disrupted many incumbent industries but facilitated the emergence of many more – and created trillions of dollars of new value – by reducing the marginal cost of information to near zero, the SWB disruption will have a similar impact by reducing the marginal cost of energy to near-zero for a substantial portion of the year.
- 100% SWB systems will produce a very large amount of surplus power output, or *Clean Energy Super Power*, on most days of the year. In California, for example, super power from the lowest cost SWB system combination of SWB of 309 terawatt-hours is greater than the state's total existing electricity demand of 285 terawatt-hours.
- Clean energy superabundance from near-zero marginal cost SWB super power will create a new possibility space for novel business models, products, services, and markets across dozens of industries, with dramatic increases in societal capabilities and economic prosperity for regions that adopt a 100% SWB system.
- Examples of super power applications include electrification of road transportation and heating, water desalination and treatment, waste processing and recycling, metal smelting and refining, chemical processing and manufacturing, cryptocurrency mining, cloud computing and communications, and carbon removal.
- At national scale, super power in the United States would create trillions of dollars of economic value and millions of jobs across the wider economy.
- Super power can help repatriate industries, particularly in heavy industry, that stand to benefit from superabundant near-zero marginal cost clean energy.
- SWB can be autocatalytic by dedicating a portion of super power to the manufacture of solar panels, wind turbines, and batteries themselves.
- The clean energy U-curve shows that incremental investments in additional solar generation capacity beyond the lowest cost combination of SWB capacities will yield disproportionally large increases in super power. For example, a 20% incremental investment in California would increase super power output by over 190% from 309 terawatt-hours to 592 terawatt-hours.
- The construction of a 100% SWB system in the continental United States would cost less than $2 trillion over the course of the 2020s – just 1% of GDP – and would support millions of new jobs during that time.
- The amount of super power produced by 100% SWB systems is so large that it could displace up to half of all fossil fuel energy use outside of the existing electric power sector.
- 100% SWB systems will not only eliminate virtually all greenhouse gas emissions from the existing electric power sector but will also reduce emissions by displacing fossil fuel energy use in other sectors – residential, commercial, industrial, transportation, and agriculture – as well.
- Combined with electric vehicles, a 100% SWB system could eliminate all fossil fuel use and greenhouse gas emissions in both the electricity sector and road transportation sector simultaneously, thereby mitigating half of the country's total carbon footprint.
- Efficiency in the new system will mean maximizing output and utilization because there is no fuel or waste to minimize.
- Conservation in the new system will mean maximizing rather than minimizing energy use, because it is not harmful to utilize electricity generated from sunshine and wind but rather it is harmful to let it go to waste.

Table 1. Summary of Findings

CALIFORNIA	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
Capital cost	$115 billion	$127 billion	$139 billion
Solar PV capacity	213 gigawatts	278 gigawatts	328 gigawatts
Wind capacity	25 gigawatts	25 gigawatts	25 gigawatts
Generation capacity	3.8x	4.8x	5.6x
Battery capacity	1194 gigawatt-hours	945 gigawatt-hours	833 gigawatt-hours
Battery average demand hours	37 hours	29 hours	26 hours
Annual super power	309 terawatt-hours	466 terawatt-hours	592 terawatt-hours
Fraction of days with super power	93%	98%	98%
Electricity cost (0% of super power utilized)	3.1 cents/kilowatt-hour	3.4 cents/kilowatt-hour	3.8 cents/kilowatt-hour
Electricity cost (50% of super power utilized)	2.0 cents/kilowatt-hour	1.9 cents/kilowatt-hour	1.8 cents/kilowatt-hour
Electricity cost (100% of super power utilized)	1.5 cents/kilowatt-hour	1.3 cents/kilowatt-hour	1.2 cents/kilowatt-hour

Source: RethinkX

TEXAS	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
Capital cost	$197 billion	$218 billion	$239 billion
Solar PV capacity	362 gigawatts	505 gigawatts	583 gigawatts
Wind capacity	40 gigawatts	40 gigawatts	40 gigawatts
Generation capacity	4.9x	6.7x	7.6x
Battery capacity	2325 gigawatt-hours	1610 gigawatt-hours	1498 gigawatt-hours
Battery average demand hours	49 hours	34 hours	32 hours
Annual super power	504 terawatt-hours	814 terawatt-hours	983 terawatt-hours
Fraction of days with super power	93%	96%	97%
Electricity cost (0% of super power utilized)	3.5 cents/kilowatt-hour	3.9 cents/kilowatt-hour	4.0 cents/kilowatt-hour
Electricity cost (50% of super power utilized)	2.2 cents/kilowatt-hour	2.0 cents/kilowatt-hour	1.9 cents/kilowatt-hour
Electricity cost (100% of super power utilized)	1.6 cents/kilowatt-hour	1.3 cents/kilowatt-hour	1.3 cents/kilowatt-hour

Source: RethinkX

NEW ENGLAND	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
Capital cost	$91 billion	$100 billion	$109 billion
Solar PV capacity	87 gigawatts	158 gigawatts	197 gigawatts
Wind capacity	27 gigawatts	27 gigawatts	27 gigawatts
Generation capacity	3.8x	7.3x	10.8x
Battery capacity	1232 gigawatt-hours	835 gigawatt-hours	729 gigawatt-hours
Battery average demand hours	89 hours	58 hours	43 hours
Annual super power	61 terawatt-hours	143 terawatt-hours	189 terawatt-hours
Fraction of days with super power	64%	84%	91%
Electricity cost (0% of super power utilized)	6.1 cents/kilowatt-hour	6.6 cents/kilowatt-hour	7.2 cents/kilowatt-hour
Electricity cost (50% of super power utilized)	4.9 cents/kilowatt-hour	4.2 cents/kilowatt-hour	4.1 cents/kilowatt-hour
Electricity cost (100% of super power utilized)	4.0 cents/kilowatt-hour	3.1 cents/kilowatt-hour	2.8 cents/kilowatt-hour

Source: RethinkX

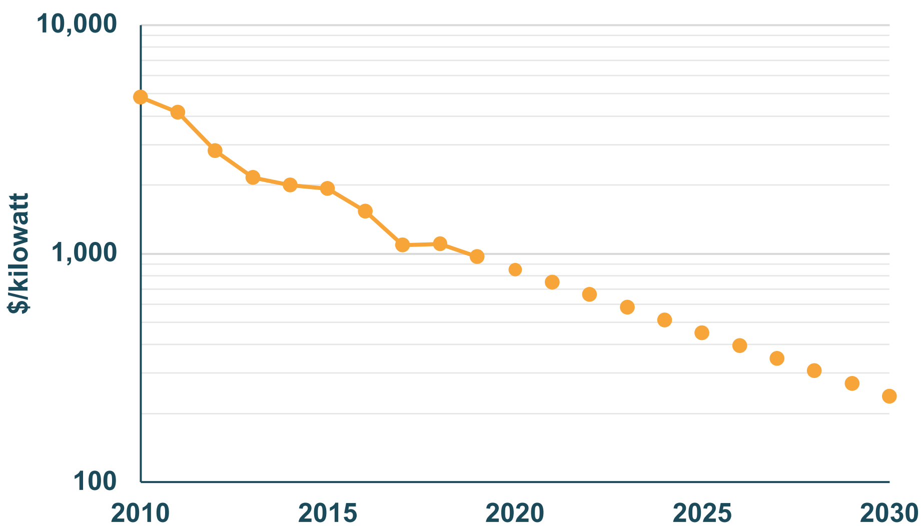
Part One

Disruption

The disruption of the energy sector by 100% solar, wind, and batteries (SWB) electricity systems is inevitable and has already begun because these technologies are now cost-competitive with coal, natural gas, and nuclear power incumbents.

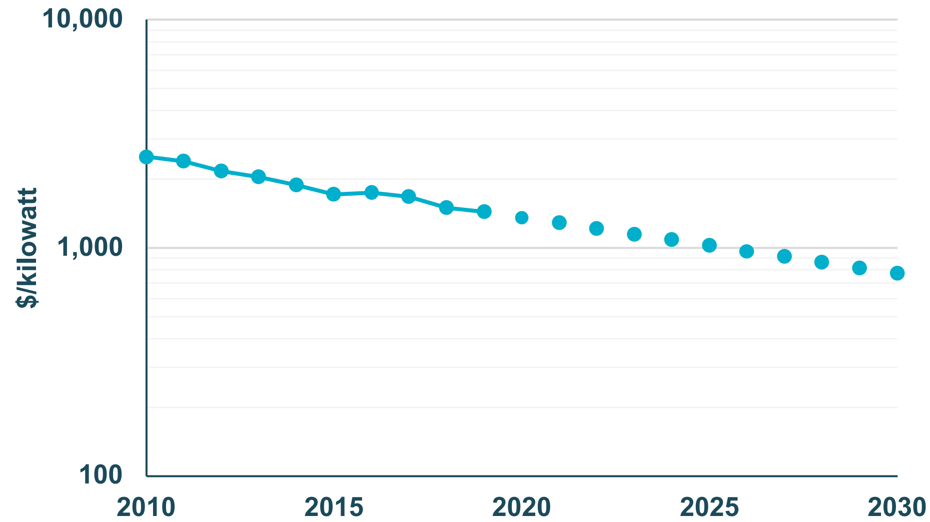
Cost improvements in solar PV, onshore wind power, and lithium-ion battery technologies have been consistent and predictable for over two decades. Moreover, for solar PV and lithium-ion batteries these improvements have been nothing short of spectacular. The combination of incremental improvements in the underlying technology together with scaling of manufacturing creates a strong correlation between unit cost and production volume, as is common across technologies of many kinds. Solar PV, onshore wind power, and lithium-ion batteries are thus each tracing their own experience curve.[a] Ongoing adoption growth of these technologies will continue worldwide from now until at least 2030, and we will continue to see costs improve accordingly.[b]

Figure 1. U.S. Solar PV Capital Cost (logarithmic plot)



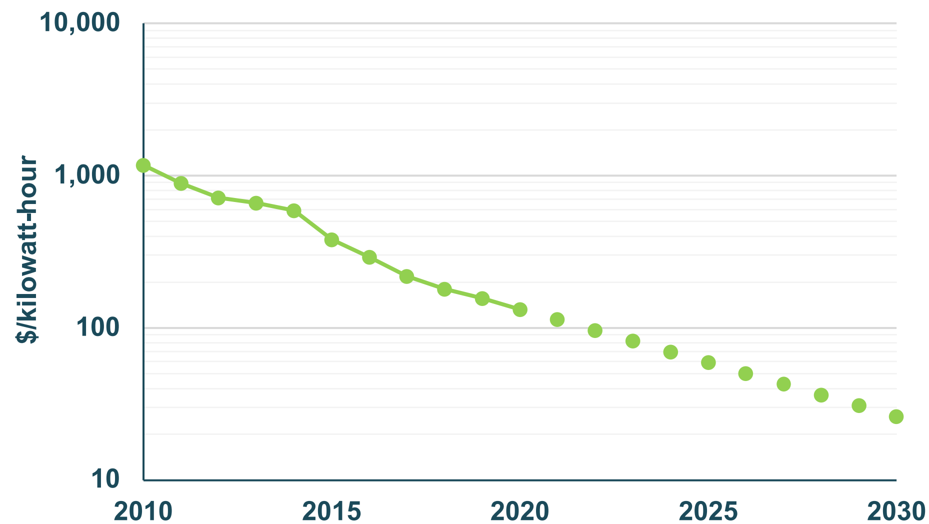
Source: NREL, 2018.[1] RethinkX projections 2019-2030.

Figure 2. U.S. Onshore Wind Power Capacity Cost (logarithmic plot)



Source: Lawrence Berkeley National Laboratory, 2018.[3] RethinkX projections 2019-2030.

Figure 3. U.S. Stationary Lithium-Ion Battery Energy Storage Capacity Cost (pack level) (logarithmic plot)



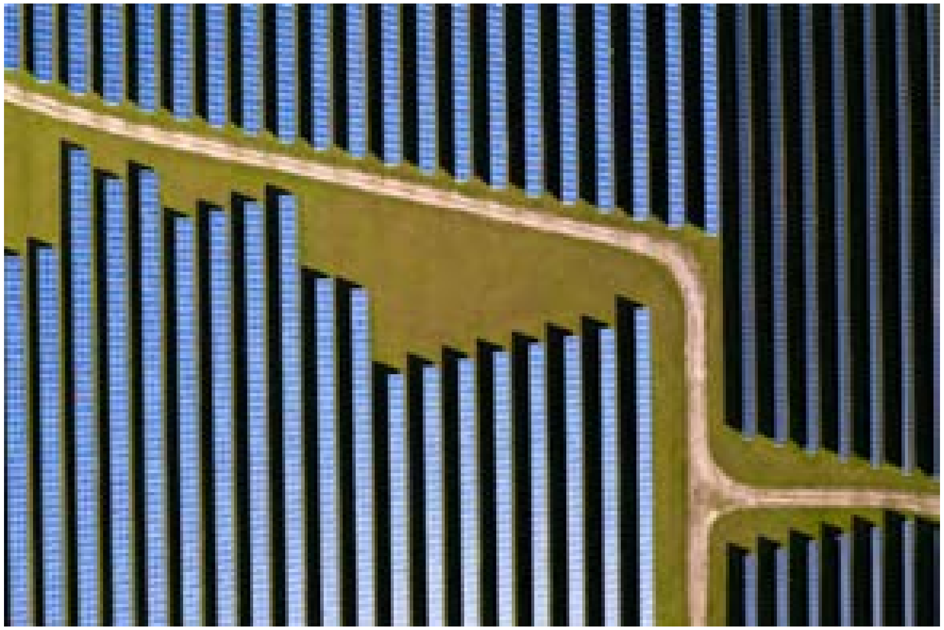
Source: BNEF, 2019.[4,7,8] RethinkX projections 2020-2030.

Solar PV Capital Cost Improvements

For solar PV, the capital costs per kilowatt of installed capacity have declined by a factor of nearly 1,000x since they were first introduced in the late-1970s. In the United States, capital costs have fallen at an average rate of 16.1% each year over the last decade, and when viewed correctly on a logarithmic plot instead of a linear plot the consistency of the trend is unmistakable.[1,2] Our analysis conservatively assumes that solar PV capital costs will continue to decline throughout the 2020s at an average annual rate of 12% (Figure 1).

Onshore Wind Power Cost Improvements

For onshore wind power, the decline in capital costs has not been as spectacular as that of solar PV, but in the United States these costs have nevertheless fallen at an average rate of 6.2% each year over the last decade.[3] The consistency of the trend is again apparent when the data are viewed correctly on a logarithmic plot. Our analysis conservatively assumes that onshore wind capacity costs will continue to decline over the course of the 2020s at an average annual rate of 5.5% (Figure 2).[c]



Lithium-Ion Batteries Capital Cost Improvements

For lithium-ion batteries, which are a newer technology than solar PV or wind power, the capital costs in the United States have improved at an average rate of 19.7% each year over the last decade.[4,5,6] Once again, the consistency of the trend is clear when the data are viewed correctly on a logarithmic plot. Our analysis conservatively assumes that battery energy storage capacity costs will continue to decline over the course of the 2020s at an average annual rate of 15% (Figure 3).

Forecasting Based on Future Costs

Conventional analyses commonly assume current rather than future costs when calculating the total expenditure required to build a clean electricity system. Although there may be legitimate reasons for doing so, as for example when clients prefer present-day baselines in contracted external research that then inform their own confidential internal analysis, this practice is obviously not realistic. Nevertheless, headlines such as, *"The $2.5 trillion reason we can't rely on batteries to clean up the grid"* and *"The Price of a Fully Renewable US Grid: $4.5 Trillion,"* frequently misconstrue the findings of these analyses as actual forecasts.[9,10] This source of confusion has helped perpetuate the misconception that a 100% SWB system will not be affordable for many decades.[11,12]

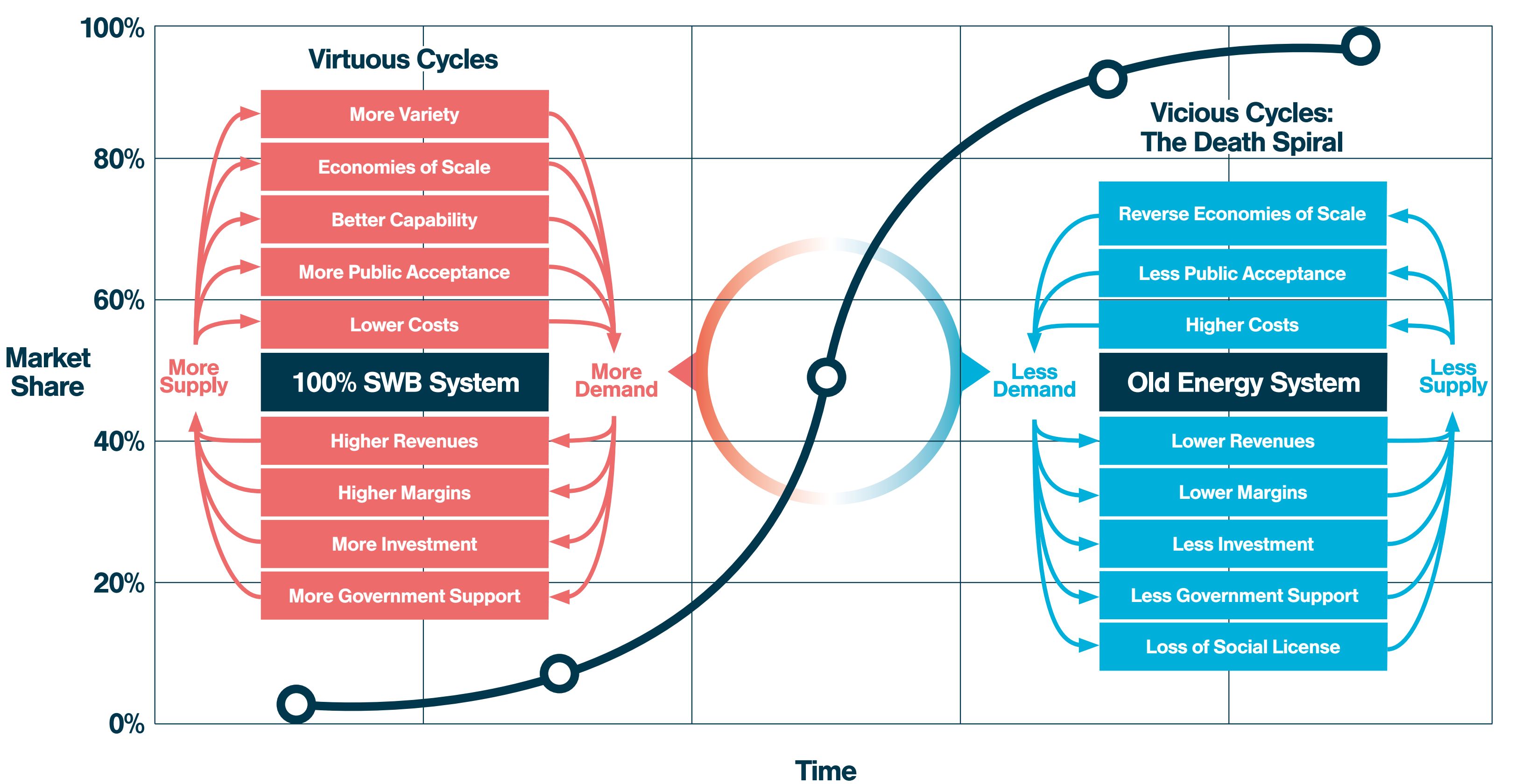
It is no longer acceptable to continue making unrealistic assumptions that allow this misconception to persist, given how high the social, economic, political, and environmental stakes have become. In order to help rectify the situation and undo the damage to public perception that has already been done, our analysis emphasizes the critical importance of accounting for foreseeable cost improvements in solar PV, onshore wind power, and lithium-ion batteries looking ahead to 2030 as supported by the evidence shown above.

Causal Feedback Loops Drive Disruption

Disruptions are driven by the convergence of new technologies that trigger causal feedback loops. These feedback loops accelerate adoption of the new system and at the same time push the existing system into a death spiral (Figure 4).

As with many previous disruptions throughout history, the new energy system that emerges will have a very different architecture that follows different rules and must be understood with different metrics. In this case, the new system will be based on near-zero marginal cost energy from sunshine and wind instead of high marginal cost energy from fuels. The shift from high marginal cost to near-zero marginal cost is a profound one whose consequences we have seen before in the information sector with computers and the Internet wiping out incumbent industries that were based on selling physical copies of information in the form of newspapers, magazines, books, photographs, music records, VHS tapes, DVDs, and other tangible products. These old industries were replaced by a much larger information economy that operates on entirely different principles and supports new business models that were difficult to imagine prior to the disruption.[13] What happened to the world of bits is now poised to happen to the world of electrons.[d]

Figure 4. Causal Feedback Loops Drive Disruption

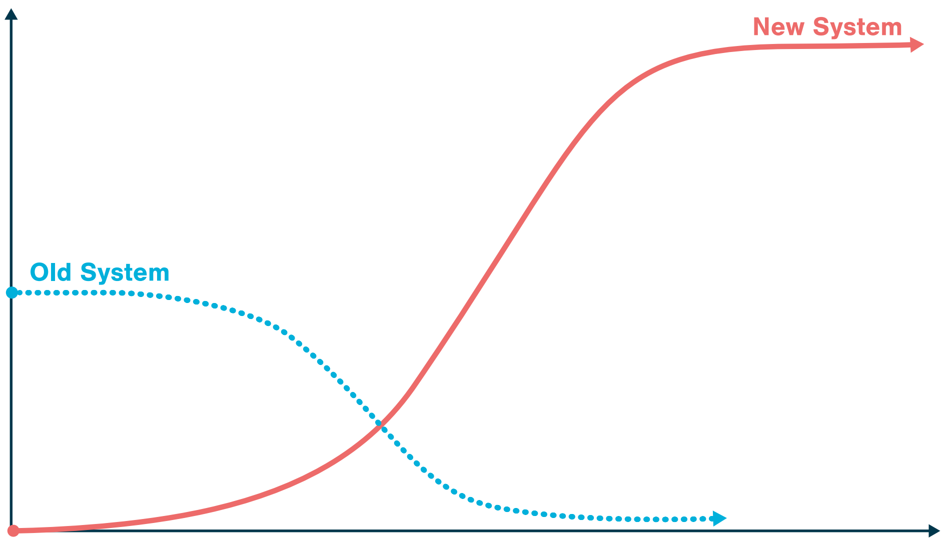


History shows that technology disruptions are nonlinear because they are driven by reinforcing causal feedback loops. These loops interact with and amplify one another, accelerating the adoption of new technology in a virtuous cycle while at the same time accelerating the abandonment of old technology in a vicious cycle. The net result of these systems dynamics is that disruption tends to unfold with surprising swiftness.

Source: RethinkX.

In this disruption, as in many others before, the new system will grow following an S-curve while the old system collapses simultaneously. This forms what we call a *disruption X-curve* (Figure 5).

Figure 5. Disruption X-Curve

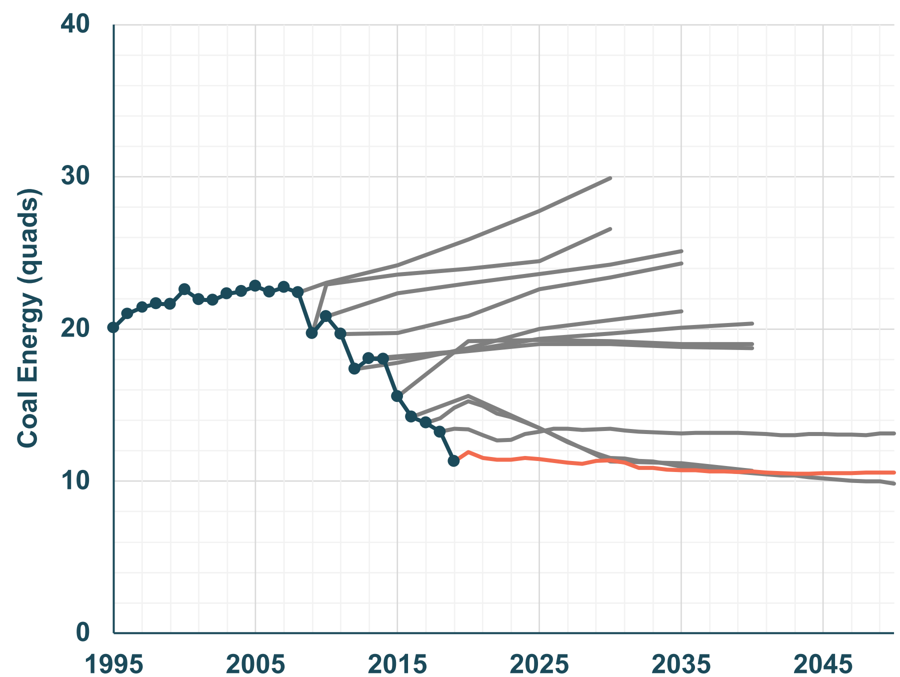


Source: RethinkX

The characteristic disruption X-curve that results from overlapping growth and collapse S-curves is a consistent feature of disruptions that we see throughout history. The same pattern now applies to the clean disruption of energy by 100% SWB systems that will unfold over the course of the 2020s.

The disruption of energy by SWB starting in the 2020s will exhibit the same characteristic disruption X-curve as many previous technology disruptions throughout history. In addition to seeing the continued exponential adoption growth of the new technologies, we are also already seeing the incumbent technologies enter their death spiral. For example, coal in the United States was initially disrupted by unconventional well-stimulation technologies (collectively known as "fracking") and is now continuing to collapse under pressure from SWB (Figure 6).

Figure 6. Disruption of Coal Power in the United States



Source: US EIA Annual Energy Outlook series, 1995-2020.[14]

Coal use peaked in the United States in 2008 and is now charting a textbook disruption trajectory toward collapse. Conventional forecasts from the U.S. Energy Information Administration fail to understand disruption and have made linear projections for the recovery or stabilization of coal power each year for over a decade, with the latest projection for 2020 continuing the same erroneous pattern.

Part Two

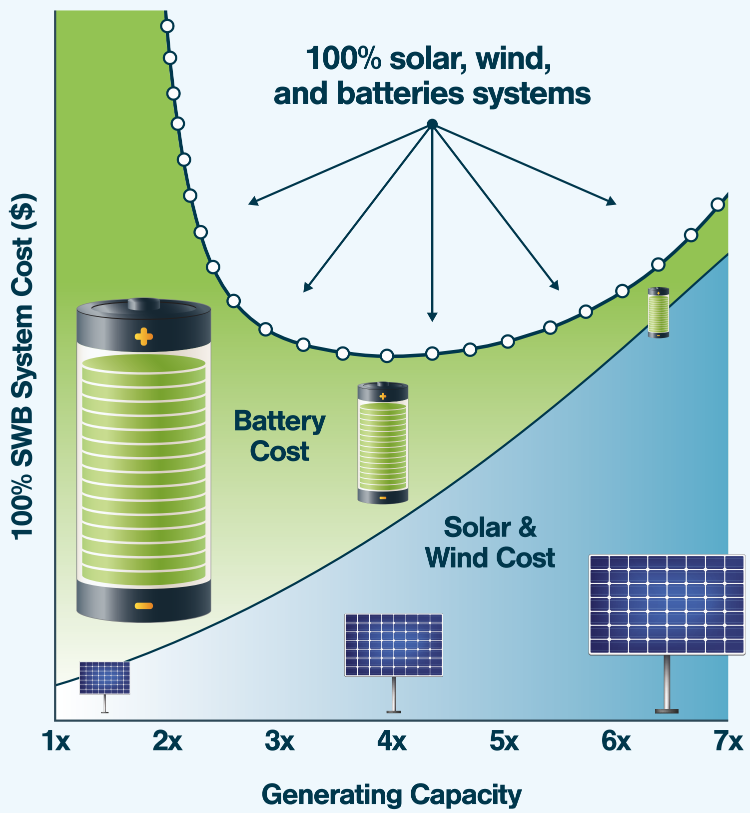
Rethinking 100% Solar, Wind, and Batteries Electricity Systems

Up until recently, most conventional analyses have simply assumed that meeting all of our electricity needs with a 100% SWB system is simply impossible – at least economically, if not also physically. However, because the cost of both solar PV and batteries has declined over 80% since 2010 and will continue to fall throughout the 2020s, this hardline stance has softened over the last several years. Nonetheless, most conventional analyses to date have still been based on pessimistic assumptions about building sufficiently large quantities of SWB capacity to meet 100% of electricity demand year round.[9,15] In reality, it is cost-effective to construct very large quantities of solar and wind capacity because that generation capacity offsets energy storage requirements, and by doing so the resulting system will naturally produce an enormous surplus of clean energy at near-zero marginal cost.[16,17]

The Clean Energy U-Curve

A key highlight of our analysis is that generation and storage capacity can be traded off against one another within the space of possible 100% SWB systems according to the convex U-shaped cost function that we call the *Clean Energy U-Curve*, shown in Figure 7.

Figure 7. The Clean Energy U-Curve



Source: RethinkX

Long stretches of cloudy winter days when available sunshine is at its minimum present the greatest challenge to SWB systems. On the one hand, a 100% SWB system could meet demand by having a very large amount of solar and wind generating capacity paired with a comparatively modest battery energy storage capacity. Solar and wind could then still meet demand during the day, even with meager winter sunshine, while at the same time charge the batteries so that electricity could continue to be supplied throughout the night.[e] Although effective, this capacity mix would be expensive (top right of Figure 7).

On the other hand, a 100% SWB system could instead meet demand by having a comparatively small amount of solar PV and wind generating capacity paired with an extremely large and expensive battery capable of storing weeks' worth of average hourly electricity demand. The battery could be charged in advance during sunnier and windier periods, and then drawn upon day after day during times of overcast winter weather. This too would be expensive (top left of Figure 7).

In order to minimize overall system capital expenditure (capex), an optimal balance between the two must be identified. Very importantly, this tradeoff relationship is not linear. Rather, the capital cost tradeoff relationship between generation and storage capacity is characterized by convex (U-shaped) curve. On a 2D chart it is not possible to visualize both generation capacity and battery capacity on their own axes simultaneously, and so one of the two must be selected as the horizontal axis. A U-curve pattern emerges regardless of which is selected, but generation capacity is the more sensible choice for visualization because it also allows us to see the disproportional return on additional investments in super power (Figure 8). The precise shape of the clean energy U-curve differs substantially from one geographic region to another because of the variation in sunshine and wind resource availability.

Moreover, the clean energy U-curve is not perfectly symmetrical, but instead tends to be skewed toward greater generation capacity. Matters are further complicated by the fact that the costs of solar PV, onshore wind power, and lithium-ion batteries are all declining at different rates.[f]

Although a small handful of other researchers have also begun to recognize the potential of trading off generation and storage capacity to identify cost-effective SWB options, the full implications are still largely unrecognized among policymakers, investors, and the public at large.[16,18,19]

Clean Energy Super Power

A key finding of our analysis is that when the SWB capacity mix is optimized for cost, this least-expensive system will have 3x-5x more generating capacity than today's grid. As a result, any 100% SWB system will produce an extremely large amount of surplus electricity at near-zero marginal cost that we call clean energy super power.

Super power is a natural feature of all 100% SWB systems. The need to build sufficient solar and wind generation capacity to meet electricity demand when sunshine and wind are least abundant gives the system the ability to produce far more electricity at most other times of the year. (The same pattern is found in many systems, including machines and organisms, because any such system must have the capacity to deal with rare peaks of stress or adversity).

Three aspects of super power are particularly counterintuitive:

1. Availability

Even in regions like New England with relatively poor sunshine and wind resources, super power is available for some hours of the day on the majority days throughout the year. For example, our analysis shows that the lowest cost 100% SWB system produces super power on 64% of all days of the year in New England, on 93% of all days in California, and 93% of all days in Texas (see Findings below).

2. Scale

Because super power is available on most days of the year, the total quantity produced by 100% SWB systems is very large relative to existing electricity demand. In California and Texas, for example, the lowest cost 100% SWB system will produce more super power output than today's total annual electricity demand (see Findings below).

3. Disproportionality

Super power does not grow linearly with investment in capacity. This is a counterintuitive feature of systems that produce near-zero marginal cost outputs. Increasing system capex by just 20%, for example, will *double* super power output in California and Texas, and *triple* super power output in New England (see Findings below).

Super Power Applications

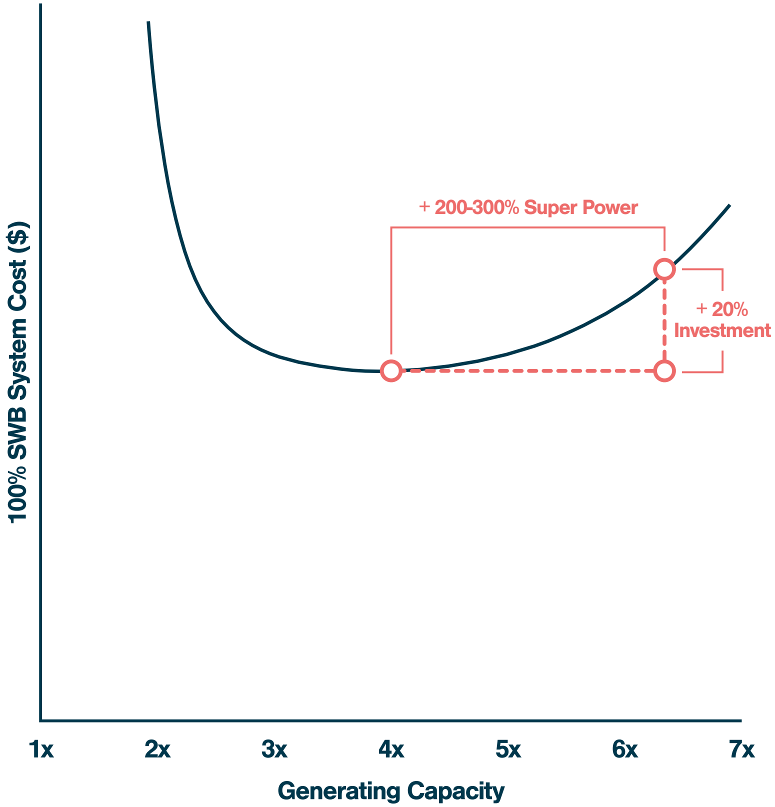
The potential applications for super power are extraordinary. A superabundance of clean electricity at near-zero marginal cost that is available on most days of the year will enable the emergence of new business models across a wide range of industries. Examples of applications include electrification of road transportation and heating, water desalination and treatment, waste processing and recycling, metal smelting and refining, chemical processing and manufacturing, cryptocurrency mining, distributed computing and communications, fuel production, carbon removal, and manufacturing of solar panels, wind turbines, and batteries themselves – to name just a few.

It is difficult to overstate how significant the impact of super power will be. History shows that energy abundance enables and supports social and economic development in the broadest sense, and so a superabundance of extremely cheap energy with little or no social or environmental externalities will create unprecedented opportunities for every region that chooses to adopt a 100% SWB system, in both less-developed and more-developed countries alike.

Disproportional Returns on Super Power Investments

A remarkable property of 100% SWB systems is that they show disproportional returns on investment for super power. The reason why is that the bottom of the U-curve is relatively shallow, as shown in Figure 8.

Figure 8. Disproportionate Super Power Returns on Additional System Capex Investment



Source: RethinkX

For a small investment premium (e.g. 10-20%), policymakers and investors could choose from a very large range of generation capacity and super power options (see Table 4, Table 6, and Table 8). Given that super power has such profound secondary benefits which stand to affect dozens of industries and have a transformative impact on the entire economy, it will be rational for most regions to make these additional investments in their SWB system.

Conventional Analyses Fail to Understand Super Power

Conventional analyses which assume clean energy systems should aim for no more than 90% SWB fail to recognize the value of super power. The ability of solar and wind generating assets to produce surplus clean energy at near-zero marginal cost has long been mischaracterized as a problem. The conventional "solution" to the "problem" of "overproduction" is curtailment, which artificially suppresses super power output in order to avoid destabilizing the grid with excess supply and also to spare conventional powerplants from disruption.[20,21,22] However, deliberately wasting huge quantities of clean energy produced at near-zero marginal cost is not rational and indicates that the existing system lacks the ability to successfully adapt to the introduction of disruptive new technologies. Just like when incumbents tried to implement anti-copying measures for CDs and DVDs that only accelerated the digital disruption of music and movies, history shows that behavior patterns of this kind indicate the old system is poised to be replaced by a new system with a dramatically different architecture.

Part Three

100% Solar, Wind, and Batteries – the RethinkX Limit Scenario

Purpose

Technology convergence and disruption create new possibility spaces. Products, services, business models, processes, and ideas that were not previously feasible become possible – and often inevitable. For instance, the convergence of the smartphone (with embedded GPS) and cloud computing made ride-hailing possible, and so it is no coincidence that Uber was founded just two years after the release of the iPhone and three years after the launch of Amazon Web Services. Solar PV, wind power, and lithium-ion batteries have reached a similarly pivotal point of convergence and are set to open a new and radically different possibility space for the energy sector.

The question of whether or not a 100% SWB electricity system is feasible, both physically and economically, has been the subject of substantial research across the academic, private, and nonprofit sectors (for a comprehensive review of the literature and its surrounding debates, see Brown et al. 2018).[23] Our analysis contributes to this body of research, and – we believe – shows that the answer to the above question is clearly and unequivocally yes: a 100% SWB system is both physically possible and economically affordable by 2030.

The purpose of the limit scenario that we explore in this analysis is to demonstrate that even under the most challenging assumptions where SWB must meet 100% of all electricity demand without any support from conventional reserve capacity or electricity imports, the disruption of conventional coal, natural gas, and nuclear power generation technology is not just achievable but inevitable. In particular, by demonstrating that this is even the case in New England where sunshine and wind resources are relatively poor, we show that 100% SWB systems are feasible in almost all other populated areas, not just in the United States but worldwide.

Three Regional Case Studies

The availability of sunshine and onshore wind varies substantially across the continental United States. We selected California, Texas, and New England as three representative regional cases that can inform generalizations of our findings to other similar regions. California enjoys abundant sunshine but comparatively little wind, Texas possesses an abundance of both sunshine and wind, and New England has more modest endowments of both resources.[24,25] It is important to note, for purposes of wider generalization of our findings, that the vast majority of the world's population lives in areas where sunshine is much more abundant than in New England.

Data

Our model takes as inputs each region's historical hourly electricity demand, hourly solar PV power generation, and hourly wind power generation for the 2-year period of July 1 2017 through June 30 2019.[g] For the California region, our analysis takes raw data from California ISO (CAISO) whose service area provides 79% of the state's electricity demand as well as a small part of Nevada, and adjusts it proportionally to represent the entire state.[26] For the Texas region, our analysis takes raw data from the Electric Reliability Council of Texas (ERCOT) whose service area provides 90% of the state's electricity demand, and adjusts it proportionally to represent the entire state.[27] For the New England region, our analysis applies to the ISO New England (ISO-NE) service area which provides 100% of grid-scale electricity generation for the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont.[28]

Highlights of these data are summarized in Table 2.

Table 2. Regional Demand Highlights

Region	Annual Demand (terawatt-hours)	Average Hourly Demand (gigawatts)	Peak Hourly Demand[h] (gigawatts)	Peak Demand Date and Time
California*	285	32.5	63.0	5pm September 1, 2017
Texas*	414	47.2	81.5	4pm July 19, 2018
New England	122	13.9	25.7	6pm August 29, 2018

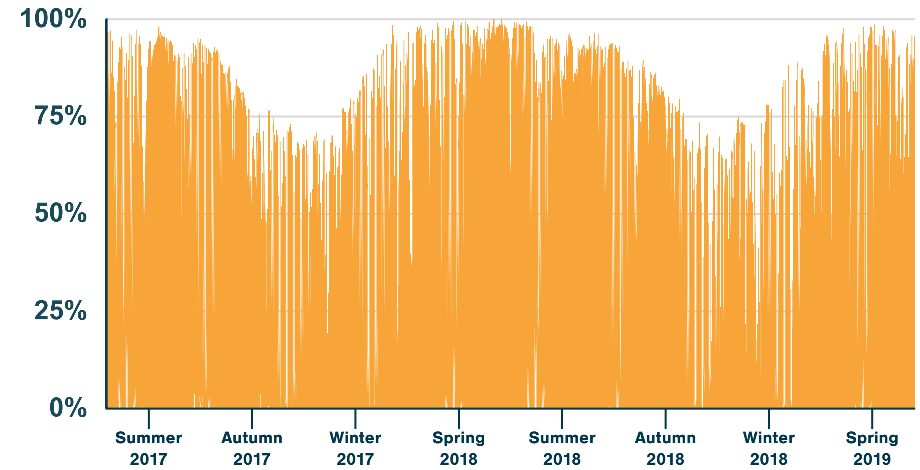
** Proportionally adjusted from operator service area data.*

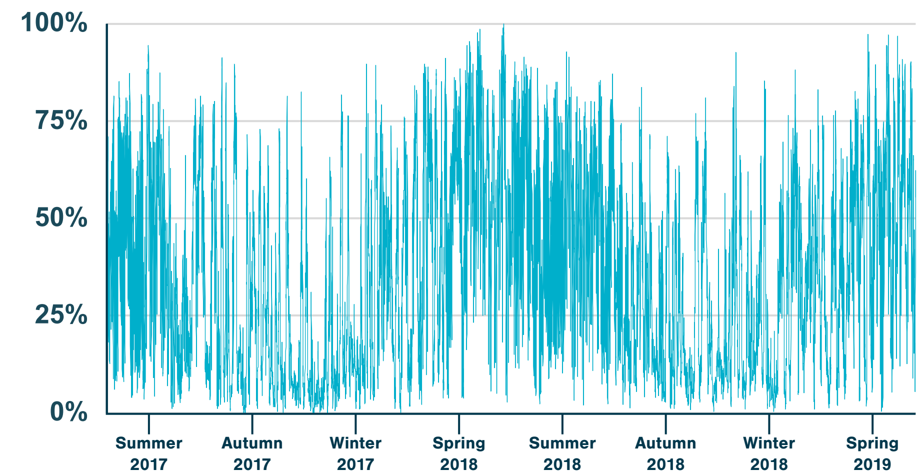
Sources: CAISO 2020; ERCOT 2020; ISO-NE 2020.

Note that electricity imports from other regions, decentralized generation capacity from rooftop solar PV installations, decentralized battery storage capacity, geothermal heat pumps offsetting heating and cooling needs, and active demand response resources such as commercial and industrial buildings with on-site generators and building automation systems that can adjust energy load that can reduce their electricity demand upon request are all excluded from the data in Table 2. Note also that *demand* is defined as the quantity of electricity, or load, that the system must generate in order to meet all end users' needs, but that this is necessarily larger than the quantity of electricity consumption by end users because of transmission losses which average 5% in the United States (see Constraining Assumptions below).[29]

We normalize the raw hourly solar and wind generation data and adjust for capacity additions such that the resulting data ranges from 0% to 100% for each calendar year. This approach based on real-world electricity output from installed solar and wind capacity provides accurate proxies for the natural variability profile and thus the availability of sunshine and wind resources in each of the three geographic regions.[i] Once normalized, the values can then be scaled to simulate any quantity of solar and wind generation as needed. (See our Methodology documentation at www.rethinkx.com for additional detail).

Figure 9. CAISO Normalized Solar and Wind Resource Profiles – July 1 2017 through June 30 2019

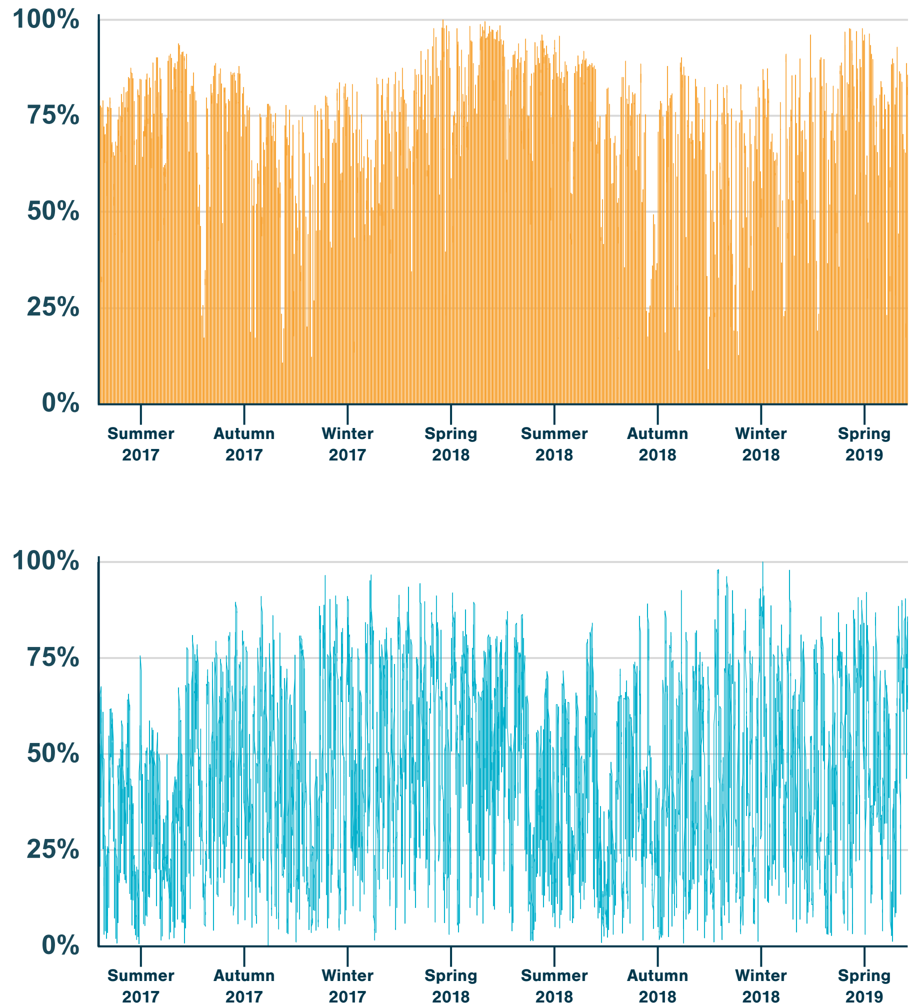




Source: CAISO, 2020.[30]

These charts show solar (gold) and wind (blue) resource availability for California on a scale of 0-100% at hourly intervals. The 2-year time period of our analysis begins on July 1 2017 and ends June 30 2019. Seasonal patterns are visible, but there is substantial day-to-day variation because of regional weather conditions.

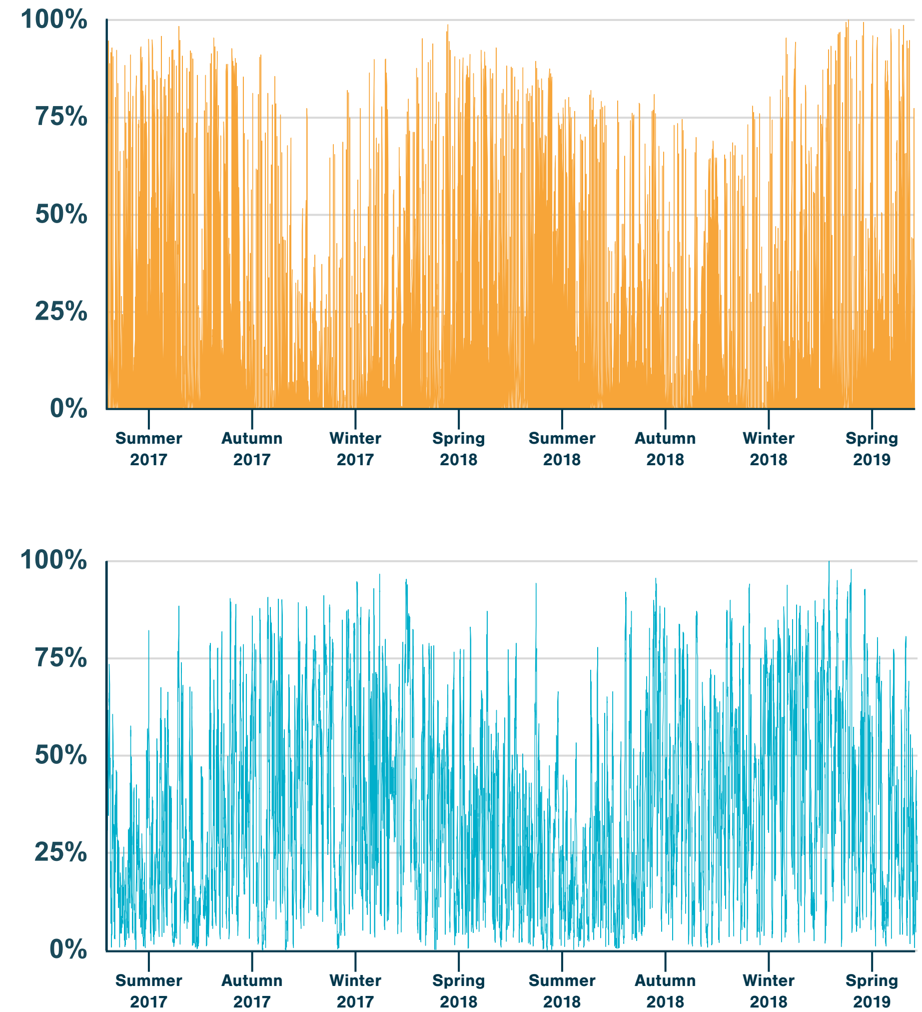
Figure 10. ERCOT Normalized Solar and Wind Resource Profiles – July 1 2017 through June 30 2019



Source: ERCOT, 2020.[31]

These charts show solar (gold) and wind (blue) resource availability for Texas on a scale of 0-100% at hourly intervals. The 2-year time period of our analysis begins on July 1 2017 and ends June 30 2019. Seasonal patterns are visible, but there is substantial day-to-day variation because of regional weather conditions.

Figure 11. ISO-NE Normalized Solar and Wind Resource Profiles – July 1 2017 through June 30 2019



Source: ISO-NE, 2020.[32]

These charts show solar (gold) and wind (blue) resource availability for New England on a scale of 0-100% at hourly intervals. The 2-year time period of our analysis begins on July 1 2017 and ends June 30 2019. Seasonal patterns are visible, but there is substantial day-to-day variation because of regional weather conditions.

Constraining Assumptions

Our limit scenario makes a number of severely constraining assumptions for the purpose of emphasizing what is possible for 100% SWB systems. The bar for clean energy will not be nearly so high in most locations.

Assumption 1: no electricity imports

It is common practice for regions to trade electricity with their neighbors. Moreover, even if all regions had 100% SWB systems there would still be significant advantages to importing and exporting electricity because adjacent geographic areas naturally experience different weather conditions. At present, California and New England both import about 25% of their electricity on average.[32, 33] ERCOT in Texas is more isolated, and does not routinely import electricity except in emergencies.

Assumption 2: no conventional operating reserve

As we approach the 100% limit, retaining a modest reserve capacity from existing (not new) conventional generating assets could reduce capital costs in many regions. The reason why is that a small conventional reserve functioning as peakers offsets a disproportionately large amount of SWB generation and/or storage capacity requirements.[j] However, these short-term savings would eventually be exceeded by the cost of continuing to operate high marginal cost facilities and would also mean forfeiting a disproportionately large amount of super power output, and would therefore be suboptimal in most cases.

Assumption 3: no other renewables

Some regions already have hydropower, geothermal, or other renewable generation capacity installed because of regional geographic conditions. Our analysis excludes these other renewables, but in the near term any existing generation capacity of this kind will temporarily offset the requirement for new solar and wind power.

Assumption 4: no distributed generation or storage

Distributed generation and storage such as rooftop solar PV and onsite batteries make the electric grid dramatically more robust and resilient. The point at which self-generation falls below the cost of transmission – known as Generation on Demand (GOD) parity – will enable many residential, commercial, and industrial customers to adopt on-site solar PV and batteries for purely economic reasons.[34] However, we have excluded the additional complexity of these distributed energy resources (DER) from the limit scenario analyzed here. In reality, however, the adoption of DER is growing exponentially and will be profoundly disruptive to large-scale centralized generation and storage. Note also that the broader implications of the clean energy U-curve and clean energy super power remain valid irrespective of what fractions of a 100% SWB system are centralized or distributed.

Assumption 5: no impacts from electric vehicle energy storage

In our 2017 report *Rethinking Transportation 2020-2030,* we showed that electric and autonomous vehicles providing transportation-as-a-service (TaaS) will disruption conventional road transportation during the 2020s.[35] Electric vehicles will make the grid more robust and resilient while at the same time decreasing the capacity (and cost) requirements of the system's stationary storage by providing vehicle-to-grid energy services. However, we exclude the impacts of electric vehicles on energy storage from the analysis presented here.

Assumption 6: no demand response, load shifting, energy arbitrage, or peak shaving

Residential, commercial, and industrial users all have scope to adjust the time of day during which they utilize electricity. In regions with well-functioning electricity markets, supply and demand will be coordinated via price signaling facilitated by advanced "smart" metering technology, and as a result overall electricity demand will be redistributed throughout the day according to when solar and wind resources are abundant.[36,37,38,39] We exclude these mechanisms from our analysis, but they will in fact serve to lower peak demand and thus reduce the minimum electricity generation and storage capacity that must be installed in 100% SWB systems.

Assumption 7: no technology breakthroughs

Our analysis does not assume that there will be any breakthroughs in SWB technologies. However, a number of major advances are in fact already in commercial development that are poised to bring substantial improvements to solar PV panels such as dual-layer perovskites or bifacial modules, and very large improvements to lithium-ion batteries such as solid-state or semi-solid-state electrolytes, silicon anodes, and graphene cathodes. These imminent advancements will accelerate the disruption and lower the overall cost of electricity systems beyond the already impressive improvements that scaling alone will achieve. Our analysis also presumes that no game-changing energy technologies such as "cold fusion" will reach the market before 2030.

Assumption 8: no subsidies, carbon taxes, or other financial innovations

Our analysis does not assume that there will be any subsidies, carbon taxes, or other financial innovations to support SWB technologies. However, policies that incentivize investment in and deployment of SWB already exist in a number of regions of the United States and elsewhere around the globe. These are very likely to expand over the course of the 2020s as the social license of incumbent fossil fuel and nuclear fission technologies continues to erode.

Each of the assumptions listed above artificially constrain our limit scenario. In reality, each of these factors will accelerate the trajectory to 100% SWB systems over the next decade.

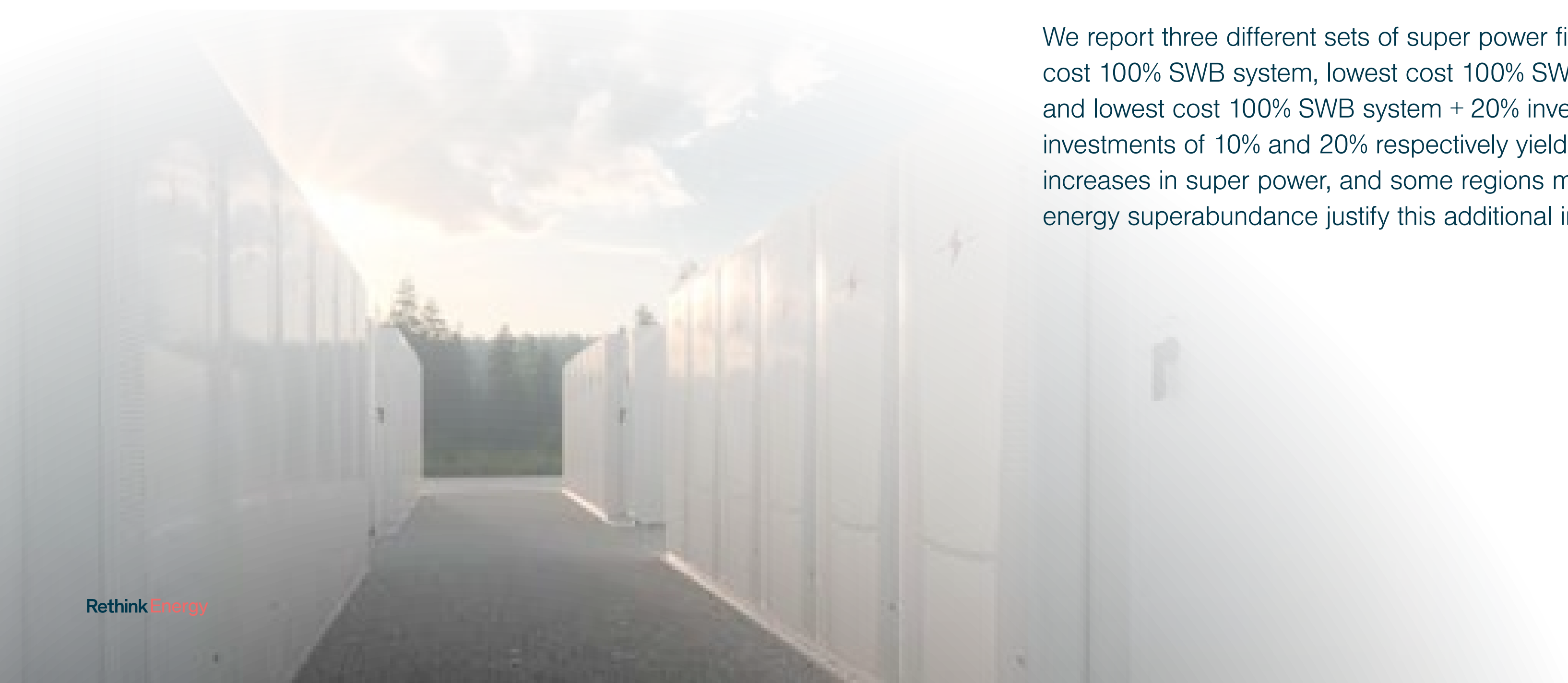
Disruption Versus Integration

Our analysis applies only to electricity generation and storage, and deliberately excludes interconnection, transmission, and distribution. The reason why is that interconnection, transmission, and distribution requirements will be dramatically impacted by each of the factors listed in the constraining assumptions above, as well as by the addition of SWB assets themselves.[40] Some of these factors will serve to increase infrastructure requirements and associated interconnection, transmission, or distribution costs, while others will serve to decrease them. Without modeling those factors in detail, which will vary greatly from one region to another, it is impossible to make meaningful estimates for future infrastructure requirements and costs.

It is important to note here, however, that it is an error to presume that the SWB disruption cannot occur without a clear and smooth pathway to integration with the existing electricity system. By their nature, disruptions fundamentally transform existing systems. We are not facing a slow, smooth, or linear energy transition based on a proportional 1-to-1 phase out of existing power plants via incremental attrition across many decades. To presume that the existing system must be accommodated is therefore tantamount to presuming that SWB will not actually cause a disruption. History is filled with analogous situations where incumbents believed new technologies would be adopted slowly and incrementally over a decades-long transition, when in reality the existing system was either drastically transformed and expanded or else wiped out entirely – i.e. disrupted.

In the early 20th Century, for example, the incumbent horse-based road transportation industry in the United States was skeptical and outright dismissive of automobiles because there were almost no paved roads, the petroleum industry was in its infancy, there were no fueling stations, manufacturing capacity and supply chains were limited, the rules of the road had not yet been developed, and almost nobody knew how to drive. Nevertheless, automobiles fully disrupted road transportation in less than 15 years.[41]

Similarly, in 1992 the incumbent telecommunications, media, and other information-based industries were skeptical of the nascent Internet for similar reasons: computing power and transmission infrastructure were limited, rules and protocols were not fully developed for security, reliability, or user-friendliness, almost nobody was online, websites and browsers did not yet exist, and it was not at all clear what business models and regulations would need to emerge to navigate the shift to near-zero marginal cost information. Nevertheless, within 15 years the Internet fully disrupted the media and telecommunications industries while at the same time radically transforming the global economy and creating tens of trillions of dollars in new value across dozens of other existing and new industries. It is worth noting that incumbents largely failed to capture this value, and that the five largest companies in the United States by market capitalization today – Amazon, Apple, Alphabet/Google, Microsoft, and Facebook – were all outsider upstarts.



Findings

Our analysis covers three different regions of the United States – California, Texas, and New England – that together provide a geographically representative picture of the entire continental United States, and by extension much of the rest of the populated world as well. Here we present findings for each region's clean energy U-curve, system costs, and super power output.

Many different combinations of solar, wind, and battery capacity are physically capable of meeting 100% of electricity demand in each given region. We show the lowest cost 100% SWB system for each region based on the logic of the clean energy U-curve.

It is crucial to recognize that the configuration of the lowest cost 100% SWB system varies over time because the costs of solar PV, wind power, and lithium-ion batteries are all improving at different rates. The lowest cost 100% SWB system for each region in 2030 will therefore be significantly different than if the system were constructed overnight in 2020. Moreover, the overwhelming majority of generation capacity in any future 100% SWB system will be solar because it will become much less expensive than wind over the course of the 2020s. Our analysis takes account of these cost dynamics, and it is crucial that policymakers, investors, and other decision makers do the same because failure to base analyses on future rather than current costs produces badly misleading results.

We report three different sets of super power findings for each region: lowest cost 100% SWB system, lowest cost 100% SWB system + 10% investment, and lowest cost 100% SWB system + 20% investment. These additional capital investments of 10% and 20% respectively yield disproportionately large increases in super power, and some regions may decide that the benefits of energy superabundance justify this additional investment.

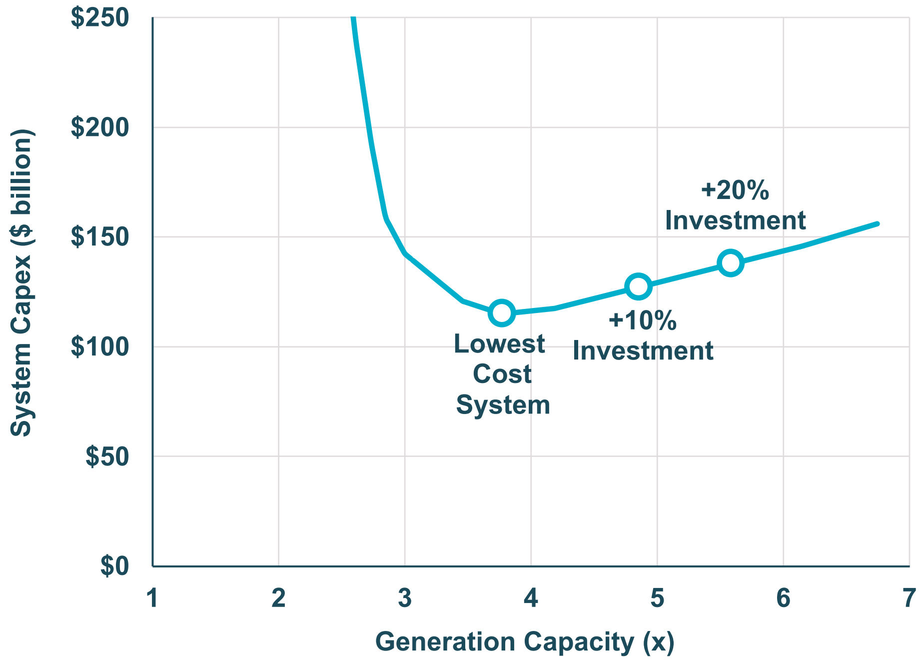
Case Study 1. California

California possesses an abundance of sunshine but relatively modest onshore wind resources. Many other populated regions around the globe, particularly among the low- and middle-income countries, receive a similar amount of sunshine and wind. The state is extraordinary relative to other regions in that it has been an aggressive early adopter of clean technology and associated public policy in general for several decades, and of solar PV in particular. This forward-looking stance has positioned California to be a leader in the SWB disruption of the energy sector, and other regions looking to take a leadership position have previously benefitted and will continue to benefit from learning by the state's example.

California Clean Energy U-Curve

Figure 12 shows the clean energy U-curve for California. The curve is asymmetrical, which indicates that costs escalate dramatically as generating capacity decreases below 3.8x, or 3.8 times the amount currently required to meet peak electricity demand. This is because the battery energy storage requirement of the 100% SWB system rises dramatically as generating capacity shrinks.

Figure 12. The Clean Energy U-Curve for California



Source: RethinkX

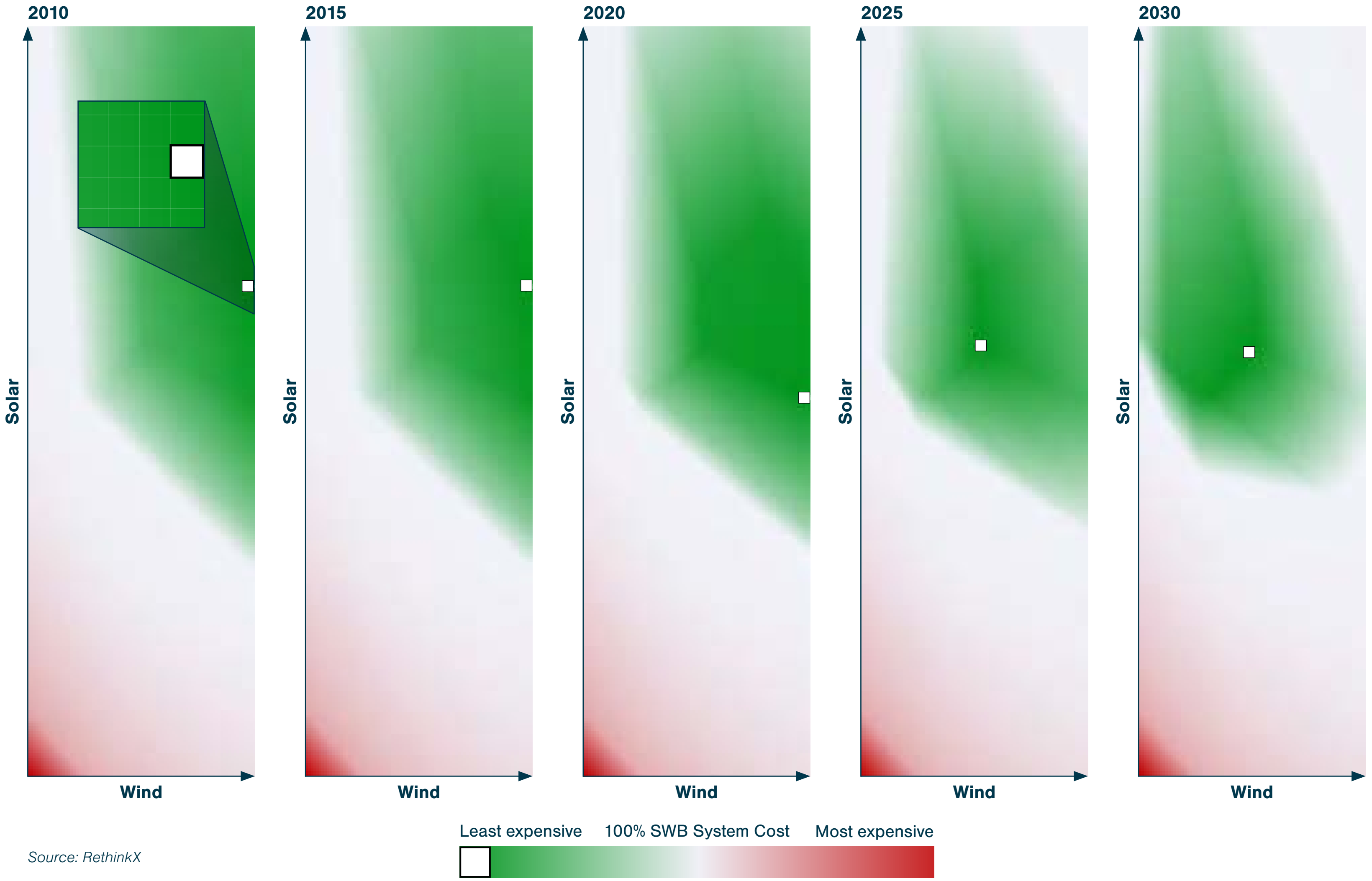
The Clean Energy U-Curve for California shows that there is a nonlinear tradeoff relationship between generation capacity and battery energy storage. Most conventional analyses to date have assumed that building more than 1.5x generation capacity is infeasible, and as a result many weeks of battery energy storage would be required at enormous cost. Using the Clean Energy U-Curve, our analysis shows that in California the lowest cost 100% SWB system combination of these technologies comprises 3.8x generation capacity with only 37 hours of battery energy storage for a total system capex of $115 billion. This is much less expensive than most conventional analyses have claimed.

Today California already has 28 gigawatts of solar PV and 6 gigawatts of wind power installed, so the lowest cost 100% SWB system would require 185 gigawatts of additional solar PV and 19 gigawatts of additional onshore wind power for a total of 213 gigawatts and 25 gigawatts respectively.[42,43] This stark difference between the two technologies reflects the fact that solar PV will become considerably less expensive than onshore wind power going forward through the 2020s, and will inevitably become the preferred choice for new generating capacity.

California Lowest Cost 100% Solar, Wind, and Batteries System

The time-series of heatmaps in Figure 13 shows how the combination of solar and wind power in the lowest cost 100% SWB system for California changes over time. In 2010, the optimal mix would have been comprised largely of wind power. But because the cost of solar PV has fallen so much faster than the cost of wind power over the last decade, the lowest cost 100% SWB system today would have much less wind power, and even less in 2030.

Figure 13. Capital Costs of a 100% SWB System in California



This time-series of heatmaps shows which combinations of solar and wind capacity in California are more expensive (red) and less expensive (green). The least expensive combination is highlighted in white. Capital costs include not just solar and wind capacity themselves, but also the amount of batteries required to support them. Because costs of solar PV, onshore wind power, and lithium-ion batteries are each decreasing at different rates, the least expensive combination changes over time. In 2010, when wind power was comparatively cheap, the least expensive combination would have contained much less solar PV. In 2030, however, the least expensive combination will be overwhelmingly solar PV because its costs are falling so rapidly compared to wind power.

Source: RethinkX

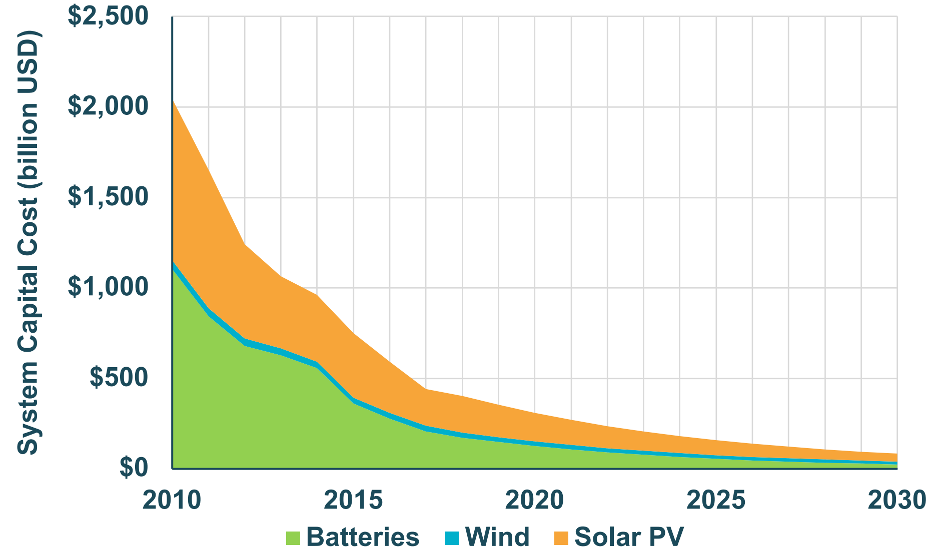
Assuming an exponential buildout starting in 2021, the specific lowest cost 100% SWB system for California comprises:

- 213 gigawatts of solar PV generation capacity
- 25 gigawatts of wind power generation capacity
- 3.8x system generation capacity relative to current peak electricity demand
- 1194 gigawatt-hours (37 average demand hours) of battery energy storage capacity

California System Capital Cost

The capital cost (capex) of solar PV, onshore wind power, and lithium-ion batteries have improved so dramatically that what was economically unthinkable a decade ago will be economically inevitable a decade hence. Since 2010, the combined capital cost of solar PV, wind power, and batteries has fallen 85%, and it will decline a further 75% by 2030 (Figure 14). This represents a 96.5% decline, or a 30x improvement, in just 20 years.

Figure 14. California 100% Solar, Wind, and Batteries System Capital Cost 2010-2030



Sources: Berkeley Labs, 2019; NREL, 2019; BNEF, 2019; RethinkX, 2020.[1,3,8]

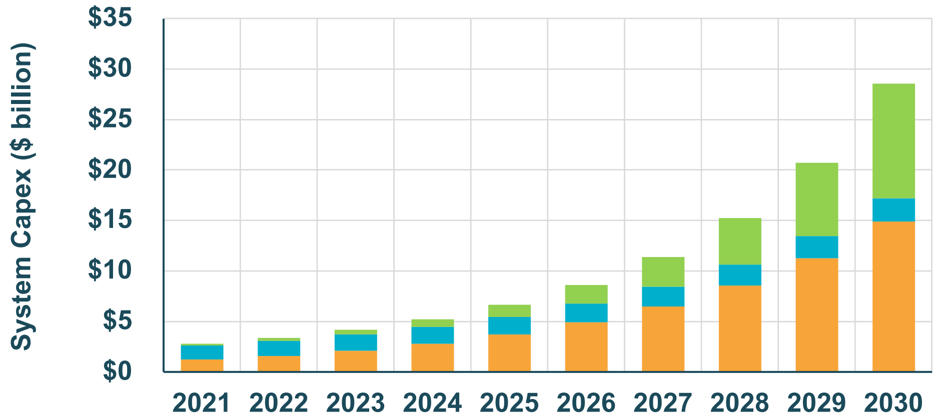
The capital cost of a 100% SWB system in California has fallen by 85% since 2010, and will decline another 75% by 2030.

Even though these technologies are on steep deflationary cost trajectories, California does not need to wait until 2030 to begin investing in solar, wind, and batteries. The difference between starting to build now and waiting until 2030 to begin is relatively modest – just 28% under our model's assumptions – because the bulk of new capacity additions will be added in the final years when costs are lowest.[k]

The advantages of early adoption such as energy independence, job creation, new entrepreneurial opportunities, cost savings from avoided operation and maintenance of existing fossil infrastructure, reduced environmental impacts, and human health benefits more than make up for this additional cost.

Figure 15 shows system capex by year for an exponential buildout starting in 2021 that culminates in the lowest cost 100% SWB system for California in 2030 at a total cost of $115 billion. For comparison, California has already invested $67 billion in solar PV to date.[43]

Figure 15. California 100% SWB System Capex by Year for Exponential Buildout



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Batteries	$0.2	$0.3	$0.5	$0.8	$1.2	$1.9	$2.9	$4.6	$7.2	$11.4
Wind	$1.4	$1.5	$1.6	$1.7	$1.7	$1.9	$2.0	$2.1	$2.2	$2.3
Solar PV	$1.2	$1.6	$2.1	$2.8	$3.7	$4.9	$6.5	$8.6	$11.3	$14.9

Source: RethinkX

Annual investments in the exponential buildout of a lowest cost 100% SWB system in California totaling $115 billion are dominated by solar PV and wind power in early years, and by solar PV and batteries in later years.

California System Electricity Cost

In order to have a complete financial picture of a 100% SWB system in California, it is necessary to account for operational expenditures as well. Solar PV, wind power, and lithium-ion battery installations all have very low fixed operations and maintenance costs compared to conventional technologies, and solar PV in particular has near-zero variable operations and maintenance costs as well. And, of course, solar PV, wind power, and batteries do not consume fuels. As a result, the total operational expenditures (system opex) and corresponding marginal cost per unit of electricity for a 100% SWB system will be extremely low compared to coal, natural gas, or nuclear power. Moreover, SWB systems are even more competitive when the full social, political, and environmental externalities of fossil and nuclear fuels and their supply chains are accounted for.

Taken together, total system capex and system opex can be averaged across all kilowatt-hours supplied by a 100% SWB system over a given period of time to arrive at a *system electricity cost,* or SEC. This metric's unit of measurement is cents per kilowatt-hour, so although SEC applies to the entire system it nevertheless provides a cost indicator that can be compared directly to the *levelized cost of energy* (LCOE) of individual conventional power plants, despite the latter metric's serious flaws.[l]

Because SEC averages all costs across all kilowatt-hours of electricity utilized, its calculation is contingent upon what fraction of super power is actually consumed by end users (see California Clean Energy Super Power below). Table 3 shows the SEC of 100% SWB system in California, and how this value varies depending upon super power investment and utilization.[m] Note that the SEC of the lowest cost 100% SWB system in California is just 3.1 cents per kilowatt-hour even if no super power were utilized at all.

Table 3. California System Electricity Cost with Super Power Investment and Utilization

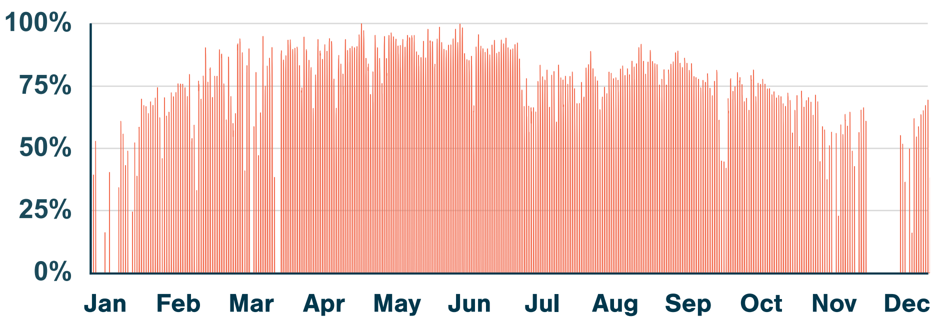
	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
0% Super Power Utilization	3.1 cents/ kilowatt-hour	3.4 cents/ kilowatt-hour	3.8 cents/ kilowatt-hour
50% Super Power Utilization	2.0 cents/ kilowatt-hour	1.9 cents/ kilowatt-hour	1.8 cents/ kilowatt-hour
100% Super Power Utilization	1.5 cents/ kilowatt-hour	1.3 cents/ kilowatt-hour	1.2 cents/ kilowatt-hour

Source: RethinkX

California Clean Energy Super Power

Our modeling shows that in California a 100% SWB system will produce super power on more than 93% of the days of year, with surprisingly modest seasonal variation. Extended periods of more than several days without super power occur infrequently, and only in early winter (Figure 16).

Figure 16. California Super Power in the Lowest Cost 100% SWB System (2018 by hour)



Source: RethinkX

This hourly chart of 2018 calendar year shows that a lowest cost 100% SWB system in California would produce super power throughout much of the year with surprisingly modest seasonal variation.

Additional investment in SWB capacity yields disproportionately large returns of super power in California. A 20% increase in system capex, for example, nearly doubles annual super power production from 309 terawatt-hours to 592 terawatt-hours, while also increasing super power availability from 93% to 98% of all days of the year (Table 4).

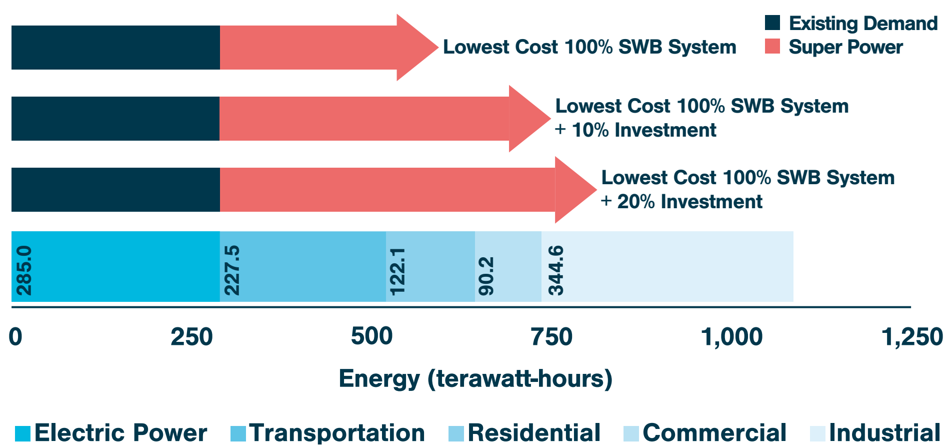
Table 4. California Super Power – Summary of Findings

	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
System capex	$115 billion	$127 billion	$139 billion
Annual super power	309 terawatt-hours	466 terawatt-hours	592 terawatt-hours
Fraction of annual demand	109%	164%	208%
Fraction of all days	93%	98%	98%
Fraction of all hours	28%	31%	33%

Source: RethinkX

Even in the lowest cost 100% SWB system, super power would provide enough energy to electrify all road transportation in California (assuming electrification of vehicles). Alternatively, it is an amount of energy greater than all fossil fuel energy use in the residential and commercial sectors combined (Figure 17).

Figure 17. California Super Power – Energy Use Comparison by Sector



Source: RethinkX

This chart shows that super power output in California would be large enough to offset a substantial fraction of all other energy use in the state, and that modest increases in capital investment yield disproportionately large increases in super power. If California chose to invest in an additional 20% in its 100% SWB system, the super power output could be used to replace most if not all fossil fuel use in the residential, commercial, and road transportation sectors combined (assuming electrification of vehicles and heating).

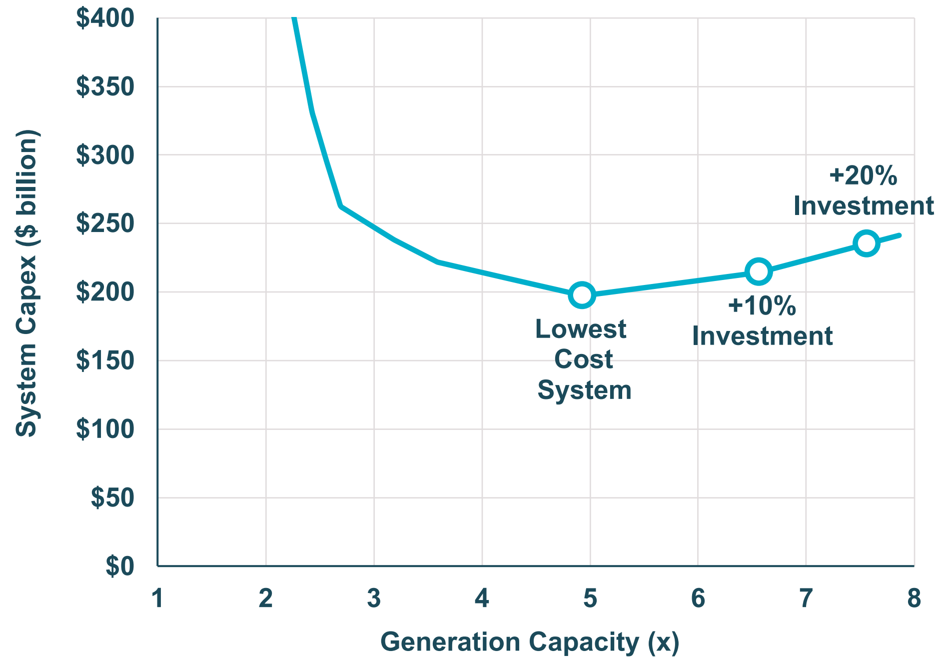
Case Study 2. Texas

Texas is a geographic region that enjoys an abundance of both sunshine and wind resources. Few other populated areas of the globe have such a bountiful clean energy endowment. Texas also has an extraordinarily large and energy-intensive industrial sector compared to other regions of the United States, so the state offers exceptional opportunities for the clean disruption of fossil fuel energy use outside of the electric power sector alone.

Texas Clean Energy U-Curve

Figure 18 shows the U-curve for Texas. The curve is asymmetrical, indicating that costs escalate dramatically as generating capacity decreases below 4.9x, or 4.9 times the amount currently required to meet peak electricity demand. This is because the battery energy storage requirement of the 100% SWB system grows enormously as generating capacity shrinks.

Figure 18. The Clean Energy U-Curve for Texas



Source: RethinkX

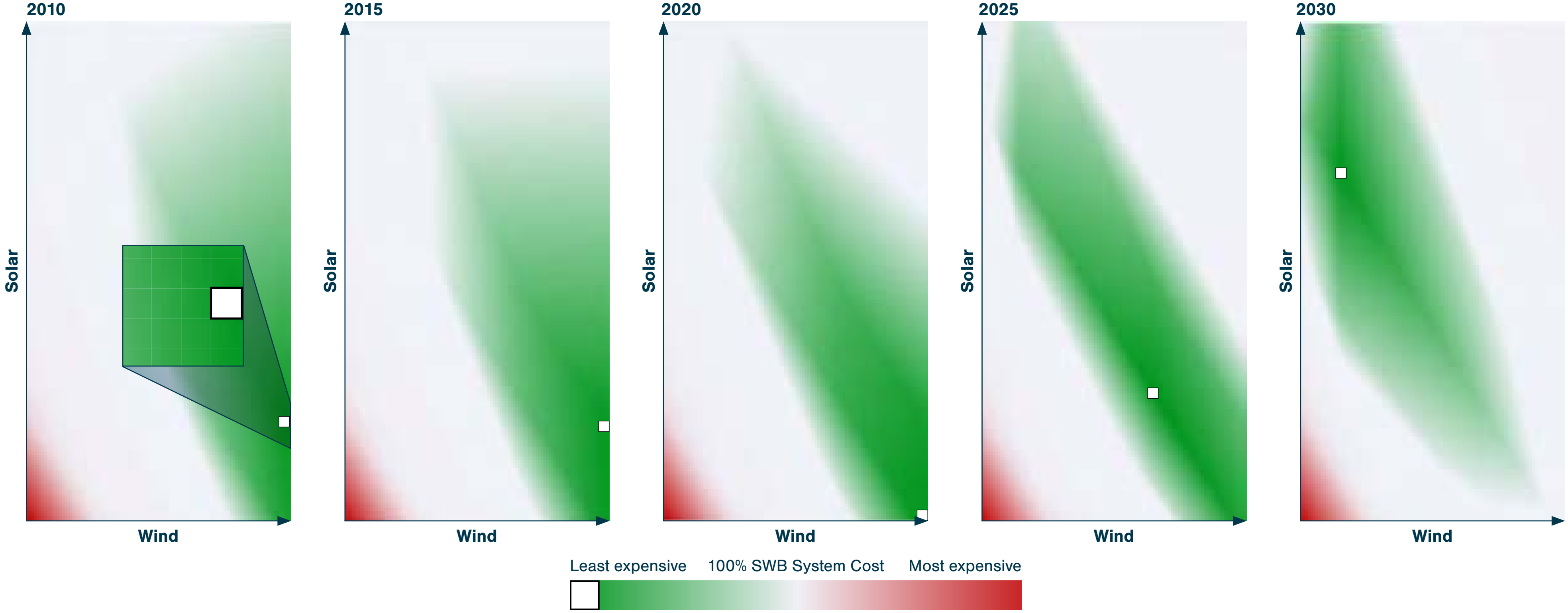
The Clean Energy U-Curve for Texas shows that there is a nonlinear tradeoff relationship between generation capacity and battery energy storage. Most conventional analyses to date have assumed that building more than 1.5x generation capacity is infeasible, and as a result many weeks of battery energy storage would be required at enormous cost. Using the Clean Energy U-Curve, our analysis shows that in Texas the most affordable combination of these technologies comprises 4.9x generation capacity with only 49 hours of battery energy storage for a total system capex of $197 billion. This is much less expensive than most conventional analyses have claimed.

At present, Texas only has 4.6 gigawatts of solar PV installed compared to 29.4 gigawatts of wind power installed, so in our scenario new solar PV capacity would amount to 357 gigawatts and new wind capacity would amount to just 11 gigawatts for a total of 362 gigawatts and 40 gigawatts respectively.[44,45] As in the case of California, the difference between the two technologies in Texas reflects the fact that solar PV will be the less expensive and therefore preferred option going forward through the 2020s.

Texas Lowest Cost 100% Solar, Wind, and Batteries System

The time-series of heatmaps in Figure 19 shows how the lowest cost 100% SWB system for Texas has changed and will continue to change over time. In 2010, the optimal mix would have been comprised predominantly of wind power, and indeed this remains the case at today's costs. But over the course of the 2020s the logic shifts in favor of solar PV, such that by 2030 the amount of wind power in the lowest cost 100% SWB system would actually be less (6 gigawatts) than the 29 gigawatts of capacity that is already installed in Texas.

Figure 19. Capital Costs of a 100% SWB System in Texas



Source: RethinkX

This time-series of heatmaps shows which combinations of solar and wind capacity in Texas are more expensive (red) and less expensive (green). The least expensive combination is highlighted in white. Capital costs include not just solar and wind capacity themselves, but also the amount of batteries required to support them. Because costs of solar PV, onshore wind power, and lithium-ion batteries are each decreasing at different rates, the least expensive combination changes over time. In 2010, when wind power was comparatively cheap, the least expensive combination would have contained much less solar PV. In 2030, however, the least expensive combination will be overwhelmingly solar PV because its costs are falling so rapidly compared to wind power.

Assuming an exponential buildout starting in 2021, the specific lowest cost 100% SWB system for Texas comprises:

» 362 gigawatts of solar PV generation capacity

» 40 gigawatts of wind power generation capacity[n]

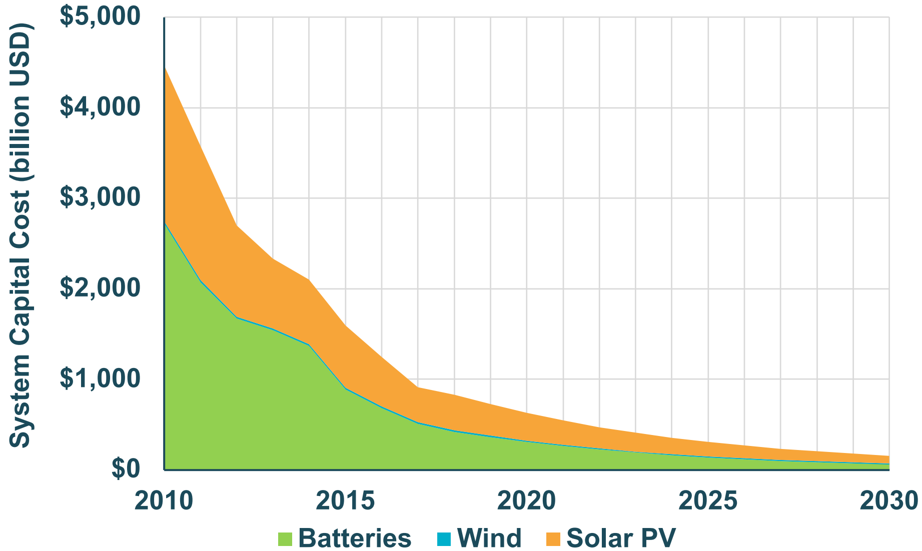
» 4.9x system generation capacity relative to current peak electricity demand

» 2325 gigawatt-hours (49 average demand hours) of battery energy storage capacity

Texas System Capital Cost

The capital cost (capex) of solar PV, wind power, and lithium-ion batteries have been so dramatic that what was economically unthinkable a decade ago will be economically inevitable a decade hence. Since 2010, the combined capital cost of solar PV, wind power, and batteries has fallen 85%, and it will decline a further 75% by 2030 (Figure 20). This represents a 96.5% decline, or a 30x improvement, in just 20 years.

Figure 20. Texas 100% Solar, Wind, and Batteries System Capital Cost 2010-2030



Sources: Berkeley Labs, 2019; NREL, 2019; BNEF, 2019; RethinkX, 2020.[1,3,8]

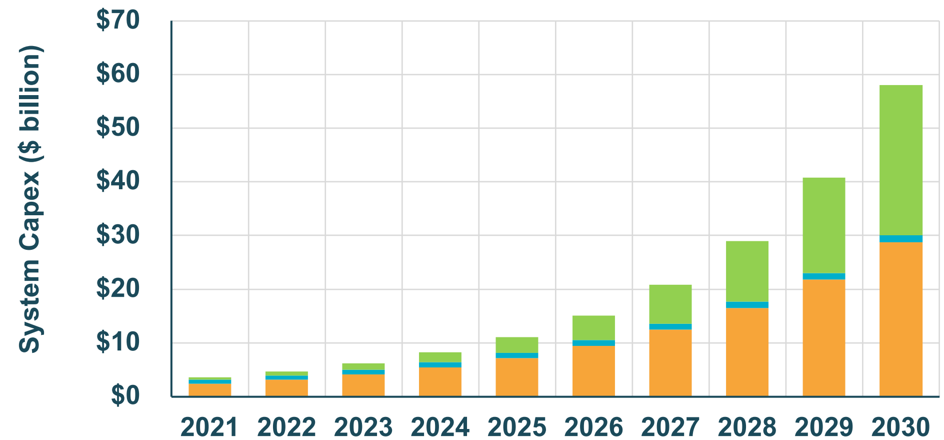
The capital cost of a 100% SWB system in Texas has fallen by 85% since 2010, and will decline another 75% by 2030.

Even though these technologies are on steep deflationary cost trajectories, Texas does not need to wait until 2030 to begin investing in solar, wind, and batteries. The difference between starting to build now and waiting until 2030 to begin is relatively modest – just 28% under our model's assumptions – because the bulk of new capacity additions will be added in the final years when costs are lowest.

The advantages of early adoption such as energy independence, job creation, new entrepreneurial opportunities, cost savings from avoided operation and maintenance of existing fossil infrastructure, reduced environmental impacts, and human health benefits more than make up for this additional cost.

Figure 21 shows system capex by year for an exponential buildout starting in 2021 that culminates in the lowest cost 100% SWB system for Texas in 2030 at a total cost of $197 billion.

Figure 21. Texas 100% SWB System Capex by Year for Exponential Buildout



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Batteries	$0.5	$0.7	$1.2	$1.8	$2.9	$4.6	$7.2	$11.3	$17.8	$27.9
Wind	$0.8	$0.8	$0.9	$0.9	$1.0	$1.0	$1.1	$1.2	$1.2	$1.3
Solar PV	$2.4	$3.1	$4.1	$5.4	$7.2	$9.5	$12.5	$16.5	$21.8	$28.8

Source: RethinkX

Annual investments in the exponential buildout of a lowest cost 100% SWB system in Texas totaling $197 billion are dominated by solar PV and wind power in early years, and by solar PV and batteries in later years.

Texas System Electricity Cost

In order to have a complete financial picture of a 100% SWB system in Texas, it is necessary to account for operational expenditures as well. Solar PV, wind power, and lithium-ion battery installations all have very low fixed operations and maintenance costs compared to conventional technologies, and solar PV in particular has near-zero variable operations and maintenance costs as well. And, of course, solar PV, wind power, and batteries do not consume fuels. As a result, the total operational expenditures (system opex) and corresponding marginal cost per unit of electricity for a 100% SWB system will be extremely low compared to coal, natural gas, or nuclear power. Moreover, SWB systems are even more competitive when the full social, political, and environmental externalities of fossil and nuclear fuels and their supply chains are accounted for.

Taken together, total system capex and system opex can be averaged across all kilowatt-hours supplied by a 100% SWB system over a given period of time to arrive at a *system electricity cost,* or SEC. This metric's unit of measurement is cents per kilowatt-hour, so although SEC applies to the entire system it nevertheless provides a cost indicator that can be compared directly to the *levelized cost of energy* (LCOE) of individual conventional power plants, despite the latter metric's serious flaws.

Because SEC averages all costs across all kilowatt-hours of electricity utilized, its calculation is contingent upon what fraction of super power is actually consumed by end users (see Texas Clean Energy Super Power below). Table 5 shows the SEC of 100% SWB system in Texas, and how this value varies depending upon super power investment and utilization. Note that the SEC of the lowest cost 100% SWB system in Texas is just 3.5 cents per kilowatt-hour even if no super power were utilized at all.

Table 5. Texas System Electricity Cost with Super Power Investment and Utilization

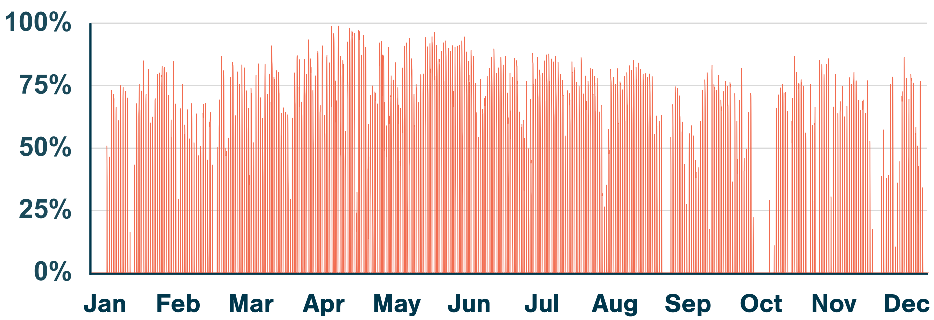
	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
0% Super Power Utilization	3.5 cents/ kilowatt-hour	3.9 cents/ kilowatt-hour	4.2 cents/ kilowatt-hour
50% Super Power Utilization	2.2 cents/ kilowatt-hour	2.0 cents/ kilowatt-hour	1.9 cents/ kilowatt-hour
100% Super Power Utilization	1.6 cents/ kilowatt-hour	1.3 cents/ kilowatt-hour	1.3 cents/ kilowatt-hour

Source: RethinkX

Texas Clean Energy Super Power

Our modeling shows that in Texas a 100% SWB system will produce super power on more than 93% of the days of year, with surprisingly modest seasonal variation. Extended periods of more than several days without super power occur in the late summer and autumn as well as in the early winter (Figure 22).

Figure 22. Texas Super Power with Lowest Cost 100% SWB System (2018 by hour)



Source: RethinkX

This hourly chart of the 2018 calendar year shows that a lowest cost 100% SWB system in Texas would produce super power throughout much of the year with surprisingly modest seasonal variation.

Additional investment in SWB capacity yields disproportionately large returns of super power in Texas. A 20% increase in system capex, for example, nearly doubles annual super power production from 504 terawatt-hours to 983 terawatt-hours, while also increasing super power availability from 93% to 97% of all days of the year (Table 6).

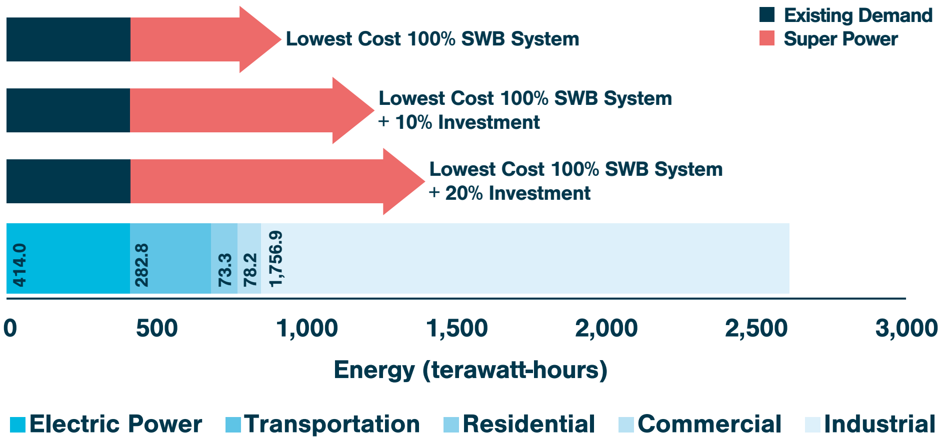
Table 6. Texas Super Power – Summary of Findings

	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
System capex	$197 billion	$218 billion	$239 billion
Annual super power	504 terawatt-hours	814 terawatt-hours	983 terawatt-hours
Fraction of annual demand	122%	197%	238%
Fraction of all days	93%	96%	97%
Fraction of all hours	30%	33%	34%

Source: RethinkX

Even in the lowest cost 100% SWB system, super power would provide enough energy to electrify all road transportation in Texas (assuming electrification of vehicles). Alternatively, it is an amount of energy greater than all fossil fuel energy use in the residential and commercial sectors combined (Figure 23).

Figure 23. Texas Super Power – Energy Use Comparison by Sector



Source: RethinkX

This chart shows that super power output in Texas would be large enough to offset a substantial fraction of all other energy use in the state, and that modest increases in capital investment yield disproportionately large increases in super power. If Texas chose to invest in an additional 20% in its 100% SWB system, the super power output could be used to replace most if not all fossil fuel use in the residential, commercial, and road transportation sectors combined (assuming electrification of vehicles and heating).

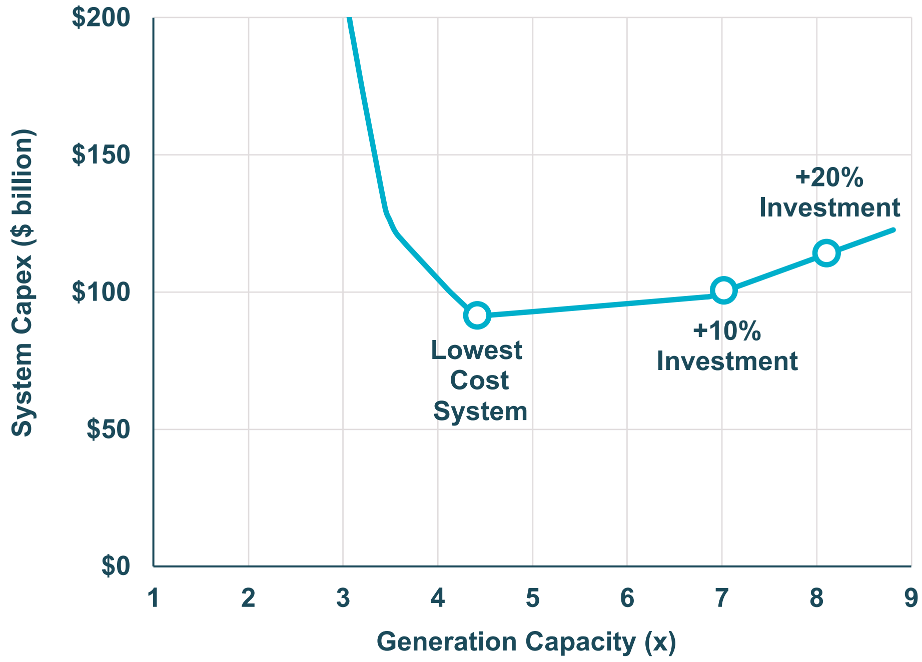
Case Study 3. New England

New England is the region of the continental United States with the poorest combined endowment of sunshine and wind resources. Globally, regions with similar resources include countries of Northern Europe, Japan, parts of Russia, and parts of China. Nevertheless, our analysis shows that even in these areas a 100% SWB system is possible and affordable by 2030, and offers impressive super power benefits as well.

New England Clean Energy U-Curve

Figure 24 shows the U-curve for New England. The curve is asymmetrical, indicating that costs escalate dramatically as generating capacity decreases below 4.4x, or 4.4 times the amount currently required to meet peak electricity demand. This is because the battery energy storage requirement of the 100% SWB system grows enormously as generating capacity shrinks.

Figure 24. The Clean Energy U-Curve for New England



Source: RethinkX

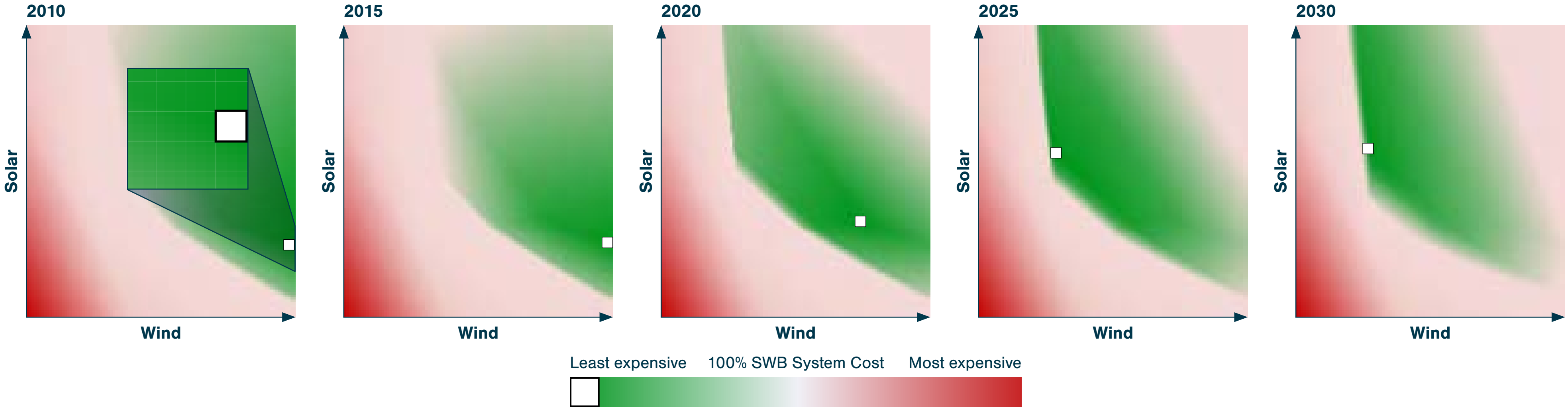
The Clean Energy U-Curve for New England shows that there is a nonlinear tradeoff relationship between generation capacity and battery energy storage. Most conventional analyses to date have assumed that building more than 1.5x generation capacity is infeasible, and as a result many weeks of battery energy storage would be required at enormous cost. Using the Clean Energy U-Curve, our analysis shows that in New England the most affordable combination of these technologies comprises 4.4x generation capacity with only 89 hours of battery energy storage for a total system capex of $91 billion. This is much less expensive than most conventional analyses have claimed.

New England currently has 1.5 gigawatts of solar PV installed and 1.5 gigawatts of wind power installed.[46] In our lowest cost 100% SWB system scenario, new solar PV generating capacity would amount to 85.5 gigawatts and new wind would amount to 25.5 gigawatts, for a total of 87 gigawatts and 27 gigawatts respectively. Although solar PV will extend its cost lead on wind over the course of the 2020s, the New England region's relatively poor sunshine resources means that the optimal generation mix for New England comprises proportionally more wind power than is the case for California or Texas.

New England Lowest Cost 100% Solar, Wind, and Batteries System

The time-series of heatmaps in Figure 25 shows how the lowest cost 100% SWB system for New England has changed and will continue to change overtime. In 2010, the optimal mix would have been comprised predominantly of wind power. Today the optimal mix would be made up of roughly equal amounts of solar and wind power. But over the course of the 2020s the logic shifts in favor of solar PV, such that by 2030 the optimal mix will be predominantly solar.

Figure 25. Capital Costs of a 100% SWB System in New England



Source: RethinkX

This time-series of heatmaps shows which combinations of solar and wind capacity in New England are more expensive (red) and less expensive (green). The least expensive combination is highlighted in white. Capital costs include not just solar and wind capacity themselves, but also the amount of batteries required to support them. Because costs of solar PV, onshore wind power, and lithium-ion batteries are each decreasing at different rates, the least expensive combination changes over time. In 2010, when wind power was comparatively cheap, the least expensive combination would have contained much less solar PV. In 2030, however, the least expensive combination will be overwhelmingly solar PV because its costs are falling so rapidly compared to wind power.

Assuming an exponential buildout starting in 2021, the specific lowest cost 100% SWB system for New England comprises:

» 87 gigawatts of solar PV generation capacity

» 27 gigawatts of wind power generating capacity

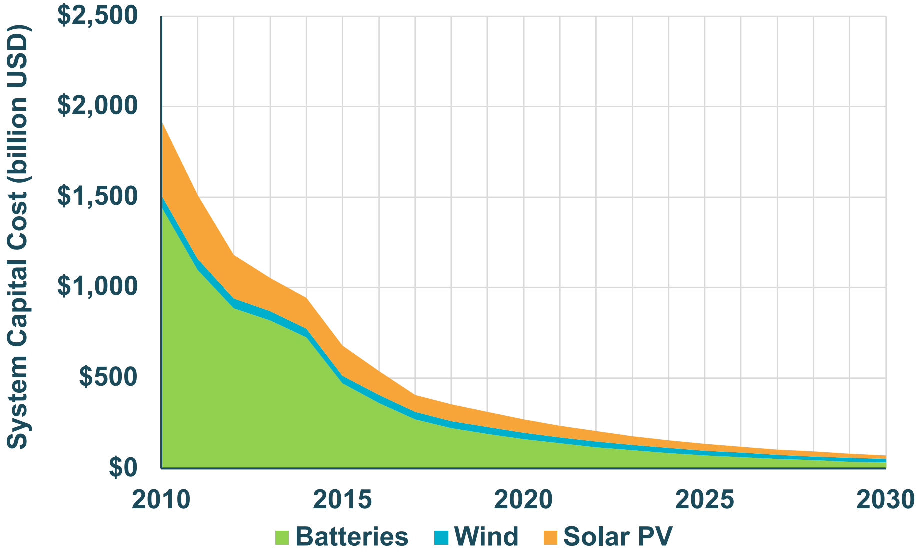
» 3.8x system generation capacity relative to current peak electricity demand

» 1,232 gigawatt-hours (89 average demand hours) of battery energy storage capacity

New England System Capital Cost

The capital cost (capex) of solar PV, wind power, and lithium-ion batteries have been so dramatic that what was economically unthinkable a decade ago will be economically inevitable a decade hence. Since 2010, the combined capital cost of solar PV, wind power, and batteries has fallen 85%, and it will decline a further 75% by 2030 (Figure 26). This represents a 96.5% decline, or a 30x improvement, in just 20 years.

Figure 26. New England 100% Solar, Wind, and Batteries System Capital Cost 2010-2030



Sources: Berkeley Labs, 2019; NREL, 2019; BNEF, 2019; RethinkX, 2020.[1,3,8]

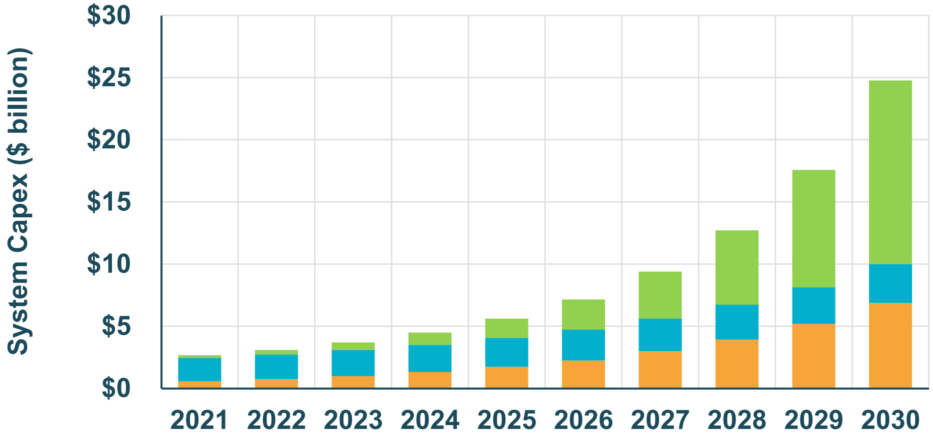
The capital cost of a 100% SWB system in New England has fallen by 85% since 2010, and will decline another 75% by 2030.

Even though these technologies are on steep deflationary cost trajectories, New England does not need to wait until 2030 to begin investing in solar, wind, and batteries. The difference between starting to build now and waiting until 2030 to begin is relatively modest – just 27% under our model's assumptions – because the bulk of new capacity additions will be added in the final years when costs are lowest.

The advantages of early adoption such as energy independence, job creation, new entrepreneurial opportunities, cost savings from avoided operation and maintenance of existing fossil infrastructure, reduced environmental impacts, and human health benefits more than make up for this additional cost.

Figure 27 shows system capex by year for an exponential buildout starting in 2021 that culminates in the lowest cost 100% SWB system for New England in 2030 at a total cost of $91 billion.

Figure 27. New England 100% SWB System Capex by Year for Exponential Buildout



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Batteries	$0.3	$0.4	$0.6	$1.0	$1.5	$2.4	$3.8	$6.0	$9.4	$14.8
Wind	$1.9	$2.0	$2.1	$2.2	$2.3	$2.5	$2.6	$2.8	$2.9	$3.1
Solar PV	$0.6	$0.7	$1.0	$1.3	$1.7	$2.3	$3.0	$4.0	$5.2	$6.9

Source: RethinkX

Annual investments in the exponential buildout of a lowest cost 100% SWB system in New England totaling $91 billion are dominated by solar PV and wind power in early years, and by solar PV and batteries in later years.

New England System Electricity Cost

In order to have a complete financial picture of a 100% SWB system in New England, it is necessary to account for operational expenditures as well. Solar PV, wind power, and lithium-ion battery installations all have very low fixed operations and maintenance costs compared to conventional technologies, and solar PV in particular has near-zero variable operations and maintenance costs as well. And, of course, solar PV, wind power, and batteries do not consume fuels. As a result, the total operational expenditures (system opex) and corresponding marginal cost per unit of electricity for a 100% SWB system will be extremely low compared to coal, natural gas, or nuclear power. Moreover, SWB systems are even more competitive when the full social, political, and environmental externalities of fossil and nuclear fuels and their supply chains are accounted for.

Taken together, total system capex and system opex can be averaged across all kilowatt-hours supplied by a 100% SWB system over a given period of time to arrive at a *system electricity cost,* or SEC. This metric's unit of measurement is cents per kilowatt-hour, so although SEC applies to the entire system it nevertheless provides a cost indicator that can be compared directly to the levelized cost of energy (LCOE) of individual conventional power plants, despite the latter metric's serious flaws.

Because SEC averages all costs across all kilowatt-hours of electricity utilized, its calculation is contingent upon what fraction of super power is actually consumed by end users (see New England Clean Energy Super Power below). Table 7 shows the SEC of 100% SWB system in New England, and how this value varies depending upon super power investment and utilization. Note that the SEC of the lowest cost 100% SWB system in New England is still quite competitive at 6.1 cents per kilowatt-hour even if no super power were utilized at all.

Table 7. New England System Electricity Cost with Super Power Investment and Utilization

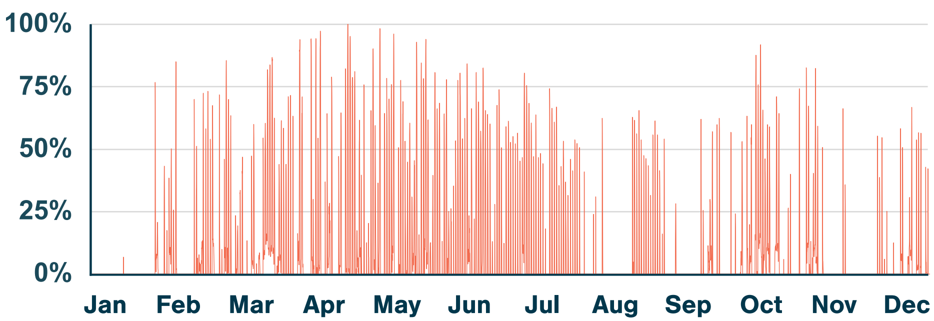
	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
0% Super Power Utilization	6.1 cents/ kilowatt-hour	6.6 cents/ kilowatt-hour	7.2 cents/ kilowatt-hour
50% Super Power Utilization	4.9 cents/ kilowatt-hour	4.2 cents/ kilowatt-hour	4.1 cents/ kilowatt-hour
100% Super Power Utilization	4.0 cents/ kilowatt-hour	3.1 cents/ kilowatt-hour	2.8 cents/ kilowatt-hour

Source: RethinkX

New England Clean Energy Super Power

Our modeling shows that in New England a 100% SWB system will produce super power on more than 64% of the days of year. The total fraction of all hours with super power is roughly the same in New England as in California and Texas at around 30%, but these hours will be compressed into fewer days and generate a smaller surplus than in the other two regions. A clearer seasonal pattern of super power availability will be evident in New England, with extended periods of more than several days without super power becoming more common in fall and continuing through the winter until spring (Figure 28).

Figure 28. New England Super Power in the Lowest Cost 100% SWB System (2018 by hour)



Source: RethinkX

This hourly chart of the 2018 calendar year shows that a lowest cost 100% SWB system in New England would produce super power for a surprisingly large fraction of the year with relatively modest seasonal variation.

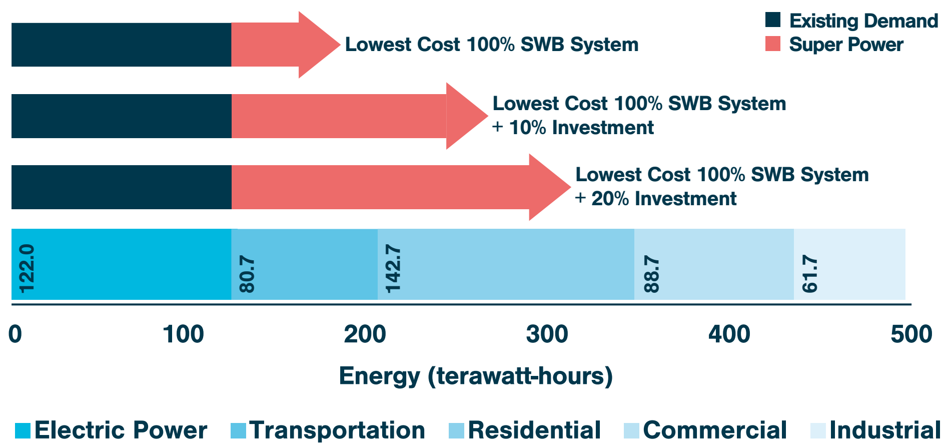
Additional investment in SWB capacity yields disproportionately large returns of super power in New England. A 20% increase in system capex, for example, more than triples annual super power production from 61 terawatt-hours to 189 terawatt-hours, while also increasing super power availability from 64% to 89% of all days of the year (Table 8).

Table 8. New England Super Power – Summary of Findings

	Lowest Cost 100% SWB System	Lowest Cost 100% SWB System + 10% Investment	Lowest Cost 100% SWB System + 20% Investment
System capex	$91 billion	$100 billion	$109 billion
Annual super power	61 terawatt-hours	143 terawatt-hours	189 terawatt-hours
Fraction of annual demand	50%	118%	155%
Fraction of all days	64%	84%	89%
Fraction of all hours	28%	39%	42%

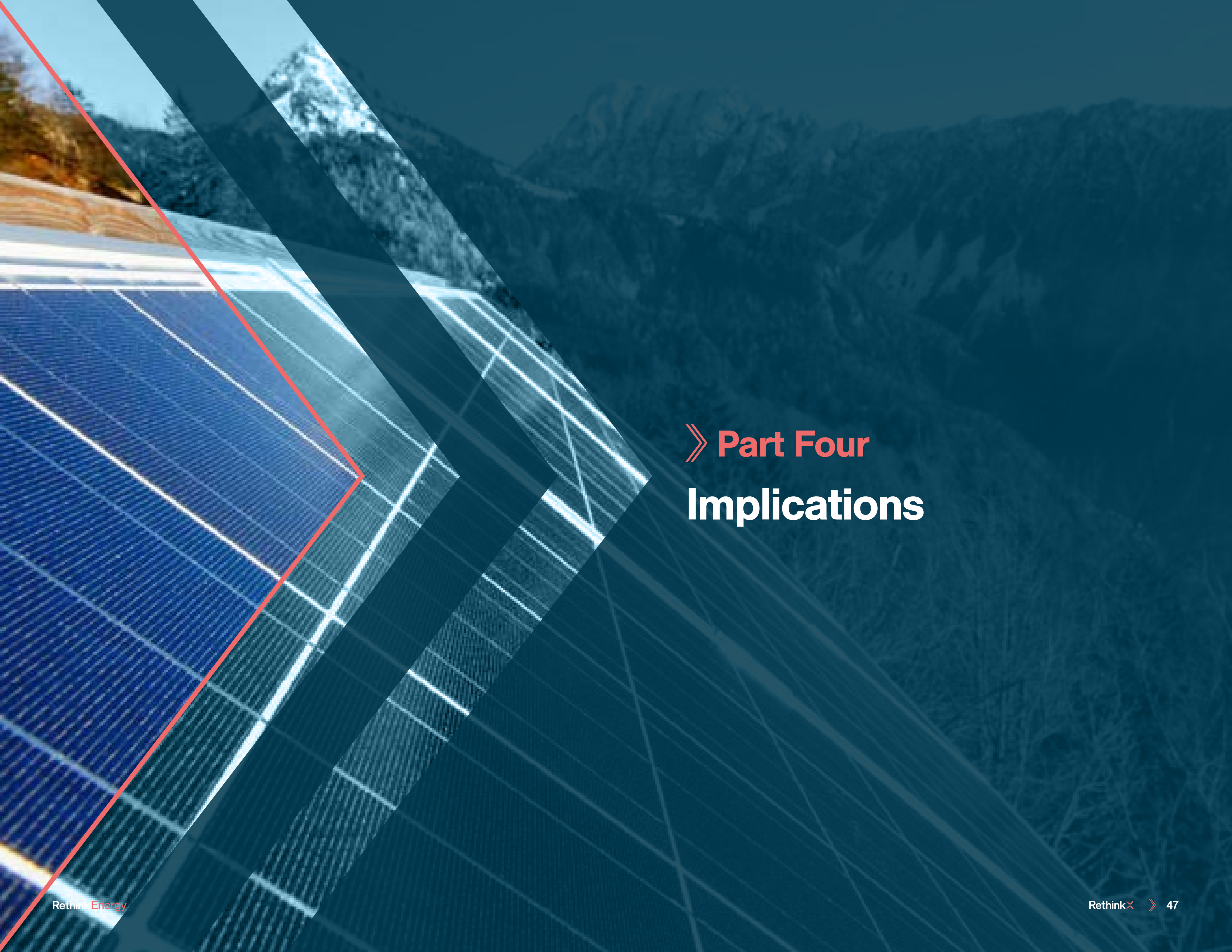
Source: RethinkX

Figure 29. New England Super Power – Energy Use Comparison by Sector



Source: RethinkX

This chart shows that super power output in New England would be large enough to offset a substantial fraction of all other energy use in the state, and that modest increases in capital investment yield disproportionately large increases in super power. If New England chose to invest in an additional 20% in its 100% SWB system, for example, then the super power output could be used to replace most fossil fuel use in the residential and road transportation sectors combined (assuming electrification of vehicles and heating).



Part Four

Implications

It is no longer a matter of *if* the disruption of energy by solar, wind, and batteries will happen, it is only a matter of *when.* Conventional clean energy scenarios make the common error of misunderstanding that disruptive new technologies do not simply replace old ones on a 1-to-1 basis. Solar photovoltaics, onshore wind power, and lithium-ion batteries do not operate by the traditional rules of extractive, depletable, and polluting resources that have governed humanity's relationship with energy for over a century. Like other disruptive technologies throughout history, they will disproportionately replace the old system with a new and much larger system that has dramatically different architecture, boundaries, and capabilities. Incumbents that do not take drastic measures to adapt will be wiped out as surely and as swiftly as horse-drawn carriages were wiped out by automobiles, steam locomotives were wiped out by diesel engines, celluloid film was wiped out by digital imaging, and record and video rental stores were wiped out by streaming services. The collapse of coal is already well underway in the United States, and natural gas and petroleum will follow beginning in the mid-2020s.

Given this framing of the disruption, our analysis does not describe how the existing energy system will integrate solar, wind, and batteries. Instead, our analysis aims to help policymakers, investors, and other decision makers rethink the future of energy by asking what extraordinary possibilities the new system based on 100% SWB will offer for their regions. The social, economic, political, environmental outcomes over the course of the 2020s depend on the choices we make today, and the benefits that accrue to those who lead the disruption rather than follow or resist it will be profound.

Our analysis makes severely constraining assumptions, and by extrapolating our results from California, Texas, and New England to the entire country we find that the continental United States as a whole could achieve 100% clean electricity from solar PV, onshore wind power, and lithium-ion batteries by 2030 for a capital investment of less than $2 trillion, with an average system electricity cost nationwide of under 3 cents per kilowatt-hour if 50% or more of the system's super power is utilized.

Box 1: Super Power: Flipping Local Economic Development from Extraction to Creation

How do we turn super power into jobs and economic development? As the electric power system is flipped from centralized, scarce, and expensive to decentralized, superabundant, and cheap, the ripple effects across the economy and society will be even bigger than the disruption of energy itself.

Businesses, especially the ones who need massive amounts of energy, have the incentive to cut energy costs and increase predictability of future supply and costs. Aluminum smelters, steel mills, and data centers have historically packed up and moved to where energy costs are low. Add up all the energy required to produce a given good (a car, a roofing tile, a smartphone) and the result is its *embodied energy*. According to Volkswagen, it takes about 18,000 kilowatt-hours to produce a Golf A3. At the current average price of 12 cents per kilowatt-hour, assuming electrification of all processing, it would cost nearly $2,160 in energy to build such a car. Reducing that cost to 1.3 cents per kilowatt-hour with super power throughout the entire supply chain would save the company more than $1,900 on each vehicle.

State, county, and city government officials have traditionally offered corporations billions of dollars to move to their regions in the hope of creating local jobs and spurring economic and social development. These subsidy schemes make for good PR but are usually expensive ways to bring jobs. Google received $360 million to bring a data center to Oregon that promised to create 175 jobs ($2 million per job), while Apple received $321 million in incentives for a data center in North Carolina that created 50 jobs ($6.4 million per job).[47] These local incentives have turned into an extractive winner-take-all game where the corporate winners siphon as much from taxpayers as possible, with most of that money flowing up to headquarters and little to show in terms of economic benefits across society. Shell Oil, for instance, was offered $1.65 billion in incentives by the state of Pennsylvania despite making more than $32 billion in corporate profits.[48]

Super power would transform this extractive model because investments in super power would actually decrease costs for everyone within that energy market. Consider the example of Texas. Our analysis shows that the lowest cost 100% SWB system would generate power at 3.5 cents per kilowatt-hour even if none of the system's super power were utilized. That would be enough to attract energy-intensive manufacturers to the region. However, an extra 20% investment in SWB together with a concerted effort to maximize super power utilization would generate 95% more energy (983 terawatt-hours versus 504 terawatt-hours) and bring the average cost of electricity down for everyone by two-thirds to just 1.3 cents per kilowatt-hour. Volkswagen would save over $1,900 building the hypothetical Golf A3 if its entire supply chain were able to take advantage of electricity at that cost. These are the positive multiplier effects of super power. Within the conventional power system, additional investments in generation drive the cost of electricity *up* for everyone (negative externalities). A well-designed SWB system does the opposite: additional investments drive electricity costs *down* for everyone (positive externalities). The economics of energy, now based on expensive and scarce resources will soon resemble information economics, with superabundant kilowatt-hours approaching the marginal cost of photons: zero. Like the Internet, this will enable companies and governments to create new products, business models, and organizational capabilities to harness this superabundance.

A big box company like Walmart could give away energy to attract shoppers to its physical stores. If someone has a Tesla Model Y with a 75-kilowatt-hour battery, Walmart could offer to recharge their car battery while they shop.[49]

The cost to attract this customer with super power at 1.3 cents per kilowatt-hour would be less than a dollar. Mall operators and restaurants could also give away free EV charging while customers shop or dine, and extend the perks to groups as well as individuals. A Proterra ZX5 electric bus can seat 29 people and has a battery that holds 440 kilowatt-hours.[50] A restaurant could offer a coupon to fill up that battery while a busload of people dined at their establishment. The cost would be under $6, or roughly 20 cents per patron.

Super power also changes the dynamics of local economic development. Instead of handing cash or tax breaks to corporations to attract single companies like Tesla, US Steel, or Amazon to a state like Texas, the local government could encourage or subsidize the developments of additional SWB super power. These companies would benefit from superabundant energy at near-zero marginal cost while generating local jobs and development.

This would not be the traditional extraction-based model, but a creation-based model of economic development: everyone would benefit from investments in super power. Residential, commercial, and industrial users would all see their electricity costs tumble as Tesla moved to town. As power costs go down, the cost of transportation, food, or materials to build a new home would drop, helping to lower cost of living and saving everyone money. This would set off a virtuous cycle as more businesses would be attracted to the lower costs of electricity and more people would be attracted to the higher living standards, creating demand for even more investment in super power, which would lower electric power costs even more, and so on. Government investment in super power generates a multiplier effect just like investing in education: knowledge benefits the degree holder and has positive effects for society as a whole.

Going a step further, super power will be so cheap and abundant that forward-thinking governments could actually give it away to attract energy-intensive manufacturing or technology companies. Global data centers consumed 200 terawatt-hours of electricity in 2018.[51] As our analysis shows, the investment to build 10% additional SWB capacity in Texas would be $21 billion and would produce 310 terawatt-hours of additional super power. (For comparison, Germany, the fourth largest economy in the world, produced a total of 516 terawatt-hours of electricity in 2019).[52] With that 10% incremental investment in super power, Texas could attract every data center in the world to locate within its borders (200 terawatt-hours) and power all the Bitcoin miners in the world (69 terawatt-hours), and still have 41 terawatt-hours (the total electricity output of New Zealand or Hong Kong) left over to manufacture even more SWB in an autocatalytic process.[53,54]

Super power is a race to the top: the sooner a region adopts SWB super power, the more companies, talent, and investment it will attract. Super power will lower the cost of energy across an entire region and trigger a virtuous cycle in which more individuals move in attracted by higher quality of life, more companies move in attracted by low energy costs (and talent), and more investments move in attracted by growth opportunities, all of which further lowers costs of energy across society and attracts even more, companies, talent, and investment. The SWB disruption will move us from an extraction-based winner take all model of local development to a creation-based production model whereby a seed investment grows and creates opportunities for all.

Key Implications

1. A 100% SWB system is both physically possible and economically affordable.

Contrary to the predominant narrative in public discourse worldwide, it is possible to meet all electricity needs with a 100% solar, wind, and batteries system in California Texas, and New England – and by extension the rest of the continental United States as well. Moreover, because the overwhelming majority of the global population lives in areas with more abundant solar and wind resources than New England, it follows that solar PV, wind, and batteries can meet the electric power needs of the overwhelming majority of the world's population.

2. The amount of battery energy storage required to support a 100% SWB system is much lower than is widely believed.

News headlines and conventional analyses have consistently perpetuated the myth that a 100% solar PV and wind powered electricity system would require weeks' worth of battery energy storage. Our analysis shows that even in an area with relatively poor solar and wind resources like New England, only 89 hours of battery energy storage are required in the lowest cost 100% SWB system, and as little as 43 hours are required in a system that invests 20% more capex. Moreover, the limit scenario we describe here is unrealistically constrained by the assumption of no electricity imports, no conventional reserve capacity, no decentralized/rooftop solar PV and battery installations, no electric vehicles, no energy arbitrage, and no technological breakthroughs. As investors, policymakers, and other decision makers build upon our work and make more detailed case studies for their specific regions that take into account the factors above, they will continue to find that the actual battery capacity requirements are substantially lower than the upper limit our analysis establishes here.

3. A 100% SWB system is much more affordable than is widely believed, and will be the cheapest option for electricity generation in most populated areas by 2030.

Even in New England and other similar regions with relatively poor solar and wind resources, a 100% solar, wind, and batteries electricity system can generate power at an average cost of under 5 cents per kilowatt-hour if they utilize 50% or more of the system's super power. In areas with abundant sunshine and wind, the cost will be less than 2 cents per kilowatt-hour. By 2030, a 100% SWB system will therefore be directly cost-competitive with natural gas and far cheaper than coal or nuclear power, even without accounting for the additional social, political, and environmental externalities associated with fossil and nuclear fuels and their supply chains. The disruption has already begun, and any investments in conventional assets – past, present, and future – are at extreme risk of being stranded.

4. The buildout of a 100% SWB system will create millions of jobs.

According to the U.S. Bureau of Labor Statistics, "solar photovoltaic installers" and "wind turbine service technicians" are already the two fastest-growing jobs in the United States.[55] Even though we can fully expect that labor efficiency in the manufacture and installation of solar PV, wind power, and lithium-ion battery technologies will increase greatly as deployment scales up exponentially, it is likely that spending over $1 trillion on the buildout of a 100% SWB system in the continental United States during the 2020s will result in the full-time employment of at least several million Americans. A full assessment of job creation potential both in the United States and worldwide lies outside the scope of the analysis we present here, but this is an important area for additional research.

5. The shift to a 100% SWB system could directly eliminate 50% or more of all greenhouse gas emissions.

Today, 27% of greenhouse gas emissions in the United States are from electricity and 23% are from road transportation.[56,57] Together, these two sectors account for half of the country's greenhouse gas emissions.

A 100% SWB system would mitigate virtually all ongoing greenhouse gas emissions from electric power, and if the manufacture and deployment of the SBW system were repatriated and electrified then life cycle emissions could be substantially reduced as well.

A 100% SWB system could also mitigate virtually all ongoing greenhouse gas emissions from road transportation, assuming electrification of the fleet. Electric vehicles themselves are 77% energy efficient compared to just 12-30% for internal combustion engine vehicles, which acts as a multiplier on the quantity of fossil fuel energy that is displaced. In most regions, super power is sufficient to provide all of the energy required to power a fully electrified road transportation fleet.

To the extent that clean energy super power replaces fossil fuel energy use in other sectors, it will mitigate associated greenhouse gas emissions there as well.

6. Using clean energy super power to electrify all road transportation would reduce total oil demand in the United States by over 60%.

Today, the United States consumes 12.5 million barrels of oil each day for road transportation, which accounts for 62.5% of total national oil consumption.[58] A nationwide 100% SWB system would produce more than enough super power to electrify all road transportation and wipe out virtually all of its associated demand for oil. For comparison, this would be equivalent to eliminating all of China's oil consumption, or all oil consumption in India, Japan, and Russia combined.[59]

7. Clean energy super power is a solution, not a problem.

Nearly all conventional analyses frame super power as an "overproduction" problem resulting from solar and wind "overcapacity" that electricity systems ought to actively minimize. Our analysis shows that, to the contrary, super power ought to be maximized because of the staggering array of economic, social, and environmental benefits it offers – including a solution to the challenge of replacing fossil fuel use beyond the electric power sector across the wider economy. Incumbents will naturally continue to advocate for curtailment of super power, but deliberately wasting huge quantities of clean energy produced at near-zero marginal cost is inherently irrational and indicates that the existing system lacks the ability to adapt to the introduction of disruptive new technologies. As with previous disruptions throughout history, behavior patterns of this kind indicate that the old system is poised to be replaced by a new system with a dramatically different architecture.

8. The superabundance of near-zero marginal cost electricity that results from clean energy super power will have a transformative impact on energy markets, energy-related and energy-intensive industries, and the economy as a whole.

A 100% SWB system would naturally produce a very large quantity of near-zero marginal cost super power. We are already seeing the effects of super power in early adoption regions such as California and Germany. Even at market penetrations of less than 20%, near-zero marginal cost electricity from solar and wind is causing wholesale electricity prices to clear at or below zero some of the time.[60,61] Today this supply of super power is often curtailed rather than utilized, but as the erosion of sympathy and protections for incumbent generators and utilities accelerates, and as battery energy storage and smart infrastructure expand, wasteful curtailment will inevitably be abandoned in favor of intelligent utilization.[20,62] If a large fraction of super power is utilized, the effective per-kilowatt-hour cost of electricity produced by a 100% SWB system will be much lower than any conventional power plant options. In sunny locations like California and Texas (and by extension, much of the populated areas of the world), the cost will be so low that a 100% SWB system would provide power for less than the opex of existing coal, natural gas, and nuclear power plants.[63]

The applications of superabundant near-zero marginal cost energy will enable the emergence of radically new business models across a wide array of industries. Applications include electrification of road transportation and heating, water desalination and treatment, waste processing and recycling, metal smelting and refining, chemical processing and manufacturing, cryptocurrency mining, distributed computing and communications, fuel production, and carbon removal – to name just a few.

It is difficult to overstate how transformative the overall impact of super power will be on regional economies (see Box 1). The shift from high marginal cost to near-zero marginal cost energy will parallel what we have already witnessed with the shift from expensive to nearly costless information, with equally profound implications for affected industries, the economy, and society at large.[13]

9. Conventional clean energy scenarios that presume we should aim for no more than 90% solar, wind, and batteries are mistaken because they fail to recognize the value of clean energy super power.

Conventional analyses and the general perception around SWB systems assumes that costs escalate and feasibility decreases as we approach 100% market saturation. Our analysis shows that this is false. 100% SWB systems are not only possible and affordable for virtually all populated areas of the world by 2030, but the extraordinary benefits of super power mean that it will be irrational not to maximize market saturation of SWB in most regions.

10. The benefits of super power may justify additional investment beyond the lowest cost 100% SWB system.

Because the bottom of the clean energy U-curve is shallow, regions will have the option to double or even triple super power output for just 20% additional capital investment. Given that super power will have such transformative social, economic, and environmental impacts, any region that wishes to seize this extraordinary opportunity and maximize the benefits that accrue from the disruption will need to strongly consider making such additional investments (see Box 1).

11. The exponential buildout of 100% SWB systems is already affordable and can begin immediately.

There is no reason to wait to build a 100% SWB system. Although the rapid advancement of solar PV and battery energy storage technology places us in a steep deflationary regime, it is nevertheless economically rational to start the buildout today. The reason why is that any buildout will naturally be exponential, and as a result the vast majority of capacity additions will occur in the last several years of construction, by which time costs will have declined a great deal. As a result, the premium for commencing the buildout immediately rather than waiting until 2030 to begin is only 25-30% under our model's assumptions. The advantages of early adoption such as energy independence, job creation, repatriation of industries, new entrepreneurial opportunities, cost savings in maintaining the existing fossil infrastructure, reduced environmental impacts, and human health benefits far outweigh this modest premium.

Evidence that the buildout has already commenced in some regions can be seen in the interconnection queues of service operators like CAISO, ERCOT, and ISO-NE. New generation capacity additions are already dominated by solar PV and onshore wind power while conventional coal, natural gas, and nuclear power capacity additions are fast approaching zero, and at the same time lithium-ion battery capacity additions are growing dramatically as well.[64]

12. Electricity systems must be analyzed based on future rather than current costs.

The mix of generation and storage capacity in the lowest cost 100% SWB system is a moving target, and in order to hit the bullseye we must accurately project where the target will be in the future. Over the last decade the cost of solar PV capacity has fallen by 82%, the cost of wind power capacity has fallen by 46%, and the cost of lithium-ion battery capacity has fallen by 89%.[1,3,7] All three technologies will continue to improve during the 2020s, and based on the consistency of their previous trajectories we conservatively estimate that they will further decline by about 70%, 40%, and 80% respectively. Although there are some legitimate reasons why conventional analyses make projections assuming current costs, this has historically created a great deal of confusion and material misallocation of investment capital. It is therefore essential that all policymaking, investment, planning, and other system design choices going forward be based explicitly on future costs.

13. The SWB disruption is already inevitable, and is not dependent upon subsidies, carbon taxes, or other market interventions.

Subsidies to date for the development and deployment of various solar power, wind power, and battery energy storage technologies in the United States and around the world have accelerated the SWB disruption. Similarly, subsidies (both direct and indirect) for the fossil fuel and nuclear power industries to date have slowed the SWB disruption. Although market interventions in the form of subsidies, taxes, and regulatory requirements could hasten or delay the SWB disruption by a marginal amount, it is important to note that such interventions are not required in order to ensure the rise of SWB or the demise of fossil fuels and nuclear power. The disruption is now inevitable for purely economic reasons: solar PV, onshore wind power, and lithium-ion batteries now offer the cheapest way to generate electricity. It is not a matter of if, it is only a matter of when. Different regions around the world are likely to make a variety of different choices with respect to market intervention, but as a general guideline the best path forward is to intervene as little as possible except to protect individuals and communities (not industries) and allow the disruption to unfold according to its own internal dynamics.

14. We must rethink efficiency in 100% SWB systems in economic rather than physical terms.

In the past, physical and economic efficiency in electricity-generating systems were so tightly correlated that physical efficiency could be used as a direct proxy for cost. But this way of thinking is obsolete for technologies that have near-zero marginal cost like solar PV, onshore wind power, and lithium-ion batteries – just as it is for information technologies. It is therefore no longer rational to make decisions in the electric power sector based on outdated physical efficiency metrics such as capacity factor, intermittency, or curtailment.

15. We must rethink conservation in 100% SWB systems because it is wasteful to not utilize near-zero marginal cost clean energy.

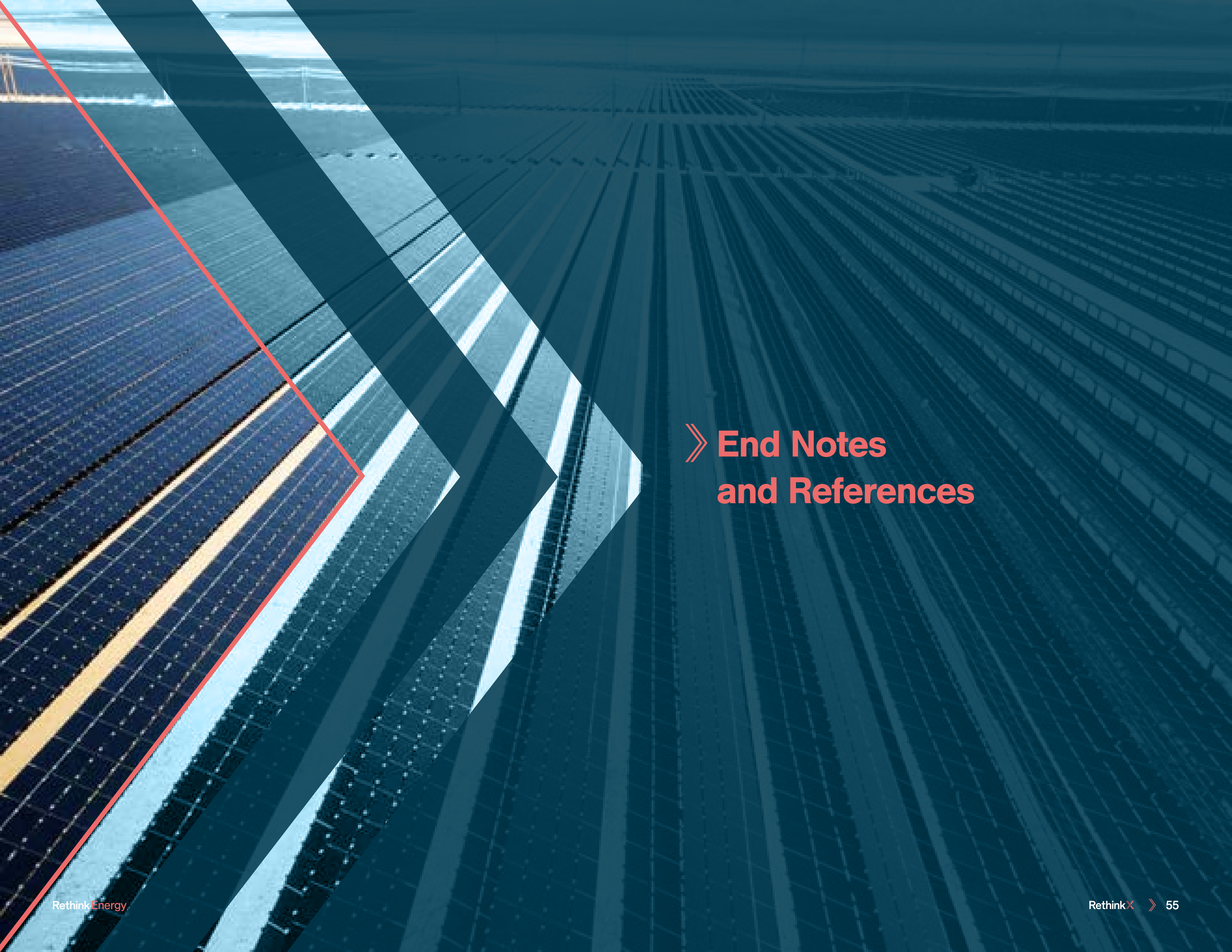
Up until now, the majority of our energy has come from burning fossil fuels. But because each unit of energy obtained from coal, gas, and oil carries both an economic and an environmental cost, most societies and individuals have enculturated a reflexive belief that we ought to minimize our energy use in order to avoid being wasteful. In a paradigm where energy has a near-zero marginal cost and near-zero negative externalities, this logic no longer holds. To the contrary, it is wasteful not to utilize energy that is nearly costless and has little or no impact on the environment. This conservation concept of not letting good things go to waste is ancient and familiar, but will need to be reasserted in the domain of energy after more than a century of living in an extractive regime. We have already witnessed a transformation of this kind via information technologies in the world of bits, and now the transformation of energy technologies in the world of electrons will follow. For example, the disruption of film cameras by digital cameras upended more than a century of being careful to avoid wasting film, but now it is wasteful to not fully utilize a digital camera by taking plenty of pictures.

16. The SWB disruption of energy will accelerate the disruption of transportation.

In our report *Rethinking Transportation 2020-2030* we provided an analysis that shows how electric and autonomous vehicles that provide transportation-as-a-service are poised to disrupt the transportation sector over the course of the 2020s. Regions that choose to maximize super power from a 100% SWB system will be able to accelerate this disruption by turbocharging adoption of electric vehicles. These electric vehicles will in turn be able to share some of the battery energy storage load of the system, creating a reinforcing feedback loop that amplifies the economic, social, and environmental benefits of the SWB disruption itself.

17. The SWB disruption of energy will accelerate the disruption of food and agriculture.

In our report *Rethinking Food and Agriculture 2020-2030* we provided an analysis that shows how precision fermentation and food-as-software are poised to disrupt the food and agriculture sector over the course of the 2020s. Regions that choose to maximize super power from a 100% SWB system will be able to accelerate this disruption by lowering the cost of energy inputs into these new industries. The disruption of conventional farming and food production will lead to a freeing up of tens of millions of acres of land which could be repurposed for co-utilization by SWB facilities.



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End Notes

a Experience curves chart the relationship between cost and cumulative production volume, which for nearly all industries – including solar PV, wind power, and lithium-ion batteries – consistently follows a power law function. This power law function is commonly expressed as the percentage cost decline for each doubling of production volume, which is termed the *learning rate.* See our Methodology documentation at www.rethinkx.com for more detail.

b Note that our analysis conservatively assumes smaller cost improvements than would otherwise be expected according to the historical trend for each of these technologies. Our reason for making this conservative assumption is that even if any single region decides to commit to the required adoption rate necessary to achieve 100% solar PV, wind, and batteries by 2030, there is no guarantee that all regions of the world will do so. Nevertheless, it is important to emphasize that the default assumption must be that costs will continue to decline along their current trajectory as long as global adoption is still growing exponentially based on the multi-decade cost history of SWB together with the preponderance of evidence from dozens of other historical disruptions. Unfortunately, for over two decades conventional analyses have assumed that SWB cost improvements will begin to level off in the very near future, only to be disproven time and again. Any analysis that does not extend the historical cost curve by default must therefore offer a compelling empirical and theoretical explanation why, or else can be dismissed out of hand as unrealistic.

c The wind energy industry has benefited over the years by increasing the turbine (i.e. blade and swept area) size, increasing tower height (making higher quality laminar flow wind available), better generators and gearboxes, controls, and windfarm designs that allow for better capturing and conversion of wind energy. Note also that experience from offshore wind power developing contributes directly to the experience curve and learning rate for onshore wind power, and vice versa.

d New systems created by disruption tend to be larger than old ones because the goods and services they provide are cheaper, and price elasticity of demand results in an increase in aggregate demand across each affected market along with the creation of entirely new markets as well. Note that this rebound effect does not result in a net increase in environmental impact (known as the *Jevons Effect* or *Jevons Paradox)* if the technologies used to produce the goods and services in question change and ephemeralize production. Digital photography, for example, has disrupted film photography and led to production and consumption of images increasing by a factor of a million or more, but at the same time there has been a *decrease* in the use and environmental impact of celluloid film because image production was ephemeralized by the new technology. In the case of clean energy from solar and wind, rising demand from falling prices will not result in a Jevons Effect because these technologies reduce per-unit impact of each kilowatt-hour to near-zero.

e Battery performance is characterized by a number of metrics, including energy storage capacity, power output capacity, cycle life, and temperature tolerance among others. For the purposes of our analysis here, we are concerned only with energy storage capacity because the level of performance of lithium-ion battery chemistries across most other metrics is superlative.

f The changing costs of SWB mean that the optimal mix identified by a specific clean energy U-curve is time-dependent. A time series of clean energy U-curves can therefore provide additional insight for decision makers. However, it is important to note that as SWB become cheaper, the absolute magnitude of their cost changes decreases over time. Any time series of clean energy U-curves will therefore appear, in practical terms, to converge upon a "final" optimal mix. Our analysis uses 2030 as a basis for computing clean energy U-curves for this reason.

g See our Methodology documentation at www.rethinkx.com for a more detailed explanation of our use of data.

h Peak demand values reported here are hourly averages, and so they are slightly less than the momentary peak that will have occurred at some time during that hour.

i Our modeling approach of using variability of output from existing solar PV and wind power installations as a direct proxy for sunshine and wind resource variability minimizes error by avoiding the need to simulate and/or estimate numerous endogenous and exogenous variables. Models with large numbers of variables, each adding uncertainty and thus a potential source of compounding error, often suffer from the problem of spurious sophistication.

j Most existing hydropower and nuclear power capacity was constructed decades ago, is now fully amortized, and today operates at relatively low cost. Some nuclear power is likely to remain online for strategic reasons to support the defense sector, irrespective of financial considerations.

k The exponential buildout trajectory is contingent upon assumed deployment rates for solar, wind, and batteries. This trajectory in turn affects the cost premium of an exponential buildout compared to a hypothetical "overnight" buildout in 2030. Our analysis assumes that the trends from the last 5-10 years will hold during the 2020s: 50% annual growth in solar PV, 12% annual growth in wind power, and 85% annual growth in battery energy storage. See our Methodology documentation at www.rethinkx.com for more detail.

l The standard LCOE methodology at the plant level is a severely flawed because it is highly sensitive to the assumed capacity factor of the power plant, meaning the fraction of its achievable output that it will actually succeed in supplying (i.e. selling) to the grid on average each year. Conventional analyses assume capacity factor remains constant for the entire decades-long life of a power plant, whereas in reality the capacity factor for disrupted power plants will rapidly plummet to zero. With fewer kilowatt-hours sold to average all costs across on a 20+ year time horizon, the LCOE of coal, gas, and nuclear power plants for which disruption is inevitable will in reality be much higher than conventional analyses assume. Standard LCOE methodology (which is used by virtually all conventional analyses) therefore grossly underestimates the actual cost of electricity from coal, natural gas, and nuclear power plants looking forward into the 2020s and 2030s. See our energy report series and Methodology documentation at www.rethinkx.com for more detail.

m Our calculation of SEC assumes a 20-year financial lifetime of the solar, wind, and batteries assets. However, it is likely that solar PV assets will continue to perform at over 80% of their original generating capacity for at least 40 years. Wind turbines can last 25 years or more, although their blades can require replacement earlier depending on local wind and weather conditions. Batteries remain uncertain, but some existing lithium-ion chemistries designed for durability can retain over 80% performance capacity after 7,000 cycles (i.e. 20 years, even assuming a full cycle each day which is unrealistic), and new chemistries are now entering production that have much greater durability. It is likely that the majority of batteries built during the 2020s will have a working lifespan of at least 20 years.

n As of Q1 2020, Texas has 29.4 gigawatts of installed wind capacity and a further 7.1 gigawatts of new wind capacity under construction, so our analysis assumes a minimum of 40 gigawatts installed by 2030, even though this is not cost-optimal on a timeframe to 2030.

Adam Dorr

Adam Dorr is an environmental social scientist and technology theorist whose current research with RethinkX is focused on the disruption of the global energy sector by new energy generation and storage technologies, and its intersection with similar disruptions set to unfold across the economy. He completed his MS at the University of Michigan's School for the Environment and Sustainability and his PhD at UCLA's Luskin School of Public Affairs, where he studied the environmental politics, policy, and planning around disruptive technologies. He has a decade of teaching, lecturing, and presenting experience.

Tony Seba

Tony Seba is a world-renowned thought leader, author, speaker, educator, angel investor and Silicon Valley entrepreneur. He is the author of the #1 Amazon best-selling book "Clean Disruption of Energy and Transportation", "Solar Trillions" and "Winners Take All", and co-author of "Rethinking Transportation 2020-2030", "Rethinking Food and Agriculture 2020-2030", and "Rethinking Humanity".

He has been featured in several movies and documentaries including Bloomberg's Forward Thinking: A Sustainable World, 2040, and SunGanges. He is recipient of many awards including the Savvy Awards (2019), Solar Future Today's Visionary Influencer Award (2018), and Clean Energy Action's 2017 Sunshine Award. He is the creator of the Seba Technology Disruption Framework™. His work focuses on technology disruption, the convergence of technologies, business model innovation, and product innovation that is leading to the disruption of the world's major industries. He has been a keynote speaker at hundreds of global events and organizations including Google, the European Commission, Davos, COP21, CLSA, J.P. Morgan, Nomura, National Governors Association, Conference on World Affairs, the Global Leaders Forum, Intersolar and China EV100. He has taught thousands of entrepreneurs and corporate leaders at Stanford Continuing Studies. He has a Stanford MBA and an MIT degree in Computer Science and Engineering.

The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

Rethinking Energy 2020-2030

We are on the cusp of the fastest, deepest, most profound disruption of the energy sector in over a century. Like most disruptions, this one is being driven by the convergence of several key technologies whose costs and capabilities have been improving on consistent and predictable trajectories – namely, solar photovoltaic power, wind power, and lithium-ion battery energy storage. Our analysis shows that 100% clean electricity from the combination of solar, wind, and batteries (SWB) is both physically possible and economically affordable across the entire continental United States as well as the overwhelming majority of other populated regions of the world by 2030. Adoption of SWB is growing exponentially worldwide and disruption is now inevitable because by 2030 they will offer the cheapest electricity option for most regions. Coal, gas, and nuclear power assets will become stranded during the 2020s, and no new investment in these technologies is rational from this point forward. But the replacement of conventional energy technology with SWB is just the beginning. As has been the case for many other disruptions, SWB will transform our energy system in fundamental ways. The new system that emerges will be much larger than the existing one we know today and will have a completely different architecture that operates in unfamiliar ways. One of the most counterintuitive and extraordinary properties of the new system is that it will produce a much larger amount of energy overall, and that this superabundance of energy output – which we call *super power* – will be available at near-zero marginal cost throughout much of the year in nearly all populated locations. The SWB disruption of energy will closely parallel the digital disruption of information technology. Just as computers and the Internet slashed the marginal cost of information and opened the door to hundreds of new business models that collectively have had a transformative impact upon the global economy, so too will SWB slash the marginal cost of electricity and create a plethora of opportunities for innovation and entrepreneurship. What happened in the world of bits is now poised to happen in the world of electrons.