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# Renewables and decarbonization: Studies of California, Wisconsin and Germany

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ABSTRACT

An analysis of electricity systems in Germany, California and Wisconsin finds that balanced portfolios made up of zero- and low-carbon baseload resources, as well as wind and solar, are the most cost-effective means of producing electricity and reducing carbon.



## 1. Introduction

The electric utility industry is in the midst of a multi-decadal transformation, driven by growing market competition, increasingly stringent environmental regulations, and significant technological innovation. Unchanged by this transformation is the fact that electricity remains a necessity of modern industrialized life, indispensable to virtually every home and business. In the United States, electricity is inexpensive, invisible, and remarkably reliable—qualities which encourage consumers to take it for granted.

Beginning with the Public Utility Regulatory Policies Act of 1978 (PURPA) and continuing to the present, electric utilities (which had traditionally been vertically integrated and rate-regulated) have been subjected to increasing competition. The Clean Air Act of 1970, and particularly its 1990 Amendments, initiated a series of increasingly stringent air quality regulations. The U.S. Environmental Protection Agency's Clean Power Plan, aimed at limiting carbon dioxide ($CO_2$) emissions from power plants, will bring new pressures on the industry. Technological innovation is a third driver of transformation. Encouraged, in part, by evolving industry structure and new environmental laws, often supported by state and federal subsidies and mandates, new technologies now compete with traditional power plants and wires to serve the once-captive utility customer.

In recent years, these separate transformative forces have coincided under the rubric of climate change. Driven by growing scientific alarm and political mobilization, the pressure to reduce greenhouse gas emissions (GHGs) from the utility sector is intense and growing. Electric power plants, which produce about one-third of U.S. GHGs, are the focus of unprecedented political and regulatory scrutiny.

Due to the inability of Congress to agree upon climate legislation, climate policy has been pursued by proxy in diverse, fragmented measures such as subsidies and mandates for specific technologies, creating a patchwork of politically preferred energy policies rather than a system-based, comprehensive approach to achieving long-term emission reductions. Partly because of that dynamic, the debate over how to reduce GHGs from the utility sector has become a drama of confused ends and means, where political and intellectual support for solar and wind power have distracted policymakers' attention from the larger goal of cost-effective decarbonization.

A prime example of this confusion is a body of studies arguing that the GHG reduction burden can be met solely or mainly by renewable energy alone (Jacobson and Delucci, 2009; Kombikraftwerk2; Chandler et al., 2014). In seeking to demonstrate that renewables can by themselves replace all fossil fuels *and* nuclear energy, these studies run the risk of treating renewables as a societal end in itself, instead of just one among a suite of technologies that could be used to achieve the combined goals of environmental protection, cost-containment, and electric system reliability.

In most of these studies, wind and solar power (mostly solar photovoltaic, or PV) dominate the resource mix in the future. So it is important to ask: *What do systems that are highly reliant on intermittent renewable resources (IR), such as wind and solar, look like?* How do they compare to other possible system configurations in terms of cost, size, and carbon emissions?

We report here on the results of three studies we have done that examine these questions. We will highlight our most important findings and then discuss their policy implications.

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## 2. Overview of the studies

We undertook these studies to better understand and illustrate the system consequences of high penetrations of intermittent renewables (IR)—primarily wind and solar PV—and to compare such systems to potential decarbonization pathways that include low-carbon baseload generation technologies (i.e., nuclear and fossil fuels with carbon capture and sequestration), along with more modest (25%) contributions from wind and solar. We refer to these mixed scenarios as balanced strategies. These studies focused on three widely varying geographies: Germany, California, and Wisconsin. We used historical wind and solar production patterns as the basis for the analysis; these patterns were used to estimate the hourly contributions from wind and PV sufficient to satisfy renewable portfolio standards (RPS) of 50 and 80%, we then calculated residual hourly non-renewable generation required for each hour of the year. We also developed estimates for IR systems that performed equivalently in terms of $CO_2$ reductions to the balanced scenarios; these are labeled CA 195, WI 172 and Germany 154, respectively.

Germany's energy transition policy, the *Energiewende,* aspires to provide 80% of Germany's electricity from renewable sources by 2050 while retiring the German nuclear fleet and implementing an ambitious energy efficiency effort. These policies have stimulated a rapid increase in the use of both wind and solar PV. As of the end of 2014, Germany had installed about 35 GW each of wind and PV; renewable electricity (including hydro and biomass) accounted for about 28% of total supply. The rate of new capacity addition has slowed dramatically in the past three years as the country has struggled with rapidly rising electricity prices.

California is on track to meet a 33% RPS by 2020; the legislature has approved a proposal to increase the RPS to 50%, and there is support in the state for raising the RPS to 80%.

Wisconsin currently has a modest 10% RPS. A recent study by the Wisconsin Academy of Sciences, Arts and Letters has stimulated calls for increasing the standard, with some organizations advocating a 60% RPS.

These three areas have widely varying geographies, and significantly different energy systems today, providing the opportunity to explore the implications of renewables policies in different contexts. For each of these areas, we compared RPSs of 50% and 80% to a balanced portfolio of low-carbon energy sources including nuclear and a 25% IR contribution. For each scenario, we calculated cost ($/MWH), system size (MW) and carbon performance (tons $CO_2$ and $ per ton of $CO_2$ reduced).

We relied on data from the U.S. Energy Information Administration (USEIA) (2015) Annual Energy Outlook for generating technology costs for these studies (USEIA, 2015). To test the outer bounds of these scenarios, we conducted sensitivity analyses that assumed rapid and significant cost declines for wind and solar (capital costs of $1000/kW, compared to projected EIA costs of $1850 for wind and $3123 for solar PV) as well as increased costs for nuclear ($6500/kW capital costs, as opposed to EIA assumptions of $4646). These scenarios are designated below as OR/PN (optimistic renewables/pessimistic nuclear).

## 3. Key findings

- IR-heavy systems are significantly larger than conventional counterparts; this is because intermittent resources like wind and PV have low capacity factors; to generate the same amount of output, a larger system is needed.
- Using EIA assumptions for technology costs, IR-heavy systems are more expensive on a dollars-per-megawatt-hour basis.
- Combining optimistic assumptions about renewable costs with pessimistic assumptions about nuclear costs produces results indicating balanced systems would be more expensive in Wisconsin and California, but still cheaper in Germany.
- Under ordinary cost assumptions, 80% RPS scenarios yield about a 70% reduction in $CO_2$ emissions; balanced generation systems produce reductions between 80 and 87%.
- To achieve $CO_2$ reductions on par with balanced portfolios, IR systems must be built much larger, to between 154 and 195% RPS levels.
- Wind and solar output exhibit seasonal episodes of both sustained oversupply and undersupply that overwhelm any conceivable storage strategy. Battery storage technologies may have a role in managing shorter-term imbalances but are unlikely to solve the very large seasonal swings in generation output under high-penetration IR scenarios. Pumped hydroelectric storage (PSH) is the only available technology applicable to longer-term storage; however, storing the large seasonal surpluses produced in these scenarios would require much more PSH than could be reasonably installed. While some long-term storage may be feasible, wasted surplus is unavoidable in high-IR systems, and backup conventional generation remains necessary.

## 4. Discussion

### 4.1. IR systems are larger

Modern wind plants produce power at capacity factors (CF) between 30 and 40%; solar PV system CF ranges between 10% and 25%. To produce the same energy output (in kilowatt-hours, or kWh) as conventional power plants (with CFs ranging from 80 to 90%), more wind and solar capacity will have to be built. In addition, as Table 1 shows, even with very high levels of wind and solar, considerable conventional capacity (here designated as NGCC-natural gas combined cycle) must be retained to ensure continuity of supply when it is calm or cloudy. In these analyses, the default scenario represents a system unconstrained by $CO_2$ limitations and without binding requirements for renewables. The default system is composed entirely of natural gas combined cycle units.

Under 50% RPS scenarios, more than 40% of the installed capacity remains gas-powered; under 80% RPS scenarios, the NGCC component of the system remains almost as large, only supplemented with much larger renewables systems that produce smaller emissions reductions. This data suggests that building

**Table 1**
System size under multiple scenarios for California, Germany, and Wisconsin.

| Configuration | Total size (MW) | NGCC | Wind | Solar | Nuclear |
|---|---|---|---|---|---|
| CA default | 53,633 | | | | |
| CA 50 RPS | 90,534 | 39,433 | 19,449 | 23,609 | 0 |
| CA 80 RPS | 123,589 | 38,926 | 34,614 | 42,017 | 0 |
| CA balanced | 63,662 | 22,925 | 6868 | 8337 | 17,500 |
| CA 195 RPS | 251,734 | 36,923 | 93,400 | 113,379 | |
| WI default | 811 | | | | |
| WI 50 RPS | 1799 | 765 | 324 | 710 | 0 |
| WI 80 RPS | 2383 | 756 | 540 | 1087 | 0 |
| WI balanced | 1265 | 508 | 162 | 355 | 240 |
| WI 172 RPS | 4383 | 727 | 1026 | 2630 | |
| Germany default | 67,028 | | | | |
| Germany 50 RPS | 150,111 | 56,030 | 45,038 | 41,531 | 0 |
| Germany 80 RPS | 233,185 | 55,721 | 88,274 | 81,401 | 0 |
| Germany balanced | 79,859 | 34,556 | 9308 | 8583 | 20,000 |
| Germany 154 RPS | 437,600 | 54,956 | 195,163 | 179,969 | |

more renewables is not an efficient or effective way to displace conventional generation capacity.

Why must generation systems retain so much conventional generation even when large amounts of renewables are added to the system?

Intermittence means that wind and solar PV do not contribute to the system *capacity* needs in the same fashion as conventional plants. Capacity is a reflection of the ability to meet the instantaneous demand on the electric grid at any time. Most utility systems are engineered to meet projected peak demand, plus reserves to account for outages of various sorts. (An exception is hydro-heavy systems, where planning for total annual energy is the bigger challenge.)

The probability that a conventional plant will not be available when needed is represented statistically by its forced outage rate. Modern thermal plants can reliably deliver their full output (if needed) 90–95% of the time. In contrast, a 100 MW wind farm can only be relied upon for 10–20 MW of power. For solar, the situation is more complicated; capacity value can be higher in summer peaking systems but is usually zero in winter peaking systems, such as in Germany. Consequently, there is a persistent need for some kind of backup for most of the wind and solar capacity.

Larger electric systems, with more dispersed generating assets, will also require more transmission. A major study conducted by the National Renewable Energy Laboratory (NREL) confirms that a high-IR system will mean dramatic expansion of transmission infrastructure. Indeed, NREL concluded that transmission building would need to expand 100-fold over the baseline in order to facility a national 80% RPS. Virtually all energy infrastructure projects generate public opposition; systems that are two to three times larger and that entail more transmission than conventional ones are certain to be more controversial.

To fully appreciate the reliability challenge associated with high penetration of variable resources, it is also important to consider variability across all relevant time periods—hourly, daily, seasonally, and annually. In Wisconsin, for example, December and January are the windiest months, while the summer is best for PV. In California, summer is best for both PV and wind, while winter is poor for both. The challenge is that customer demand must be served year-round, 24 h per day, regardless of meteorological conditions. The system must be planned for the worst months, not the best.

Fig. 1 presents monthly capacity factors for wind in California in two years, 2009 and 2014. It is clear from this picture that wind production peaks in the summer months and tapers off during the spring and fall. It is also apparent that, although the general pattern of production is similar, the annual variability is not trivial in some months.

In the northern hemisphere, solar output peaks are highest during the summer and lowest in the winter. Fig. 2 presents solar radiation data for four widely separated locations in the United States; the annual rise and fall in production can be seen for each of these locations.

*4.2. IR systems are costlier*

Using current EIA estimates for capital and operating costs, IR-dominated systems will produce electric rates that are higher than balanced portfolios. Table 2 shows that, under these assumptions, the balanced generation portfolio is cheaper than both RPS levels while delivering higher levels of carbon reduction (see Table 3 for emissions data). In each scenario, a balanced portfolio (using only 25% IR generation) achieves greater emissions reductions than an 80% RPS at a cost below that of a 50% RPS.

Assertions that wind and solar PV are cost-competitive with other resources rely using the “levelized cost of electricity” (LCOE) as the comparative metric, which does not account for the differences in CF between conventional resources and IR and the resulting system cost increases that come with greater penetration of these resources. Indeed, a number of analysts have pointed to the failing of the LCOE as a meaningful basis for comparison.

As noted, 1 MW of wind or PV is not equivalent to 1 MW of a dispatchable generation source such as a nuclear plant or NGCC unit; a wind unit produces less power, much less reliably, requiring

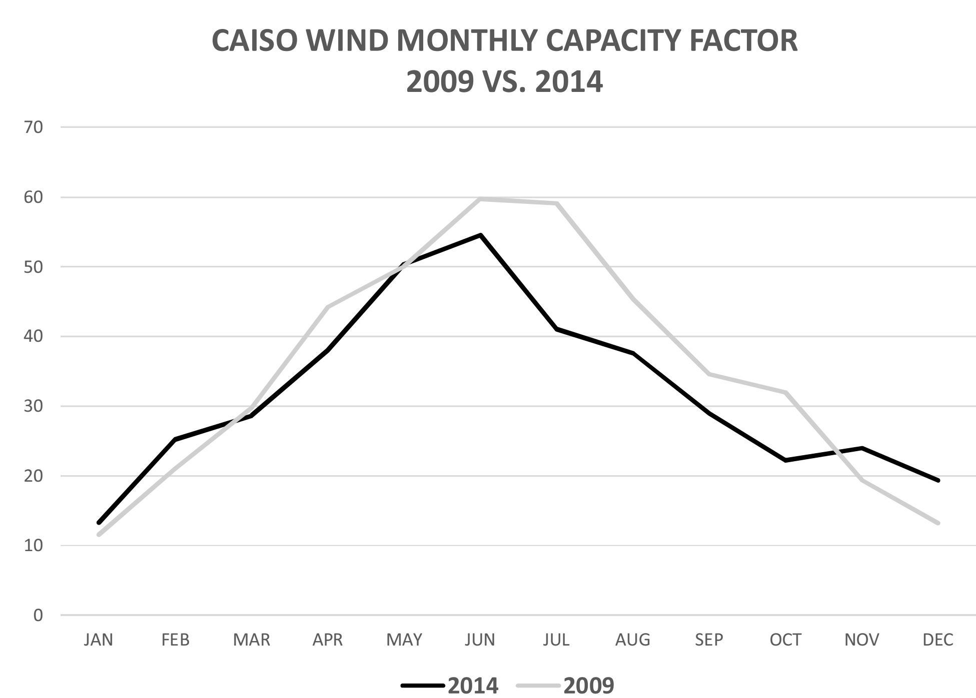


**Fig. 1.** Month-to-month wind variation in California.

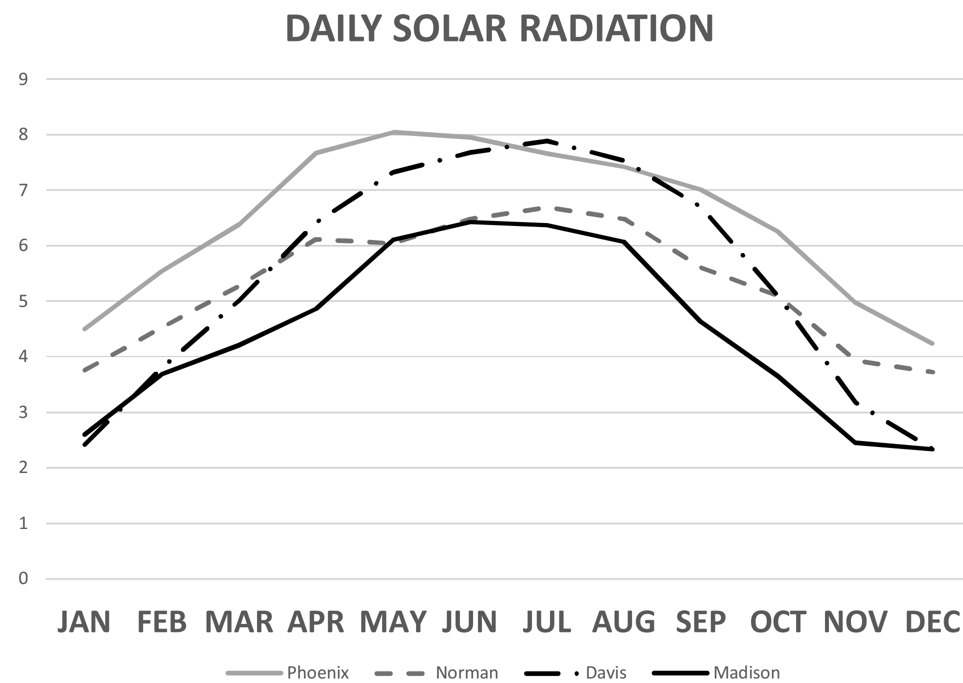


**Fig. 2.** Monthly variation in solar radiation in four US locations.

transmission, storage, and backup generation capacity. Ratepayers pay the full cost of the electric system, and studies that ignore system costs run the risk of misrepresenting the consequences of policies that affect system configuration.

Claims that renewables are at "grid parity" obscure significant engineering and economic questions. In the case of PV, grid parity often means that the cost of solar (minus subsidies) is about equal to the *retail* electric rate. Since the retail electric rate represents the rolled-up costs of generation, transmission, distribution, and administration, using it as basis for comparing PV to other generating options is inappropriate and exaggerates the benefits provided by solar significantly. In addition, this measure ignores the cost to the rest of the system for providing backup to the PV system. This metric is useful for determining economics for the potential owner of the PV system, but as an expression of how the *system at large* will be affected, it is useless.

For wind, "grid parity" is usually taken to mean that the generating cost of power from the wind project is at or near other that of other generation technologies. This metric still fails to account for the effect of wind's low CF and the need to maintain significant conventional backup resources for system reliability.

Looking at total system costs, we find default costs ranging from \$52 MWh in California and Wisconsin to \$73 MWh in Germany. Cutting $CO_2$ emissions by half via RPSs would double the cost of electricity in California (raising it to \$96 per MWh), and have even greater effects in Wisconsin (\$147 per MWh) and Germany (\$126 per MWh). But for roughly comparable costs, a balanced system of low-carbon sources could reduce emissions by more than 80%, a far better performance.

Deeper emissions reductions are more expensive—and the cost and performance penalty for greater reliance on IR generation grows significantly at high levels of system penetration. For an 80% RPS, the cost of electricity would rise to \$140 per MWh in California, \$202 per MWh in Wisconsin, and \$194 per MWh in Germany, a tripling (or more) of electricity costs.

These projections reflect the important system configuration effects that come with a strong reliance on IR generation—but naturally, core technology costs are also relevant. Recognizing the inherent uncertainties in future technology costs and wanting to test the outer bounds of our findings here, we developed a scenario with optimistic assumptions about cost reductions for renewables coupled with pessimistic assumptions about rising costs of nuclear power; data from that scenario are presented in the right-hand column of Tables 2 and 3.

Even under such favorable assumptions for renewables, an 80% RPS would be more expensive than a balanced system in Germany and only slightly cheaper than a balanced system in Wisconsin and California. However, the balanced portfolio achieves deeper $CO_2$ cuts than the 80% RPS in all cases (as discussed below), which must be considered as electric systems are designed. When this is taken into account, balanced systems are cheaper, even with steep cost declines for wind and solar.

### *4.3. Balanced systems achieve deeper $CO_2$ reductions*

Table 3 shows that balanced systems (nuclear baseload plus 25% wind and solar) do a better job of cutting carbon than high-IR

**Table 2**
System costs under multiple scenarios for California, Germany, and Wisconsin.

| Cost | EIA (\$/MWH) | OR/PN (\$/MWH) |
|---|---|---|
| CA default | 52 | 52 |
| CA 50 RPS | 96 | 61 |
| CA 80 RPS | 140 | 78 |
| CA balanced | 93 | 98 |
| CA 195 RPS | 324 | 128 |
| | | |
| WI default | 52 | 52 |
| WI 50 RPS | 147 | 85 |
| WI 80 RPS | 202 | 106 |
| WI balanced | 128 | 112 |
| WI 172 RPS | 413 | 189 |
| | | |
| Germany default | 73 | 73 |
| Germany 50 RPS | 126 | 83 |
| Germany 80 RPS | 194 | 109 |
| Germany balanced | 84 | 88 |
| Germany 154 RPS | 377 | 190 |

**Table 3**
$CO_2$ emissions and costs under multiple scenarios for California, Germany, and Wisconsin.

| | % $CO_2$ reduction | EIA (\$/ton $CO_2$ reduced) | OR/PN (\$/ton $CO_2$ reduced) |
|---|---|---|---|
| CA 50 RPS | 50 | 280 | 42 |
| CA 80 RPS | 70 | 393 | 91 |
| CA balanced | 87 | 150 | 128 |
| CA 195 RPS | 87 | 775 | 300 |
| WI 50 RPS | 48 | 633 | 174 |
| WI 80 RPS | 67 | 729 | 210 |
| WI balanced | 81 | 303 | 192 |
| WI 172 RPS | 81 | 1168 | 440 |
| Germany 50 RPS | 50 | 348 | 103 |
| Germany 80 RPS | 69 | 553 | 184 |
| Germany balanced | 86 | 207 | 88 |
| Germany 154 RPS | 86 | 877 | 335 |

systems. Each of the RPS-80 scenarios reduces $CO_2$ emissions in the range of 70%, while balanced systems produce reductions over 80%; the difference is due to the fact that not all of the IR electricity can be used, as discussed above. Even assuming the existence of storage with an 85% round-trip efficiency leaves the RPS-80's $CO_2$ performance short of the balanced portfolio. It is important to remember that the storage would add significant cost to the equation, which is considered below.

How far would IR have to be pushed to achieve $CO_2$ reductions comparable to the balanced portfolio? Without storage, the answer is very far, indeed. The last entry for each jurisdiction in our analysis shows that, without storage, RPSs of between 154 and 195% would be required to achieve $CO_2$ reductions comparable to the balanced portfolios. The cost per ton of $CO_2$ removed is substantially higher than for the balanced scenarios.

In almost every scenario, under a wide range of assumptions and across three widely varying geographies, cutting $CO_2$ emissions with a balanced portfolio of low-carbon generation sources is more effective, and more cost-effective, than relying on renewables alone. As Tables 3 and 4 show, a balanced low-carbon system consistently achieves significantly greater emissions reductions at far less cost.

Decarbonization is not cheap in any of these scenarios, but there are very large differences in cost for different system configurations. While ~80% decarbonization through a balanced system would nearly double the cost of energy in California and Germany, and almost triple costs in Wisconsin, the cost per ton is typically half (or less) than the RPS-driven scenarios, making balanced systems twice as cost-effective as IR-centric systems.

Even a relatively modest 50% reduction in $CO_2$ emissions relying on a 50% RPS would be expensive, with a cost-effectiveness ranging from, at best, \$280 per avoided ton of emissions in California down to \$348/ton in Germany and a staggering \$633/ton in Wisconsin.

The cost-effectiveness gap is even greater when the desired emission reductions increase. An 80% RPS (which, as noted above, only cuts emissions by 70% or less) has a cost-effectiveness ranging from \$393 per ton of avoided emissions in California to \$553/ton in Germany and \$729 per ton in Wisconsin.

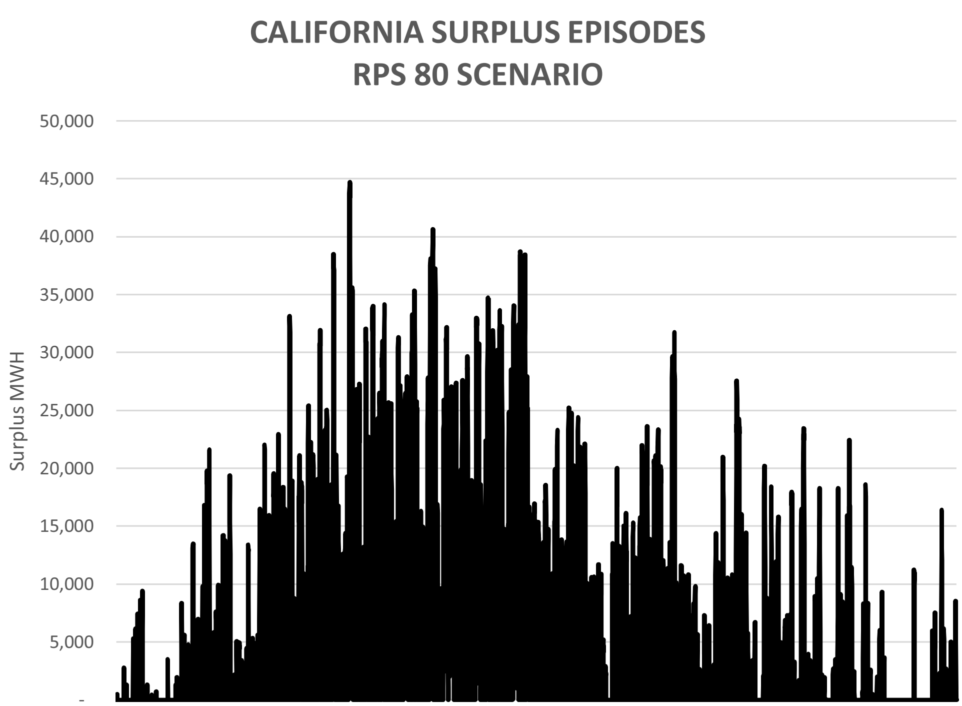


**Fig. 3.** Annual surplus generation episodes in California under RPS 80 scenario.

In contrast, a balanced system in California could produce emissions reductions well over 80% at a cost of $150/ton in California, $207/ton in Germany, and $303 per ton in Wisconsin.

It is worth noting that all of these figures are greater than most current estimates of the social cost of carbon, which are typically around $40/ton.

### 4.4. Large seasonal imbalances cannot be completely managed by storage

Storage is frequently seen as the solution to the imbalances created in high-IR systems; developing cost-effective energy storage systems is widely thought to be the key to decarbonizing the electricity grid. Our studies (as well as other literature) suggests otherwise.

The issue is not merely what might be possible in an engineering sense but what is economical and socially acceptable. Adding storage technologies to the grid at large scale will have significant costs, which will grow as IR penetration rises. Even if innovation reduces the cost of storage, whatever technologies evolve will still represent an additional cost to the system. The electricity that is used to charge the storage system is not free, the act of storage itself produces efficiency losses of 10–20%, and storage systems require significant investment. To be economical, such equipment must be used frequently—yet seasonal intermittency requires storage capacity with a very low utilization rate.

The dynamics of storage are trickier than might first appear, due to both the seasonal variation in surplus production (which is observed in virtually every location) and the day-to-day variations. Fig. 3 presents the hourly surpluses generated in the RPS80 scenario for California for an entire year. It can be clearly seen that these surpluses are not evenly distributed throughout the year. The largest surplus episode is about 45,000 MWh; the average episode, however is about 4100 MWh. Clearly, a system designed to store 45,000 MWh would be grossly underutilized most of the time, and consequently uneconomic from a system standpoint. An ideally sized storage system would not be able to capture all of the surplus, given the unevenness of its production.

The problem becomes even more daunting when we consider the *cumulative* storage required, instead of only the largest instantaneous need. Fig. 4 shows that for the California 80 RPS scenario, the balance of stored energy grows by mid-year to 8 million MWh; this means that 8 million MWh of storage would be required to save and later utilize this electricity. At present costs of around $500/kWh for battery storage, this would add about $480 billion per year in annual costs. The total annual costs of the 80% RPS for California without storage are around $30 billion, so this storage would increase system costs by a factor of 16. Even with storage costs cut in half, the impact on electric rates of such an expenditure would be extraordinary.

Total pumped-storage hydroelectric (PHS) capability in California is currently less than 150,000 MWh, spread over an installed capacity of about 5200 MW (Anon., 2016). PHS would need to be expanded more than 100-fold to accommodate the surplus projected in our study. Sites for PHS are extremely limited, and, given environmental concerns over siting, making such a vast expansion of PHS capacity in California seems quite unlikely.

### 4.5. What do other studies say?

There is broad agreement between numerous studies on the first core conclusion of our work: *energy systems relying heavily on IR will necessarily be larger than conventional systems*. The degree to which other studies consider and agree upon the implications of that fact—for cost, and cost-effectiveness as a decarbonization strategy—vary.

Jacobson et al. (2014) in a simulation of an all-renewable future for California, project that installed generation capacity would grow from present levels of around 70 GW to an astounding 621 GW, nearly a nine-fold increase in electricity generation infrastructure. Conventional electric demand is shrunk substantially in this scenario through ambitious energy efficiency efforts, but then increased to incorporate transportation and industry.

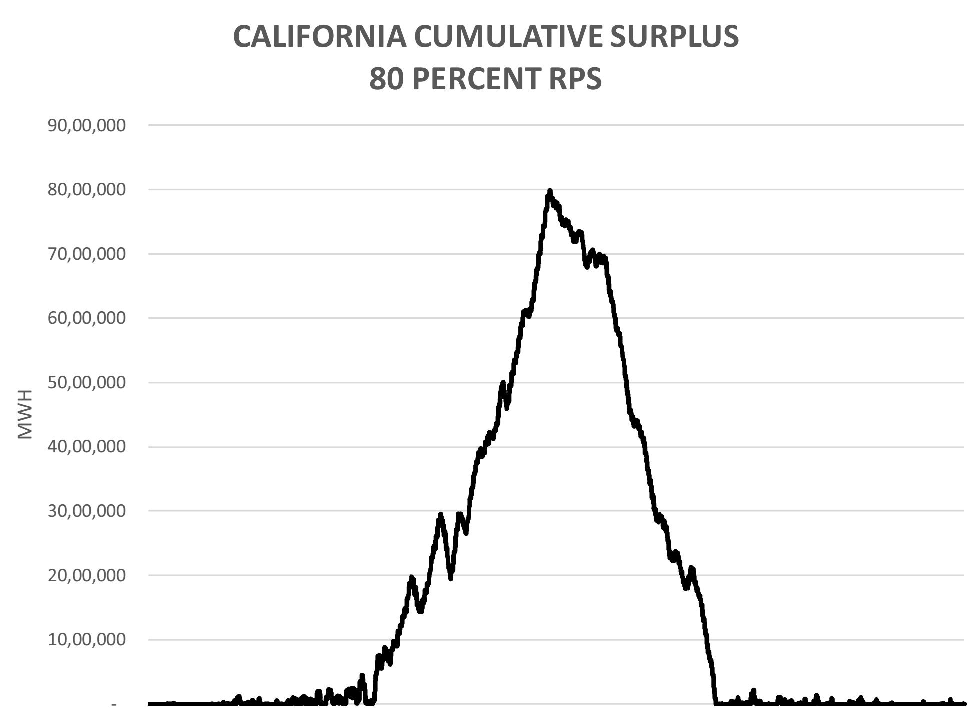


**Fig. 4.** Cumulative annual surplus generation in California under RPS 80 scenario.

The World Wildlife Fund conducted a study for China that reached similar conclusions. To meet 80% of electric supply renewables, and to serve peak demand of 2000 GW, WWF devised a 5000 GW system that still retains 1100 GW of conventional NGCC capacity to balance the wind and PV. A 2400 MW conventional system could meet that demand reliably.

China's NDRC (NDRC, 2015) recently released a high-renewable scenario with similar findings, except that it retains 800 GW of coal to balance the system.

It should be noted that the authors of these studies see them as demonstrating the feasibility of these scenarios, while we find the practical implications of these figures daunting.

In the United States, the Deep Decarbonization Pathway Project study (Williams et al., 2015) considered three scenarios: high renewables, a mix of renewables and conventional, and low-carbon conventional (i.e., nuclear and fossil fuels with carbon capture and storage). All three scenarios produce comparable $CO_2$ reductions; the low-carbon conventional pathway is the cheapest (and smallest) system.

## 5. Conclusions

The ongoing transformation of the nation's electric grid is a matter of great importance to our economy, national security, and environmental quality. The significance of these questions is only matched by their complexity. Given the competing values affected by these choices, it is essential that analysis of these questions compare alternate pathways that could perform well in multiple dimensions—that is, policies that could most cost-effectively reduce $CO_2$ emissions significantly over time while maintaining the affordability and reliability of the electric system and minimizing other environmental harms.

How to best meet those goals despite potential tradeoffs between their different elements is a complex question that requires careful analysis—yet for many, the presumptive answer has been almost self-evident (as suggested by the failure of much of the literature to compare alternatives): Renewables are the technology of choice, and the only question considered is how to deploy them. This is a dangerous confusion of ends and means.

In the studies presented here, we see that the intermittency of wind and solar PV means that systems that are heavily reliant on them must be significantly larger than conventional systems; this increases their cost and capital requirements dramatically. (Although not examined here, wind and solar's low power density means these systems also have a vastly larger geographical footprint.) Increasing reliance on IR generation brings increasing demands for storage (and/or transmission) technologies to manage their intermittency; the costs (and land-use effects) are also significant.

Given these facts, it is hard to avoid the conclusion that heavy use of intermittent renewables may not be the most cost-effective way to reduce $CO_2$ emissions from the power sector.

Efforts to promote an all- (or nearly all-) renewables future are, in effect, a commitment to building the largest electric power system possible. It might be better to start from the presumption that the smallest power system that meets our needs is likely to be the most efficient, and have the least social and environmental impact.

Licensing any new energy infrastructure—whether nuclear power plants, hydroelectric dams, transmission lines, or industrial-scale wind farms and PV installations—is almost always difficult; lawsuits and delays are inevitable, given the effects these projects have on communities and the environment. Calls for an all-renewables future are an implicit commitment to a nearly never-ending political and legal battle over licensing of this infrastructure, with potentially significant consequences for our landscape and ecology if renewables developers are successful.

Rather than building a system that is much larger and more expensive than necessary, we should rigorously seek to ascertain the most cost-effective way to maintain reliability and cut carbon emissions.

We should also be wary of efforts to see energy policy choices through the lens of job creation: rather than seeking an energy system that employs the most people, we might find the greatest efficiency in systems that can be operated and maintained by the fewest number of employees possible. Electricity, as an input to most every single good and service in the world, should be as inexpensive as possible, and not a vehicle for pursuit of tangential social goals.

When considering these policy options, it is essential to look at *systems as systems*. Without this, without the ability to compare and debate multiple pathways for achieving complex, interlinked goals, we are flying blind—making decisions of enormous social and economic consequence with partial data. We must be realistic about the scope and complexity of this transformation, acknowledge that difficult tradeoffs are involved, and ensure all options are rigorously considered and compared.

## References

Anon., 2016. DOE Global Energy Storage Database. http://www.energystorageexchange.org/.

Chandler, et al., 2014. China's Future GenerationWorld Wildlife Fund. . February http://d2ouvy59p0dg6k.cloudfront.net/downloads/chinas_future_generation_report_final__1_.pdf.

Jacobson, Delucci, 2009. A Path to Sustainable Energy by 2030. Scientific American November.

Jacobson, et al., 2014. A roadmap for repowering California for all purposes with wind, water, and sunlight. Energy 73, 875–890.

Kombikraftwerk2. http://www.kombikraftwerk.de/mediathek/english.html.

NDRC, 2015. China 2050 High Renewable Energy Penetration Scenario and Roadmap Study. . April, 2015 http://www.efchina.org/Attachments/Report/report-20150420/China-2050-High-Renewable-Energy-Penetration-Scenario-and-Roadmap-Study-Executive-Summary.pdf.

US Energy Information Administration (USEIA), 2015. Annual energy outlookElectricity Market Module, . . September, 2015 http://www.eia.gov/forecasts/aeo/assumptions/pdf/electricity.pdf.

Williams, et al., 2015. Pathways to Deep Decarbonization in the United States. . http://deepdecarbonization.org/countries/#united-states.

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