BUILDING A LEAST-COST, LOW-CARBON ELECTRICITY SYSTEM WITH EFFICIENCY, WIND, SOLAR, & INTELLIGENT GRID MANAGEMENT:

WHY NUCLEAR SUBSIDIES ARE AN UNNECESSARY THREAT TO THE TRANSFORMATION

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July 2021

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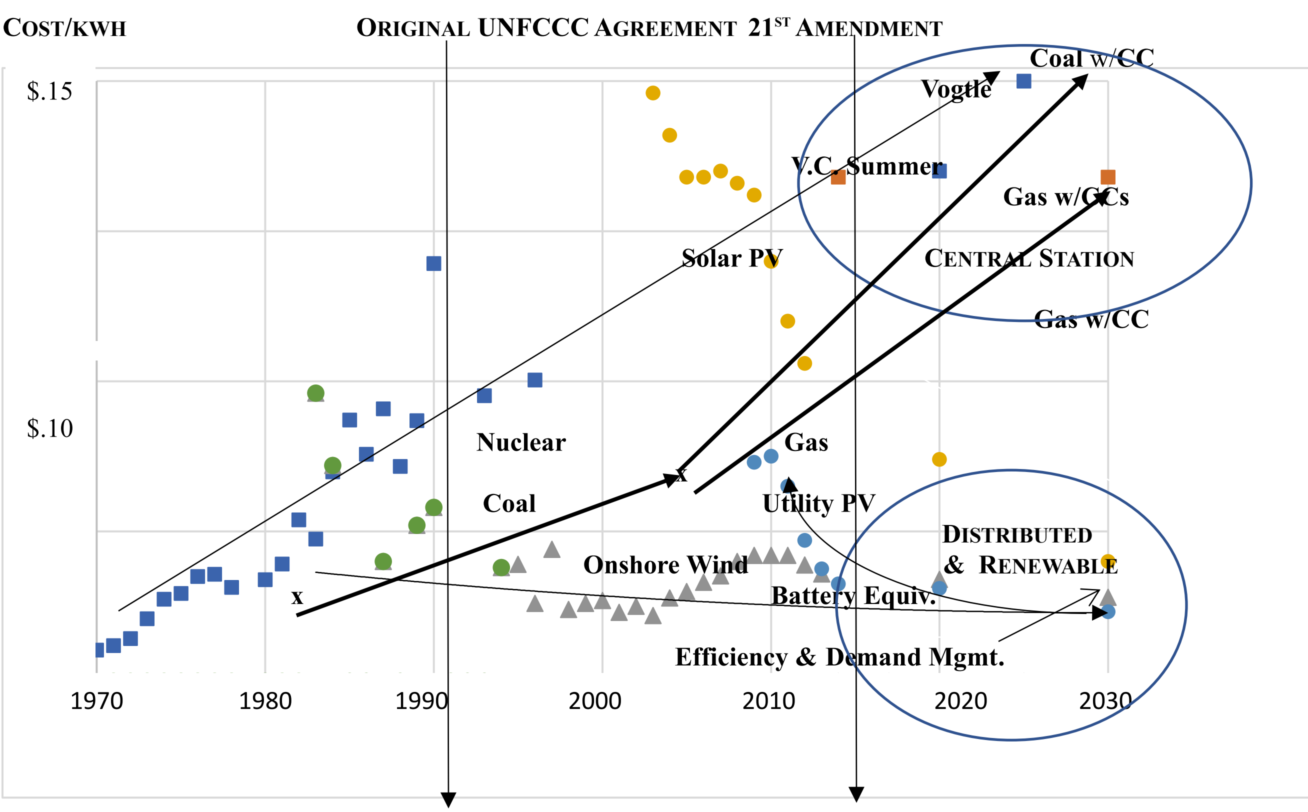
EXECUTIVE SUMMARY

This paper demonstrated that the ongoing revolution in the electricity sector is based on

- two supply-side technologies (onshore wind and utility photovoltaics) and
- two demand-side technologies (efficiency investments that reduce the amount of energy consumed per unit of "output" and demand response that creates a better match between supply and demand by using digital communications, computers, and advanced control technologies).

As a result, a 21st-century electricity system based on a radically different approach to system operation – small, decentralized, and dynamic – is replacing the 20th-century station system, which was based on huge, inflexible "must-run" generators. The paper shows (Exhibit ES-1) that this transformation was not possible when the United Nations Framework Convention on Climate Change (UNFCCC) was signed in the early 1990s, but it has been made possible by the dramatic recent technological progress.

ES-1: BROAD, LONG-TERM RESOURCE COST TRENDS



Source: See Figure 2.1.

The four alternative resources yield power that is lower in cost, achieves faster economic growth, creates more jobs, and reduces concerns about public health and safety, while fully decarbonizing the electricity sector. With such clear advantages, the question arises as to why the 21st-century alternative needs aggressive public policy to be implemented on a pervasive scale. The answer is, as it has always been during technological revolutions, the new system must overcome the resistance of the dominant, entrenched incumbents who have had a century to cement their power and influence. The new system needs not only extensive physical assets but also institutional supports to become dominant.

The new system must overcome two barriers, one from deniers who say it is unnecessary or cannot be done and one from those who claim decarbonization cannot be accomplished without relying on nuclear power. The barriers are backed by powerful interests. Coal accounts for 23% of total generation, gas 37%, and nuclear 20%.

PART I: AFFORDABLE RESOURCE COST

Part I examines the evidence on the resource cost of the electricity system. Exhibit ES-2, which shows a comparison of projected costs of resources from EIA and Lazard, is similar to many other projections, and they lead to the following conclusions:

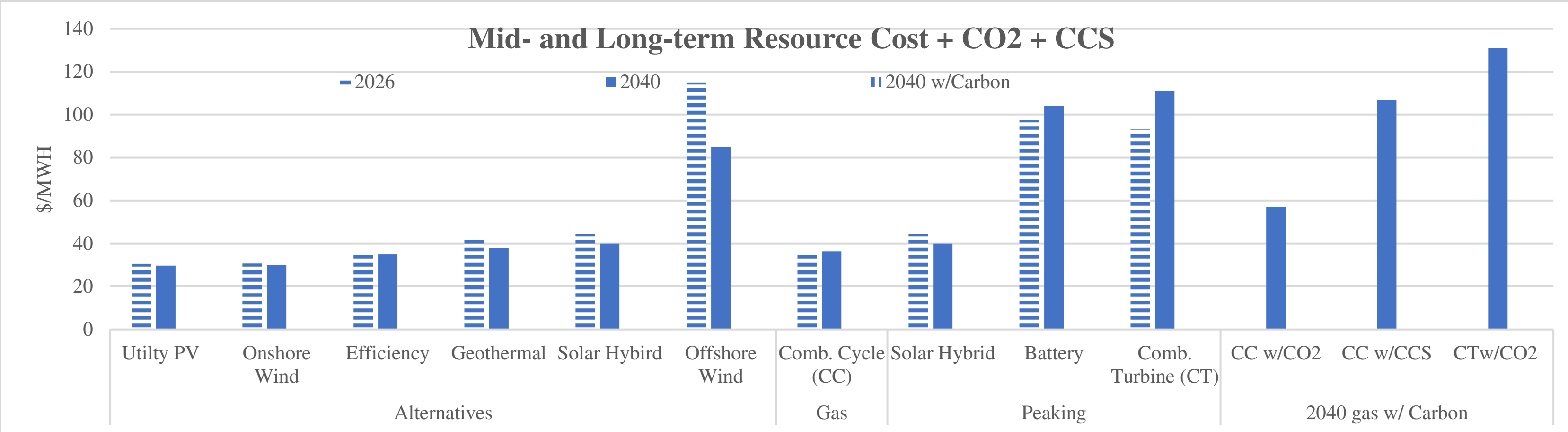
1) The alternative sources are the least-cost option in the midterm and are likely to increase their advantage in the long term. Other low-carbon options, new nuclear, and fossil fuels with carbon capture are much more costly.

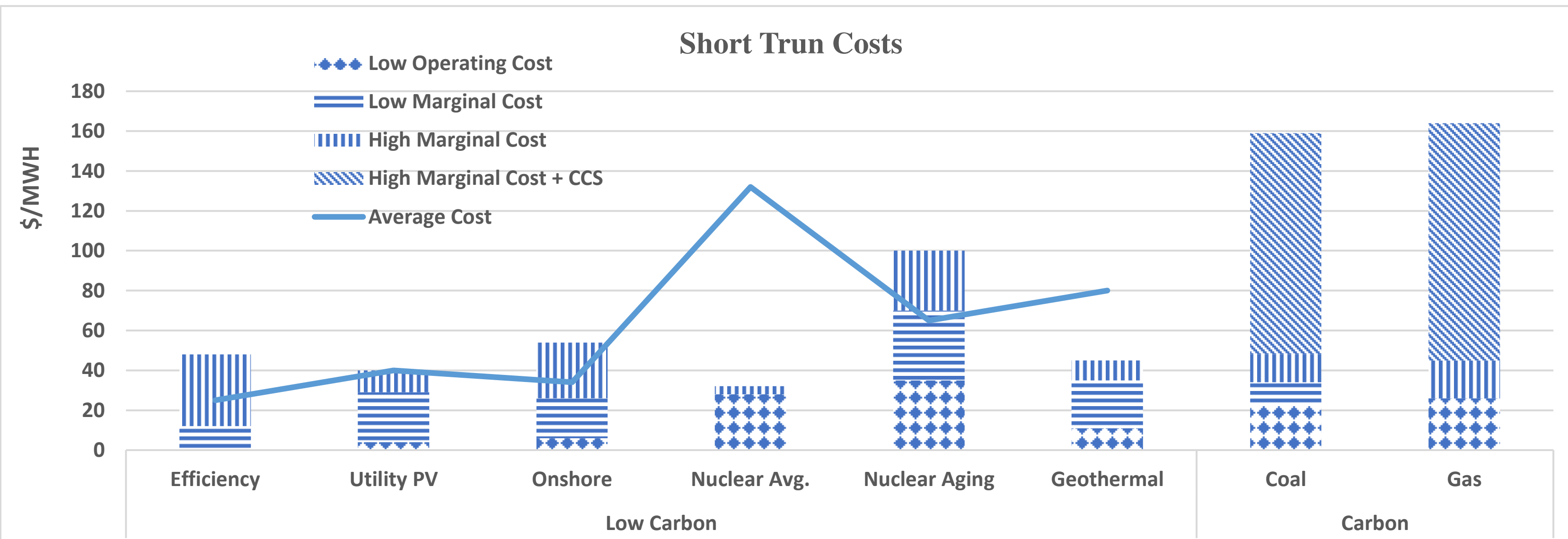
2) EIA is higher on offshore wind but lower on geothermal and advanced nuclear, both of which are not supported by other analyses. EIA does make a significant contribution by including the cost of solar with a battery (hybrid), which is quite low in cost and the technology choice of many utilities at present. The four main resources – efficiency, wind, utility PV, and hybrid PV – make a compelling case for the superiority of the alternatives. Trends of all four are declining much more rapidly than the central-station alternatives.

The analysis should begin with the long-run costs, because that is where the electricity sector will end up. Short-run costs matter too, especially if they differ dramatically from long-run costs. If such a difference exists, then a trade-off must be made between short-run and long-run costs. It turns out, as shown in Figure 2.5, that with respect to electricity resources at present, there is no difference and no need to make a trade-off. The alternatives are competitive with the existing resources in the short run, while they enjoy a substantial long-run advantage. Therefore, selecting resources that minimize long-term costs is the same as resources selected to minimize short-term costs.

Lazard compares the full cost of new-build wind or solar to the marginal cost of existing conventional generation. This is a very demanding comparison, since it is a comparison of all-in costs for alternatives to marginal costs for central-station technologies. To give a sense of a comparison that is "apples-to-apples," however, I also include two other cost numbers.

ES-2: Resource Costs





Sources: Figure 2.3.

First, I use marginal cost for all types of resources. I have included the estimate of the low operating cost provided in the long-run analysis. Needless to say, renewables are very attractive. I have also included the cost of operating aging reactors at only their cost of operation, as expressed in recent subsidy proceedings. Necessary capital costs would increase their total near-term "cost" dramatically, which is what the operators of these reactors are demanding. I also note external costs, which should be included in the short-term analysis, since there are emissions. Here, I include the cost of carbon capture.

I do not include rooftop solar in the main alternatives, because the estimate of resource cost for residential application is quite high. However, these costs have exhibited a rapid decline in recent years, and commercial and industrial rooftop solar are much lower. More importantly, in the case of residential rooftop solar, which is the only individual-level supply-side (behind-the-meter) resource considered in the Lazard analysis, there are several "system" benefits that enhance their value that are increasingly being recognized. I will include residential rooftop solar when I examine the most important external cost: decarbonization.

PART II: OTHER POLICY GOALS

Deploying new technologies stimulates greater economic growth in three ways, as the Illinois Department of Commerce noted:

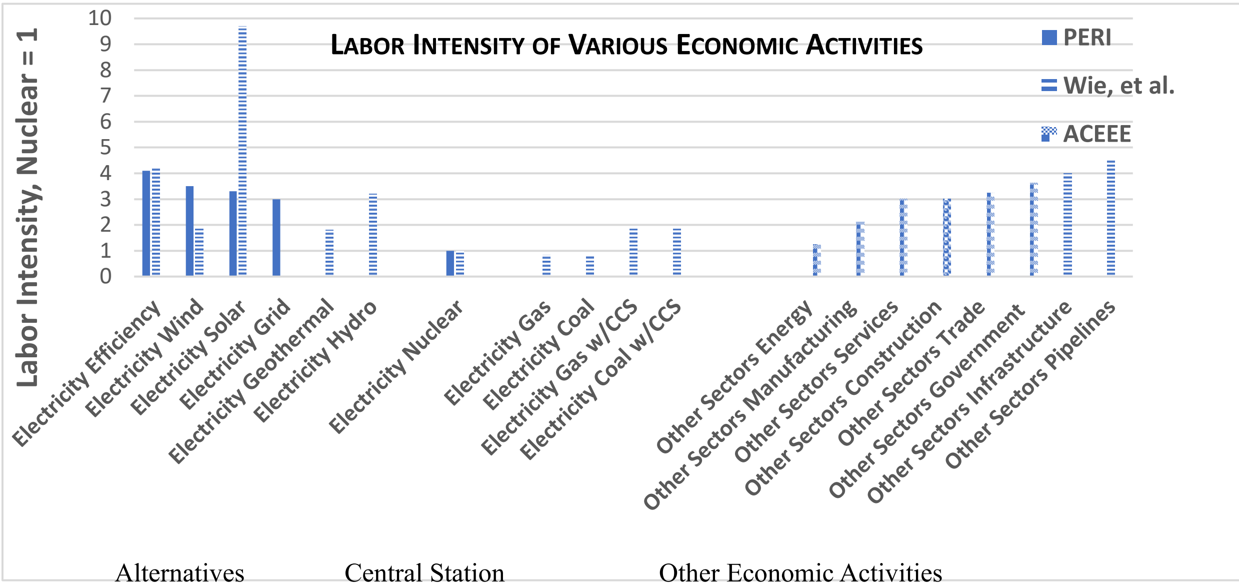
> (Direct) initial economic activity would include the sale of electricity, capacity, and ancillary services effects to the market, and secondary economic activity would include the subsequent economic resulting from how suppliers, employees, and owners of the power plant utilize their earnings that result from those initial sales. ... Indirect effects are those influencing the supply chain that feeds into the business in which the economic activity is located. …. Induced effects come from payments made to employees and subcontractors by the plant that lead to spending by local households.1

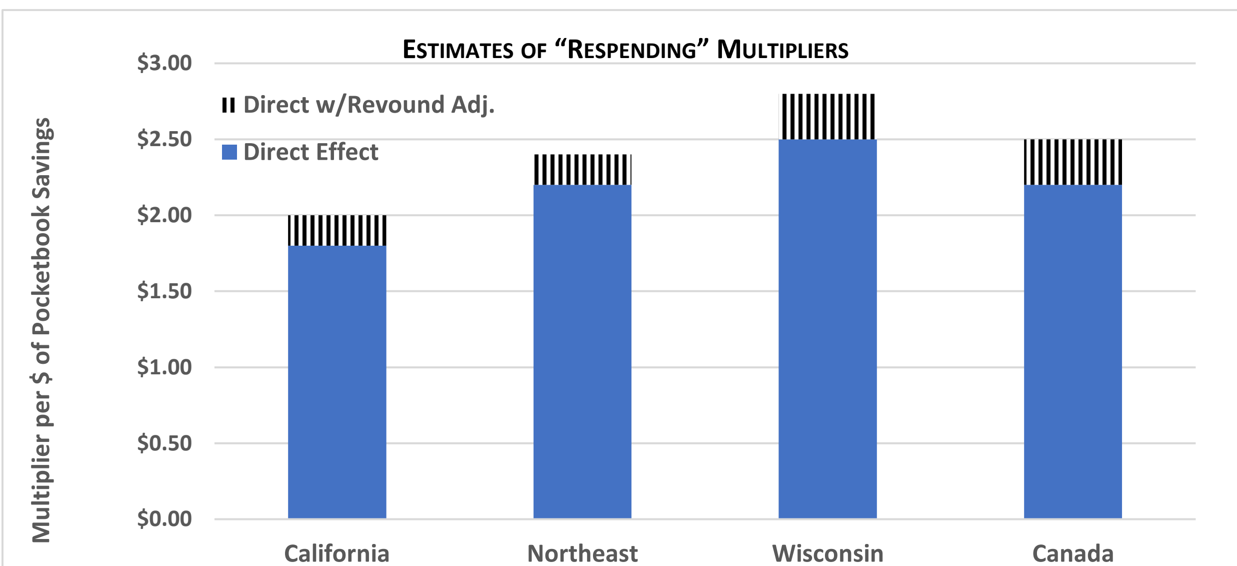
Exhibit ES-3 shows, in the upper graph, the relative job stimulation of various economic activities as calculated by a number of sources. While direct and indirect effects are important, because the renewables are so much lower in cost, the induced effects are particularly large. Lower in cost means the alternatives have a higher multiplier when the energy cost savings are "respent." As shown in the lower graph of ES-3, for every one dollar that is saved and not spent on energy, the economy grows almost an additional dollar.

PART III: MEETING NEEDS WITH ALTERNATIVES AND EXCLUDING NUCLEAR POWER

While the direct and indirect economic effects clearly favor the alternatives, a major question that must be answered is whether or not the alternatives can meet the need for power. Three sets of data reviewed in this paper suggest that the answer is affirmative. Frist, the resource base is huge. Second, a number of states and nations have achieved much higher levels of reliance on alternatives. Third, there are at least three dozen tools available for matching supply and demand in the new, dynamic environment.

EXHIBIT ES-3: IMPACT ON JOBS AND THE ECONOMY





Estimates of Macroeconomic Multipliers as a Multiple of Net Pocketbook Savings

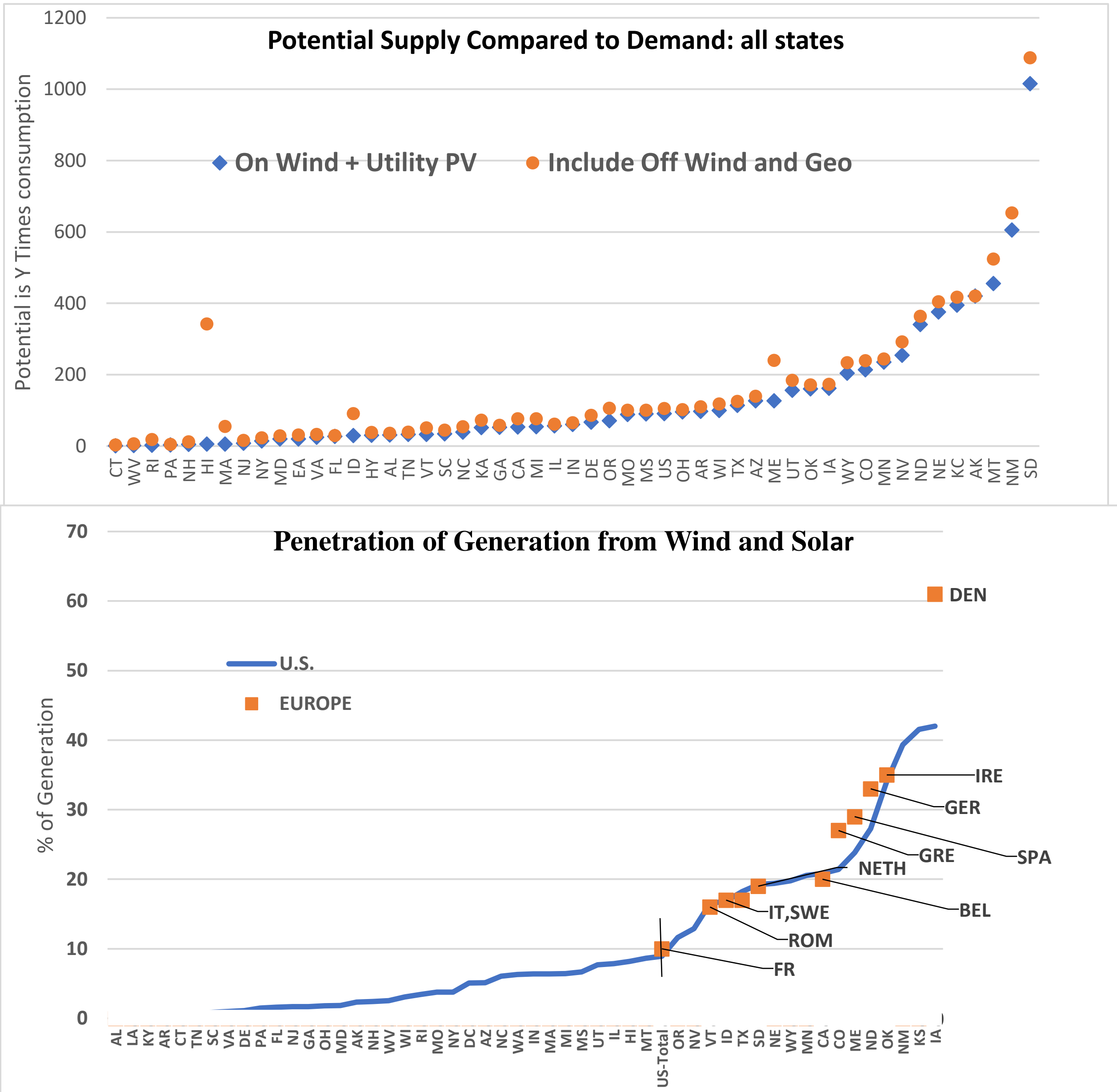
Modeler	Model	Policy Assessed	Region	GDP/$ of Net Savings Base Case	Rebound Adjustment
Roland-Holst	DEAR	Computer Standard	California	1.8	2.0
ENE	REMI	Utility Efficiency	Northeast	2.2	2.4
Cadmus	REMI	Utility Efficiency	Wisconsin	2.5	2.8
Arcadia	REMI	Utility Efficiency	Canada	2.7	3.0

Sources: See Tables 4.3 and Figure 4.4.

Exhibit ES-4 presents data on the available resources and the levels of penetration of wind and solar achieved in various states. All but a few states have abundant resources.

Even those where the supply might be constrained are near states with plentiful resources. Large, densely interconnected grids and diversity are key tools.

ES-4: ASSESSING THE ADEQUACY OF RESOURCES AND PENETRATION OF ALTERNATIVES



Source See Figure 5.4.

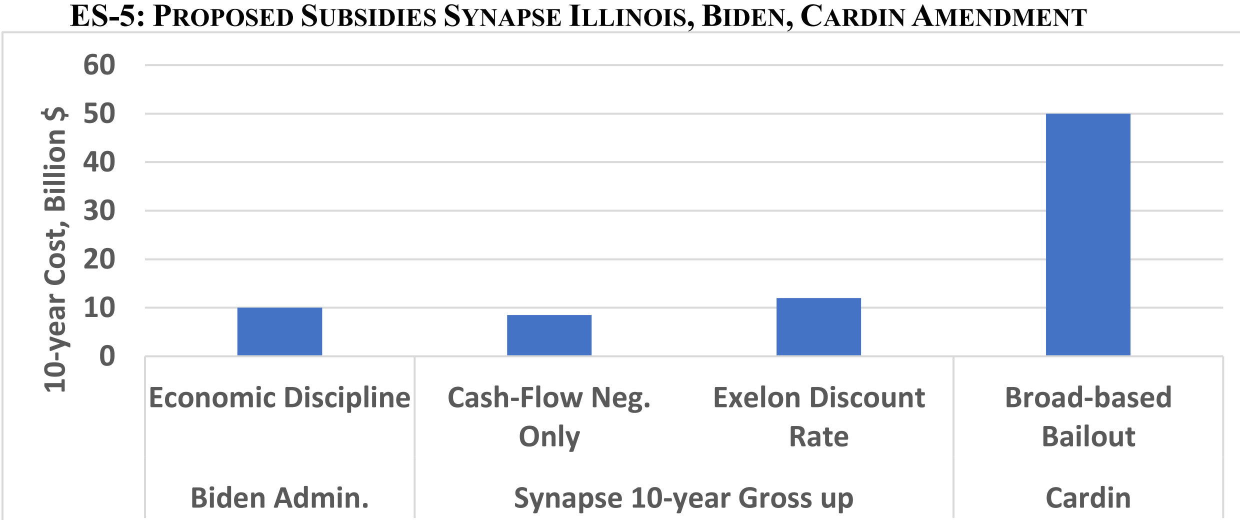
NUCLEAR NIGHTMARES

This analysis makes it clear that no subsidies for nuclear power are justified to achieve the goals. Moreover, nuclear power has been the recipient of subsidies throughout its entire existence – ten times as much as renewables – but it has never delivered on its promise of low-cost power. Small modular reactors appear to be repeating the path of large reactors, with rising costs and increasing delays. Much of the battle to meet the challenge of climate change will be over before even one of these reactors is online. Current special treatments enjoyed by nuclear power are massive.

In spite of 70 years of economic failure (more likely *because* of the failure), nuclear advocates have returned to a favorite strategy, insisting that it is indispensable and hoping for (hyping) a new technology. Nuclear power would like to squeeze into the picture by claiming to solve niche problems at the beginning and the end of the transformation. In the beginning, they threaten to undermine reliability by retiring many reactors. At the end, they claim that only the new technology of small modular reactors (SMRs) can meet a critical need.

A sensible set of rules to keep any reactors that are needed for short-term reliability is already on the books. If more is needed, a small regulatory must-run program can be created. The Biden proposal does so, requiring the nuclear reactor operator show the need and keeping the cost to $1 billion per year (see ES-5). This is consistent with a recent analysis of the need in Illinois by Synapse.

ES-5: PROPOSED SUBSIDIES SYNAPSE ILLINOIS, BIDEN, CARDIN AMENDMENT



Source: See Figure 7.

Given that the need for additional low-carbon resources on the back end of the transformation process is highly doubtful, as is the ability of SMRs to actually get built at an affordable cost, there is no need to subsidize these reactors.

1. BACKGROUND

PURPOSE

In presenting and defending its infrastructure proposal, the Biden administration has argued that it is seizing the opportunity to create millions of new jobs and grow the economy by transforming the nation's energy sector. The greatest opportunity exists in the electricity sector for half a dozen reasons:

- First, electricity is the core of the energy sector of a 21st-century economy, not only because it powers many residential and commercial uses but also because it is central to computing and communications.
- Second, the electrification of much of the transportation sector and many industrial processes in which electricity replaces fossil fuels is possible and necessary to respond to climate change.
- Third, because the alternatives – efficiency, wind, solar, and use of computers and communications to actively manage and match supply and demand – are least-cost options that represent the deployment of new technologies, they also will have the largest impact – not only in lowering costs and reducing pollution but also in terms of increasing employment and growing the economy.
- Fourth, the opportunity to expand the use of electricity has been made possible by a remarkable technological revolution that lowered the cost of alternative resources. This decline in cost is the equal of the reduction in cost that has typified key economic inputs of each of the industrial revolutions that have taken place in the past three centuries.[2]
- Fifth, the alternative system is not only the lowest in cost, it also achieves the greatest reduction in carbon emissions and results in the least concern about environmental impacts.
- Finally, there is no doubt that this is a key infrastructure of a 21st-century economy that is clearly "shovel ready." The core technologies are in hand and need only a strong commitment to implementing the physical and institutional structures that will ensure their rapid growth. The opportunity created by the technological revolution has been recognized for over a decade.

This paper is based on over 550 studies that examine all aspects of the transformation of the electricity sector. Because there are so many citations, I have categorized them as issues and will footnote the themes, as described in Table 1.1. An earlier paper focused on tools for managing the 21st-century electricity systems (based on about 250 papers identified at the time), but the literature has grown as rapidly as the deployment of the key technologies, so this paper takes a slightly different approach. I give the primary location to about 300 studies that identify the nature of the alternatives and the opportunity to build a sector on 100% decentralized and renewable supply, with a big assist from efficiency and intelligent management.

TABLE 1.1
GUIDE TO BIBLIOGRAPHY

Category Issues.

Category		Issues
Scenarios		
a	1	Scenario Broad
a	2	Challenges & solutions
a	3	Evaluations
a	4	Nations/States
Technology Revolutions		
b	1	General
b	2	Energy
Costs and Benefits		
c	1	Cost components
c	2	System values
c	3	Externalities
Meeting Needs		
d	1	Resources
d	2	Supply
d	3	Demand/Eff.
d	4	EVs
e	1	Infrastructure
f	1	Integration
g	1	Sustainable/Reliable
h	1	Behavior
Nuclear		
i	1	Nuclear: Large
i	2	Old
j	1	Subsidies Historic
j	2	Contemporary
j	3	Bailout v. Order - RMR
j	4	Nuclear Hail Mary, SMR

Category Issues.

Category	Issues
(t) Tools	
7	**Generation (Supply)**
8	Geographic diversity
9	Technological diversity
10	Peak targeted solar
11	Quick start/rapid ramp
12	Shed inflexible baseload
13	Shift to flexible
14	Flexible central
15	Firm renewables
16	Value ancillary services
17	Avoid lumpy investment
18	**Load (Demand)**
19	Supply-side
20	Target peaks
21	Use more in slack, less scarcity
22	Demand-side
23	Aggressive demand response
24	Smart controllers manage use
25	**Transmission**
26	Expand balance areas
27	**Storage**
28	Dispatchable, traditional
29	Distributed
30	Electric vehicles
31	**Operational Procedures**
32	Flexibility/integration
33	Integrated transactions
34	Strategic curtailment
35	Improve forecasting
36	**Market Design**
37	Positive and negative prices
38	Target fixed cost recovery
39	TOU (cut peaks, fill valleys)
40	**Prosumer**
41	Smart Grid
42	CHP
43	Buildings

Citations

a	1	3, 18-22, 26, 34,41,135,136, 171, 172, 251, 258, 258, 261-263, 265, 267-272, 300, 458, 460, 507, 515 ,517, 531
a	2	2, 8, 47, 278, 288, 290-292, 430, 497, 560
a	3	9, 15, 40, 264, 293-299, 331, 472, 495
a	4	16, 48, 51,-60, 62, 63, 67, 68, 132, 155, 259, 266, 268,273, 279, 280, 284-287, 539
b	1	334, 500, 508-510, 513, 533
b	2	32, 386, 158, 164, 230, 304-319, 453, 467, 499, 595 508-511, 542, 514, 568
c	1	15, 87, 147, 332, 337, 418-422, 425-427, 434, 548, 605
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d	1	35, 38, 73,154, 216, 238, 255, 333, 336, 366, 369,382, 455, 464, 469, 503, 506, 583, 590
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d	3	89, 90, 169, 227,-229, 254, 354-365, 444-446, 448-451, 454, 475, 476, 494, 505, 535, 559, 577,606, 607
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e	1	125, 126, 161, 254,367,368, 474
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h	1	72, 105-108, 112, 388,391-398, 408, 442, 462
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i	2	403-405, 586,598, 599, 600
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j	2	274, 276, 416, 417
j	3	192, 239, 277, 463, 481, 516-528, 574, 575, 585, 596, 603
j	4	323, 333, 381, 406-411,4 21, 533, 534, 558, 540, 541, 543

Citations

t	7	531. 3, 35, 38, 44, 153, 163, 245-247, 471
t	8	531 96, 156, 237, 429
t	9	531, 131, 134, 156, 240
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t	11	1, 7, 10, 23, 151, 146
t	12	5317, 27, 151, 230, 232, 247
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t	15	531, 1, 226, 84, 85, 96
t	16	1, 2, 7, 8, 48, 52, 59, 60, 138-140, 182, 185
t	17	7, 55
t	18	531, 1, 3, 26, 70, 105-113, 224, 262
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t	21	531, 1, 7,105, 160, 571
t	22	531, 7, 12, 13, 27, 36, 38, 85, 173-179, 261
t	23	531, 115-119, 173, 175-180
t	24	531, 7,27, 186, 187, 495
t	25	531, 56-67, 72, 89, 90, 102
t	26	531
t	27	531, 39, 43, 49, 99, 101, 157, 196-202, 204, 235, 436, 502, 559, 570
t	28	531, 103, 104, 150, 206, 207,
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t	30	531, 1, 11, 13, 35, 104, 113, 114, 233, 266, 272, 273, 276, 277, 279, 549, 580, 550
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t	35	531, 143-145, 441
t	36	531, 8, 12, 14, 30, 33, 69, 70, 83, 88, 95, 98, 148, 149, 181,183, 234 235, 241, 248, 252, 253, 420, 553, 567
t	37	531, 86, 91, 92
t	38	9, 14, 181, 183,184
t	39	7, 8, 27, 64, 105-109, 112
t	40	531, 116, 241 - 442
t	41	531, 11, 79-82, 224-226, 452
t	42	531, 50, 253, 297, 303, 385
t	43	531, 113, 114, 433, 572, 573, 572, 580

Category a-1 identifies major studies that support the possibility of a 100% reliance on the alternatives, while a-2 thru a-4 give various perspectives on the scenarios. Category b-1 puts the transformation of the electricity sector in the context of the prior technological revolutions (the first and second industrial revolutions of the capitalist era). Category b-2 shows that this energy transformation is, itself, a technological revolution. Categories c-1 thru h-1 provide analysis of the key elements of the 21st-century model for the electricity sector. These are linked to an earlier analysis that emphasized the individual tools.

Because of the large number of citations, I have adopted the following conventions in the bibliography and footnotes. Frist, I list the category in which the citation primarily falls. This is composed of a letter and a number for a total of 65 issues areas. I then assign a number to the citation. This number is shown in Table 1.1 where each citation is linked to one or more categories. Because the "tools" are frequently mentioned secondarily in many of the sources, the bibliography only identifies those sources where a tool is the primary focus. However, Table 1,1 lists all the sources where the tool plays an important role. The number is also the key link in the footnotes (which identify the author and the number). Because the citations were culled from "recommended citations" and in many cases and the recommended format varies widely, I have adopted the following lowest common denominator. I use the first author as the reference, followed by other authors. I use "et al." whenever there are more than three authors. I then show the title of the work. Using quotations for articles, followed by the journal name in italics. For a report, I put the title in italics and put the publisher in plain text, followed by the month of publication, where available For journals, I show the volume number, but not the issue, or month, which is quite inconsistent across the recommended citations. I use periods, rather than commas as the separator. The information provided is adequate to locate the sources.

With all this going for them and increasing penetration of the alternatives in the U.S. and globally, why do the new technologies need strong support from public policy? As new technologies based upon a new infrastructure and behavioral principles, flexibility, and small-scale distributed resources, they must displace the incumbent system that has dominated the economy for a century: large, inflexible central-station resources. Simply put, the power source of the third industrial (digital) revolution must replace the power source of the second industrial revolution. This challenge is substantial, and it must overcome the claim that it is not necessary because decarbonization in response to climate change is not a legitimate concern or one that cannot be addressed by policy or because it is simply impossible to change the core of the energy system.

Even among those who accept the need for decarbonization, there is another obstacle that must be overcome. Nuclear power has been a source of low-carbon power in the past, but its future contribution to decarbonization is highly doubtful. Its organizational principle is the most "central-station" of all the central-station sources, involving huge reactors that "must run" because of the nature of the technology and the need to recover massive upfront capital costs and that take a decade or more to build. The nuclear claim is fundamentally similar to the claim of fossil fuel advocates, in the sense that they argue alternatives cannot do the job. Thousands of nuclear power plants would need to power the third industrial revolution and eliminate fossil fuels. The long lead times, high costs, large size, and inflexible operation of central-station reactors have made it clear that they are a bad choice, so the industry has spawned a “new” option: small modular reactors, none of which have ever been built in the U.S.

This paper addresses these obstacles and shows that a 21st-century electricity system can replace the 20th-century system, at lower cost, with much more economic and environmental benefit. It begins in Part I by showing the economic superiority of the alternatives. Part II shows their superiority in terms of “externalities,” economic and environmental. Part III addresses the issue of the ability to meet the need for power with alternative sources and shows why nuclear power has no role to play in a low-carbon future and why any effort to extend the life of nuclear reactors, beyond very short-term needs, is a huge mistake.

OUTLINE

The paper is divided into three parts.

Part I examines the resource costs of the available options, which must be the foundation on which a sound energy policy is based.

Chapter 2 examines the resource costs of the available approaches to meeting the need for electricity. It focuses on supply-side resource but also notes the contribution of low-cost, demand-side measures.

Chapter 3 examines the potential for demand-side contributions, since it is a resource that could replace one of the other central-station resources (either coal or nuclear).

Part II considers the other primary goals that policy has laid out for the electricity sector, examining the important policy issues that play a prominent role in contemporary resource selection.

Chapter 4 presents a discussion of decarbonization, which affects the cost of resources.

Chapter 5 focuses on the issues of creation of jobs and stimulation of economic activity by the various resources. It also briefly mentions other public health and environmental impacts.

Part III addresses the question of whether the alternative, 21st-century system outlined in this paper can deliver adequate, affordable, reliable power.

Chapter 6 discusses the many tools that have been and are being developed to ensure the new electricity system meets or exceeds the performance of the 20th-century system and the many ways a 21st-century system meets demand.

Chapter 7 shows why another huge subsidy for nuclear power cannot be seen as a matter of "fairness" in the treatment of resources and how a large role for nuclear power is antithetical to the transformation of the electricity sector.

Although Chapter 7 deals exclusively with nuclear power, nuclear also appears in the graphs in Chapter 2 and 5, and there are lengthy discussions (almost a dozen pages) in Chapters 4 and 5. The reason that nuclear takes up about one-third of the analysis is simple: After we dispose of the deniers and naysayers (which is increasingly the case across the globe), we encounter nuclear advocates who support decarbonization because they claim nuclear is a low-carbon resource. The analysis disposes of nuclear power as a mistake for a host of reasons: cost, slowness, public health and environmental concerns, but also because it could be a mistake that is fatal to the transformation of the electricity sector.

PART I

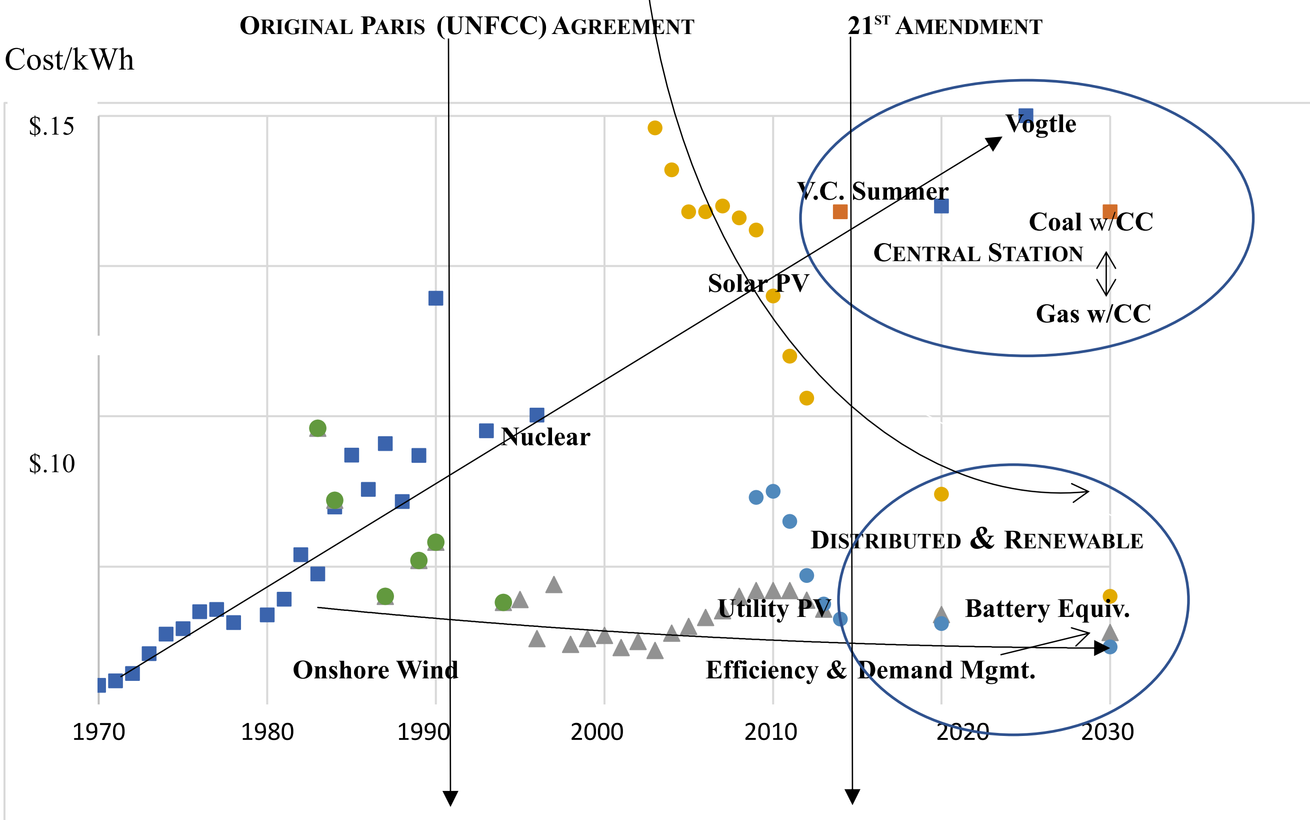
PRIMARY GOAL:
AFFORDABILITY AND RESOURCE COSTS

2. THE ECONOMIC ADVANTAGE OF THE ALTERNATIVES: THE OPPORTUNITY TO TRANSFORM THE ELECTRICITY SYSTEM

TECHNOLOGY-DRIVEN OPPORTUNITY

In my recent book on the transformation of the electricity sector, I argued that the correct approach to climate change confronts a basic dilemma that must balance "development and decarbonization."[3] Further, as shown in Figure 2.1, I argued that when the treaty underlying the Paris Agreement was negotiated in the early 1990s, "it was impossible to pass through the horns of the dilemma." Aside from significant energy efficiency which could lower demand – by as much as 30% – the technologies did not exist to produce low-cost, low-carbon electricity to meet demand. However, as also shown in Figure 2.1, the dramatic technological revolution of the past three decades changed that.

FIGURE 2.1
BROAD, LONG-TERM RESOURCE COST TRENDS



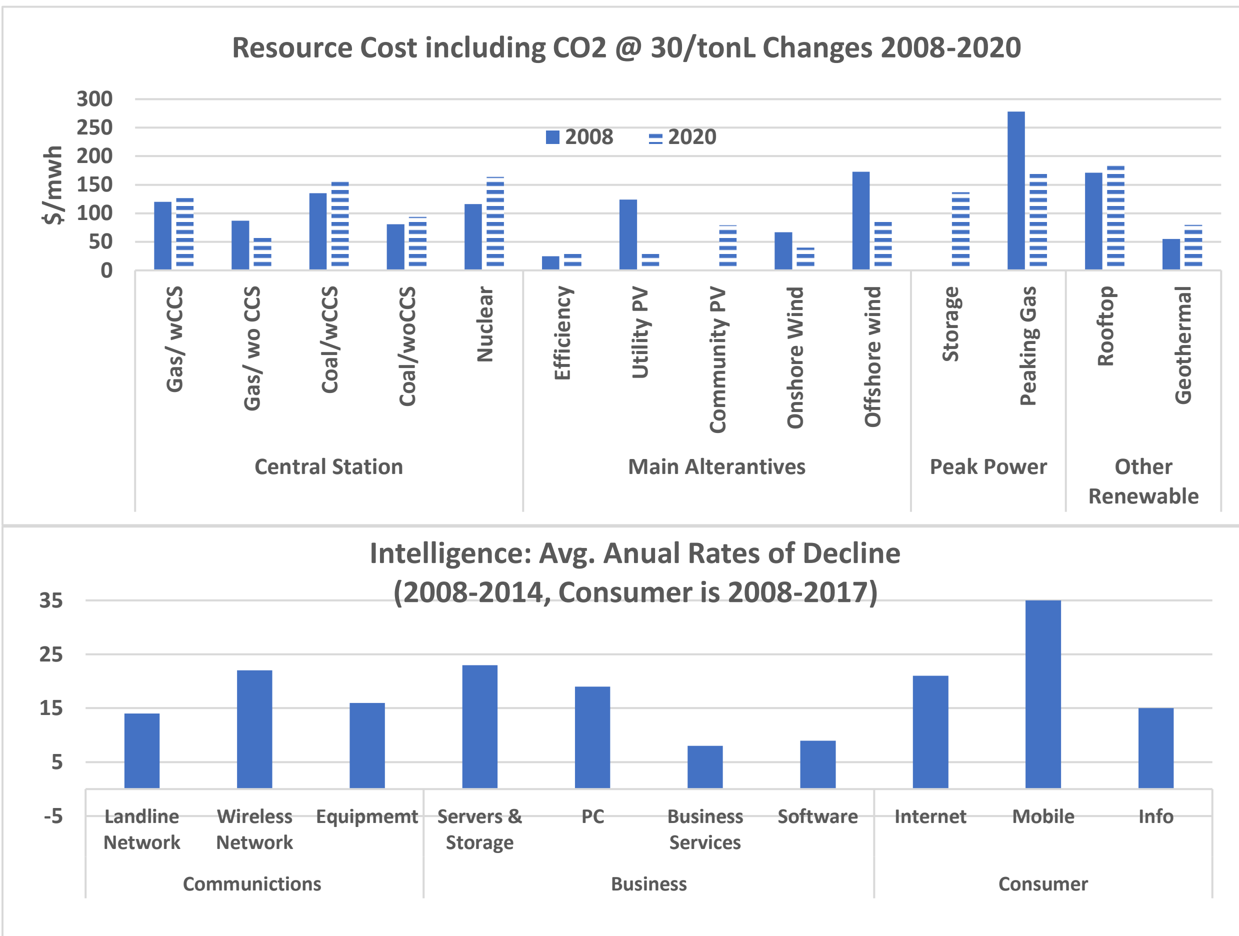
Source: Updated and adapted from Mark Cooper, *The Political Economy of Electricity: Progressive Capitalism and the Struggle to Build a Sustainable Sector* (Santa Barbara, Praeger, 2017), Figure 2.1 and accompanying text. (Overnight cost for capital-intensive technologies, fuel-intensive technologies based on relative cost per kWh.)

Not only has it become possible to achieve the balance between economic growth and reduced carbon emissions, that possibility has become compelling. The least-cost approach to the future requires policymakers and regulators to use the alternatives to the fullest extent possible. The least-cost approach is also preferable in pursuit of decarbonization, economic development, pollution reduction, public health, and protection of the environment, as discussed in Chapter 4.

THE TECHNOLOGICAL REVOLUTION AND MIDTERM COSTS

As shown in Figure 2.2, the past dozen years have seen a dramatic growth in the potential to meet demand with low-carbon resources, not only because of the continued decline in the cost of alternatives – decentralized resources such as wind, solar, and storage – but also because of the dramatic decline in the cost of digital communications and the increase in computational power.

FIGURE 2.2
A CRITICAL JUNCTURE[4] IN MEETING ELECTRICITY NEEDS

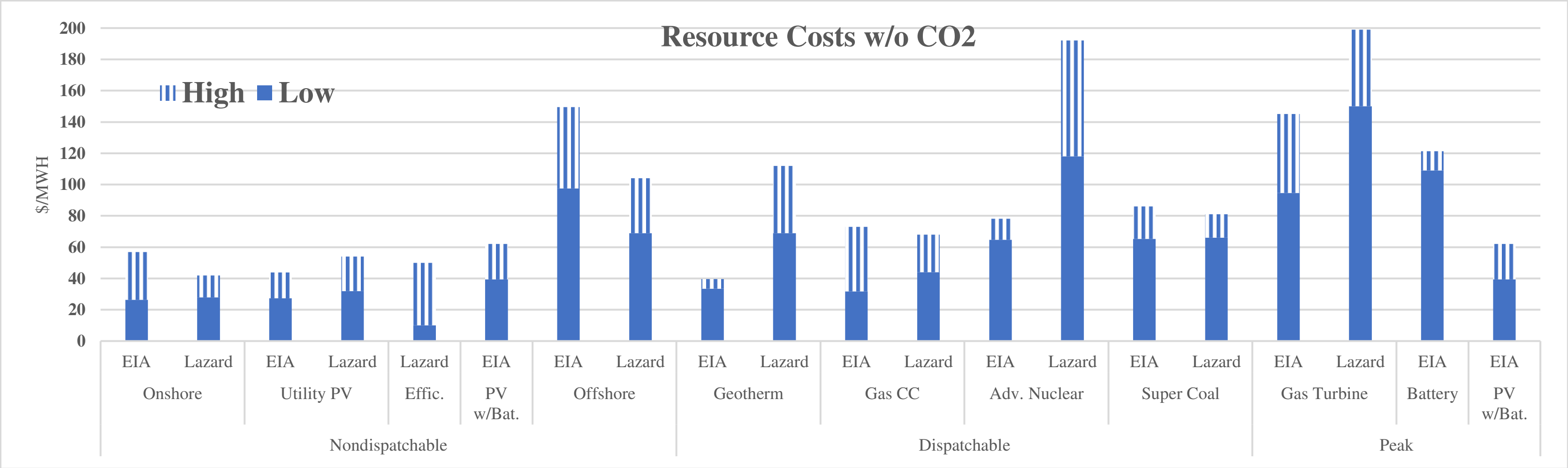


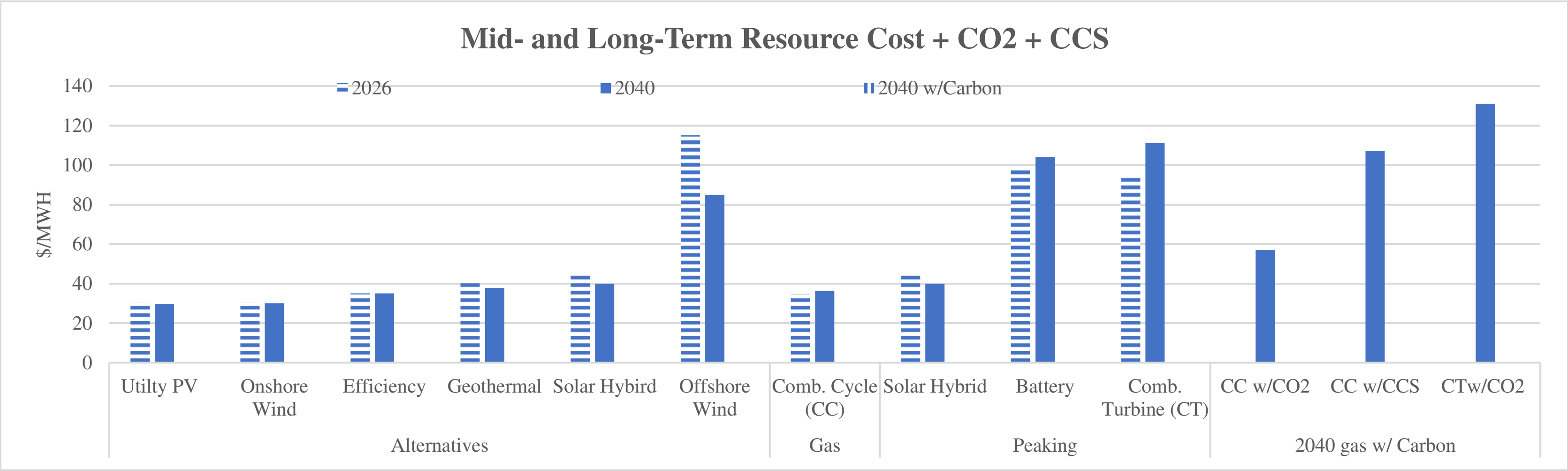
Sources: Energy costs, Lazard, Version 2.0-14.0; ICT, David M. Byrne and Carol A. Corrado, 2015, *Price for Communications Equipment: Rewriting the Record;* 2017, *ICT Services and their Prices: What do they tell us about Productivity and Technology?* Finance and Discussion Series, Federal Reserve Board Paper No. 2015-069, 2017-015; 2015, "Recent Trends in Communications Equipment Prices," *Fed Notes,* September 29, This broad technological revolution brings us to the possibility for a major advance in the ability to meet energy needs. For the past decade, I have used the cost estimates offered in the electricity analysis of a Wall Street financial analysis firm, Lazard,[5] for a number of reasons:

- First and foremost, Lazard's projections have tracked the actual development of costs over the past decade much more closely than others.
- From the outset, Lazard's analysis included efficiency.
- Lazard's was among the first of the comprehensive analyses to note the strong downward trend in the cost of solar and to begin arguing that solar was cost-competitive for peak power in some major markets.
- The analysis always included estimates for coal with carbon capture and storage, and later added an estimate for the cost of natural gas with carbon capture and storage.
- Lazard recognized the high cost of nuclear and increased the estimates as cost overruns undermined the "nuclear renaissance."
- The analysis includes regional estimates for resources whose economics vary by location.
- The more recent analysis adds important storage technologies, utility-scale solar with storage, and utility-scale battery storage. It also presents a cost trend for storage that is similar to the trends from other renewable and distributed sources.
- The analysis always included natural gas peaking capacity costs and, in a recent analysis, added a cross-national comparison of peaking technologies that might displace gas as the peaker resource.
- The analysis has also recently added comparisons of carbon abatement costs, as the determination to deal with climate change has grown.
- Most recently, Lazard has made the case that building new alternatives (new builds) is less costly that the operating (marginal) cost of traditional, central-station facilities.

As shown in Figure 2.3, efficiency is still low cost, and the main renewables, utility photovoltaics and onshore wind, have experienced dramatic cost declines. The alternatives now beat central-station alternatives by a substantial margin, even before the cost of carbon is taken into account. Community PV and offshore wind are certainly competitive with central-station generation when carbon is taken into account. The decline in resource costs makes it possible to dynamically integrate supply and demand to organize and manage a decentralized 21st-century electricity system, but a second technological revolution plays an important part. The dramatic decline in the cost of intelligence and communications means that decentralization and dynamic management reduce the system size and shift system demand sufficiently to yield a transformation dividend. The dividend is a 15-20% reduction in size, which lowers costs compared to the antiquated 20th-century approach.[6]

FIGURE 2.3
RESOURCE COSTS IN THE MIDTERM: EIA VS. LAZARD





Sources: Energy Information Administration (EIA), Cost of Generation; Lazard, Levelized Cost of Energy, v. 14; v. 13 for carbon costs, CCS.

The differences between EIA and Lazard are obvious. EIA is low on geothermal and gas peakers and extremely low on advanced nuclear but high on offshore wind. One particularly important addition of the EIA analysis is the consideration of "hybrid" solar applications. These are solar facilities combined with six hours of battery storage. Since this is what many utilities are adding, it deserves attention. The EIA discussion about how to classify this technology application suggests an uncertainty between considering it as dispatchable and non-dispatchable.

> Solar photovoltaic (PV) hybrid technology is represented by LCOE … because EIA assumes it operates as an integrated unit supplying electricity to the grid .…The solar PV hybrid LCOE is included under non-dispatchable technologies because, much like hydroelectric generators, solar PV hybrid generators are energy-constrained and so are more limited in dispatch capability than generators with essentially continuous fuel supply … solar PV generating assets have seasonal and diurnal storage, respectively, so that they can be dispatched within a season or a day, but overall operation is limited … by daytime for hybrid solar PV … the capacity-weighted average value-cost ratio is greater than one for both standalone and hybrid solar PV and geothermal in 2026, suggesting that these technologies will be built in regions where they are economically viable. …. For battery storage, capacity might be added in regions with higher renewables penetration, particularly solar, to capture any curtailments that would otherwise occur during the daytime, allowing for higher levels of capacity additions in those regions.7

Reflecting the ambiguity, I list this hybrid twice, once as a non-dispatchable resource and once as a peaking resource, since the battery component is generally intended to make power available at the peak or around it. EIA has separate listing for batteries, which is clearly a peaking resource, although as discussed below, it serves a number of functions that can reduce the need not only for peak generation but also for transmission and distribution infrastructure.

A second issue that arises in the analysis is the question of carbon cost. The fossil fuels are significant emitters. Therefore, in a low-carbon world, their cost is an understatement, which ignores the cost of carbon. Lazard has prepared a separate analysis of the "value of carbon" reduction, which I have incorporated in the lower graph. The cost of carbon capture and storage for these fossil fuels would actually be about $30/MWh higher.

The reality of resource costs comes out when EIA estimates the capacity-weighted cost of various resources. (EIA does not offer capacity-weighted averages for coal or advanced nuclear for 2026.) They are considered "technologies for which capacity additions are not expected [and] do not have a capacity-weighted average and are marked as *NB*, or *not built*." The absence of coal or advanced nuclear new builds continues in 2040. In short, no new nuclear or coal projects take place. By that time, the battle against climate change will be significantly over, one way or the other. If the U.S. follows a least-cost, low-carbon approach, the electricity sector will be largely transformed. The options effectively on the table are alternatives and gas. The alternatives are less costly – and much less costly if carbon is taken into account.

As shown in Figure 2.1, above, nuclear reactors are an "old" technology with a long track record of high cost. No reactor has been delivered at a cost suggested by EIA in at least a quarter of a century. The only reactors under construction are running two to three times as high as the EIA estimate, and the cost overruns are not done yet.

If EIA is thinking about a new technology, small modular reactors, it is sorely mistaken to include such a low estimate. More importantly, none of these reactors has been built, cost estimates have been escalating, and current costs appear to be twice the EIA estimate. Moreover, it would be two decades before enough of these reactors could be built to have an impact on carbon emissions.

The key takeaway from Figure 2.3 is that the alternatives are not only the lowest cost, low-carbon resources, they are also the least-cost resource, ignoring the value of carbon reduction. If the focus is on building new facilities, the alternatives are much less costly in the midterm (at present and for the next five years).

KEY COST TRENDS

Long-term cost trends paint an even rosier picture of the alternatives. The cost declines are projected to continue, moderately for wind and solar, dramatically for storage. Figure 2.4 presents Lazard's estimates of unsubsidized cost trends for the main renewable resources: utility PV and onshore wind. The graphs include a projection of the next decade. In both, a simple exponential curve fits the data well. Clearly, it is reasonable to expect these costs to continue to decline. In the less optimistic view, where the early large cost declines have been excluded and we use only the last eight years as the basis for projection, we arrive at costs in the range of $20-$35 per MWh.

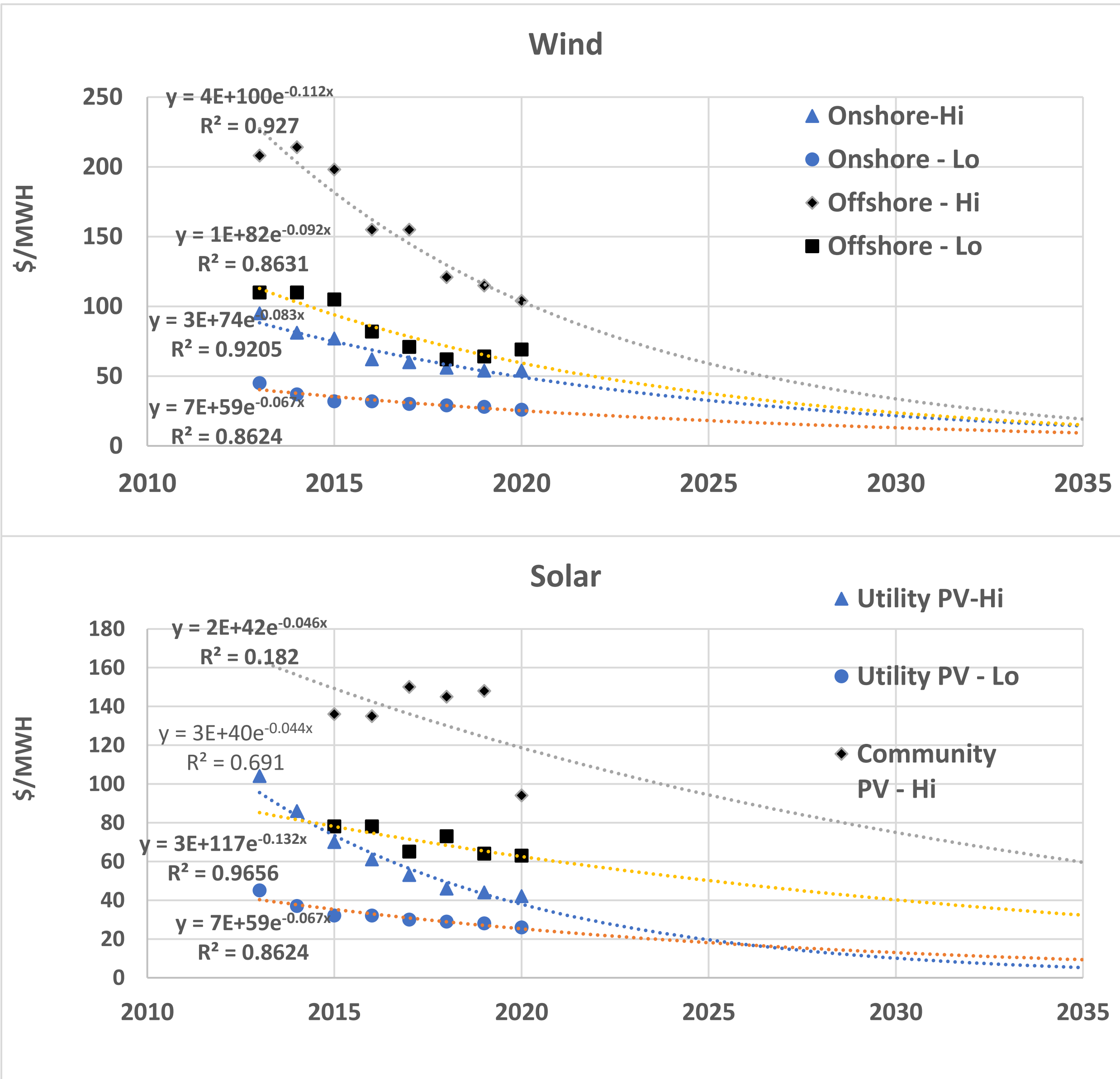
Projecting storage (battery) costs is difficult because of the complexity of applications. Lazard identified five functions,[8] five contexts,[9] and nine technologies,[10] for a total of over 60 combinations,[11] with high and low unsubsidized cost estimates for each.[12] Nevertheless, in 2016, he estimated that battery storage was viable or nearly so based on internal rates of return in three of the five largest grid organizations.[13] Utility management was very bullish on future cost declines for several of these, first among them lithium-ion batteries at an annual decline in cost of almost 36%.[14]

> Lazard's latest annual Levelized Cost of Storage Analysis (LCOS 6.0) shows that storage costs have declined across most use cases and technologies, particularly for shorter-duration applications, in part driven by evolving preferences in the industry regarding battery chemistry.
>
> Sustained cost declines were observed across the use cases analyzed in our LCOS for lithium-ion technologies (on both a $/MWh and $/kW-year basis). The cost declines were more pronounced for storage modules than for balance-of-system components or ongoing operations and maintenance expenses.
>
> Project returns analyzed in our "Value Snapshots" continue to evolve as hardware costs decline and the value of available revenue streams fluctuates with market fundamentals.

Project economics analyzed for standalone behind-the-meter applications remain relatively expensive without subsidies, while utility-scale solar PV + storage systems are becoming increasingly attractive.

Long-duration storage is gaining traction as a commercially viable solution to challenges created by intermittent energy resources such as solar or wind.[15]

FIGURE 2.4
LAZARD TRENDS FOR WIND AND SOLAR



Source: Lazard, Levelized Cost of Energy, various years

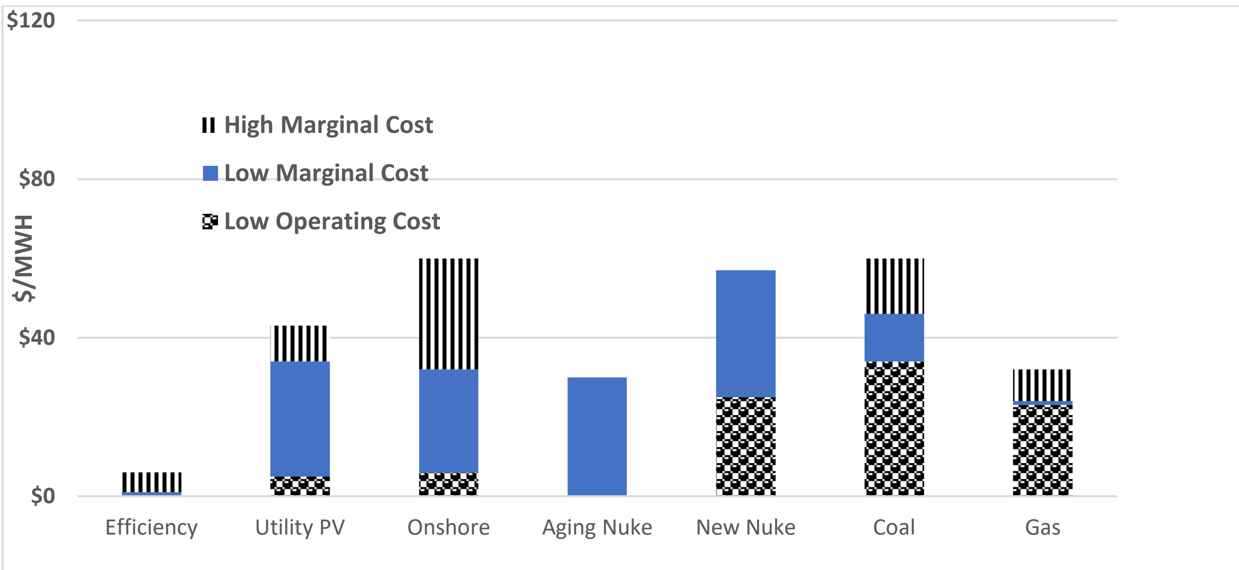
EIA puts the growth in storage capacity at 35% per year from 2015 to 2018.[16] It projects a declining cost for lithium-ion batteries at 10% to 13% per year for 2020-2030 with a massive increase in storage.[17]

SHORT-RUN COSTS

The analysis should begin with the long-run costs, because that is where the electricity sector will end up. Short-run costs matter too, especially if they differ dramatically from long-run costs. If such a difference exists, then a trade-off must be made between short-run and long-run costs. It turns out, as shown in Figure 2.5, that with respect to electricity resources at present, there is no difference and no need to make a trade-off. The alternatives are competitive with the existing resources in the short run, while they enjoy a substantial long-run advantage. Therefore, selecting resources that minimize long-term costs is the same as resources selected to minimize short-term costs.

FIGURE 2.5
SHORT-RUN COST OF RESOURCES

Costs Per MWh



Source: Lazard, *Lazard's Levelized Cost of Energy Analysis – Version 14.0,* October 2020. Long-terms costs are from the section "Levelized Cost of Energy—Key Assumptions," with efficiency from Version 9.0, and gas carbon capture from Version 8.0. Low capture costs reflect the utilization rates that that are used in the low estimate of unabated costs (83% for coal and 70% for gas). Low cost for aging reactors is the operating cost subsidy they have demanded, while the high-cost estimate includes capital cost recovery. Short-term costs are from Lazard, "Levelized Cost of Energy Comparison – Renewable Energy Versus Marginal Cost of Selected Existing Conventional Generation" and "Levelized Cost of Energy Components – Low End," for low operating costs.

These comparisons in Lazard raise questions. First, there is an assumption implicit in Lazard's analysis that leads to an underestimation of the cost of traditional central-station technologies. As is the case with almost all cost estimates, Lazard uses a high capacity factor for all three of the traditional technologies, which is well above the actual average observed in the U.S. As a result, costs are underestimated.

Second, Lazard compares the full cost of new-build wind or solar to the marginal cost of existing conventional generation. This is a very demanding comparison, since it is a comparison of all-in costs for alternatives to marginal costs for central-station technologies. Nevertheless, the conclusion Lazard reaches is that certain renewable energy generation technologies have an LCOE [levelized cost of electricity] that is competitive with the market cost of existing conventional generation.[18]

To give a sense of a comparison that is "apples-to-apples," however, I use marginal cost for all types of resources. I have included the estimate of the operating cost provided in the long-run analysis. Needless to say, renewables are very attractive. I have also included the cost of operating aging reactors, as expressed in recent subsidy proceedings, at only their cost of operation. Necessary capital costs would increase their total near-term cost by about 25% to 50%. I also note external costs, which should be included in the short-term analysis, since there are emissions. The point is that the short-term comparisons are not at odds with the long-term results. Since the alternatives are least cost in the long term and competitive in the short term, there is no trade-off necessary. The alternatives are preferable.

3. THE HIDDEN FUEL: ENERGY EFFICIENCY

While the costs of key generation resources (wind, solar) are important, there are also two key technological revolutions that have taken place on the demand side. First and foremost is the large role that energy efficiency can play in the transformation of the electricity system. The second is what I call the "transformation dividend," which is a result of the development and application of intelligent technologies to the management of the grid. This is a mixture of supply-side and demand-side developments. Because demand management plays an important role here, I discuss the dividend in this chapter. However, the chapter begins with the much larger and "pure" benefits of energy efficiency.

THE POTENTIAL CONTRIBUTION: QUANTITY AND COST

A recent comment[19] on the International Energy Agency[20] report on energy efficiency notes that energy efficiency can be called the "hidden fuel."

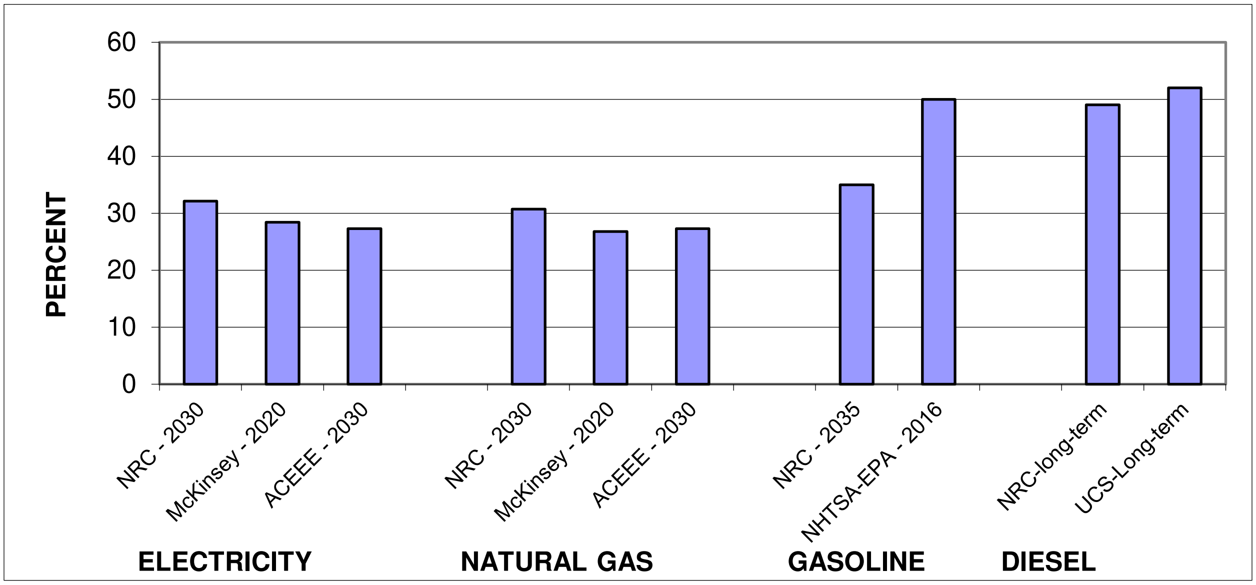
> What is the World's most important fuel? (Hint: It is also the energy resource that all countries have in abundance.) The answer to this riddle is energy efficiency, which is sometimes referred to as the "hidden fuel." That is the powerful message of the *Energy Efficiency Market Report 2016* published by the International Energy Agency.
>
> A strong energy efficiency policy is vital to achieving the central policy goals of improving energy security and reducing CO2 emissions as well as air pollution in the most cost-effective way. More countries are discovering that the safest and cleanest power plant is the one you don't have to build thanks to higher efficiency.
>
> Whereas energy policy has traditionally been dominated by a supply-side bias (i.e., how do we produce more oil, gas, electricity?), policymakers increasingly understand we need to focus more on the demand side of the equation (i.e., how do we consume less energy?).[21]

The report he cites supports this observation by estimating that about 30% of projected demand could be met with efficiency.

U. S. Potential

Current estimates for the near-term ability to reduce energy consumption without reducing energy services are in the range of 15% to 30% for 2030 and 2050, respectively, as shown in Figure 3.1. It includes some estimates that are 20 years old, as well as more-recent estimates, all from leading research institutions in the field. The 30% figure is a good, midterm estimate. The potential long-term reduction in consumption of diesel fuel, which is used by heavy-duty trucks, is considerably larger, primarily because the first fuel economy standards were only recently adopted, almost 40 years after the first fuel economy standards for light-duty vehicles were adopted.

FIGURE 3.1
SIZE OF THE EFFICIENCY GAP ACROSS U.S. ENERGY MARKETS:
TECHNICALLY FEASIBLE, ECONOMICALLY PRACTICABLE POTENTIAL ENERGY SAVINGS



Sources: Cooper, Mark, 2013, *Energy Efficiency Performance Standards: The Cornerstone of Consumer-Friendly Energy Policy,* Comments of the Consumer Federation of America, October.. Electricity and natural gas savings based on Gold, Rachel, Laura, et. al., Energy Efficiency in the American Clean Energy and Security Act of 2009: Impact of Current Provisions and Opportunities to Enhance the Legislation, American Council for an Energy Efficient Economy, September 2009), McKinsey Global Energy and Material, Unlocking Energy Efficiency in the U.S. Economy (McKinsey & Company, 2009); National Research Council of the National Academies, America's Energy Future: Technology and Transformation, Summary Edition (Washington, D.C., 2009). The NRC relies on a study by Lawrence Berkeley Laboratory for its assessment (Richard Brow, Sam Borgeson, Jon Koomey, and Peter Biermayer, U.S. Building-Sector Energy Efficiency Potential (Lawrence Berkeley National Laboratory, September 2008). Gasoline based on National Highway Traffic Safety Administration, *Corporate Average Fuel Economy for MY2012-MY 2016 Passenger Cars and Light Trucks*, *Preliminary Regulatory Impact Analysis*, Tables 1b, and 10. The 7% discount rate scenario is used for the total benefit = total cost scenario; NAS -2010, National Research Council of the National Academy of Science, *America's Energy Future* (Washington, D.C., 2009), Tables 4.3, 4.4; MIT, 2008, Laboratory of Energy and the Environment, On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions Cambridge: July, 2008), Tables 7 and 8; EPA-NHTSA - 2010, Environmental Protection Agency Department of Transportation In the Matter of Notice of Upcoming Joint Rulemaking to Establish 2017 and Later Model Year Light Duty Vehicle GHG Emissions and CAFE Standards, Docket ID No. EPA-HQ-OAR-0799 Docket ID No. NHTSA-2010-0131, Table 2, CAR – 2011. Diesel based on Northeast States Center for a Clear Air Future, International Council on Clean Transportation and Southwest Research Institute, *Reducing Heavy Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions,* October *2009;* Don Air, *Delivering Jobs: The Economic Costs and Benefits of Improving the Fuel Economy of Heavy-Duty Vehicles,* Union of Concerned Scientists, May 2010; Committee to Assess Fuel Economy for Medium and Heavy Duty Vehicles, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles,* National Research Council, 2010.

In an earlier paper, I summarized the analytic consensus as follows:

In the past year, four major national research institutions have released reports that document the huge potential for investments in energy efficiency to lower consumers' bills and greenhouse gas emissions, creating a win-win for consumers and the environment. The National Research Council of the National Academy of

> Sciences has estimated the potential reduction in electricity, natural gas, and gasoline at approximately 30%, similar to the estimates of NHTSA/EPA. McKinsey & Company and the American Council for an Energy-Efficient Economy have reached a similar conclusion on electricity and natural gas. Across these three sectors, saving energy costs about one-third of the price of producing it. With the publication of these studies, the question is no longer "Can efficiency make a major contribution to meeting the need for electricity in a carbon-constrained environment?"
>
> These studies demonstrate that it can.[22]

The figure includes potential efficiency gains in all forms of fossil fuels, in addition to electricity, for several reasons.

First, the existence of the "efficiency gap" across all the uses and the forms of energy is testimony to the pervasive market failure that afflicts energy markets. These market imperfections are not the subject of this paper, but they are important to note, as measured by the gap.[23]

Second, the effort to eliminate carbon emissions would inevitably include a significant electrification of the end uses for natural gas, gasoline, and diesel, in addition to the decarbonization of the electricity sector. That is, more efficient use of these fossil fuels would still leave each with a substantial carbon footprint. Electrification with zero carbon resources would eliminate that footprint.

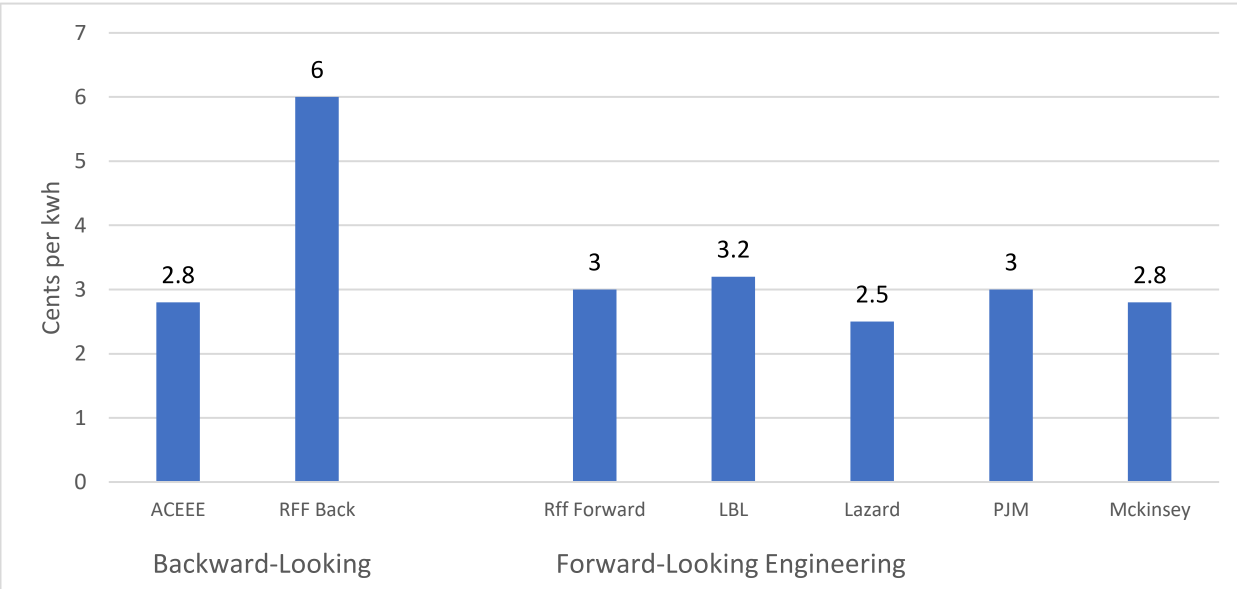
Third, although much of the efficiency gap that could be filled involves technologies applied to the use of fossil fuels – i.e., improving the combustion characteristics of internal combustion engines – some of the improvement comes from the design and operating characteristics of the durable good.[24] Those gains are available to improve performance, even with the shift to electrification.

Ironically, although significant progress has been made in capturing energy efficiency gains, the potential contribution of energy efficiency has been constant for several decades, since it first attracted attention. The fact that the potential has not been diminished can be explained by factors of technological and economic progress, which are discussed below. However, since similar processes affect the cost of efficiency, I will discuss the stable, even declining, cost of efficiency first.

Cost

As shown in the lower graph of Figure 3.2, the cost of efficiency has remained low for decades, and there is every indication that the cost of efficiency is not rising. In fact, the cost of energy efficiency has exhibited a similar pattern for several decades. Vast quantities of energy can be saved at a very low cost, with the economically attractive opportunities expanding as new technologies convert what was known as "technical potential" into "economically attractive potential." The forward-looking cost is about $.03/kWh, below the backward-looking cost.[25] The reasons for the stable and slightly declining cost are learning-by-doing, economies of scale, and improving technology. There is also a significant reduction in electricity demand that occurs from the effect of shifting to decentralized technologies that better match supply and demand, which I call the "transformation dividend." Thus, efficiency is cost-competitive with the other alternatives and makes a substantial contribution to meeting need.[26]

FIGURE 3.2
THE COST OF SAVED ELECTRICITY



Source: Kenji Takahasi and David Nichols, "Sustainability and Costs of Increasing Efficiency Impact: Evidence from Experience to Date," *ACEEE Summer Study on Energy Efficient Buildings* (Washington, D.C., 2008), pp. 8-363; McKinsey Global Energy and Material, *Unlocking Energy Efficiency in the U.S. Economy* (McKinsey & Company, 2009); National Research Council of the National Academies, *America's Energy Future: Technology and Transformation, Summary Edition* (Washington, D.C., 2009). The NRC relies on a study by Lawrence Berkeley Laboratory for its assessment (Richard Brown, Sam Borgeson, Jon Koomey and Peter Biermayer, *U.S. Building-Sector Energy Efficiency Potential* (Lawrence Berkeley National Laboratory, September 2008).

Engineering economic analyses provided the initial evidence for the efficiency gap. *Ex ante* analyses indicated that there would be substantial net benefits from including technologies to reduce energy consumption in consumer durables. As these policies were implemented, *ex post* analyses were conducted to ascertain whether the *ex ante* expectations were borne out.

Combining the observations on quantity and price for electricity leads to an extremely important and surprising economic transformation, as shown in Table 3.1. The link between electricity consumption and economic growth has been broken. In contrast to the three decades after World War II (1950-1980), where electricity consumption per dollar of per capita GDP grew by almost 3%, the figure was flat between 1980 and 1995 and declined by 2% per year between 1995 and 2019.

TABLE 3.1
ANNUAL CHANGE IN U.S. ELECTRICITY GENERATION PER DOLLAR OF GDP PER CAPITA

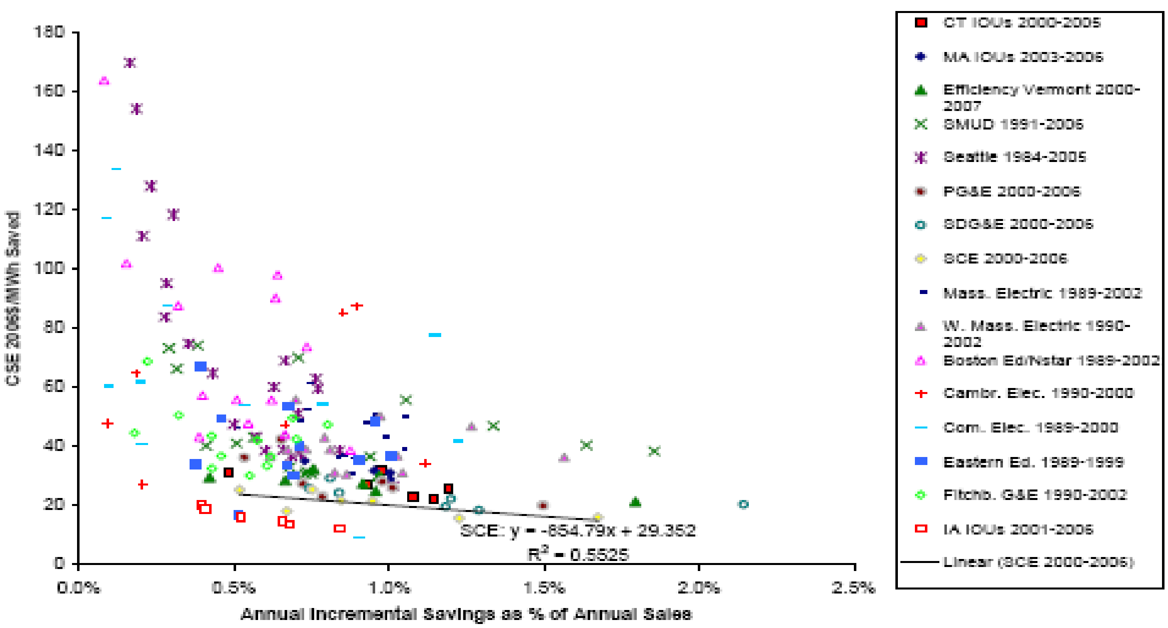
Period	Annual % Change Electricity	GDP/capita	Electricity/ GDP/capita
1950-1980	+6.4	+3.5	+2.89
1980-1995	+1.9	+2.2	-0.000
1995-2019	+1.3	+3.3	-2.0

Source: U.S. Energy Information Administration, *Monthly Energy Review,* various, and *US Real GDP by Year.*

CONSTANT QUANTITY AND COST: TECHNOLOGICAL & ECONOMIC PROGRESS

The most intense and detailed studies were conducted by utilities subject to regulation. Figure 3.3 shows the results of analyses of the cost of efficiency in 16 states over various periods covering the last 20 years. The data points are the annual average results obtained in various years at various levels of energy savings. The graph demonstrates two points that are important for the current analysis.

FIGURE 3.3
UTILITY COST OF SAVED ENERGY VS. INCREMENTAL ANNUAL SAVINGS AS A % OF SALES



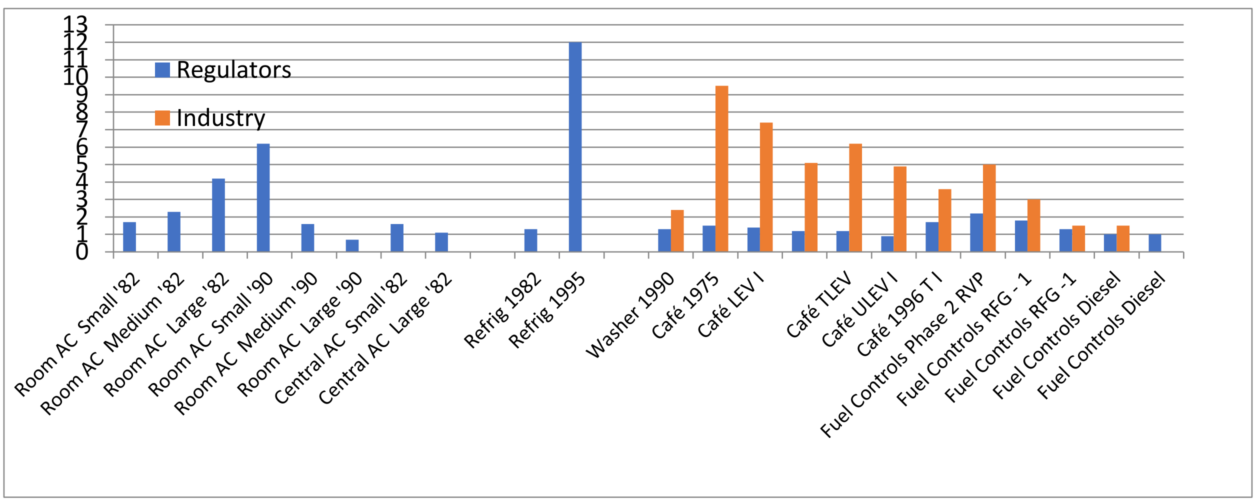
Source: Kenji Takahasi and David Nichols, "Sustainability and Costs of Increasing Efficiency Impact: Evidence from Experience to Date," *ACEEE Summer Study on Energy Efficient Buildings* (Washington, D.C., 2008), pp. 8-363.

The authors suggest that declining costs for higher levels of efficiency can be explained by economies of scale, learning, and synergies in technologies.[27] As utilities implement more of the cost-effective measures, costs decline. In addition, when technical potential is higher than achievable savings, then economies of scale, scope, and learning can pull more measures in without raising costs. This analysis supports the assumption that the cost of efficiency will not increase in the midterm.

Consistent with these findings and observations, it is important to briefly note the analysis of minimum-efficiency performance standards for consumer appliances and vehicles. There is a long (30+ years for vehicles) and rich (20+ for appliance standards) history that affects billions of devices. This is precisely the type of broad and sustained impact that policies to promote and achieve the transformation to a carbon-free economy will have to have.

In Figure 3.4, we show the systematic overestimation by regulators of the cost of efficiency-improving regulations in consumer durables. The cost for household appliance regulations was overestimated by over 100%, and the costs for automobiles were overestimated by about 50%. The estimates of the cost from industry were even farther off the mark, running three times higher for auto technologies.[28] Broader studies of the cost of environmental regulation find a similar phenomenon, with overestimates of cost outnumbering underestimates by almost 5-to-1, with industry numbers being a "serious overestimate."[29]

FIGURE 3.4
THE PROJECTED COSTS OF REGULATION EXCEED THE ACTUAL COSTS: RATIO OF ESTIMATED COST TO ACTUAL COST BY SOURCE



Sources: Winston Harrington, Richard Morgenstern, and Peter Nelson, "On the Accuracy of Regulatory Cost Estimates," *Journal of Policy Analysis and Management* 19(2) 2000; *How Accurate Are Regulatory Costs Estimates?,* Resources for the Future, March 5, 2010; Winston Harrington, *Grading Estimates of the Benefits and Costs of Federal Regulation: A Review of Reviews,* Resources for the Future, 2006; Roland Hwang and Matt Peak, *Innovation and Regulation in the Automobile Sector: Lessons Learned and Implications for California's CO_2 Standard,* Natural Resources Defense Council, April 2006; Larry Dale et al., "Retrospective Evaluation of Appliance Price Trends," *Energy Policy* 37, 2009.

Standards that stimulate investment to improve energy efficiency consumption have broader effects.

> The case-study review suggests that energy efficiency investments can provide a significant boost to overall productivity within industry. If this relationship holds, the description of energy-efficient technologies as opportunities for larger productivity improvements has significant implications for conventional economic assessments. ... This examination shows that including productivity

benefits explicitly in the modeling parameters would double the cost-effective potential for energy efficiency improvement, compared to an analysis excluding those benefits.[30]

The doubling of the effect on economic activity has important implications for the macroeconomic analysis discussed in the next chapter.

These findings of declining cost are not merely descriptive. Several analyses have introduced controls for quality and underlying trends using regression techniques. The findings are affirmed in these more sophisticated analyses.[31] With such strong evidence of costs far below predictions by regulators who undertake engineering analysis, many authors have sought to identify the processes that account for this systematic phenomenon. For both vehicles and appliances, a long list of demand-side and supply-side factors that could easily combine to produce the result has been compiled.

On the supply side, a detailed study of dozens of specific energy efficiency improvements pointed to technological innovation.[32] A comprehensive review of *Technology Learning in the Energy Sector* found that energy efficiency technologies are particularly sensitive to learning effects and policy.[33] This was attributed to increases in R&D expenditures, information gathering, learning by doing, and spillover effects. Increases in competition and competitiveness also play a role on the supply side. As noted above, a comparative study of European, Japanese, and American automakers prepared in 2006, before the recent reform and reinvigoration of the U.S. fuel economy program, found that standards had an effect on technological innovation. The U.S. had lagged because of the long period of dormancy of the U.S. standards program and the fact that the U.S. automakers did not compete in the world market for sales (i.e., they did not export vehicles to Europe or Japan).

While the supply-side drivers of declining costs are primarily undertaken by manufacturers, a number of demand-side effects are also cited, which are more the direct result of policy. Standards create market assurance, reducing the risk that cheap, inefficient products will undercut efforts to raise efficiency. Economies of scale lead to accelerated penetration, which stimulates and accelerates learning-by-doing. The effects of demand stimulus by increasing the growth of the economy (macroeconomic stimulus) also accelerate innovation. Experiencing increasing economies of scale and declining costs in an environment that is more competitive leads to changes in marketing behaviors.

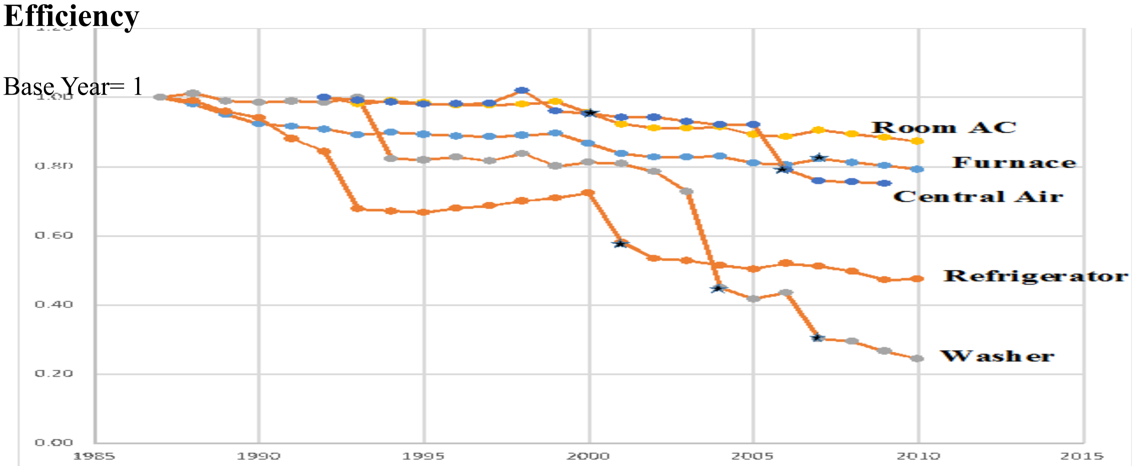
APPLIANCE EFFICIENCY STANDARD

The track record of efficiency standards for household consumer durables is even more eye-catching and important because it is a primary driver of residential electricity consumption and a significant driver of commercial consumption. Examining the trends in individual consumer durables suggests three important observations. First, the implementation of standards improved the efficiency of the consumer durables. Second, furnaces have been far less efficient than they should be, since the DOE has set and maintained weak standards. Third, after the initial implementation of a standard, the improvement levels off, suggesting that if engineering-economic analyses indicate that additional improvements in efficiency would benefit consumers, the standards should be strengthened on an ongoing basis.[34]

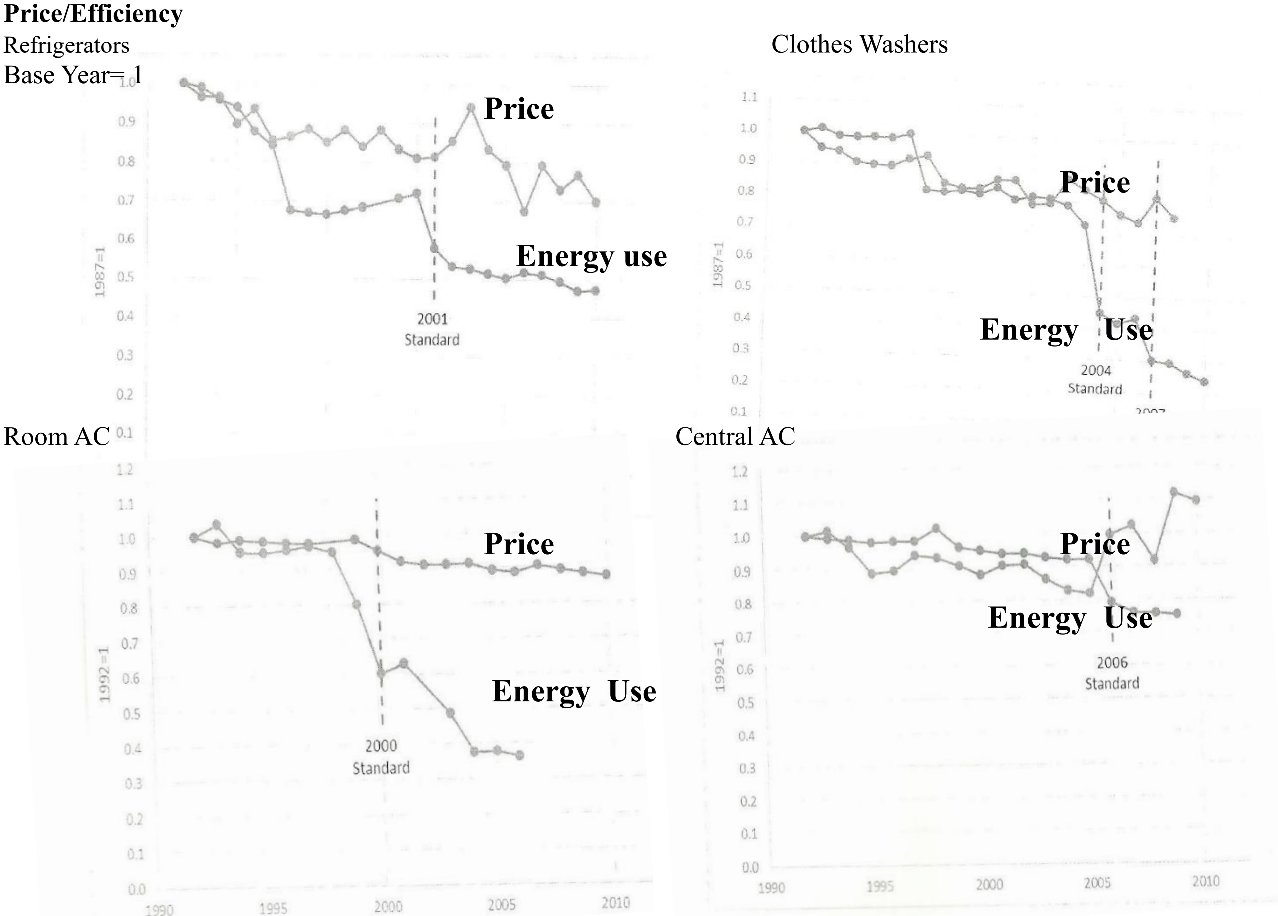
Figure 3.5
Efficiency and Price after the Adoption of Appliance Standards

Efficiency

Base Year= 1



Price/Efficiency



Sources: Nadel, Steven, and Andrew deLaski, *Appliance Standards: Comparing Predicted and Observed Prices,* American Council for An Energy-Efficient Economy, July 2013; *Steven* Nadel, Neal Elliott, and Therese Langer, *Energy Efficiency in the United States:35 Years and Counting,* June 2015.

I do not mean to suggest that the price increase was too big, compared to the engineering-economic analysis or that the standards lowered costs, although there are theories that would support such a rationale (e.g., suppliers take the opportunity of having to upgrade energy efficiency through redesign to make other changes that they might not have made otherwise). However, this does indicate that the standards can be implemented without having a major, negative impact on the market.

In three of the cases (refrigerators, clothes washers – second standard – and room air conditioners), there was a slight increase in price with the implementation of the standard, then a return to a pre-standard downward trend. In one case (clothes washers – first standard), there was no apparent change in the pricing pattern. In one case (central air conditioners), there was an upward trend.

Table 3.2 shows the results of econometric analysis of the data.[35] The statistical analysis created (dummy) variables that identify each consumer durable and whether a standard was in place or not. I use the year to estimate and control for the underlying trend. Table 3.2 shows what is obvious to the naked eye in Figure 3.5: Stricter standards as set by the DOE lead to measurable improvements in appliance efficiency.

TABLE 3.2
MULTIVARIATE ANALYSIS OF APPLIANCE STANDARDS IMPACT ON ENERGY USE

Variable	Statistic	5 Years Before/After			All Years		
		1	2	3	4	5	6
Standard	β	-.1637	-.1386	-.1086	-.2260	-.1079	-.0803
	Std. Err.	(..0485)	(.0587)	(.0382) (.0366)	(.0414)	(.0227)	
	p <	.000	.023	.007	.000	.010	.001
Trend	β	NA	-.0053	-.0111	NA	- .0107	-.0135
	Std. Err.		(.0081)	(.008)		(.0026)	(.0019)
	p <		.51	.176		.000	.000
Refrig	β	NA	NA	-.2775	NA	NA	-.2242
	Std. Err.			(.0382)		(.0289)	
	p <			.000			.000
Washer	β	NA	NA	-.2889	NA	NA	-.2144
	Std. Err.			(.0561)		(.0391)	
	p <			.000			.000
RoomAC β		NA	NA	.0478	NA	NA	-.0895
	Std. Err.			(.0642)		(.0321)	
	p <			.383			.009
CAC	β	NA	NA	-.0050	NA	NA	.0383
	Std. Err.			(.0292)		(.0260)	
	p <			.864			.143
R^2	.20	.21		.85	.29	.36	.75

Statistics are beta coefficient and robust standard errors.

The impact of standards is statistically significant and quantitatively meaningful in all cases. The coefficient in column 6 (All Years, All Variables) indicates that the standard lowers the energy consumption by about 8%. This finding is highly statistically significant, with a probability level less than .0001. There is a very high probability that the effect observed is real. The underlying trend is also statistically significant, suggesting that the efficiency of these consumer durables was improving at the rate of 1.35% per year.

Given that the engineering-economic analysis had justified the adoption of standards and that standards were effective in lowering energy consumption, this means the market trend was not sufficient to drive investment in efficiency to the optimal level.

Price

The engineering-economic analysis indicates that although the standards may increase the cost of the consumer durable, the reduction in energy expenditures is larger, resulting in a net benefit to consumers. We have also pointed to evidence that the costs of energy-saving technologies tend to be smaller than the *ex ante* analysis suggests, because competition and other factors lower the cost. The experience of the implementation of standards for the household consumer durables is consistent with this interpretation. While the efficiency was increasing, the cost of the durables was not, as shown in Figure 3.5. There are five standards introduced for the four appliances.

The analysis of consumer durables also shows that there was no reduction in the quality or traits of the products. The functionalities were preserved while efficiency was enhanced at modest cost. A recent analysis of major appliance standards adopted after the turn of the century shows a similar and even stronger pattern.[36] Pre-standard estimated cost increases are far too high. There may be a number of factors that produce the result, beyond an upward bias in the original estimate and learning in the implementation, including pricing and marketing strategies.[37]

Under most circumstances, this economic analysis would be dispositive. However, there are other policy concerns that enter the picture. The next part addresses the two most important of these.

PART II

OTHER MAJOR POLICY GOALS: JOB GROWTH AND DECARBONIZATION

4. ECONOMIC IMPACTS, JOBS, AND GROWTH

This chapter examines the other economic policy goal that has been set for the transformation of the electricity system: its impact on jobs and the economy. I use nuclear power as the point of comparison, since aging, but not new, reactors are the only low-carbon resource that could be competitive with the alternatives. We find that the alternatives are much more attractive on both counts and tip the scale strongly against existing nuclear reactors. However, the discussion begins with a broad view of the nature and impact of the ongoing technological revolutions that are affecting the electricity sector.

How New Technologies Create Jobs and Growth

The effect of developing and deploying new technologies on the economy and employment has long been recognized to flow through three processes: direct, indirect, and induced changes. In the energy sector in general, and for the alternatives in particular, these processes have particularly strong effects because of the complexity of the system and its role in society. A major change in technology that relies on different power sources causes changes in a complex system that includes not only generation but also transmission and distribution. Because energy is such an important part of the overall economy, the effect on consumers can be large and induce more-profound changes.

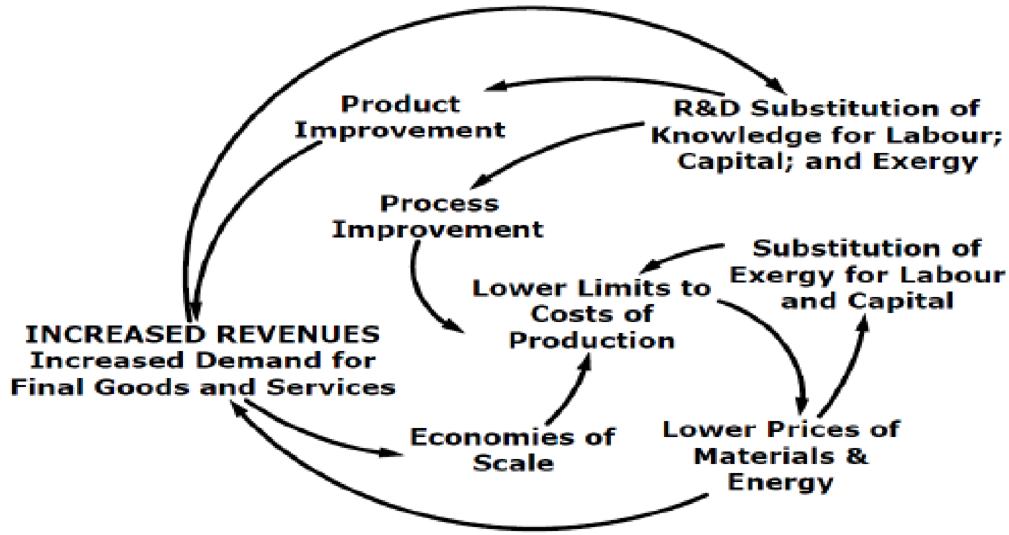
Energy in general, and the electricity system in particular, must be considered critical infrastructure for the 21st-century economy. Although focused on regulation, Kahn concluded that utilities (like electricity and communications) could justify regulation because they were infrastructural in nature:

> The importance of these industries, as measured not merely by their own sizeable share in total national output, but by their very great influence, as suppliers of essential inputs to other industries, on the size and growth of the economy. These industries constitute a large part of the "infrastructure" uniquely prerequisite to economic development. On the one hand they condition the possibilities of growth (as Adam Smith recognized …). On the other hand, because many of these industries are characterized by great economies of scale, their own costs and prices depend in turn on the rate at which the economy and its demand for their services grows.[38]

The importance of the transformation of the energy sector is amplified by the effects of economics of scale within the sector itself. Expansion of use of the sector has the impact of increasing economies of scale and lowering costs. Factors that retard the growth of the alternatives undermine this benefit of the rapid transformation.[39]

In fact, when it comes to technological revolutions, the dynamic of change can take on a life of its own (see Figure 4.1). Especially in the digital age, some technological changes that induce economic change are said to result in virtuous cycles.[40] One innovation leads to other innovations and increased demand, which feeds back on the original innovation to create a need for further innovation. As a virtuous cycle unfolds, costs fall not only because innovators find less costly ways to do things but because powerful economies of scale (larger numbers) and scope (different uses) drive the cost per unit down.

FIGURE 4.1
VIRTUOUS CYCLE DRIVING ECONOMIC GROWTH FROM TECHNICAL INNOVATION TO IMPROVE ENERGY PRODUCTIVITY



Source: Michael Smith, 2015, *Doubling Energy & Resource Productivity by 2030 – Transitioning to a Low Carbon Future through Sustainable Energy and Resource Management*. ANU.

The technological revolution in the electricity sector also benefits from another factor. It is closely tied to and partially dependent on a separate virtuous cycle in a separate sector: the ICT sector. Information communication and computing technologies have direct applications in the electricity sector that reinforce its underlying dynamic. The essence and impact of the third industrial revolution for the electricity sector is of critical importance for two reasons. On the one hand, electricity is the energy driver for the cost technologies (information and communication technologies – ICT) of the revolution. On the other hand, the changes taking place within the electricity sector are similar, consistent with the nature of change in the larger revolution. As Perez puts it:

> The ICT revolution is now entering the deployment period, as its power to increase productivity and facilitate innovation spreads to all other industries.[41]
>
> Many of the practices involved in the ICT paradigm are gradually becoming accepted and commonplace to the point of being regarded as obvious organizational "common sense." Decentralized networks with a guiding centre are replacing closed, centralized control pyramids; continuous improvement and innovation are replacing the previous practice of stable routines and planned change; the notions of human capital and of the value-creating powers of knowledge and expertise are displacing the view of personnel as "human resources." Although there is still resistance to some of those shifts, none has been more subject to debate and extreme positions than the shift towards globalization.[42]

FIGURE 4.2
ECONOMIC TECHNOLOGICAL REVOLUTIONS AND ECONOMIC DEVELOPMENT

Technological Revolutions (Perez)

Techno-economic Paradigm / **Gales of Creative Destruction**

Socio-institutional Paradigm / **Decades of Creative Construction**

Declining rate of profit
Maturation/exhaustion
Technological lock-in
Vast diffusion & massive adoption
Socio-institutional recomposition
Socio-institutional upheaval
Economic innovation
Techno-economic instability
Techno-scientific invention

MARKET Finance capital funds innovation to restore rate of profit

Ensure sufficient demand
Provide social guidance, taxation
Create effective regulation
Deploy infrastructure
Facilitate innovation & market creation

STATE *Define rights: property, labor, citizen, etc.*

Empirical Description of Five Industrial Technological Revolutions

Great Surge		**Installation Period**			**Turning Point**	**Deployment Period**			
Technological Revolution	Core Nation	Big-Bang	Irruption	Frenzy Gilded Age	Bubble	Recession	Synergy	Golden Age	Maturity
1st The Industrial Revolution	Britain	1771 Arkwright's mill opens	1770s-early 1780s	late 1780s-early 1790	Canal mania	1793-1797	1798-1812	Great British leap	1813-1829
1st Age of Steam & Rail	Britain	1829 Rocket steam engine	1830s	1840S	Railway mania	1848-1850	1859-1857	The Victorian Boom	1857-1873
2nd Age of Steel & Heavy Engineering	Britain, USA, Germany	1875 Carnegie Bessemer Steel	1875-1884	1884-1893	Global Infrastructure build-up	1893-1895	1895-1907	*Belle Époque* Progressive Era	1908-1918
2nd Age of Oil, Autos and Mass Production	USA	1908 Model T	1908-1920	1920-1929	Roaring '20s Autos, Housing Tel., Electricity, Radio, Aviation	1929 – 1943	1943-1959	Post-war Golden Age	1960-1974
3rd The ICT Revolution	USA	1971 Intel Microprocessor	1971-1987	1987-2001	Dotcom & Internet mania	2000	20??	Sustainable Knowledge society	
3rd **21st-century electricity system dynamic and static efficiency & renewables**					Financial Casino	2007-2008		Decarbonization sun, wind & water	

Sources for Figure 4.1: Mark Cooper, *The Political Economy of Electricity: Progressive Capitalism and the Struggle to Build a Sustainable Sector* (Santa Barbara, Praeger, 2017), Chapter 3. Upper graph based on Carlota Perez, "Technological Revolutions, Paradigm Shifts and Socio-Institutional Change," and Erik Reinert (Ed.), *Globalization, Economic Development and Inequality: An Alternative Perspective,* 2004. Lower graph adapted from Mark Cooper, "The ICT Revolution in Historical Perspective: Progressive Capitalism and the Digital Mode of Production, *Telecommunication Policy Research Conference,* September 28, 2015, based on Carlota Perez, *Financial bubbles, crises and the role of government in unleashing golden ages*, FINNOV, January 2012; Carlota Perez, "Technological dynamism and social inclusion in Latin America: a resource-based production development strategy," *CEPAL Review,* April 2010; Carlota Perez, *Technological Revolutions and Techno-economic Paradigms,* Working Papers in Technology Governance and Economic Dynamics, January 20, 2009. "Finance and Technical Change: A Long-term View," *African Journal of Science, Technology, Innovation and Development,* 3 (1), 2011, p. 13. Carlota Perez, "Re-Specialization and the Deployment of the ICT Paradigm - An Essay on the Present Challenges of Globalization," in R. Compañó et al. (Eds.), *The Future of the Information Society in Europe: Contributions to the Debate, Institute for Prospective Technology Studies*, 2006, p. 39.

It has also been long recognized that, while technological revolutions are a tremendous autonomous force, they also require changes in socio-institutional organization and rules to achieve their full potential (see Figure 4.2). In a sense, once technology takes on a life of its own, it needs the physical and institutional infrastructure to be transformed to support the new technological paradigm. The creative destruction stimulated by the new technology must be followed by and expressed as a phase of creative construction at the socio-institutional level.

> Technology is the fuel of the capitalist engine ... technical change has only little to do with scientific and technological reasons. It is the mode of absorption and assimilation of *innovations* in the economic and social spheres that requires technical change to occur in coherent and interrelated constellations. ... The institutional sphere is the seat of politics, ideology and of the general mental maps of society. ... It is also the network of norms, laws, regulations, supervisory entities and the whole structure responsible for social governance.[43]

The fundamental challenge of "embedding" the new paradigm to make it "common sense" has been recognized in the transformation of the electricity sector.

> Technological diffusion can be understood as a broader process of co-construction of technology and its environment … in which new technologies find their place in wider societal domains, which include immediate user contexts, cultural meanings, policies, and infrastructures…. (1) diffusion includes more actors than users/adopters, (2) user characteristics and environments are not known in advance, but are articulated during the technological diffusion process, and (3) societal embedding is full of choices and struggles that affect the directionality and thus shape of socio-technical systems.[44]

Because this is such a crucial moment in the development of the 21st-century electricity system, it is important to place it in historical context and recognize the important role of creative construction (as shown in the bottom graph of Figure 4.2). In my book on the *Political Economy of Electricity*, I described the process with a conceptual and historical presentation, which is summarized in Figure 4.2, taken directly from the book.

Locating the technological revolution in energy in this long historical process is important for several reasons. First, it will not allow us to fall into the error of technological determinism. Policy matters and the period of creative construction are as important as creative destruction. Second, Perez sees each of the first two industrial revolutions divided into two phases. The second phase involves a new source of energy to drive the emerging techno-economic paradigm. That is exactly the role of the transformation of the electricity system in the third (digital) industrial revolution. Thus, the characteristics of the revolution in the electricity sector reflect the central attributes of the overall revolution. Third, one of the most underappreciated aspects of the potential transformation of the electricity system is the key role played by digital communications. It is only a slight overstatement to say that without all aspects of the digital revolution, the dynamic flexibility and management of the 21st-century system that enables it to achieve reliability and sustainability would not have been possible. As one bibliographic reviewer put it:

> [T]he concept of renewable energy systems … has expanded the vision of the energy sector towards a diversified power grid while introducing distributed energy resources. … However, in recent years, a compelling need has arisen to understand the communications systems in distributed generation for better performance management, control and parallel power transfer.[45]

The building of physical and institutional infrastructure and the threat that nuclear power poses to it will be the topic of Part III. In the remainder of this part, I examine the empirical data on the impact of the transformation on the economy and decarbonization.

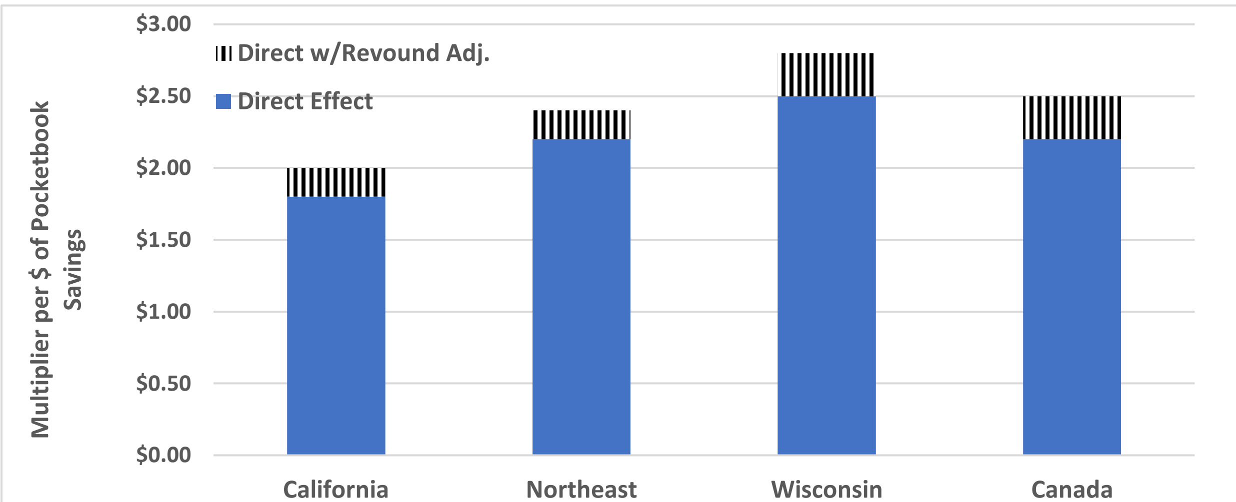
MODELING THE COMPLEX IMPACT OF TECHNOLOGICAL CHANGE IN ELECTRICITY

As a practical matter, the profound effects of changes in this infrastructure are measured by "input-output analysis [that] models the way a dollar injected into one sector is spent and re-spent in other sectors of the economy, generating waves of economic activity, or so-called 'economic multiplier' effects."[46] These changes, estimated by input-output models, were used by the Illinois Department of Commerce in its evaluation of the threat to shut down six reactors, as follows:

> (Direct) initial economic activity would include the sale of electricity, capacity and ancillary services effects to the market, and secondary economic activity … falls into two categories - indirect and induced … would include the subsequent economic activity resulting from how suppliers, employees, and owners of the power plant utilize their earnings that result from those initial sales. … Indirect effects are those influencing the supply chain that feeds into the business in which the economic activity is located. … Induced effects come from payments made to employees and subcontractors by the plant that lead to spending by local households.[47]
>
> Job losses and electricity price increases can be largely mitigated by fully developing energy efficiency and renewable energy resources.[48]

The multipliers used in the input-output models used in Illinois are similar to those used in other studies. Another way to hone in on the "induced" impact is to look at the number of jobs created per additional dollar of "respending" made possible by the shift to lower-cost resources. This is summarized in Figure 4.3, which shows the results of two different input-output models. In four different geographic contexts, lower in cost means that the alternatives have a higher multiplier when the energy cost savings are "respent." For every one dollar that is saved, as shown in Figure 4.3, the economy grows almost an additional dollar. The alternatives are also much more labor intensive. The construction jobs are much more widely distributed, as are the opportunities to collect rent for land use. This is consistent with the above observation about the potential to diversify with local resources. The efficiency jobs are also dispersed.

FIGURE 4.3
ESTIMATES OF "RESPENDING" MULTIPLIERS



Estimates of Macroeconomic Multipliers as a Multiple of Net Pocketbook Savings

Modeler	Model	Date	Policy Assessed	Region	GDP/$ of Net Savings Base Case	Rebound Adjustment
Roland-Holst	DEAR		Computer Standard	California	1.8	2.0
ENE	REMI		Utility Efficiency	Northeast	2.2	2.4
Cadmus	REMI		Utility Efficiency	Wisconsin	2.5	2.8
Arcadia	REMI		Utility Efficiency	Canada	2.7	3.0

Sources: David Roland-Holst, 2016, *Revised Standardized Regulatory Impact Assessment: Computers, Computer Monitors, and Signage Displays,* prepared for the California Energy Commission, June. ENE, *Energy Efficiency: Engine of Economic Growth: A Macroeconomic Modeling Assessment*, October 2008. Cadmus, 2015, *Focus on Energy, Economic Impacts 2011–2014*, December. Arcadia Center, 2014, *Energy Efficiency: Engine of Economic Growth in Canada: A Macroeconomic Modeling & Tax Revenue Impact Assessment,* October 30.

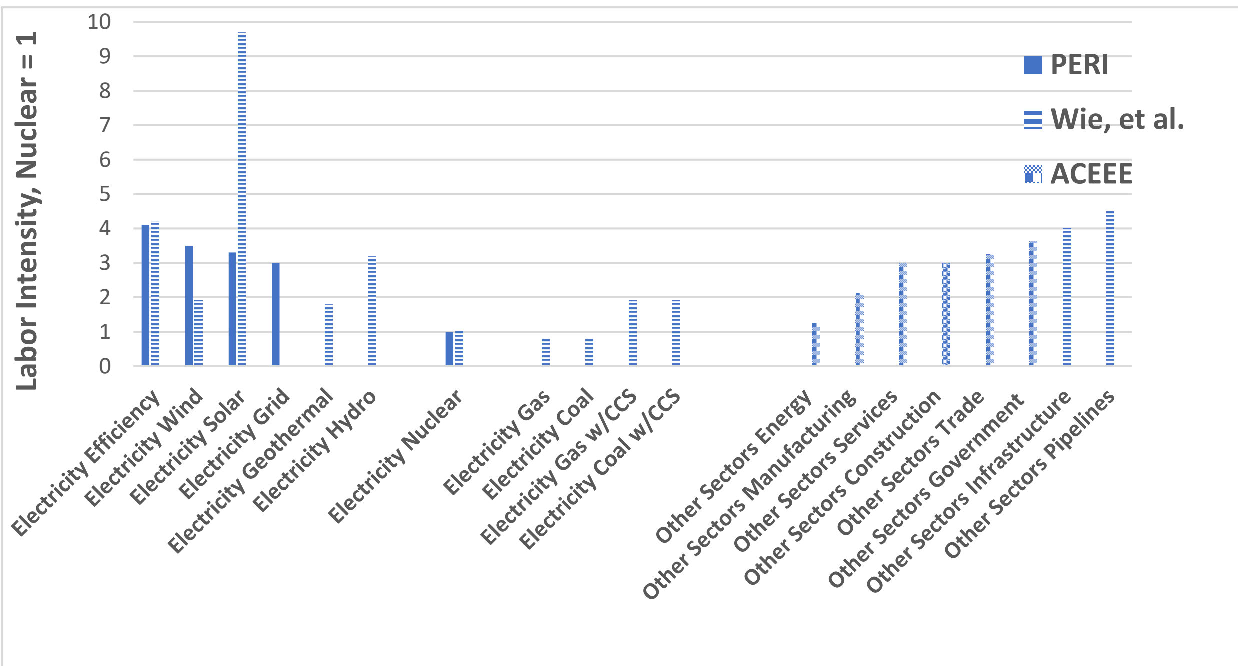
WHY SUBSIDIZING AGING REACTORS KILLS JOB AND ECONOMIC GROWTH

In contrast to the alternatives, which are powerful engines of job and economic growth, subsidizing aging reactors is a job and growth killer (see Figure 4.4). The obvious starting point is that existing facilities add no new jobs. Arguing that they deteriorate over time and require more labor is hardly a selling point. In fact, because it suggests the costs of existing reactors will rise, this suggests that nuclear will impose a cost on jobs and the economy, since it subtracts from disposable income of households, and businesses pass their costs on to consumers who inevitably pay the higher costs.

Illinois

In fact, subsidizing aging reactors dramatically reduces the total number of jobs in the short term because the construction jobs for alternatives greatly exceed the number of operating jobs in the nuclear reactors Exelon threatened to retire, and it does not even save some jobs in the short and medium term. Even more importantly, as shown in Figure 4.5, which is based on the analysis by the Department of Commerce of Illinois when it studied the question of bailouts, jobs that are lost in the operation and maintenance of the reactors are almost offset by jobs in the decommissioning of those reactors.

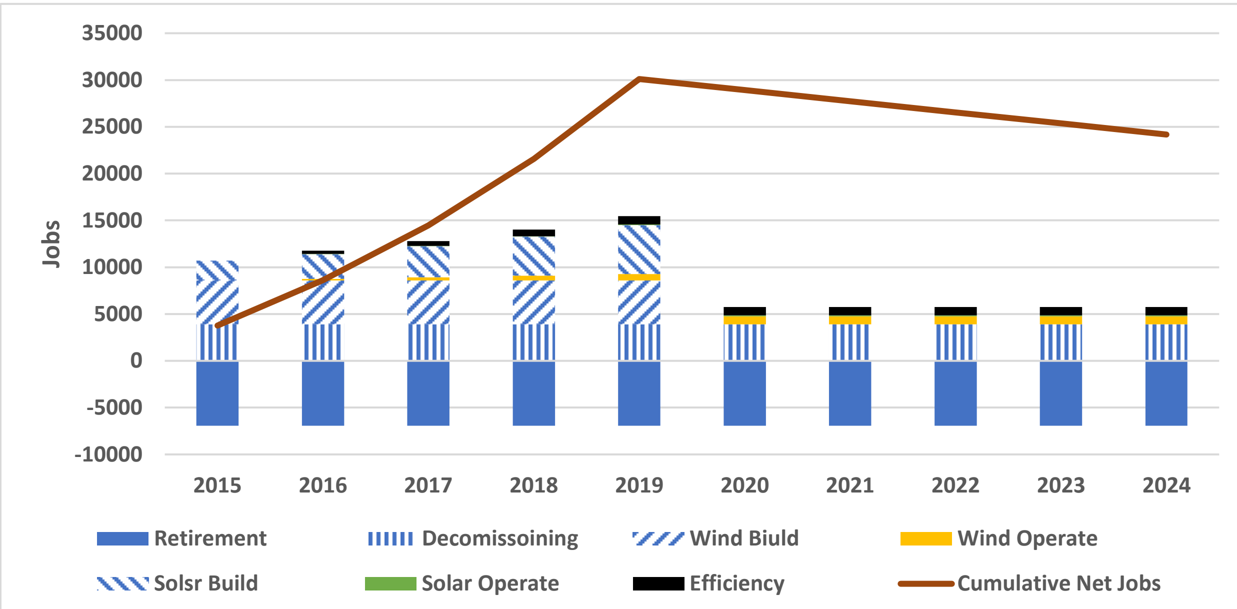
FIGURE 4.4
LABOR INTENSITY OF ALTERNATIVES



Sources: Wie, Max Shana Patadia, and Daniel Kammen, 2010, "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?, *Energy Policy,* 38. Rachel Gold, et al., *Appliance and Equipment Efficiency Standards: A Money Maker and Job Creator,* American Council for an Energy-Efficient Economy, January 2011, p. 9, based on the IMPLAN Model, 2009. *How Infrastructure Investments Support the U.S. Economy: Employment, Productivity and Growth,* James Heintz, Robert Pollin, Heidi Garrett-Peltier, Political Economy Research Institute, January 2009.

The analysis that was presented did not include the cost or job impact of decommissioning,[49] which is a mistake that can easily be corrected. Exelon and its consultants claimed a very high cost in dollars (half a billion) and jobs necessary (over 1,500) associated with the decommissioning of its Zion reactors. Including those costs on a per-MW basis creates jobs that equal roughly 56% of the jobs lost in operating the reactors. Combined with the construction jobs in renewable replacement power, this more than offsets that low of nuclear jobs.

FIGURE 4.5
JOB IMPACT OF RETIREMENT AND REPLACEMENT, INCLUDING DECOMMISSIONING



Sources: Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection agency, Illinois Department of Commerce and Economic Opportunity, *Potential Nuclear Power Plant Closings in Illinois: Impacts and Market-Based Solutions, Response to The Illinois General Assembly Concerning House Resolution 1146*, January 5, 2015, p. 139. Decommissioning is discussed on p. 134.

The analysis in Figure 4.6 assumes a small efficiency gain, half as much as I have assumed throughout this analysis. Part of the cause for this is the short-term increase in costs that will result from the immediate closure of a large number of reactors. This is the nuclear blackmail effect, which is avoidable on economic and regulatory grounds. In the graph, I have doubled the efficiency gain, which is consistent with other analyses in this paper. This change accounts for about 15% of the net job gains, which would not affect the conclusion. Alternatives create more jobs.

The argument that subsidizing nuclear reactors has the benefit of maintaining a nuclear workforce suffers a similar fate. Maintaining the workforce might make sense if one anticipated new builds, but we have seen that the cost of new builds is astronomical. The burden that nuclear power creates, in terms of reduced disposable income for households, is likely to be much larger than the value of the workforce. Near-term subsidies keep people in dead-end jobs, if least-cost supply and least-cost carbon reduction are the goals.

New York

Much like Illinois, a 2015 Brattle Group Report entitled "New York's Upstate Nuclear Power Plants' Contribution to the State Economy" ("Brattle Report")[50] makes a series of assumptions about retiring nuclear reactors that are wrong and misleading:

- Every kilowatt-hour of electricity produced by a retired reactor is replaced with a kilowatt-hour generated by natural gas.
- There will be no increase in production by wind, solar, or efficiency, at the end of the subsidy period.
- The elasticity of price with respect to supply implicit in the analysis is just under one, while the elasticity of demand with respect to price is zero.
- The macroeconomic multiplier on the use of natural gas to generate electricity is assumed to be equal to that of nuclear, so the reduction of direct and indirect jobs and economic activity resulting from the price increase is a total loss.

All of these assumptions are incorrect, which means the self-serving analysis should not be taken seriously. Above all, the "dash to gas" is not an unavoidable or inevitable outcome. If the Public Service Commission (PSC) does not put its thumb on the scale of competition but allows all low-carbon resources to compete to meet increasing levels of carbon reduction set by mandates on utilities, the lower-cost alternatives will expand rapidly.

Based on the Brattle Report's assumption at the end of the period of aging reactor subsidies, New York will find itself in exactly the same position it is in today, having less electricity produced from new renewable technologies and more electricity still being produced by aged, 60+-years-old, outdated nuclear reactor technology. Therefore, in this analysis I assume that the alternatives expand incrementally to replace nuclear (i.e., it fills 1/12 of the retiring capacity per year). Initially, there is reliance on gas, but that is eliminated over time.

Figure 4.6 shows the impact of the alternative scenarios. The upper graph shows the projected market clearing price. The impact study prepared to defend keeping the reactors online assumes complete replacement with gas, which drives up the market clearing price by almost 16%. In the alternative scenario, efficiency and non-hydro renewables replace the retired reactors incrementally. I bring these increments in at a cost of $45/MWh, consistent with the earlier analysis. Since this is almost 20% below the market clearing price, it incrementally lowers the market clearing price. The market clearing price increases initially, but by year six, it is below the base case. The cost in the early years is offset by savings in the later years, so that consumers break even shortly after the reactors are fully retired.

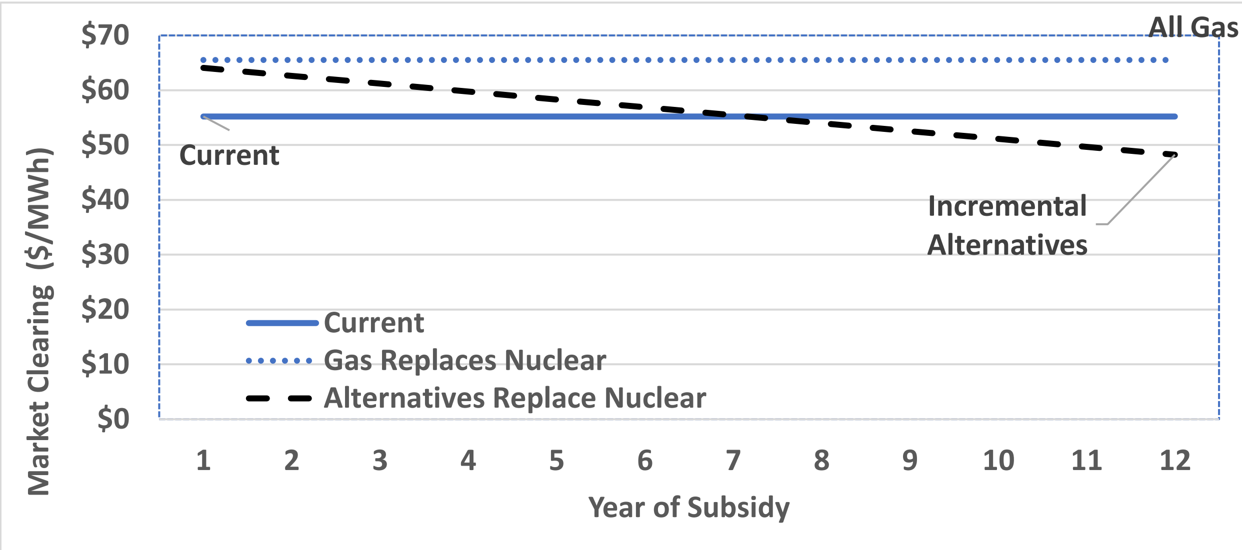
The lower graph shows the employment impact. Figure 4.7 plots the macroeconomic impacts of this alternative scenario. Since "indirect" jobs represent over 90% of total jobs, the multiplier is far and away the most important factor. In this analysis, I do not include decommissioning jobs, since those will be captured whenever the reactors close.[51] I include the alternatives at twice the labor intensity of nuclear, which is an extremely conservative level. In this orderly transition, there is no net loss of jobs, even from the beginning.

Conclusion

The challenges of building the physical and institutional infrastructure to support the 21st-century alternative in the electricity sector are great, but so too are the rewards. Because the transformation is a process, we must be cautious in projecting benefits, but even a cautious approach to calculating benefits shows the superiority of the transformation. Efficiency advocates have argued that efficiency alone can accomplish half the job of eliminating carbon emissions, although they do not give costs or include a transformation dividend.[52] Supply-side advocates argue that wind and solar can accomplish the job of decarbonization while lowering costs, without any increase in hydro and only modest efficiency gains, but they include a significant amount of rooftop solar,[53] which is quite expensive in the Lazard analysis. However, particularly in the case of rooftop solar, which is the only individual-level supply-side resource considered in the Lazard analysis, there are several "system" benefits that enhance their value that are increasingly being recognized. In fact, in Kentucky, a coal state, the utility proposed to pay only $0.035, but the commission decided the rate should be almost three times as high.[54] These benefits include mitigating distribution infrastructure costs, peak shaving and generation costs, increasing resilience, not to mention environmental benefits. In Jacobson's analysis of the 100% renewable future of the U.S., residential PV accounts for 4% of the supply, more than geothermal, traditional hydro, and community PV, with individual states as high as 14% (Hawaii), where it is the third-largest source, and 12% (Nevada), where it is the fourth-largest source.

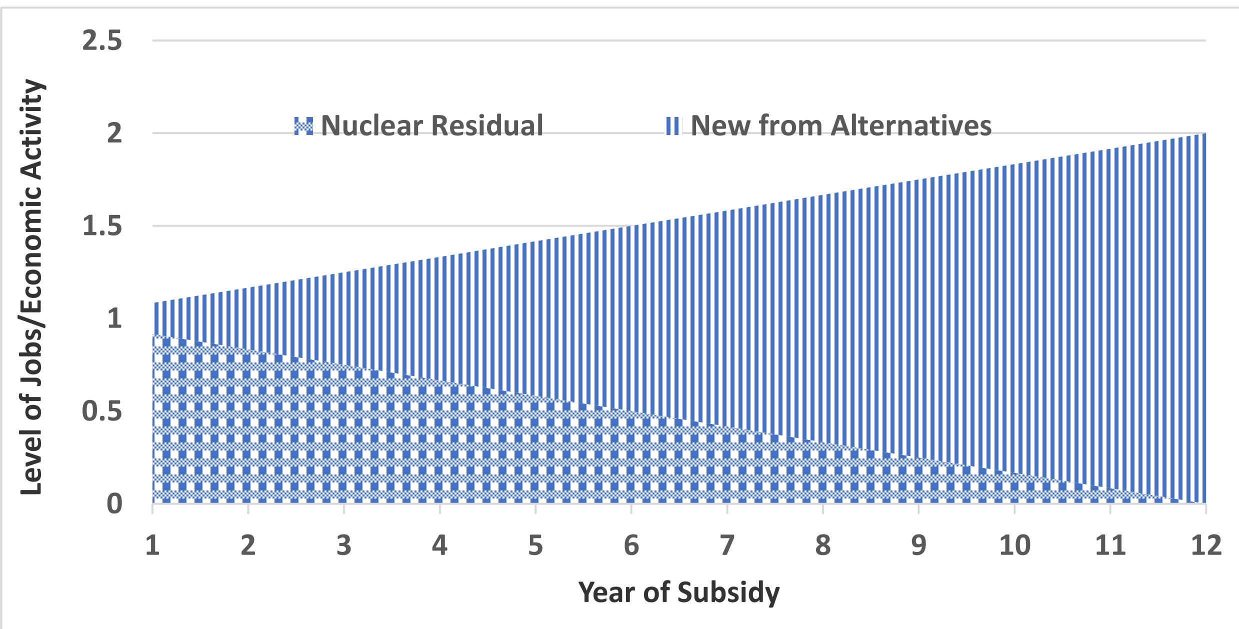
FIGURE 4.6
IMPACT OF RETIRING UPSTATE REACTORS: ALTERNATIVE SCENARIOS

MARKET CLEARING PRICE WITH RETIREMENT



Source: Calculated by author as described in text.

Jobs/Macroeconomic Impact: Assuming Multiplier for Alternatives Is 2X Nuclear



Source: Mark Berkman and Dean Murphy, *New York's Upstate Nuclear Power Plants' Contribution to the State Economy prepared for New York State IBEW Utility Labor Council, Rochester Building and Construction Trades Council, Central and Northern New York Building and Construction Trades Council,* Brattle Group, December 2015.

5. DECARBONIZATON

Having shown the current and future economic superiority of the alternatives, I next evaluate the impact that alternatives would have on the other primary policy goals: decarbonization, public health, and the environment.

VALUE OF CARBON ABATEMENT

Figure 5.1 uses a recent Lazard analysis of the net cost/benefit of carbon reduction for an estimate of the value of carbon abatement of the main options expressed in a comparison with coal.[55] The cost of the technology is subtracted from the value of the carbon saved. The original figure included the low estimate for new builds for wind, solar, gas, and nuclear.

There are a number of caveats here. Price trends indicate that the low estimate for alternatives are "high" because of declining costs, while for central-station, they are "low" because of rising costs. As noted above, the capacity factors for traditional utilities are high. In calculating the value of carbon abatement in the long term, I assume a very low (cautious) 10% reduction for all alternative sources.

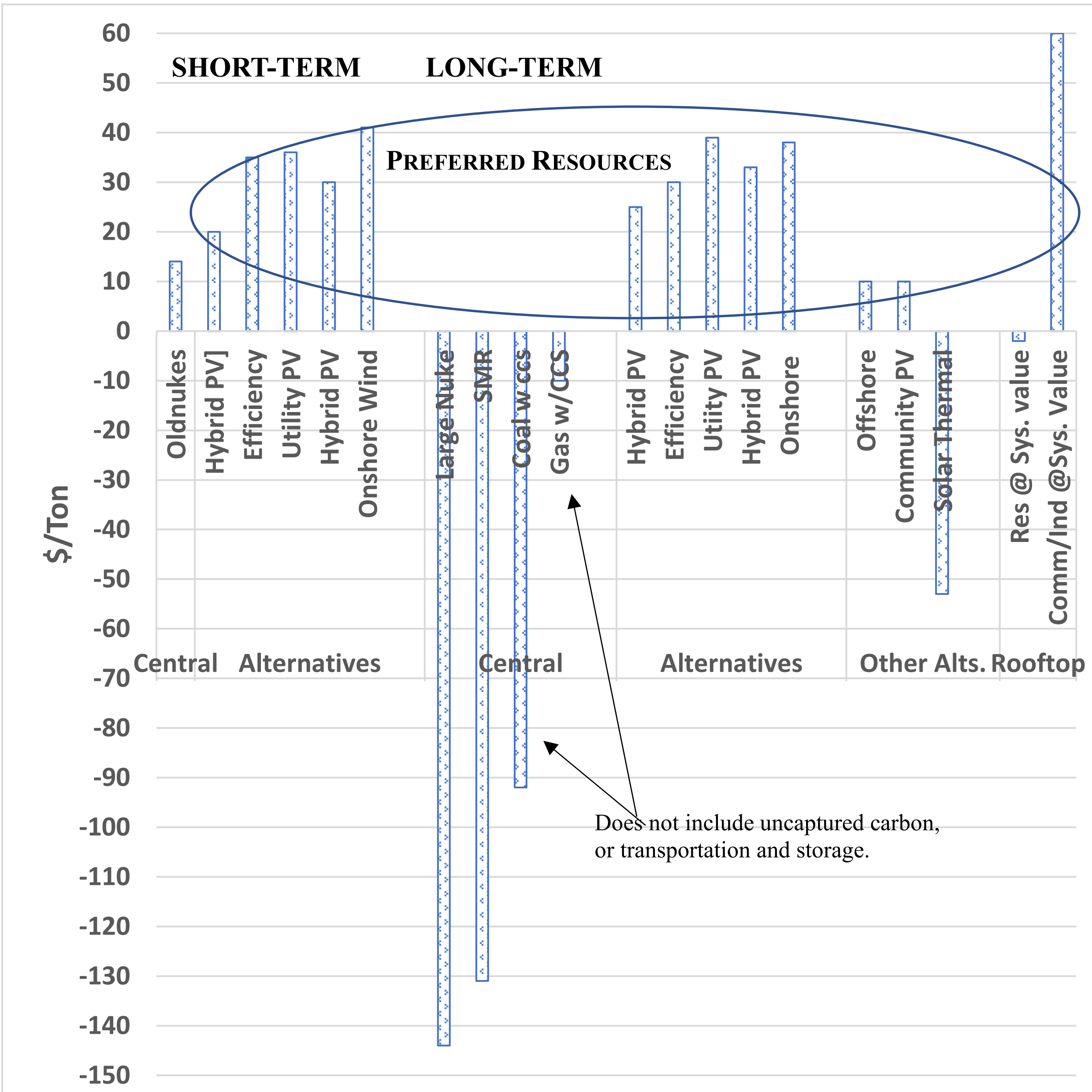
I have also added a number of estimates. I have included an estimate of the value of aging reactors with costs discussed below. I have included an estimate for the value of hybrid solar applications, with the added cost of batteries (derived by subtracting the standalone cost of solar from the total cost of solar hybrid). I have also included estimates for several of the alternatives that are not the "main" options. Rooftop solar is a long-term issue because its full value awaits decision about how to value it, but its behind-the-meter nature should be taken into account. Solar thermal with batteries and offshore wind are also included because they dramatically expand the options for decarbonization.

Keeping in mind that the higher the value the more attractive the resource, a number of conclusions can be drawn from these estimates:

- Efficiency, wind, and solar are far and away the least-cost options.
- The hybrid solar option, which includes the cost of batteries, also has a positive value.
- Since decarbonization is a central goal of policy, I consider gas and coal with carbon capture (costs from Lazard that do not take account of uncaptured carbon, transportation, or storage).
- New nuclear is prohibitively expensive. It does not make sense to construct new nuclear generation for economic or decarbonization reasons, because it is so costly.
- Old (online) nuclear reactors are the fifth-most-attractive option in the short term, very close to hybrid solar option, and, as discussed below, the cost of aging reactors is expected to rise, while the cost of the hybrid solar resources is

expected to fall. Moreover, aging reactors disappear in the long term, linking to very high-cost new nuclear.

FIGURE 5.1
VALUE OF CARBON ABATEMENT



Source: Based on Lazard, Hi, Lo taken from Levelized Cost, v. 14,0, Hybrid incremental cost of batteries from EIA, add to Lazard Solar cost. All renewables are assumed to decline 10% over the next decade.

- Offshore wind becomes slightly positive and is much more attractive than nuclear power or fossil fuels with carbon capture.

The findings of the economic resource analysis and this evaluation of decarbonization are the same, except for the fact that old nuclear reactors have a small positive value. However, closer examination of the cost of keeping aging reactors online shows that they are a bad choice.

THE COST OF AGING REACTORS

Table 5.1 provides greater detail on the cost of aging nuclear reactors. Utilities have threatened to shut down aging reactors that are "losing money," but they never make public what their costs are and what it means to "lose money" – i.e., they want all reactors to earn enough to make a contribution to capital cost recovery at a full return on equity that the nuclear utilities demand. In public statements, not regulatory proceedings which are confidential, utilities have claimed that they want a full return on investment for these plants – a 10% rate of return – at a projected subsidy cost of about $500 million/year in Illinois. In New Jersey, PSEG went further, claiming it needed the bailout to underwrite an 18% rate of return, in order to make it worth the risk to keep running them.

Although the Synapse analysis of Exelon in Illinois is heavily redacted, it does provide insight into the least-cost question. Based on market-clearing prices for energy and capacity, it appears that $0.03/KWh is available in the market. Synapse estimates that Dresden covers its out-of-pocket costs at a subsidy of $0.02/KWh. To hit the target rate of return (discount rate), the reactor needs another $0.015/KWh. Thus, the cost with capital recovery and the target discount rate is $0.065/KWh. [56]

TABLE 5.1
CASH FLOW AND SUBSIDIES AT EXELON PREFERRED DISCOUNT RATE

Reactor	5-Year NPV ($ Million)	10-Year NPV	5-Year Subsidy $/MWh	10-Year NPV w/Subsidy ($ million)
Dresden	-91	283	3.5	532
Byron	30	127	1.0	221
Braidwood	139	502	0	502
LaSalle	367	785	0	785
Total	445	1697	NA	2040

Source: Bhandari, Divita, et al., *Exelon Nuclear Fleet Audit, Findings and Recommendations*, Synapse, April 14, 2021, pp. 17, 19, H-9, H-11.

This is consistent with my earlier analysis of Illinois, New York, and aging reactors in general (as shown in Figure 5.2). The Byron reactor is cash flow positive without a subsidy, but the Synapse report estimates a $0.001/KWh subsidy would raise the rate of return to the target rate. In order for the reactor to generate the cash flow of other reactors on the list, the operating cost would have to be extremely low, or more subsidies would be necessary to hit the target, or a combination of the two. Another $0.015/KWh (to raise it to the production tax credit) would raise the NPV to a total of close to $3 billion. Even the Byron reactors, which would need a small subsidy to hit the target discount rate of the utility, are cash flow positive in the next five years. Over 10 years, it would generate over $2 billion in revenue above costs.[57] The total would be close to $5 billion. Without the subsidy, Byron and Dresden generate about $400 million in revenues above costs. The other two reactors that Synapse analyzed exceed the target discount rate for the utility, generating revenues above costs of about $1.3 billion.

The Synapse estimates for subsidies in Illinois make clear that it may not be in the interest of the state to give any subsidy at all, even though the amount proposed by Synapse is quite low, as shown in Table 3.2. It tells a very different story than the utility. In the short term, the four reactors are cash flow positive, although Dresden is negative for the first five years and Byron is slightly positive. Over 10 years, they are all positive, generating almost $1.7 billion in cash above operating expenses. Synapse suggests short-term (5-year) subsidies to raise the cash flow on two of the reactors.

Figure 5.2 provides greater detail on the cost of aging reactors. It also includes the estimates of the cost of the alternatives from the earlier analysis. The very low figures are the operating costs from Figure 2.4 above. The low and high estimates are for the all-in costs from Figure 2.3 above. The obvious point is that, at the midpoint of the range, the cost of alternatives is well below the cost of aging reactors. The Lazard estimates for new and young nuclear, with the return used in the Synapse analysis, would be well above efficiency and solar and competitive with wind.

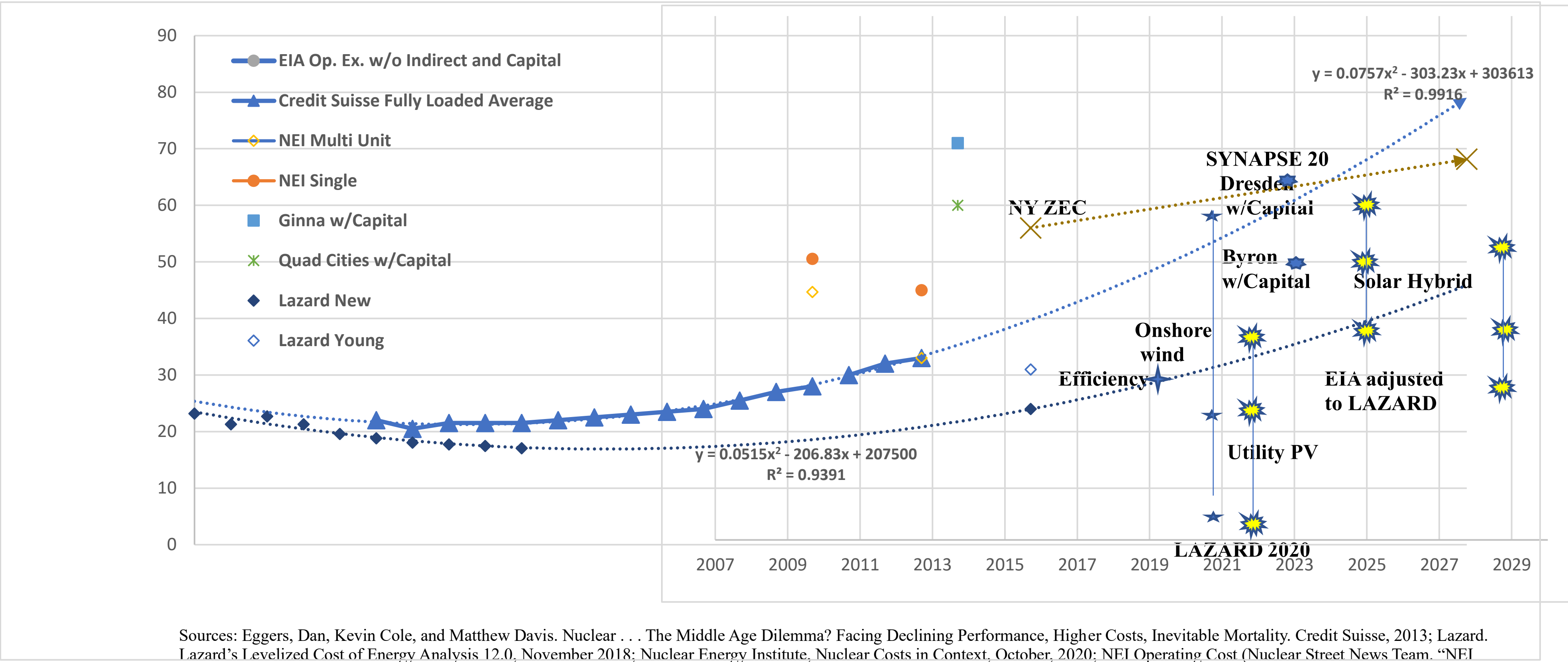
Over 10 years, those unjustified subsidies, if applied to alternatives, would purchase about 95% of the nuclear capacity (assuming a load factor of only 33%) that is displaced, but there is no reason to believe that this would be necessary, as the Synapse analysis shows.

Figure 5.3 reminds us that the target of current policy should be about the future, not the past. It shows the historic rate of improvement in carbon emissions in the electricity sector. It also shows that the recent retirement of nuclear reactors had almost no impact on the rate of decline in emissions, which occurred over the past 15 years without any such subsidy in place. Indeed, through 2020, we have no carbon policy, but the shortfall in carbon reduction in 2035 would be “only” about 700 million tons, compared to a straight line to zero.

The obvious questions become, how much of an impact will the policy initiative have, and would renewables be able to offset the reduction of nuclear output? The answers to both questions argue against a broad-based subsidy for nuclear reactors, as shown in Table 5.2. On the left side is an estimate of the amount of power that could result from the policy initiative. Per the above discussion, I include efficiency and the transformation dividend.

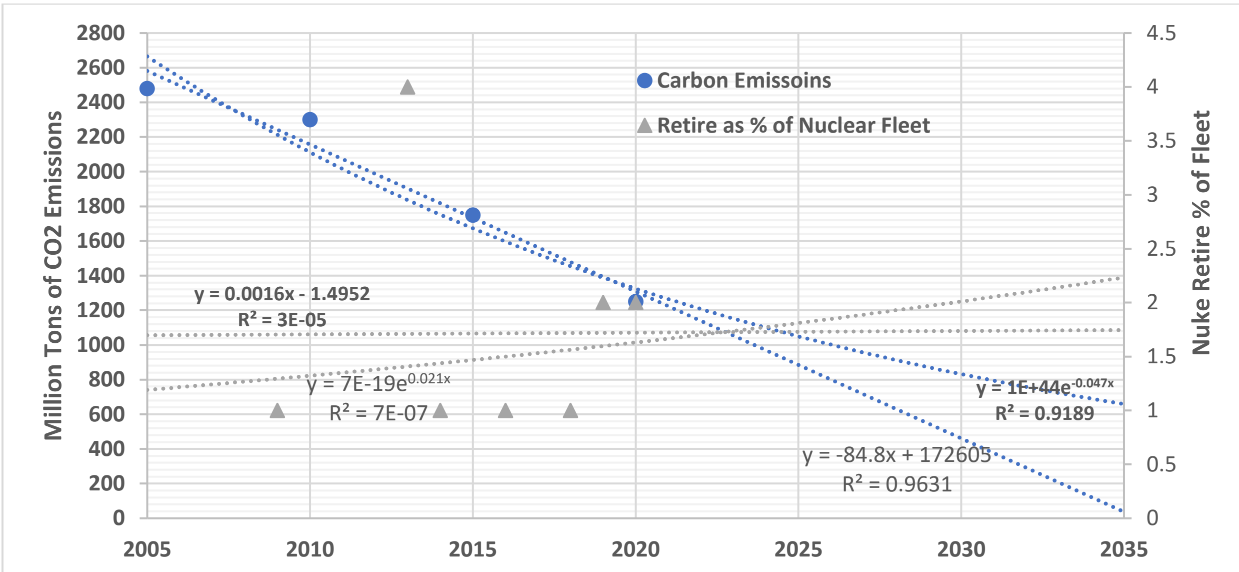
The latter question depends very much on what owners of nuclear plants do. This is dealt with in the lower part of the left-hand column, where I examine the empirical record on early retirements. Threats and blackmail aside, owners of fully depreciated plants with positive cash flow have an economic reason to continue to operate those facilities. A look at the history of early retirements shows that about 30% of capacity was retired in the period 1963-2020. Over 90% of the plants retired were single units, and the average age was just over 40 years.

FIGURE 5.2
COST OF AGING REACTORS COMPARED TO ALTERNATIVES



Sources: Eggers, Dan, Kevin Cole, and Matthew Davis. Nuclear . . . The Middle Age Dilemma? Facing Declining Performance, Higher Costs, Inevitable Mortality. Credit Suisse, 2013; Lazard. Lazard's Levelized Cost of Energy Analysis 12.0, November 2018; Nuclear Energy Institute, Nuclear Costs in Context, October, 2020; NEI Operating Cost (Nuclear Street News Team. "NEI Lays Out the State of Nuclear Power." Nuclearstreet.com. February 26, 2014; NEI Excludes Indirect (Nuclear Energy Institute, Operating Costs, http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Costs-Fuel,-Operation,-Waste-Disposal-Life-Cycle/US-Electricity-Production-Costs-and-Components); Naureen S. Malik and Jim Poulson, "New York Reactors Survival Tests Pricey Nuclear," Bloomberg, January 5, 2015, p. 2. Quad Cities is based on a $580-million subsidy (Steve Daniels, "Exelon Puts an Opening Price Tag on Nuclear Rescue: $580 Million," Crains Chicago Business, September 24, 2014), converted to $25/MWH for output-at-risk reactors. Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection Agency, Illinois Department Commerce and Economic Opportunity, 2015, Response to The Illinois General Assembly Concerning House Resolution 1146, January 5, real price increase to break even, plus $11/MWH for capital. "Comments of Dr. Mark Cooper." In the Matter of Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units, Environmental Protection Agency, RIN 2060-AR33, November 24, 2015. Comments by Alliance For a Green Economy and Nuclear Information and Resource Service, Proceeding on Motion of the Commission to Implement a Large-Scale Renewable Program and a Clean Energy Standard, Case 15-E-0302, April 22, 2016; RE: Case 15-E-0302- In the Matter of the Implementation of a Large-Scale Renewable Program and a Clean Energy Standard; Re: Case 16-E-0270: Petition of Constellation Energy Nuclear Group, LLC; R.E. Ginna Nuclear Power Plant, LLC; and Nine Mile Point Nuclear Station, LLC to Initiate a Proceeding to Establish the Facility Costs for the R.E. Ginna and Nine Mile Point Nuclear Power Plants, July 22, 2016. Energy Information Administration, Electricity Annual, 2015, Table 8.4. Lazard, *Levelized Cost of Energy Analysis,* Version. 14.0; Bhandari, Divita, et al., *Exelon Nuclear Fleet Audit, Findings and Recommendations*, Synapse, April 14, 2021.

FIGURE 5.3
U.S. POWER (CO_2) EMISSIONS



Source: Larsen et al., “Pathways to Building Back Better: Investing in 100% Clean Electricity,” Rhodium Group, p. 2.

TABLE 5. 2
WIND, SOLAR, AND EFFICIENCY CAN EFFECTIVELY DECARBONIZE WITHOUT ANY NUCLEAR SUBSIDIES.

Alternatives	**Date**	**Output b KWh**	**Traditional Central Station**	**2019 output b KWh**
Policy				
Wind & Solar				
$50b*$0.025 per Kwh	2022-2031	2000	Coal/Petrol	974
.5 * rate* 4 years	2032-2035	400	Gas	1599
Efficiency (policy)			Nuclear	809
1.5% Above base = 10%	2022-2035	620	total	
			Central station	3382
			National	4128
Transformation Gain 2035	413-826 (10-20%)			
Total (Policy)	2022-2035	3433- 3846		
Other renewables		322		
Grand Total		3755-4168		
			Nuclear Retirements	
			1963-2020	30%
			Illinois w/o subsidy	21% - 47%
			Expected Output	
			National w/o subsidy	534 (428-639)
	Total low-carbon resources w/o nuclear subsidy			
	Nuclear online		534	
	Alternatives w/policy		3755-4168	
	Total		4289-4702	

Two-thirds of the nuclear capacity is expected to stay online in the next decade and a half because, as the Synapse analysis shows, it is economic by a reasonable economic standard. Thus, there is simply no reason to subsidize aging reactors in pursuit of decarbonization. The logical economic approach is to allow reactors to retire as they become uneconomic. Others have made similar proposals.[58] If any policy is called for, it should be to remove the "special" treatment of nuclear power and let it sink (or swim) on the basis of the fundamental economics. No new reactors will be built over the next two decades because of their very high costs, and some will retire because they are uneconomic. The threat to close large numbers of reactors is blackmail, not rational economics, and should be rejected.

The problem with this careful economic analysis is that the nuclear utilities are not interested. They refuse to make their costs public, subject to audit. They do not want their required rate of return on fully depreciated plants public. They want rents, not economic profits justified as competitively fair. Ultimately, they are more interested in securing a place in the electricity system of the 21st century than in supporting least-cost supply. Given the goals of the nuclear industry, any transitional support would have to be so heavily conditioned on the exit of nuclear power from the resource mix that nuclear utilities are likely to be unwilling to accept the conditions.

ARE THE RESOURCES ADEQUATE TO MEET THE NEED WHILE DECARBONIZING?

With the costs clearly indicating the superiority of the alternative resources and approach, the next question is, how far can reliance on these resources carry us toward decarbonization of the sector? Will there be enough resources available and how will the new system operate to ensure reliable supply?

The earlier analysis showed that renewables could replace the reactors that were threatening to shut down. A similar conclusion obtains in New York (see Table 5.3). The original estimated resources for 2030 and 2040; here, we show the midpoint which is the average of the two. The midpoint is the target data for full decarbonization adopted by the Biden administration. There are four primary resources used to meet the need while eliminating carbon emissions: efficiency, a transition dividend, wind, and solar. Existing hydro is flat, and existing nuclear output is shrinking. In that proceeding, the acceleration of efficiency, the transformation dividend, and the growth in non-hydro renewables were all considered well within the available resources.

To analyze the adequacy of supply of renewables, we must first determine what demand will be. Projections of demand reductions due to efficiency vary, from about 15% in the EPA assumption to over 30%. In the following analysis, I use an EPRI estimate of the amount that demand could be reduced by 2035, which is a conservative estimate of the potential and does not take into account the transformation dividend. It assumes reduction in the range of 10-20%, with a national average of about 17%.

TABLE 5.3
MEETING NEW YORK GOALS WITH EFFICIENCY AND RENEWABLES (MILLION MWH)

Alternative Resource

	2030	midpoint	2040
Efficiency			
Base case = 1.4%/year	35	43	51
Accelerated = 2%/year	51	65	78
Load @ Accelerated eff.	135	130	124
Transformation Dividend = 17%	10	13	15
Reduction in Coincident Peak (34%) >			
Effective New Load (Reduction in load 17%)	125	117	109
Resources			
Achievable 2030, Economic 2040			
New Non-Hydro	26	57	88
Existing Hydro	36	36	36
Unsubsidized Nuclear	17	14	11
% Low-Carbon with Transformation Dividend	63%	100%	124%

Source: Staff White Paper, NYSERDA Energy Efficiency and Renewable Energy Potential Study of New York.

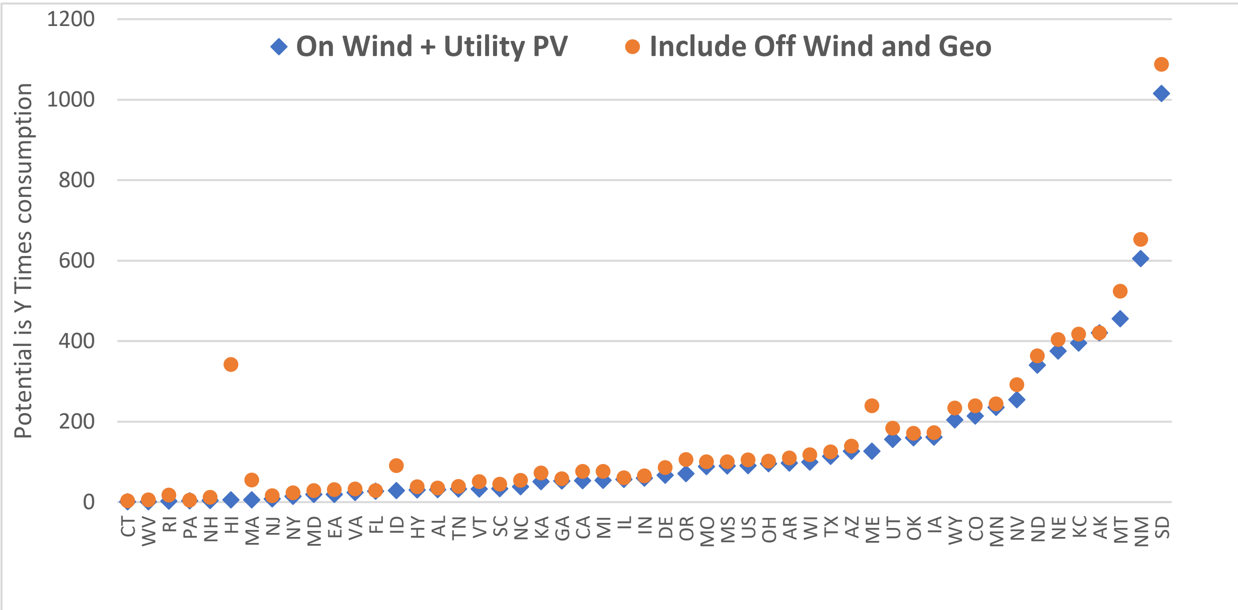
Replacing aging, inefficient reactors is one important finding, but the renewables must also be able to replace coal and gas. Figure 5.4 shows the potential for renewables to meet demand, based on NREL's evaluation of potential. It shows the currently low-cost renewables (onshore wind and utility PV) separate from the more-costly but increasingly competitive renewables: offshore wind and geothermal. Because the vast potential of some states overwhelms the graph, I also show the states where wind and solar resources are less than 50 times current demand. New York is in the middle of this group.

As the graph shows, the vast majority of states have an abundance of potential supplies of renewable resources. Only a handful have potential that is less than five times demand. And, as shown in the lower graph, meeting local demand with local supply is not the issue. Only one state (CT) has inadequate local resources. With efficiency, however, even its resources are adequate. Moreover, just under a dozen other states export little, because they are not endowed with rich, traditional resources and do not have a comparative advantage. However, the renewables are local resources, and they present a new opportunity to diversify supply. The states with resources that exceed need by a relatively small amount are surrounded by neighbors who have the potential for much larger resources. Expanding the scope of trade and cooperation is one of the hallmarks of the 21st-century approach.

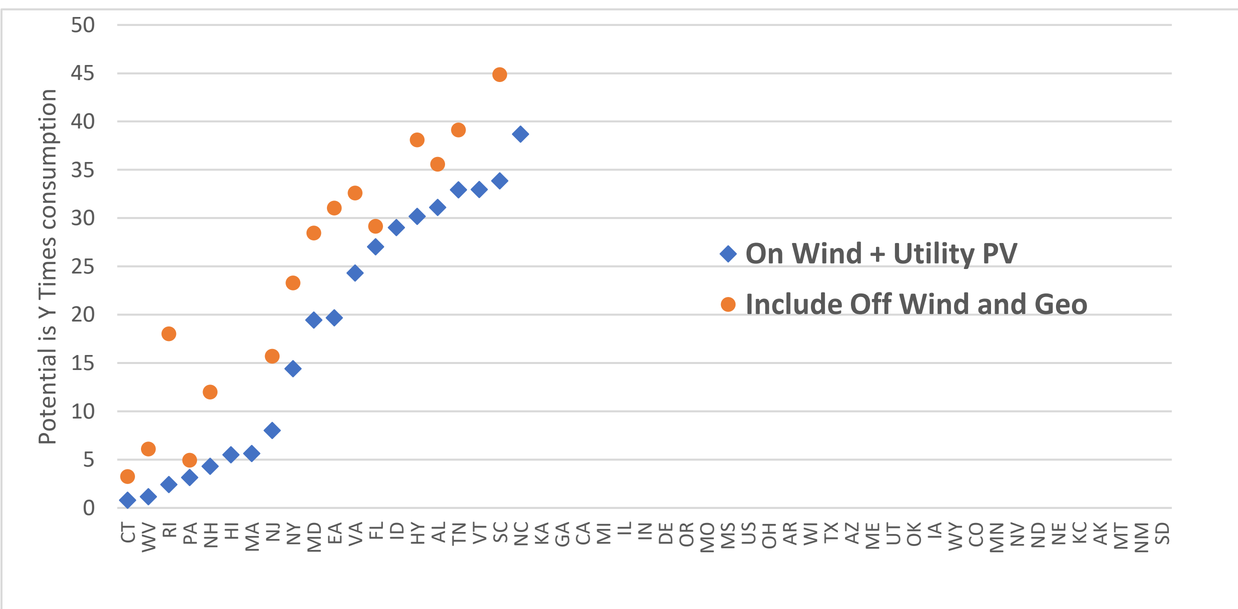
The existence of a vast resource base is one thing, but the ability to tap it in a timely fashion is quite another. Needless to say, this is and will remain a point of debate. However, one thing is clear in Figure 5.5: The U.S. and the majority of the states are far behind other advanced industrial nations in exploiting this resource. Part of the reason for that gap is that we have not had a strong national policy encouraging this path of development. Even excluding Denmark as an outlier, the other nations have achieved a penetration of renewables that is 2.5 times as great as the U.S.

FIGURE 5.4
ASSESSING THE ADEQUACY OF SUPPLY

Potential Supply Compared to Demand (all states)

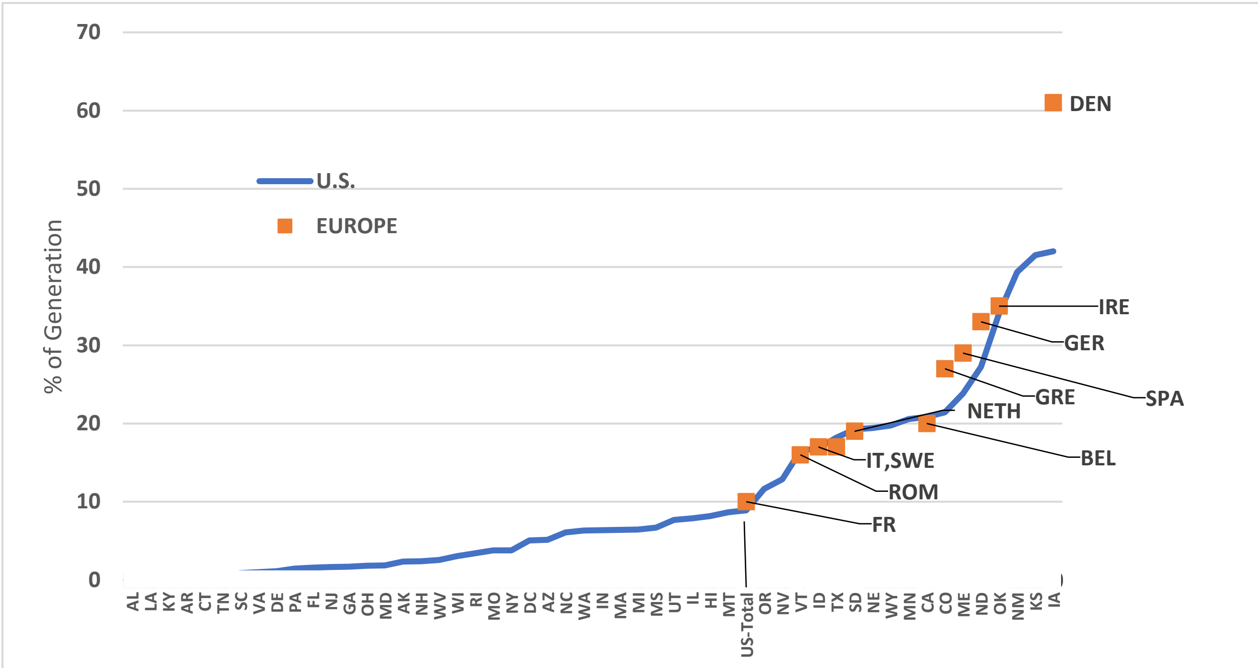


Potential Supply Compared to Demand (up to 50 times demand)

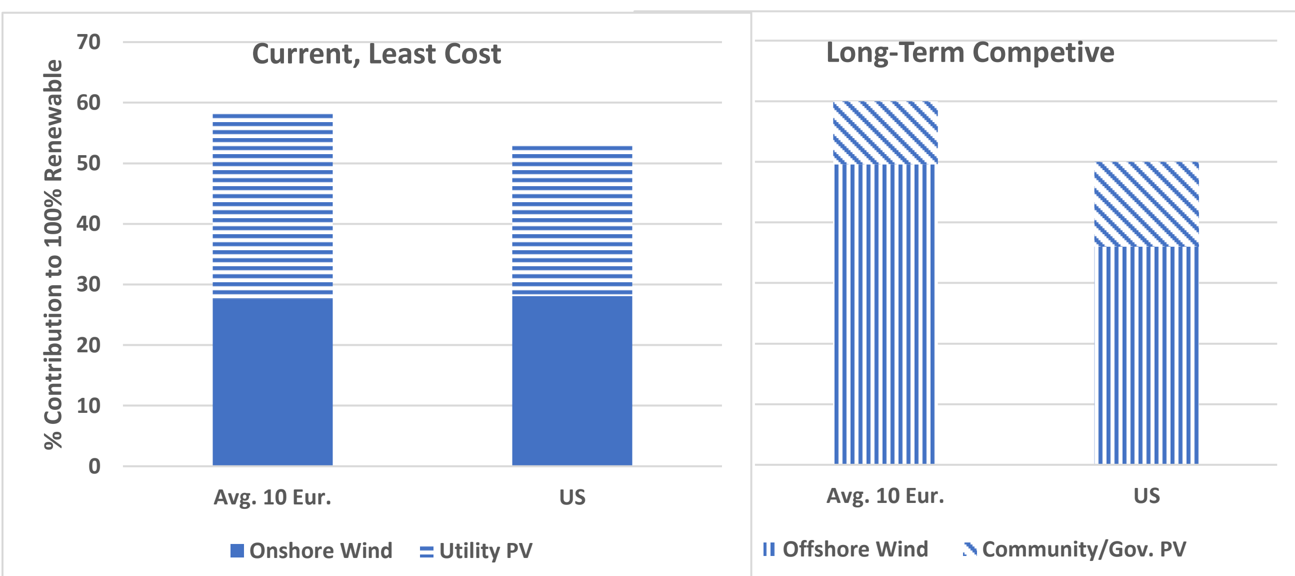


Source Lopez. Anthony. et al. 2012, U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. NREL, July. :

FIGURE 5.5
PENETRATION OF GENERATION FROM WIND AND SOLAR



Source: Energy Information Administration, Electric Supply Monthly, EMBER, *EU Power Sector is 2020.*



Source: Mark Z. Jacobson et al., 2015, 100% Clean and Renewable Wind, Water and Sunlight, All Sector Energy Roadmaps for 139 Countries of the World.

The lower graphs in Figure 5.5 show that the ultimate contribution of currently low-cost resources is not very different in the U.S. than in the 10 European nations shown. The same is true of wind and solar resources that are potentially competitive in the longer term. The potential for energy efficiency is also much greater in the U.S. Compared to the 10 European nations, the

U.S. consumes 25% more electricity per capita, and excluding the one outlier (Sweden, whose reliance on low-cost hydro power is huge), the U.S. consumes over twice as much electricity per capita.

Thus, decarbonization with the orderly exit of nuclear power appears to be possible. Given the overwhelming superiority of the alternatives on cost and economic impacts, the U.S. should follow a strategy of pursuing 100% decarbonization on the basis of the four elements of the 21st-century system: efficiency, wind, solar, and intelligence.

PART III

ENSURING A SUCCESSFUL TRANSITION

6. OPERATING A RELIABLE ENERGY SYSTEM

Low cost and adequate resources are two important ingredients to support the alternative system, as is the commitment to build one, but operating the system remains a challenge. The two chapters in this part address this issue from two points of view. Although the transformation is a process that does not happen overnight, this chapter makes it clear that the tools to successfully operate a system are developing, and, as shown in the previous chapter, many nations have made considerably more progress than the U.S. The next chapter explains why subsidizing existing nuclear reactors is a very bad idea from the point of view of promoting a successful transformation.

TOOLS TO ACHIEVE LOW-COST, RELIABLE POWER

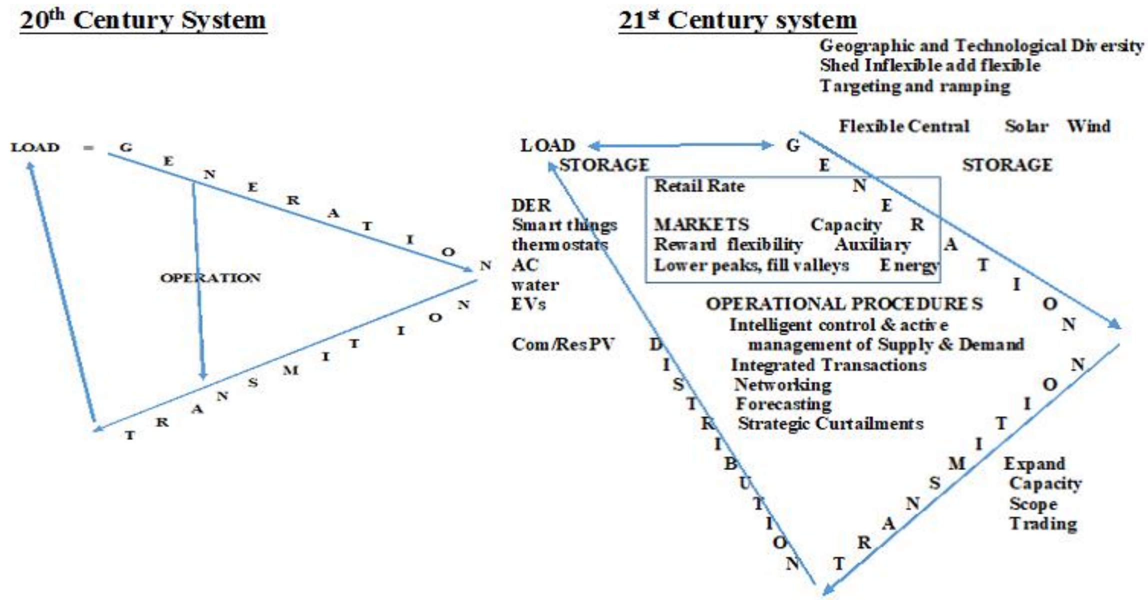
Figure 6.1 shows the many tools available to achieve low cost and reliable supply.[59] We have included over 250 references to some of the extensive literature that supports the supply-side and demand-side tools. We treat storage as a demand-side strategy. This is unarguably true for distributed storage, although less so for dispatchable storage. Both are key to balancing load and supply.

When pressed, utilities give the same answers. A California proceeding challenged parties to think about how high levels of renewables could be integrated into the grid. Utilities offered a host of approaches, and my summary concluded there were at least 10 general ways to handle the challenge.[60]

The LBNL analysis shows that the technical and economic processes by which policies work to mitigate the impact of variability are straightforward:

1. Geographic diversity, particularly for wind, reduces extremes of generation, high or low output.[61]
2. Technological diversity fosters a better fit with load.[62]
3. Storage allows more energy to be captured and used when needed,[63] both by reducing curtailment[64] and by increasing demand (and therefore prices) during slack periods.[65]
4. Demand shaping allows a better balance between supply and demand.[66]
5. Flexibility is a key attribute, achieved by
    - sub-hourly scheduling to reduce the magnitude and impact of forecasting error,[67]
    - "quick-start" generation,[68] or
    - a portfolio approach that uses a mix of generation assets that can reduce the need for flexibility of individual assets.[69]
6. Exploiting the best sites for renewable resources yields much larger economic value – three times the average.[70]

FIGURE 6.1:
CREATING THE 21ST-CENTURY ELECTRICITY SYSTEMS



Tools to Manage a 21st-Century Electricity System

Generation (100% Scenarios)
- Geographic diversity
- Technological diversity
  - Peak targeted solar
  - Quick start/rapid ramp
- Shed inflexible baseload
- Shift to flexible
- Flexible central
- Firm renewables
- Value ancillary services;
- Avoid lumpy investment

Load
- Supply-side
- Target peaks
- Use more in slack, less scarcity
- Demand-side
- Aggressive demand response
- Smart controllers manage use
- Supply-side
- Target peaks
- Use more in slack, less scarcity
- Demand-side
- Aggressive demand response

Transmission
- Expand balance areas

Storage
- Dispatchable, traditional
- Distributed (virtual powerplant)
- Electric vehicles

Operational Procedures
- Flexibility/integration
- Integrated Transactions
  - Strategic Curtailment
- Improve forecasting

Market Design
- Smart controllers manage use
- Positive and Negative prices
- Target fixed cost recovery;
- TOU (cut peaks, fill valleys)
- Smart Grid
- CHP

Source: Mark Cooper, *Avoiding Nuclear and Fossil Fuel Potholes, a Green New Deal Has a Clear Path to a Clean, Low Cost, Low Carbon, Progressive, Capitalist Electricity Sector*, April, 2019, Chapter 6.

Although the utilities in California put together an analysis that takes a very different approach than the LBNL analysis and seems much more ominous, close examination shows that when the utility analysis introduces mitigation measures, it reaches a similar end point. The utilities started with a base case of renewables at 33% and set up straw men of 40% and 50% PV scenarios. Not surprisingly, they found that this extreme approach produces major problems in matching supply and demand.

Consistent with the LBNL analysis, however, the introduction of mitigating policies immediately solves the problem. The utility study identifies four "least regrets opportunities" and a number of opportunities for "research and development for technologies to address over-generation."[71] Adding in three blocks of "flexibility solutions" reduces the curtailment of PV generation to the level of the 33% penetration, which was virtually zero. The transformation dividend is present in the utility analysis. Pursuing downward "flexibility solutions" yields 15,000 MW of reduced demand, which is equal to 10% of the capacity in the "unmitigated" PV system and 15% of the capacity in the "mitigated" PV system. This is consistent with the RAP finding discussed above.

This level of "flexibility solutions" is in the range of the planning reserve – an equivalence that the literature generally notes. As the penetration of relatively small-scale distributed technologies increases, the need for planning reserves may decline, because, in the current baseload approach, it is the threat of the loss of large units that drives up planning reserves. The potential for a trade-off between planning reserves and "flexibility solutions" could have a significant impact on the cost of meeting the need for electricity.

While the utility study does not model the specific "flexibility solutions," it does identify the likely primary candidates, which are the same as those modeled in the LBNL analysis. The utility study finds significant challenges but also opportunities. The "least-regrets" opportunities identified in the study include these:

- Pursuing a diverse portfolio of renewable resources.
- Implementing a long-term, sustainable solution to address over-generation before the issue becomes more challenging.
- Implementing distributed-generation solutions.
- Research and development for technologies to address over-generation are plentiful, including
    - promising technologies like storage (solar thermal with energy storage, pumped storage, and other forms of energy storage, including battery storage, electric vehicle charging, and thermal energy storage) and
    - flexible loads that can increase energy demand during daylight hours (advanced demand response and flexible loads).
- Technical potential to implement new solutions are also available, including
    - sub-five-minute operations,
    - creating a large potential export market for excess energy,
    - changing the profile of daily energy demand, and
    - optimizing the thermal generation fleet under high RPS.[72]

INTEGRATION COST AND SYSTEM VALUES

Baseload myopia, the claim that only large central-station facilities can ensure reliable supply, has been rejected on the basis of cost. Can it be salvaged by the claim that it is the only means of meeting the need for power at an affordable cost? Evaluation of how much it costs to operate a reliable system suggests that it cannot. The alternatives win out on integration of resources and system values.

The finding that the cost of the integration of distributed supply and actively managed demand are quite small enjoys a strong consensus in the literature.[73] It is reflected in the DOE analysis *Wind Vision,* which provides a simple explanation. The DOE *Wind Vision* analysis argues that "wind generation variability has a minimal and manageable impact on grid reliability and related costs."[74] DOE believes that operational challenges that could arise with much higher levels of wind penetration can be easily overcome by expanding the use of techniques that have been found effective in the past. "Such challenges can be mitigated by various means including increased system flexibility, greater electric system coordination, faster dispatch schedules, improved forecasting, demand response, greater power plant cycling, and—in some cases—storage options."[75] The potential for extremely rapid balancing, innovative battery technologies, and microgrids, which address the core problem of reliability in the digital age, have only begun to be appreciated.[76] These highlight the impact and necessity of changes to the grid,[77] and the prospect of achieving reliability that equals or exceeds current levels with the alternative approach is increasingly seen as quite good.[78]

In the early years of the transition, costs rise slightly because new generation resources are being deployed. The increasing cost of electricity is primarily the result of the need to replace aging and polluting generation with low-carbon alternatives, but "Wind generation variability has a minimal and manageable impact on grid reliability and related costs."[79] In sum, careful analysis shows that reliability is a nonissue; the conflict is about the future of the techno-economic structure of the electricity sector in the 21st century.

The DOE explicitly laid out the process in the case of transmission.[80] The *Wind Vision* analysis argues that transmission costs are constantly being incurred by the electricity system. In the early years, those costs are reallocated from supporting central-station generation (which is shrinking) to supporting new renewable resources. There is only a slight net increase in transmission investment. As time goes on and the share of renewables grows, transmission costs increase. However, they are complementary to the deployment of renewables, whose capital and operating costs have been declining and are much lower than the nonrenewable low-carbon alternatives.

The U.S. Energy Information Administration (EIA) recognized the increasing complexity of selecting generation resources as very different technologies began to compete for investment resources. It summarized the approach to system value at a workshop in 2013, where it argued "that levelized cost of electricity (LCOE) … reflects both the capital and operating costs of deploying and running new utility-scale generation capacity … [but] the direct comparison of LCOE across technologies … is problematic and potentially misleading."[81] The EIA analysis focused on a comparison of the marginal value to the system of individual resources, and these calculations were added to its *Annual Energy Outlook*.[82]

> Conceptually, a better assessment of economic competitiveness can be gained through consideration of avoided cost, a measure of what it would cost the grid to

> generate the electricity that is otherwise displaced by a new generation project, as well as its levelized cost. Avoided cost, which provides a proxy measure for the annual economic value of a candidate project, may be summed over its financial life and converted to a level annualized value that is divided by average annual output of the project to develop its "levelized" avoided cost of electricity (LACE). The LACE value may then be compared with the LCOE value.[83]

The difference between LCOE and LACE can be called "inflexibility waste" to capture the key concept.[84] The avoided cost is less than the levelized cost because resources are inflexible – i.e., unable to adapt their output to the needs of the system. The system cost would be lower if technologies that better fit system needs were used. Inflexibility waste can be lowered in two ways: reducing levelized cost or decreasing avoided costs – i.e., a better fit between output and system needs.

After extensively discussing the EIA system value approach to improving comparisons between alternatives, analysts at two national laboratories, Lawrence Berkeley National Laboratory and Argonne, suggested an alternative approach that rested on system costs. The levelized cost of energy was the starting point and the most important factor, as in the system value approach, but the adjustment made was not by subtracting avoided costs from LCOE, but by adding estimates of the unique system cost of individual technologies to the LCOE. The former is a top-down approach, the latter is a bottom-up approach, and the authors caution against double-counting by combining the two. This approach was also advocated by a major research institution in Germany evaluating the aggressive transition to renewables being pursued in that nation.[85]

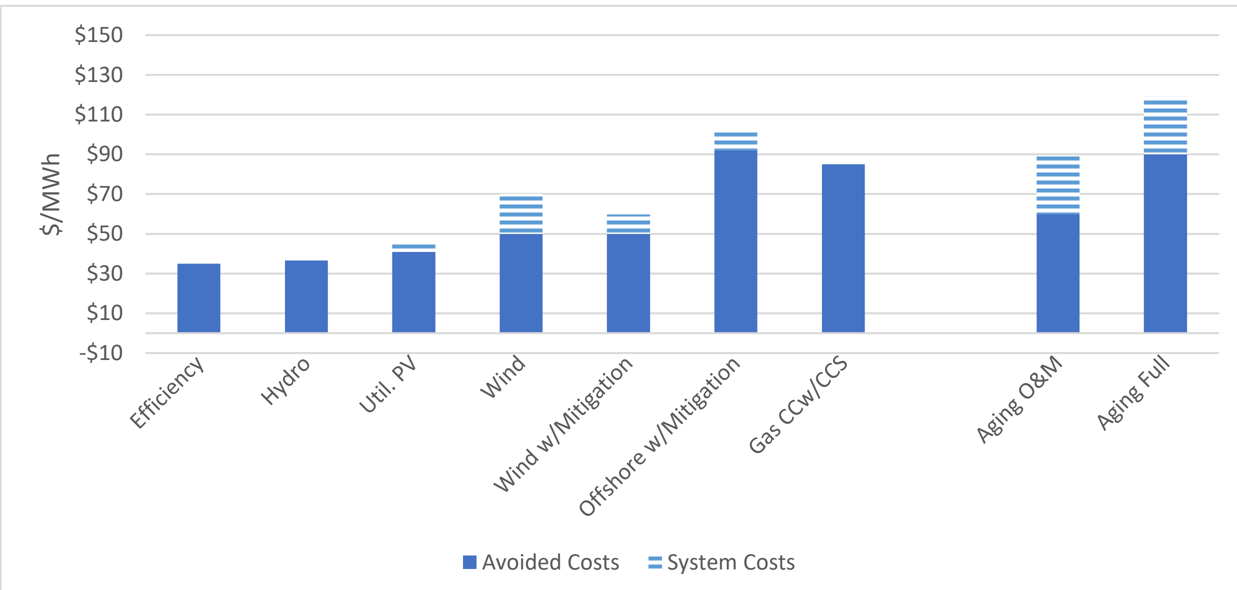
> If properly defined, the 'system cost' of VRE [variable renewable electricity] (or any other resource) combined with the plant-level technology LCOE of VRE results in a 'total system LCOE', which can then be compared (with substantial caveats) to the 'total system LCOE' of any other technology to determine which resource has the lowest total system cost. An important point to make here is that this 'system cost' perspective is related to but distinct from the 'system value' perspective described earlier. An analyst may choose to use the 'system value' perspective or the 'system cost' perspective, but it is important to avoid double counting. Moreover, as discussed in more depth later, all resources have 'system costs', and so an exclusive focus on VRE alone is inappropriate.[86]

Figure 6.2 uses Lazard unsubsidized LCOE (from 2016) and also shows the operating and full costs of aging reactors developed earlier ($6/KWh and $9/KWh), rather than new nuclear reactors. The full cost is more appropriate. To make a fair comparison between low-carbon resources, I use the cost of natural gas combined-cycle plants with 90% carbon capture. I have not included the cost of coal with 90% carbon capture, because it is so far off the charts (50% higher than natural gas on LCOE) that it is not a contender and would distort the comparison between resources that should be considered for inclusion in the portfolio. Much the same is true of new nuclear, whose LCOE is more than twice gas, and whose carbon emissions are substantially higher than aging reactors because of the long construction period and intensive carbon emissions of construction. The LCOE costs are adjusted for EIA's estimate of system value, so Figure 6.2 shows avoided cost.

I also include energy efficiency with the current LCOE of $35/MWh. I attribute system costs to efficiency equal to those for hydro, which is given a slight benefit in the EIA analysis.[87] Given all of the positive attributes of efficiency discussed above, this approach is likely to underestimate its benefit in terms of system costs.

The compelling conclusion of this analysis is quite clear. The renewables are preferable by far, and all of the underlying trends reinforce this conclusion.[88] Renewable resource costs continue to fall, particularly for batteries, which would sharply increase their system value. Other advances in integration of renewables will also improve their value.

FIGURE 6.2
CURRENT ESTIMATES OF TOTAL SYSTEM COST

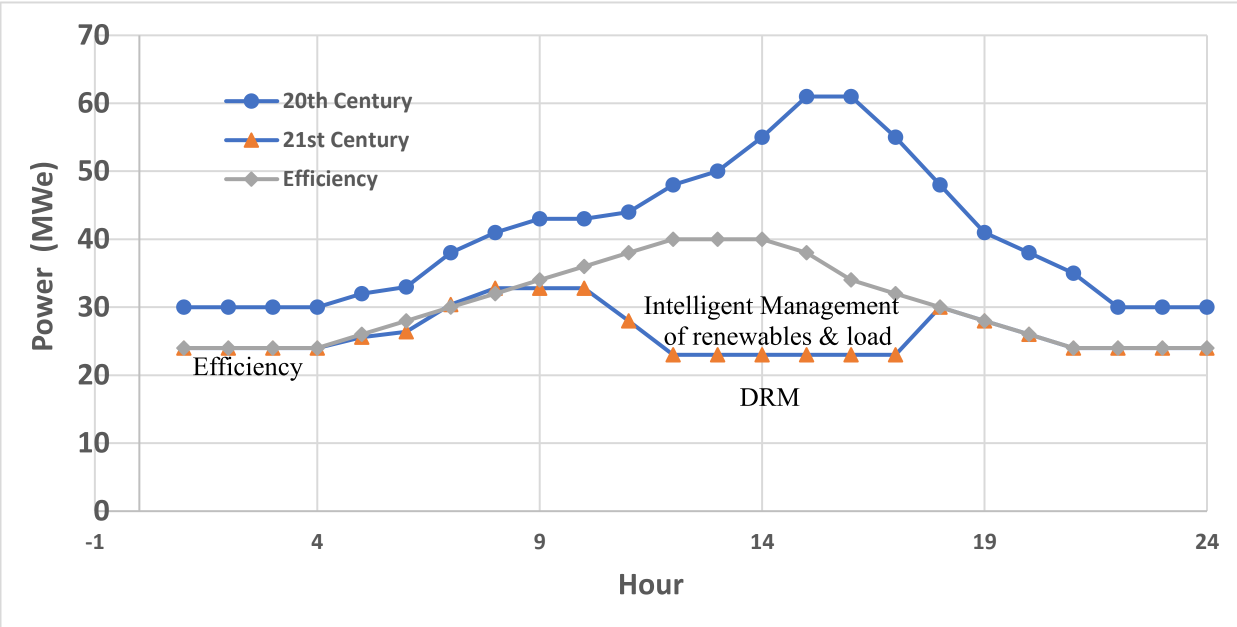


Source: EIA, 2018, *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018*, February Tables 2 and 3, for the adjustment to levelized costs to account for the value of output, using capacity-weighted averages where available and unsubsidized costs. Wiser, Ryan, Andrew Mills, and Joachim Seel, 2015. *Impact of Variable Renewable Energy on Bulk Power System Assets, Pricing and Costs,* Argonne and Lawrence Berkeley National Laboratories, Chapter 5. Lazard, 2018. Lazard's Levelized Cost of Energy Analysis – Version 12.0 for LCOE, 10. For carbon costs, NRC, 2010, *The Hidden Cost of Electricity*, for non-carbon pollution costs of gas, with other resources expressed as a multiple of gas.

THE TRANSFORMATION DIVIDEND

The transformation dividend stems from the fact that managing the balance between supply and demand reduces the amount of capacity needed and electricity used as suggested by Figure 6.3, which is a stylized depiction of the load curves and where the transformation dividend arises. Typically, the 20th-century approach required large reserve margins to provide a safety net if large units were forced offline in an unplanned outage. As the units become smaller, the reserve margins are reduced. Another benefit is that the shifting demand and available supply lower the peak and shift its timing.

FIGURE 6.3
FLATTENING THE LOAD CURVE: REDUCTION AND SHIFT IN THE TRANSFORMATION



Source: N. Shaukata , N. et al.,, 2019, "A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid," *Renewable and Sustainable Energy Reviews* 81, p.1458.

The theory is backed up with the identification of the policies and measures that can be implemented to deliver the transformation dividend, as identified in Table 3.1. This is a small subset of the management strategies that can be adopted to ensure the 21st-century system delivers reliable, affordable electricity and that are more targeted at reducing the peak, shifting the shoulder, and balancing load.

While unabated gas is less costly, the moment its carbon emissions are taken into account, the alternatives are less costly. Aging reactors are about twice as costly, although the youngest of the existing reactor fleet is equal or slightly higher in cost. The primary peaking resource in the current, central-station system is much more costly than a hybrid solar/battery combination, which is the resource of choice among utilities at present. Standalone batteries are about equal in cost, although the cost trend line greatly favors batteries. In fact, starting from the short term, where the full costs of alternatives are competitive with the marginal cost of the central-station alternatives, all of the trend lines strongly favor the alternatives.

CONCLUSION

In this part, I have analyzed the underlying economics of the resources to meet the need for electricity. I have looked at the cost of obtaining and using specific technologies to meet the need for electricity, as well as one factor that affects the level of need. In the mid- and long terms, when new facilities to generate electricity must be built, which inevitably they must, the alternatives are clearly superior in terms of the primary policy characteristics, affordably. In the short term, they are cost competitive with the 20th-century options for power throughout the day.

TABLE 6.1
MEASURES TO MANAGE DECENTRALIZED RESOURCES WHILE REDUCING LOAD

Demand
- **Efficiency**
  - Target efficiency to peak reduction
  - Aggressive demand response
  - Manage water heater loads to reduce peak
  - **Smart controllers**
- **Rates**
  - Target fixed-cost recovery to ramping hours
  - Time of use rates

Supply
- **Diversify renewable supply**
  - Geographic (particularly wind)
  - Technological (wind & solar)
  - Target solar to peak supply (west orientation)
- **Re-orient conventional supply**
- **Shed inflexible baseload**

System Integration
- **Grid management**
  - Expand balance area
  - Improve forecasting
  - Integrated power transactions
  - Import/export
- **Dispatchable storage**
  - Solar thermal electric with storage
  - Utility storage in strategic locations
- **Distributed storage**
  - Community & individual storage
  - Air conditioning water heating with storage
  - Electric vehicles
- **Deploy fast-ramp generation**

Sources: U.S. Department of Energy, *Wind Vision: A New Era for Wind Power in the United States* (Washington, D.C.: U.S. Government Printing Office, 2015), 90; citing Michael Milligan et al., *The Impact of Electric Industry Structure on High Wind Penetration Potential*, Technical Report NREL/TP-550-43273, NREL, July 2009, 23; E3, *Investigating a Higher Renewables Portfolio Standard in California*, Energy and Environmental Economics, Inc., January, 2015; Amory Lovins, *An Initial Critique of Dr. Charles R. Frank, Jr.'s Working Paper "The Net Benefits of Low and No-Carbon Electricity Technologies,"* summarized in *The Economist* as "Free Exchange: Sun, Wind and Drain" (Boulder, CO: Rocky Mountain Institute, August 7, 2014); Jim Lazar, *Teaching the "Duck" to Fly*, Regulatory Assistance Project, January 2014; Steve Nadel, "Conquering the Evening Peak," *ACEEE Blog*, November 24, 2014.

The immediate impact will be to create jobs in the development and deployment of the alternatives, including system management.

- Efficiency will lower bills and deliver mounting "respending" benefits.
- Over time, the transformation dividend will be realized as the size of the system shrinks and the diversification and wide distribution of resources takes place.
- The full benefit will come as large, costly, central-station facilities are replaced with lower-cost alternatives.
  - In the long term, with replacement of all current generation, the cost savings on electricity would be over 8% of the current bill, including the transformation dividend.
  - The macroeconomic multiplier would add indirect benefits of about 7.5%.
  - Phasing out gas also removes other line items from utility bills: gas utility fixed charges and gas transmission and distribution charges.
  - The macroeconomic multiplier would add indirect benefits of about 7.5%.

- The decarbonization and public health benefits will also be emergent as carbon emissions and pollution are reduced.
    - Our analysis of energy efficiency, before carbon was an issue, puts these benefits of reduced pollution at about one-quarter of the total economic benefit, equal to about 4% of the energy bill.
    - The benefits of decarbonization depend on the value placed upon it, but they are very large.

Consistent with the above analysis, an approach that tried to keep uncompetitive nuclear reactors online because they are low carbon emitters, which would squeeze out and delay the growth of the alternatives for a couple of decades, would forgo a substantial part of the economic benefits of the transformation and still face the problem of replacing the nuclear facilities. This would further increase the cost and risk of the electricity system. The right choice is to let nothing stand in the way of the transformation and get it done as quickly as possible.

The main obstacle to doing so is the continued existence and opposition of the 20th-century central-station approach, which is organized and thrives on a completely different approach to physical and institutional infrastructure. For this reason, the decision to consider the transformation of the energy sector as part of an infrastructure bill is exactly right.

The energy sector has all of the key traits of classic infrastructure. It is large and affects many aspects of economic activity, setting the conditions for economic growth. Many aspects of the transition also involve "shovel-ready" physical construction projects. It is also infrastructural in the sense of needing to build the institutions that will govern behavior in the sector for decades to come. This qualitative aspect of the transformation will not "cost" a lot in terms of spending on resources, but it is essential to the deployment of the physical resources.

In this sense, we are not arguing that the 20th-century approach was wrong; we have stated the case for moving on to a different system because the old system is too costly and inconsistent with the opportunity to pursue policy goals that have been opened up by technology.

Given that all low-carbon resources are at least competitive with aging nuclear reactors, and three of them are much lower in cost, it is illogical to claim that retrofitting fossil fuels or keeping central-station generation online is essential for decarbonization. The strong case for the alternatives is reinforced when we examine the other externalities that might require trade-offs in pursuit of the paramount goal of decarbonization.

To wrap up the discussion of the 21st-century alternatives, I return to the "big picture" view of the technological revolution presented in the beginning of Chapter 4. The transformation of the electricity sector fits into the broader technological revolution in two ways, as shown in Table 6.2. The upper part of the table shows the sources of economic advantage of the new system that I have described in various ways throughout the analysis. The lower graph shows the differences in the way the 21st-century system is organized compared to the 20th-century system it is replacing.

TABLE 6.2
ECONOMIC ADVANTAGES AND THE PERVASIVE IMPACT OF THE TECHNOLOGICAL REVOLUTION

Sources of Comparative Advantage of Collaborative Production
(Bold entries apply to the emerging 21st-century electricity sector.)

Activity	Shared Resource	Process	Benefits
Supply-Side Transformation Resource Savings			
Mesh Network	Spectrum	Embedded coordination algorithms	Dynamic occupation of spectrum
Open Source Software	Code	Embodied knowledge in software	Exploiting rich information in real time
Peer-to-Peer	Storage, bandwidth content	Torrenting, Viral communications	Reduction in cost and expansion of throughput, broad exchange
21st-Century Electricity System	**Local & renewable resources**	**Integration of supply & demand with embedded coordination & embodied local knowledge Using diverse geographic & technology supply (akin to torrenting)**	**Dynamic use of grid & resources storage, exploiting information (e.g., weather) in real time Reduction in cost, improvement of throughput**
Transaction Cost Reduction			
All	**Local knowledge**	**Consumer as producer**	**Fit between consumer needs and output improved**
Demand-Side Value Creation			
All	**Network effects**	**Self-organizing**	**Increased option value, supply-side support for open source property due to specialization**

Fundamental Differences between Centuries and Systems

Characteristic	20th Century	21st Century
Goal	Redundancy (as resilience)	Flexibility (resilience is a result)
Operational objective	Increase capacity to follow load	Integrate & match supply and demand
Configuration, size	Island set by economies of generations	Interconnection set by value
Supply-Demand	Segregation	Integration
Demand driver	Dumb load	Smart Retailer
System cost recovery	High, lumpy and fixed	Variable targeted and local
Organization	Centralized	Distributed
Challenges	Increase capacity to follow load	Integrate & match supply and demand
Flash point	50 most expensive hours (>$10,000)	50 least expensive hours (< $0)
Market power	High	Low
Optimization Target	Meet peaks	Shave peaks, Fill valleys (shed & shift)
End users role	Passive	Active
Flow: Output	Hub & Spoke, linear	Networked, Dynamic & Transparent
Information	Aggregate	Transparent, local
Resources: Physical	Fuel, Cement and Boiling Water	Steel, Silicon and Intelligence
Intellectual	Engineering judgement	Communications, Advanced Control
Capital	High for base, low for peak	Moderate for both
Energy intensity	High, concentrated	Low, diffuse

The manifestations of the high level macro-level similarities between digital communications sector and the emerging 21st century electricity system can be easily at a lower level, particularly when the description focuses on the aspect of the transformation that is most dependent on information, communications and control technologies. One set of authors described the contrast between the old grid and the smart grid in terms that highlight the melding of decentralized, advanced technology and the smart grid, as described in Table 6.3.

TABLE 6.3:
COMPARISON BETWEEN CONVENTIONAL ELECTRIC GRID AND THE SMART GRID

Conventional electric grid	**Smart Grid**
Electric Machinery	Digital
One way Communication	Two way Communication
Centralized Power Generation	Distributed Power Generation
A small number of sensors	Full grid sensor layout
Manual monitoring	Automatic monitoring
Manual recovery	Automatic recovery
Failures and voltage outages	Adaptive and Islanded
Few user option	More user option

Source: N. Shaukata , et al.,, 2019, "A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid," *Renewable and Sustainable Energy Reviews* 81. P. 1464/

The next chapter explains how nuclear has bungled the massive subsidies it has received in the past and continues to receive in the present and why keeping it around threatens the transition to a new system.

7. NUCLEAR NIGHTMARES

THE PAST AS PROLOGUE: WHY NUCLEAR SUBSIDIES ARE UNNECESSARY

Over the past two decades, nuclear power has suffered two major setbacks as a result of its fundamental inability to compete. First, the ill-considered "nuclear renaissance" collapsed. The effort to revive construction of nuclear reactors, heralded in the announcement of over 30 projects, failed miserably, at a huge cost to ratepayers. Almost none of the proposed reactors got off the drawing board. The few that did were abandoned at various stages of development. The only project that continues to trudge toward completion is half a decade late, with costs doubling to an astonishing $30 billion. If completed, it will yield the most expensive power in U.S. history at $0.15 to $0.20 per KWh.

The failure of the "nuclear renaissance" is the reason that huge reactors have no place in the 21st-century electricity system. It is also the reason that the industry is once again engaging in happy talk, having shifted its focus to the "next big thing," small modular reactors (SMRs). As discussed in the final chapter, SMRs cannot deliver in the fight against climate change, because they simply cannot arrive soon enough to make a difference, and they should not be counted on, because they are likely to be three times as costly as the alternatives that are now being deployed.

The failure of the "nuclear renaissance" is also the reason for the strong push for subsidies for aging reactors. There are two aspects to this push. First, if the industry had a supply chain full of reasonably priced new reactors, they would be perfectly content retiring the old to make room for the new. Second, if the aging reactors are allowed to retire as they become uneconomic, the nuclear industry will have to let the transformation take place and/or lose its ability to dictate how the sector is organized.

This second impact of the failure of the "nuclear renaissance" leads directly to the second major setback suffered by the nuclear industry. Aging reactors have begun to retire because they are too expensive to run or have suffered major technological failures. As these reactors retire, they are being replaced quite easily without any disruption in the decarbonization of the sector.

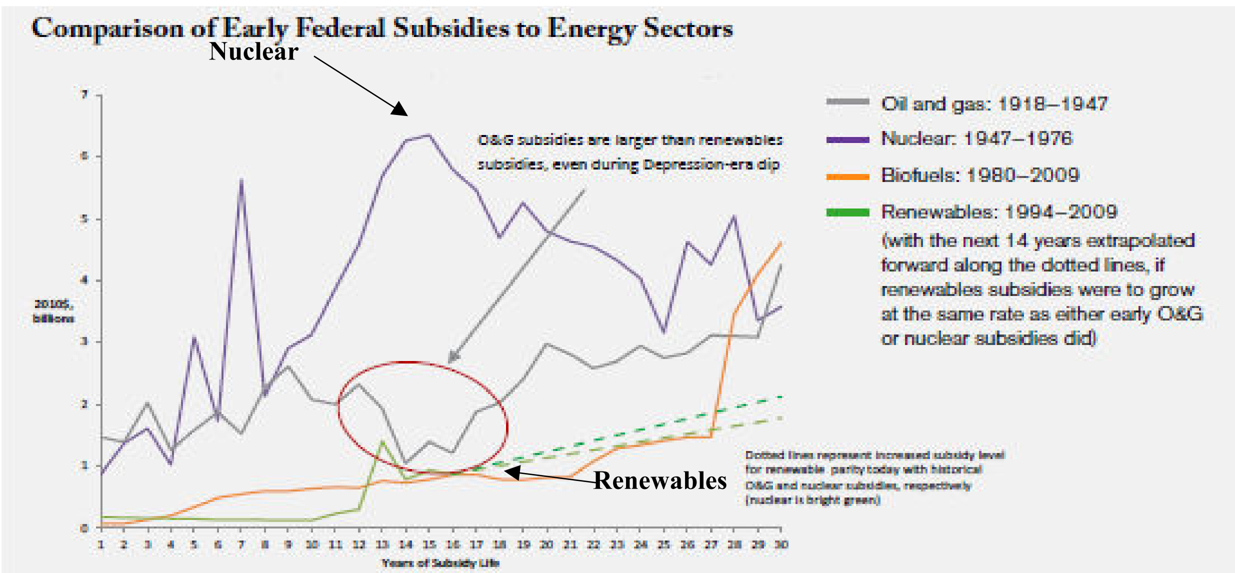
The primary lesson from that experience is not that nuclear power should be subsidized so it can continue to generate electricity; it is that more planning and lead time about retirements will make the process smoother. If grid operators are made aware in advance that reactors will retire when licenses expire or they become uneconomic, they will have more time to plan for the transition. An important corollary to this lesson is that nuclear power, which depends on a completely different organization of the sector, must not be allowed to delay or distort the transformation.

Past Subsidies and Current "Special Treatment" of Nuclear Power

The Failure of Nuclear Power to Deliver on Its Promises

One claim the industry makes is that the alternatives are unfairly being subsidized. While the nuclear industry complains about the subsidies that are bringing renewables into the market today and resists programs to promote energy efficiency, analysis of the historical pattern demonstrates that the cumulative value of federal subsidies for nuclear power dwarfs the value of subsidies for renewables and efficiency.[89] Renewables are in the early stage of development, as shown in Figure 7.1. Nuclear received much larger subsidies in its developmental stage and enjoyed truly massive subsidies since its inception, compared to other resources as it grew.

Figure 7.1
Federal Subsidies for Infant Energy Industries and Beyond



Source: Nancy Pfund and Ben Healey, *What Would Jefferson Do? The Historical Role of Federal Subsidies in Shaping America's Energy Future*, Double Bottom Line Investors, September 2011, pp. 29–30. A similar conclusion, from the point of view of the effectiveness of subsidies in innovation, can be found in Bettencourt, Louis M.A., Jessika E. Trancik, and Jasleen Kaur, "Determinants of the Pace of Global Innovation in Energy Technologies," *PLOS ONE*, October 14, 2013, p. 10.

The graph calculates the rate of growth in subsidies that would be necessary to bring renewables into parity with the early rate of growth in subsidies enjoyed by central-station resources. Renewables are more than a dozen years behind the central-station resources, but given the importance of inertia, parity may not be enough to overcome the advantages of incumbency. There can be debate about the current level of subsidies, particularly given the difficulty of valuing the nuclear insurance and waste subsidies which are existential rather than material (i.e., without the socialization of liability and waste disposal, the industry would not exist). However, there is no doubt that the long-term subsidization of nuclear power vastly exceeds the subsidization of renewables and efficiency by an order of magnitude of 10-to-1.[90]

The dramatic increase in innovative activity despite relatively low levels of R&D subsidy and much lower cumulative subsidization reflects the decentralized nature of innovation in the renewable space. It leads to the dramatic payoff in terms of declining cost. As we have seen, wind had the earlier success, and solar is now catching up.[91] Nuclear power has failed to show these results, because it lacks the necessary characteristics.

The nature of the renewable technologies involved affords the opportunity for a great deal of real-world development and demonstration work before it is deployed on a wide scale. This is the antithesis of past nuclear development. The alternatives are moving rapidly along their learning curves, which can be explained by the fact that these technologies actually possess the characteristics that stimulate innovation and allow for the capture of economies of mass production. They involve the production of large numbers of units under conditions of competition. Nuclear power involves an extremely small number of units from a very small number of firms, with the monopoly model offered as the best approach.

The above discussion of subsidies focuses on long-term patterns of subsidies and underscores the point that much more was invested in nuclear and fossil fuels. This should not be taken to mean that there are no current subsidies enjoyed by nuclear power. In fact, while advocates for nuclear power point to specific subsidies for renewables – production and investment tax credits and renewable energy credits – there are at least half a dozen policies embedded in current practices that nuclear enjoys.

Keeping in mind the principle that that sunk cost should not matter but future, marginal costs are paramount, one might argue that the past nuclear subsidies should not matter. That suggestion is incorrect for three reasons.

As shown in Figure 2.1, above, nuclear has failed to deliver on its price promises. The alternatives have performed much better and hold much greater promise. Further, as shown in Figure 7.1, it is also clear that with a much smaller level of subsidy to drive innovation and economies of scale, the renewables have achieved dramatically declining costs in a little over a decade, which is exactly the economic process that has eluded the nuclear industry for half a century. Figure 7.2 captures the essence of the subsidy issue by juxtaposing the magnitude and timing of subsidies and the extent of innovation, as measured by patents issued. The ultimate irony is that despite much smaller subsidies to drive innovation and economies of scale, renewables have achieved dramatically declining costs in just over half a decade.

The decision to shift subsidies to the alternatives should have nothing to do with fairness, however; it should be based on the likely payoff of the investment. Analyses of past subsidies globally and in the United States make it clear that renewables are a much better bet,[92] even though the estimates do not include the very large implicit subsidies nuclear enjoys from the socialization of the cost of risk and waste management.[93]

Current "Special Treatment"

Current special treatments enjoyed by nuclear power are massive. These include

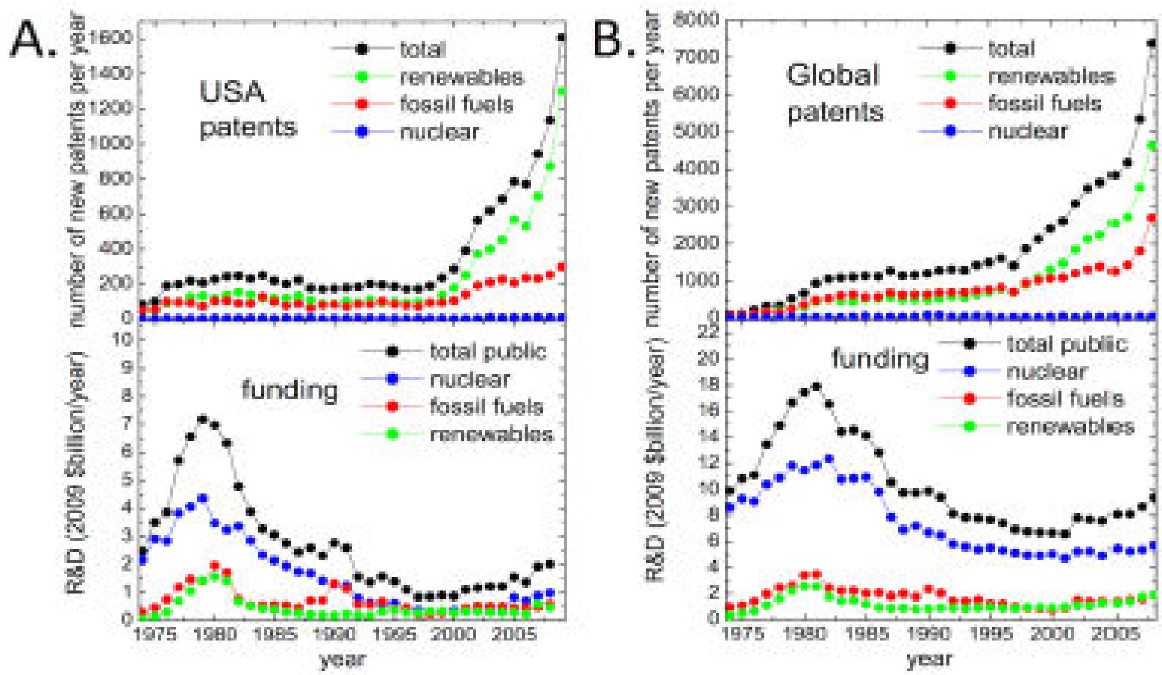
- the socialization of risk and waste management costs, now under court order to be paid by the Department of Energy to nuclear reactor owners for the failure to provide nuclear waste disposal because no such safe waste repository exists or may ever exist,
- tax treatment of capital expenditures,
- capacity payments from RTOs/ISOs,
- high system burdens due to the risk of large outages, and
- the inflexibility of nuclear, which requires higher reserve margins.

The above are all subsidies. In addition,

- nuclear power is favored by the tax code, and

- other centralized resources also get a pass in the treatment of system costs. They have their system costs "socialized" and recovered from ratepayers, while system costs are imposed directly on developers of alternative resources.

FIGURE 7.2
INNOVATION AND PUBLIC SUPPORT FOR R&D



Source: Bettencourt, Louis M.A., Jessika E. Trancik, and Jasleen Kaur, "Determinants of the Pace of Global Innovation in Energy Technologies," *PLOS ONE*, October 14, 2013, p. 10.

Specifically, variable renewables' grid balancing costs are generally borne by their developers or owners and are usually <$5/MWh, nearly always <$10. Yet coal and nuclear plants impose analogous costs on the system without being charged for them, at least outside ERCOT. Instead, the grid balancing costs of managing the intermittence (forced outages) of central thermal plants – reserve margin, spinning reserve, cycling costs, part-load penalties – are traditionally socialized, treated as "inevitable system costs," and hardly ever analyzed.

This asymmetry appears to favor fossil-fueled and nuclear plants, because their balancing costs, emerging evidence suggests, may be several times greater than those of a well-designed and well-run portfolio of PV and wind resources. Conversely, variable renewables may need less backup (or storage) than utilities have already bought to manage the intermittence of their big thermal plants.[94]

NUCLEAR NIGHTMARES

In spite of 70 years of economic failure (more likely *because* of the failure), nuclear advocates have returned to a favorite strategy, insisting that it is indispensable and hoping for (hyping) a new technology. Nuclear power would like to squeeze into the picture by claiming to solve niche problems at the beginning and the end of the transformation. In the beginning, they threaten to undermine reliability by retiring many reactors. At the end, they claim that only the new technology of SMRs can meet a critical need. In other words, by creating a problem at the beginning of the transition with threats to close reactors early and hypothesizing one late in the march toward 100% renewables, the industry hopes to secure a role for its new technology in the future. In order to squeeze into the resource mix at the beginning or the end of the transformation, nuclear needs huge subsidies and/or exceptions from the rules to operate in a manner that supports its economic needs but is antithetical to the new system.

The Fundamental Conflict

This analysis lays the groundwork for the broader consideration of technology choice. In the long term, nuclear new builds are extremely uneconomic, yet the proposal makes no provision for what will happen at the end of the short-term subsidy period. The grid is stuck with almost one-fifth of its power coming from a large, inflexible source that will have to be replaced. Based on economics, the replacement cannot be nuclear. Therefore, the economically rational approach is not to insulate nuclear from near-term competition but to let it cope with its economic fate, which means retirements will take place over the next several decades. This is not only the preferable approach from an economic point of view, it is also the preferable approach from the point of view of the transformation to a 21st-century electrical system, as discussed in the next section.

The economic conflict of interest between nuclear power and the lower-cost, low-carbon alternatives is not limited to the cost of nuclear power. It is reinforced by fundamental differences between central-station power and distributed resources, both in terms of technological competence and institutional requirements. Lovins elaborated earlier on these deep-seated sources of conflict, making it clear that a truce that tries to accommodate both sides is neither very likely nor good policy.

> "All of the above" scenarios are ... undesirable for several reasons. ... First, central thermal plants are too inflexible to play well with variable renewables, and their

market prices and profits drop as renewables gain market share. Second, if resources can compete fairly at all scales, some, and perhaps much, of the transmission built for a centralized vision of the future grid could quickly become superfluous. Third, big, slow, lumpy costly investments can erode utilities and other providers' financial stability, while small, fast granular investments can enhance it. Competition between those two kinds of investments can turn people trying to recover the former investments into foes of the latter—and threaten big-plant owners' financial stability. Fourth, renewable, and especially distributed renewable, futures require very different regulatory structures and business models. Finally, supply costs aren't independent of the scale of deployment, so PV systems installed in Germany in 2010 cost about 56–67 percent less than comparable U.S. systems, despite access to the same modules and other technologies at the same global prices. [95]

The clash of fundamental world views between the 20th-century central-station approach and the 21st-century distributed approach leads to a specific recommendation, about confronting entrenched interests.

> Even though many uncertainties of the future energy system prevail and regional challenges differ a lot, still some general no-regret options can be identified from our experiences:
> 1. Reduce energy demand through the enhancement of behavioral changes as well as technological improvements such as efficiency gains. Also, the recycling and more efficient usage of resources is essential to limit negative effects on society, environment, and nature.
> 2. Investment in renewables enables the energy system transition and provides numerous job opportunities for people around the globe. ...
> 3. Avoid additional investments in fossil fuel infrastructure (i.e., mines, oil rigs, harbor terminals, gas pipelines) which might otherwise create lock-in effects as well as potential sunk investments. By 2020, no new infrastructure should be constructed which is not compatible with a zero carbon society.
> 4. Weaken the fossil fuel regime and support alternative actors to ease a faster transition to more sustainable energy forms. The shrinking remaining CO_2-budget alarms us to (h)asten the upcoming energy transition (in) unprecedented (ways) compared to other historic industrial transition(s). This societal challenge will therefore only be possible if sufficient actors agree to join this pathway to a more sustainable, just, and in-time transition.[96]

In short, this clash is inevitable and has given rise to a frontal assault by nuclear advocates on alternative resources and the institutions that support them. Responsible policymakers should reject the "all of the above" argument, because the severely restricted market created by the forced presence of nuclear power will strangle the ability of non-hydro renewables to expand, which is likely to drive the market clearing price down as resources compete for a smaller market. If there had been no nuclear carve-out, renewables could have competed for and won this load in an orderly fashion, avoiding another "crisis" at the termination of the current subsidy, a "crisis" that the industry will inevitably invoke to demand another round of subsidies.[97]

The Front End: RMR regulation

Nuclear subsidies are certain to receive considerable attention as policy debate goes forward, particularly since it has been divided between traditional infrastructure and 21st-century infrastructure. The devil will certainly be in the details, but the above analysis offers clear and unequivocal principles that should govern any nuclear subsidies. The purpose of these principles is to ensure that the Regulatory Must Run (RMR) subsidies result in the low cost and the minimal disruption of the development of the alternative electricity system.

1) Aging nuclear reactors should not be subsidized for economic or decarbonization reasons. Nuclear power is more costly in the near term and much more costly in the long term.

2) Aging nuclear reactors should not be subsidized for purposes of decarbonization, because their current, static contribution will be quickly replaced by lower-cost alternatives.

3) Nor should aging nuclear reactors be subsidized in the hope of reducing the impact of other pollutants and externalities, because the low-cost alternatives can accomplish the same outcome without raising concerns about water, waste, decommissioning, and safety.

4) The only basis to consider a subsidy would be a concern about the impact on reliability of the retirement of one (or more) reactors. To demonstrate such a concern and a need for nuclear facilities that would be given payments as part of a "regulatory, must-run" program, the nuclear operator must give adequate notice of the intent to retire under the following conditions:

  a) advanced notice must afford the time to the system operator to assess the impact.

  b) the system operator should also develop alternatives to replace the RMR reactor as quickly as possible.

  c) to ensure that the RMR subsidy is as small as possible,

    i) it should only ensure that the reactor covers its operational costs

    ii) all suppliers should be allowed to bid for the subsidy, with the award being for the lowest cost option.

  d) The RMR plan should include measures to replace the power upon the expiration of the RMR period

5) The RMR subsidy should be short-term, lasting just long enough for the reliability concern to be eliminated.

6) At the end of the RMR period, the subsidized reactor should retire and will not be allowed to receive any future subsidy. If the reactor chooses not to retire, it will have to bid into the energy market without any consideration (no must-run status).

The adoption of these principles has clear implications for the way the program is run that deserve to be stated as principles.

7) The RMR executor defines the magnitude and awards the subsidy, based on the economics of the reactors, not the conditions (price) in the marketplace.

8) The RMR executor should ensure that any system operator that is utilizing RMR reactors is also aggressively implementing the approach to system management (flexibility, dynamic matching of supply and demand, etc.) that supports the deployment of alternatives.

The Back End: Small Modular Reactors Do Not Solve the Problem, They Are the Future Problem

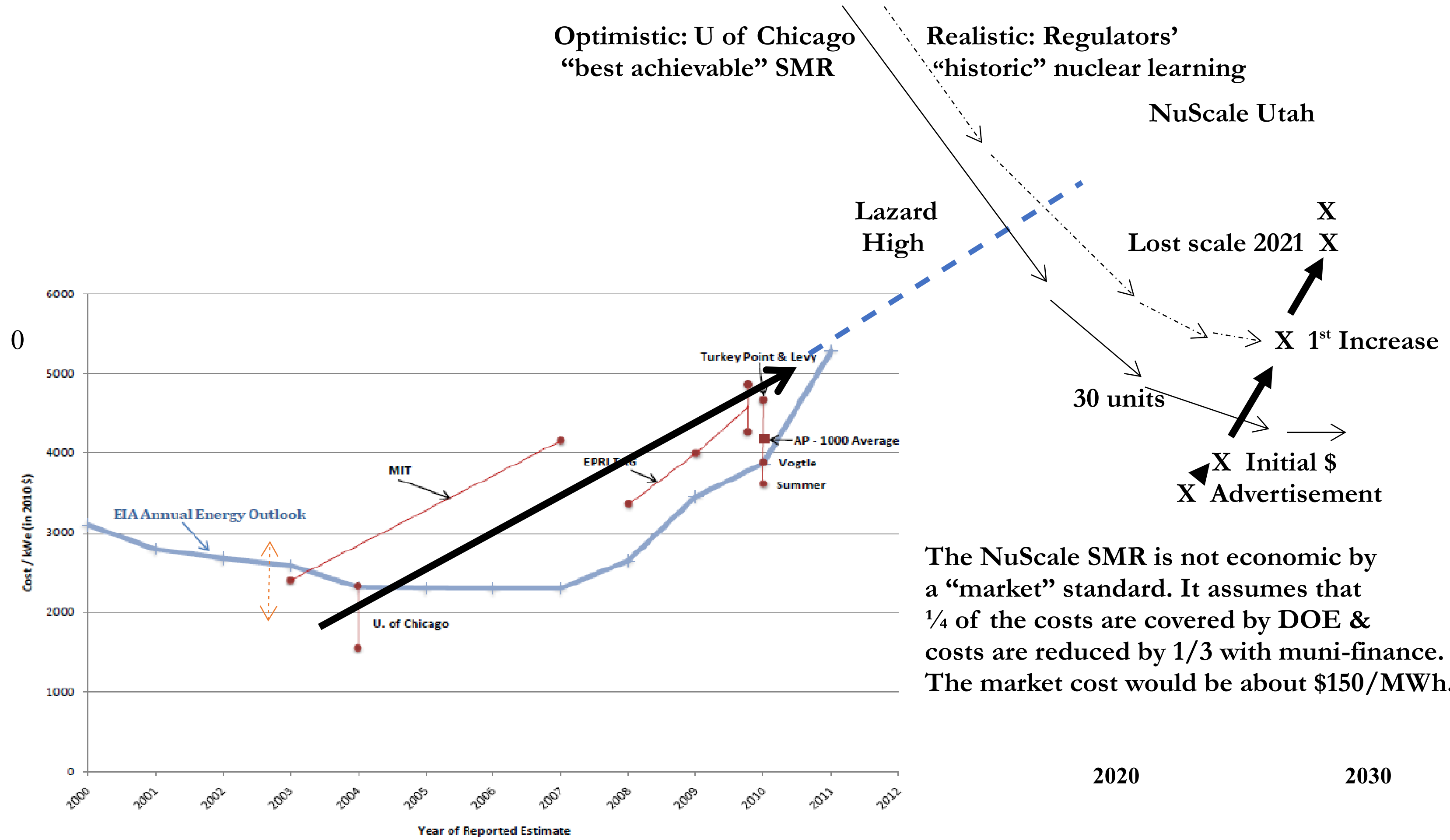
Small modular reactors are the latest in a long line of technologies that the advocates of nuclear power hope will provide answers to the many problems that have afflicted their industry. Hyped as the dream solution, they turn into a nightmare. Small modular reactors that have been on the drawing board for at least a decade exhibit all of the characteristics of failure. Like the "nuclear renaissance" before it, the initial estimates of cost have doubled before they go into construction, and cost overruns really only begin when construction does. While they can find companies to back them and governments to support them and academics to explain the theory of why they should work, the one thing they cannot do is deliver low-cost power.

While they claim to be safer than large units, they achieve that goal not by simply solving safety problems but by being excused from safety rules (like emergency planning zones). While they are low in carbon emissions, they suffer from the problem that, even if the production of small units will be possible in the future, they will arrive long after the battle against climate change is lost. While they are small, they still need "must-run" status and large numbers of units shipped in order to lower their cost. Small modular reactors are likely to be between three and five times as costly as the already available technologies to build a low-cost, low-carbon, low-pollution electricity sector. As Ramana recently put it,

> The estimated costs of the NuScale reactor design have been consistently going up. Just in the last five years, the estimated construction cost has gone up from around $3 billion in 2015 to $6.1 billion in 2020. Because the NuScale design might have to be modified to resolve the problems flagged by the Nuclear Regulatory Commission, there could be further cost increases even before construction starts. There is a long history of dramatic cost increases when paper designs are first constructed.[98]

Figure 7.3 describes the SMR cost problem. It updates my 2014 analysis by including two recent estimates. I have included the current estimate for the only active small modular reactors project. The high cost of nuclear power is apparent, and there is nothing in the SMR technology that suggests it will result in a cost revolution for nuclear. Using the math of the vendor, the first cost estimate was put at $0.055/KWh, so the current estimate is about twice that before construction cost overruns. In other words, it is at least three times as costly as the bundle of alternatives (efficiency, wind, and solar) and likely to be even more if construction takes place.

FIGURE 7.3
UNIVERSITY OF CHICAGO RECAP OF ENTHUSIAST/UTILITY ESTIMATES OF OVERNIGHT COST FOR NEW GW-SCALE NUCLEAR PLANTS AND SMRS



Sources: Mark Cooper, "Small modular reactors and the future of nuclear power in the United States," Energy Research & Social Science 3 (2014) 161; Rosner, Robert and Stephen Goldberg, 2011, *Small Modular Reactors – Potentially Key Contributors to Future Nuclear Power Generation in the U.S.*, Center for Strategic and International Studies, December 1; Rosner, Robert, et al., Analysis of GW-Scale Overnight Capital Costs, EPIC, University of Chicago, Technical Paper Nov. 2011. For the cost and other problems with the only active U.S. small modular reactor, see, M. V. Ramana, *2020, Eyes Wide Shut: Problems with the Utah Associated Municipal Power Systems Proposal to Construct NuScale Small Modular Nuclear Reactors,* Oregon Physicians for Social Responsibility. NuScale, 2015, *Value Proposition*, Feb. 18.

Ironically, the main purpose of the original research was to argue that economies of scale and learning by doing would be important factors that would drive costs down. Hence, the study was optimistic about costs after the first 30 units were built. The only active SMR project in the U.S. is heading in the opposite direction. With many of the original parties dropping out for various reasons, NuScale is considering the cost implications of reducing the initial delivery by one-quarter and one-half.

Indeed, the SMR project has begun to look like the first of the large nuclear reactor projects 60 years ago. They were built as turnkey projects and delivered to utilities at a fixed price, even though they were far more costly to build. Ultimately, the vendors sold hundreds of reactors (half of which were canceled) on a cost-plus basis. The NuScale vendor claims it will hit its target price because the federal government has underwritten almost one-quarter of the cost. It also claims that muni-finance, which is backed by a government guarantee, will also lower the cost over 30%. Thus, the guaranteed price of power is not a market price by any stretch of the imagination. The original cost of the SMR was about $100/MWh, before the cost overrun (of 50%) and without the loss of economies of scale. Therefore, the power is likely to be between three and five times as costly as the alternative.

The economic failure of SMR technology should be the end of nuclear power, since a low-cost, low-carbon, low-pollution electricity system, in which it can play no role, should be in place before any of these reactors are constructed. The principles that should govern the RMR subsidy can be reframed to govern any subsidy for SMRs. The conditions mean that no SMRs will be built, which is the correct outcome.

1) Small modular reactors should not be subsidized for economic or decarbonization reasons. Nuclear power is more costly in the near term and much more costly in the long term.

2) Small modular reactors should not be subsidized for purposes of decarbonization, because their current, static contribution will be quickly replaced by lower-cost alternatives.

3) Nor should they be subsidized in the hope of reducing the impact of other pollutants and externalities, because the low-cost alternatives can accomplish the same outcome without raising concerns about water, waste, decommissioning, and safety.

4) The only basis to consider a subsidy would be a concern about the impact on reliability or the cost of getting to full 100% reliance on renewables. Those concerns are far off in the future and not likely to materialize. It is far too soon to make commitments of large sums of subsidies, especially given the length of time before the problem emerges and the dozens of tools policymakers have to address the issues in a much less costly manner.

5) The principles of least cost and competitive acquisition should be applied to any effort to build the last 5% or 10% of the greenhouse gas solution.

6) The magnitude and direction of the subsidy should be defined by policy, based on the economics of the reactors, not the conditions (price) in the marketplace.

7) The executor should ensure that any system operator that is utilizing SMR reactors is also aggressively implementing the approach to system management (flexibility, dynamic matching of supply and demand, etc.) that supports the deployment of alternatives.

Economic challenges are not the only problems with SMRs. SMRs share the waste, water, decommissioning, and safety concerns of large reactors, with an added element of uncertainty. Much of their claimed advantage arises from claims about the lack of need for regulations that have governed nuclear power over the past 60 years, but they have not demonstrated that they deserve this relaxed treatment. Just as SMR vendors have failed to produce a single unit and are not likely to do so for another decade, they have not produced tangible evidence of overcoming the dozen and a half challenges I identified in my analysis over half a decade ago.

The vendors of SMRs have made exactly the same mistake that the vendors of large reactors made with the first units in the 1960s. They have tried to leap from the conceptualization phase to the production phase, without going through the vetting of the demonstration phase that is so important. I summarized this mistake in my analysis of SMRs, launching from an observation on early deployment of light-water reactors:

> This rush to market contributed to the crash of the Great Bandwagon Market and plagued the "Nuclear Renaissance."[99]
>
> For 15 years many of those most closely identified with reactor commercialization have stubbornly refused to face up to the sheer technical complexity of the job that remained after the first prototype nuclear plants had been built in the mid- and late 1950s. Both industry and government refused to recognize that construction and successful operation of these prototypes – though it represented a very considerable technical achievement – was the beginning and not near the completion of a demanding undertaking.[100]

With a technology as complex as nuclear reactors, prototypes and real-world experiences are crucially important before full-scale deployment is contemplated. Komanoff emphasized that in putting a safe product into the market, design review needs to not only be thorough but also ongoing with real-world deployment allowed, to continually improve the understanding of safety and therefore the need for design modifications.[101]

The problem that nuclear technology faces today is not simply a function of its inability to control its cost. As I suggested in the introduction, it is also a function of the wide range of alternatives that the technological revolution has called forth, all of which are much lower in cost, and their cost advantage keeps growing. One recent study that cautioned against assuming the "optimum" price on alternatives also concluded that many possibilities exist at small deviations from the optimum.

> Models for long-term investment planning of the power system typically return a single optimal solution per set of cost assumptions. However, typically there are many near-optimal alternatives that stand out due to other attractive properties like social acceptance. …
> Many similarly costly, but technologically diverse solutions exist. Already a cost deviation of 0.5% offers a large range of possible investments. However, either offshore or onshore wind energy along with some hydrogen storage and transmission network reinforcement appear essential to keep costs within 10% of the optimum.[102]

In this analysis, a cost deviation of 10% in the alternative system still leaves it about one-third of the cost of a low-carbon system based on central-station facilities. It is simply no contest, and subsidies for a central-station option make no sense.

CONCLUSION

The urgency of the campaign for subsidies by nuclear advocates is a function of the circumstances they face – lower-cost, more-benign alternatives that are ready to go – not the technology they are touting. Policymakers and utilities should have said no to large-scale nuclear power in the past, which would have saved consumers a great deal of money. They should say no to small reactors today.[103]

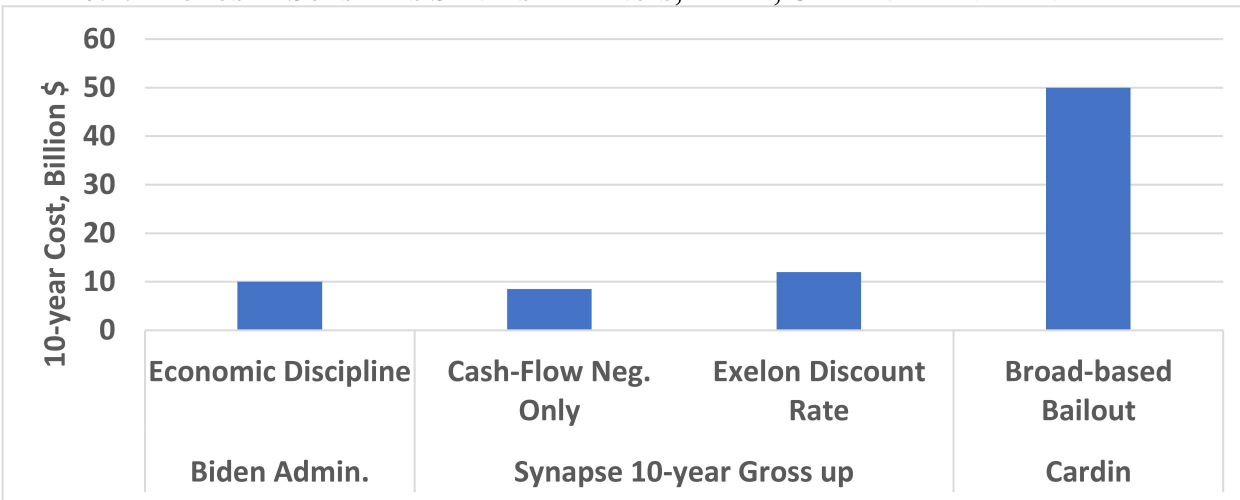
This analysis makes it clear that no subsidies for nuclear power are justified to achieve the goals. Moreover, nuclear power has been the recipient of subsidies throughout its entire existence – ten times as much as renewables – but it has never delivered on its promise of low-cost power. Small modular reactors appear to be repeating the path of large reactors, with rising costs and increasing delays. Much of the battle to meet the challenge of climate change will be over before even one of these reactors is online. Current special treatments enjoyed by nuclear power are massive.

In spite of 70 years of economic failure (more likely *because* of the failure), nuclear advocates have returned to a favorite strategy, insisting that it is indispensable and hoping for (hyping) a new technology. Nuclear power would like to squeeze into the picture by claiming to solve niche problems at the beginning and the end of the transformation. In the beginning, they threaten to undermine reliability by retiring many reactors. At the end, they claim that only the new technology of small modular reactors (SMRs) can meet a critical need.

A sensible set of rules to keep any reactors that are needed for short-term reliability is already on the books. If more is needed, a small regulatory must-run program can be created. The Biden proposal does so, requiring the nuclear reactor operator show the need and keeping the cost to $1 billion per year (see Figure 7.4). This is consistent with a recent analysis of the need in Illinois by Synapse.

Given that the need for additional low-carbon resources on the back end of the transformation process is highly doubtful, as is the ability of SMRs to actually get built at an affordable cost, there is no need to subsidize these reactors

7.4: PROPOSED SUBSIDIES SYNAPSE ILLINOIS, BIDEN, CARDIN AMENDMENT



Source: On Biden see, Treasury Department. May 2021. "General Explanations of the Administration's Fiscal Year 2022 Revenue Proposals," p.42-3; For synapse see, Bhandari. Divita. et al. 2021. Exelon Nuclear Fleet Audit, Findings and Recommendations. Synapse, April 14; On Cardin see, S.2291/HR. 4024 The Zero-Emission Nuclear Power Production Credit Act of 2021, from Sen. Cardin in the Senate and Rep. Pascrell in the House.

BIBLIOGRAPHY

Category		#	Citation
f	1	378	Abd Rahman. Jamel. A.. and A. H. Shamsuddin. 2013. “Advances in the Integration of Solar Thermal Energy with Conventional and Non-Conventional Power Plants.” *Renewable and Sustainable Energy Reviews* 20.
b	1	6	Acemoglu. Daron. and James A. Robinson, 2012. *Why Nations Fail.* Crown. Crown.
a	2	47	Advanced Energy Economy Institute. 2015. *Toward a 21st century electricity system in California.* San Francisco.
d	1	552	Aebischer. Bernard. and Lorenz M. Hilty. 2014. The Energy Demand of ICT: A Historical Perspective and Current Methodological Challenges. August. reprinted in *Advances in Intelligent Systems and Computing.*
a	1	171	AEMO. 2013. *100 Percent Renewables Study: Modelling Outcomes*. July 2013.
t	32	160	Aggarawal. Sonia and Robbie Orvis. 2016. “Grid Flexibility.: Methods for Modernizing the Power Grid.” *Energy Innovation*.” March,
t	36	148	Agora Energiewende. 2014. *Negative electricity prices: causes and effects*. Berlin
a	4	59	Agora Energiewende. 2015a. *A snapshot of the Danish energy transition*. Berlin
a	4	58	Agora Energiewende. 2015b. *The Danish experience with integrating variable renewable energy: lessons learned and options for improvement*. Berlin
a	4	54	Agora Energiewende. 2015c. *The Energiewende in the power sector: state of affairs 2014: a review of the significant developments and an outlook for 2015*. Berlin.
f	1	41	Agora Energiewende. 2015d. *The European power system in 2030: flexibility challenges and integration benefits.* Berlin
a	4	55	Agora Energiewende. 2015f. *The solar eclipse 2015: outlook for the power system 2030*. Berlin (In German.
a	4	57	Agora Energiewende. 2015g. *Understanding the energiewende*. Berlin.
f	1	74	Agora Energiewende. 2015h. *The integration costs of wind and solar power.* Berlin.
f	1	372	Agora. Energiewende. 2015i. *The Integration Costs of Wind and Solar Power: an Overview of the Debate on the Effects of Adding Wind and Solar Photovoltaic into Power Systems*. Berlin.
c	3	579	Air. Don. 2010/ *Delivering Jobs: The Economic Costs and Benefits of Improving the Fuel Economy of Heavy-Duty Vehicles.* Union of Concerned Scientists. May.
d	2	491	Akinyem., Toluwanimi O. and Olayinka J. Ramonu. 2019. “Mitigation of CO2Emissions in Transportation and Industrial Processes using Renewable Energy.” *EJERS. European Journal of Engineering Research and Science* 4.
b	2	306	Albino. Vito. et al.. 2015. “Smart Cities: Definitions. Dimensions. Performance. and Initiatives.” *Journal of Urban Technology*. 22.
h	1	112	Allcott. H. 2011. "Rethinking real--time electricity pricing." *Resource and Energy Economics* 33.
a	4	280	Alliance For A Green Economy and Nuclear Information and Resource Service. 2016.*Comment. Proceeding on Motion of the Commission to Implement a Large-Scale Renewable Program and a Clean Energy Standard.* Case 15-E-0302. April 22. August 31.
d	3	476	Al-Saadi. Mohammed. et al.. 2018. “Inductive Power Transfer for Charging the Electric Vehicle Batteries.” *Electrotehnica. Electronica. Automatica* 66.
t	43	433	Andreas Kamilaris. Andreas et al. 2014. “A Literature Survey on Measuring Energy Usage for Miscellaneous Electric Loads in Offices and Commercial Buildings,*” Renewable & Sustainable Energy Reviews 34.*
d	3	493	Andress. David. T. Dean Nguyen and Sujit Das. 2011. “Reducing GHG emissions in the United States' transportation sector.” *Energy for Sustainable Development* 15.
t	31	440	Aqeel, Ahmed Bazmia. and Gholamreza Zahedia. 2011. “Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review.” *Renewable and Sustainable Energy Reviews* 15.
t	43	572	Arcadia Center. 2014. *Energy Efficiency: Engine of Economic Growth in Canada: A Macroeconomic Modeling & Tax Revenue Impact Assessment.* October 30.
t	23	176	Arif. Ahmer. Fahad Javed. and Naveed Arshad. 2014. “Integrating Renewables Economic Dispatch with Demand Side Management in micro-Grids: A Genetic Algorithm-Based Approach.” *Energy Efficiency* 7.

t 35 144 Australian Energy Market Operator. 2014. *Australia wind energy forecasting system.* Canberra.

j 2 416 Badcock. Jeremy and Manfred Lenzen. 2010. “Subsidies for Electricity-Generating Technologies: A Review.” *Energy Policy* 38.

t 37 86 Bajwa. Maheen and Joseph Cavicchi. 2017. “Growing Evidence of Increased Frequency of Negative Electricity Prices in U.S. Wholesale Electricity Markets.” *IAEE Forum*. Fourth Quarter.

t 14 85 Balling. L. 2011. Fast cycling and rapid start--up: new generation of plants achieves impressive results. *Modern Power Systems* 31.

t 33 193 Barbose. Galen. et al. 2016. *On the Path to SunShot: Utility Regulatory and Business Model Reforms for Addressing the Financial Impacts of Distributed Solar on Utilities*. Golden. CO: National Renewable Energy Laboratory. NREL

d 4 251 Barton, Barry and Peter Schütte. 2015. *Electric Vehicle Policy: New Zealand in a Comparative Context.* Centre for Environmental, Resources and Energy Law. University of Waikato. November.

h 1 106 Bayer. Benjamin. 2015. “Current practice and thinking with demand response for power system flexibility in U.S. and German electricity markets. *Current Sustainable and Renewable Energy Reports* 2.

c 2 243 Benes. Keith J. and Caitlin Augustin. 2016. “Beyond LCOE: A simplified framework for assessing the full cost of electricity.” *The Electricity Journal.* 29.

t 23 178 Bergaentzlé. Claire Cédric Clastres. and Haikal Khalfallah. 2014. “Demand-Side Management and European Environmental and Energy Goals: An Optimal Complementary Approach.” *Energy Policy* 67.

a 4 284 Berkman. Mark and Dean Murphy. Brattle Group. 2015. *New York’s Upstate Nuclear Power Plants’ Contribution to the State Economy.* prepared for New York State IBEW Utility Labor Council Rochester Building and Construction Trades Council Central and Northern New York Building and Construction. December.

j 1 281 Berwick. .Ann G. 2012. *Comparing Federal Subsidies for Renewables and Other Sources of Electric Generation*. Massachusetts Department of Public Utilities Massachusetts Solar Summit. June 13.

h 1 388 Bettencourt L. et al. 2013. Determinants of the Pace of Global Innovation in Energy Technologies. *PLoS ONE* 8.

j 3 564 Bhandari. Divita. et al. 2021. *Exelon Nuclear Fleet Audit, Findings and Recommendations.* Synapse, April 14.

t 23 177 Biegela. Benjamin et al. 2014. “Value of Flexible Consumption in the Electricity Markets.” *Energy* 66.

d 1 154 Bikash Kumar Sahu. Moonmoon Hiloidhari. and D. C. Baruah.2013. “Global Trend in Wind Power with Special Focus on the Top Five Wind Power Producing Countries.” *Renewable and Sustainable Energy Reviews* 19.

b 2 315 Bioneers. 2015.*Climate Leadership: How California’s Climate Policy Could Change* The World.

t 34 61 Bird L. Cochran J. Wang X. 2014. *Wind and solar energy curtailment: experience and practices in the United States*. Report NREL/TP--6A20--60983. Golden. CO: NREL.

h 1 392 Bird. Stephen and Lisa Legault. 2018. “Feedback and Behavioral Intervention in Residential Energy and Resource Use: a Review.” *Current Sustainable/Renewable Energy Reports.*

t 7 153 Blade. Gavin. 2017."Steel for fuel: Xcel CEO Ben Fowke on his utility’s move to a renewable-centric.” *Utility Dive*. July 11.

t 31 439 Bloom. Aaron (NREL). 2017. *Interconnections Seam Study. TransGrid-X Symposium*. Ames. Iowa.

d 1 73 Bloom. Aaron. 2017. It's Indisputable: Five Facts About Planning and Operating Modern Power Systems. *IEEE Power and Energy Magazine.* 6.

f 1 199 Boie. Inga. et al.. 2014. “Efficient Strategies for the Integration of Renewable Energy into Future Energy Infrastructures in Europe – An Analysis Based on Transnational Modeling and Case Studies for Nine European Regions.” *Energy Policy* 67.

t 40 452 Borlase. Stuart. 2013.Smart Grids. Infrastructures. Technologies and Solutions. *CRC Press.*

f 1 197 Bose. Tapan K.. et al. 2014. Stand-Alone Renewable Energy System Based on Hydrogen Production. Institut de recherche sur l’hydrogène. Université du Québec à Trois-Rivières. Canada.

t 35 145 Botterud A. 2014. *Forecasting renewable energy for grid operations.* Research gate.

t 36 14 Botterud. Audun. 2017. *Electricity Markets and Renewable Energy: United States vs. Europe.* Argonne National Laboratory. January 27.

f 1 187 Bouzid. Allal M.. et al. 2015. “A Survey on Control of Electric Power Distributed Generation

Systems for Micro Grid Applications." *Renewable and Sustainable Energy Reviews* 44

c 1 422 Branker.K. M. J.M. Pathak. J. M. Pearce. 2011. "A Review of Solar Photovoltaic Levelized Cost of Electricity". *Renewable & Sustainable Energy Reviews* 15.

d 2 478 Brendon Baatz. James Barrett. and Brian Stickles. 2018. *Estimating the Value of Energy efficiency to Reduce Wholesale Energy Price Volatility* ACEEE. April.

a 4 51 Brinkman G. Jorgenson J. Ehlen A. Caldwell H. 2016. *California low carbon grid study: analysis of a 50% emission reduction in California.* Report NREL/TP--6A20--64884. Golden. CO: NREL.

c 3 546 Brockway. Paul E. et al. 2021. "Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications." *Renewable and Sustainable Energy Reviews* 141.

f 1 377 Brown. Patrick R. and Audun Botterud. 2021. "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System." *Joule.* January.

t 43 580 Brown. Richard. et al. U.S. 2008. *Building-Sector Energy Efficiency Potential*. Lawrence Berkeley National Laboratory. September.

f 1 470 Brown. T. et al.. 2018. Synergies of sector coupling and transmission reinforcement in a cost-optimised. highly renewable European energy system." *Energy* 160.

a 264 Brown. T.W. et al.2018,"Response to Burden of Proof: A Comprehensive review of the feasibility of 100% renewable-electricity systems." *Renewable and Sustainable Energy Reviews.* 92.

a 1 265 Budischak et al.. 2013. "Cost-Minimized Combinations of Wind Power. Solar Power. and Electrochemical Storage. Powering the Grid up to 99.9% of the Time." *Journal of Power Sources* 225.

j 1 563 Bupp, I. and J. Derian, 1981 *The Failed Promise of Nuclear Power,* New York: Basic Books

j 1 562 Bupp, I. and J. Derian. 1978. *Light Water: How the Nuclear Dream Dissolved*, New York: Basic Books.

j 2 417 BWE. German Wind Energy Association. *The Full Costs of Power Generation: A Comparison of Subsidies and Societal Cost of Renewable and Conventional Energy Sources*. BWE. Berlin. August 2012.

b 1 533 Byrne. David M. and Carol A. Corrado. 2015. *Prices for Communications Equipment: Rewriting the Record.* Finance and Discussion Series. Federal Reserve Board Paper No. 2015-069.

b 1 513 Byrne. David M. and Carol A. Corrado. 2015a. "Recent Trends in Communications Equipment Prices. *Fed Notes.* September 29.

b 1 500 Byrne. David M. and Carol A. Corrado. 2017. *ICT Services and their Prices: What do they tell us about Productivity and Technology?* Finance and Discussion Series. Federal Reserve Board Paper No. 2017-015;

c 3 142 Cadmus. 2015. *Focus on Energy. Economic Impacts 2011–2014*. December.

d 2 101 California Independent System Operator. CPUC. California Energy Commission. 2015. *Advancing and maximimizing the value of energy storage technology: a California roadmap.* Folsom. CA.

f 1 23 California Public Utilities Commission. 2015. *Beyond 33% renewables: grid integration policies for a low-carbon future*. Energy Division Staff White Paper. San Francisco.

f 1 547 Carvallo. Juan Pablo. et al. 2021. "Implications of a regional resource adequacy program for utility integrated resource planning." *The Electricity Journal* 34.

d 2 211 Cau. Giorgio . et al. 2014. "Energy Management Strategy Based on Short-Term Generation Scheduling for a Renewable Microgrid Using a Hydrogen Storage System." *Energy Conversion and Management* 87.

d 1 238 Cavicchi. Joseph. 2017. "Rethinking government subsidies for renewable electricity generation resources." *The Electricity Journal.* 30.

a 3 294 Cebullla. Felix and Mark Z. Jacobson. 2018. "Carbon emissions and costs associated with subsidizing New York nuclear instead of replacing it with renewables." *Journal of Cleaner Production.* 205.

g 1 94 Celebi . Metin. et al. 2017. *Evaluation of the DOE's Proposed Grid Resiliency Pricing Rule*. October 23.

a 1 18 Chang. Judy W. et al.. 2017. *Advancing Past "Baseload" to a Flexible Grid How Grid Planners and Power Markets Are Better Defining System Needs to Achieve a Cost-Effective and Reliable Supply Mix.* NRDC. June.

t 31 437 Changming Zheng. Tomislav Dragicevic and J. Bltbjerg. 2020. "Model Predictive Control Based Virtual Inertia Emulator for an Islanded AC Microgrid." *IEEE Transactions on Industrial Electronics* · July.

f 1 370 Chaves-Avila. J.P.. R. A. Hakvoort. and A. Ramos. 2014. “The Impact of European Balancing Rules on Wind Power Economics and on Short-Term Bidding Strategies.” *Energy Policy* 68.

d 3 356 Chellaswamy. C. and R. Ramesh. 2017. “Future renewable energy option for recharging full electric vehicles.” *Renewable and Sustainable Energy Reviews* 76.

f 1 473 Child. Michael. et al.. 2019. “Flexible electricity generation. grid exchange and storage for the transition to a 100% renewable energy system in Europe.” *Renewable Energy* 139.

a 1 300 Chmutina. Ksenia and Chris I. Goodier. 2014. “Alternative Future Energy Pathways: Assessment of the Potential of Innovative Decentralised Energy Systems in the UK.” *Energy Policy* 66.

c 1 418 Christopher. T.M.. et al.. 2020. *Why Local Solar For All Costs Less: A New Roadmap for the Lowest Cost Grid. Vibrant Clean Energy.* December.

t 32 195 Chung. Donald. Kelsey Horowitz. and Parthiv Kurup. 2016. *On the Path to SunShot: Emerging Opportunities and Challenges in U.S. Solar Manufacturing.* Golden. CO: National Renewable Energy Laboratory. NREL

g 1 260 Clyde Loutan and Vahan Gevorgian. 2018. *Using Renewables to Operate a Low Carbon Grid: Demonstration of Advanced Reliability Service from a Utility Scale Solar PV Plant.* California ISO. NREl.

g 1 84 Cochran J. Lew D. Kumar N. 2013. *Flexible coal: evolution from baseload to peaking plant*. Report BR--6A20--60575. Golden. CO: NREL and 21st Century Power Partnership.

a 1 262 Cochran. J. T. Mai and M. Bazilian.2014**.** **"**Meta-analysis of high penetration renewable energy scenario." *Renewable & Sustainable Energy Review.* 29 January.

e 1 161 Cochran. J. et al. 2012. *Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.* Golden. CO: NREL.

t 36 12 Cochran. Jaquelin. et al. 2013. *Market Evolution: Wholesale Electricity Market Design for 21st Century Power Systems*. NREL.

t 32 78 Cochran. Jaquelin. et al. 2014. *Flexibilty in 21st Century Power Systems.* NREL,

a 4 268 Cochran, Jaquelin, et al., 2021. “Chapter 1: Introduction.” In *The Los Angeles 100% Renewable Energy Study*, edited by Jaquelin Cochran and Paul Denholm. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-79444-1.

g 1 302 Cole et al. 2021. “Quantifying the challenge of reaching a 100% renewable energy power system for the United States,” *Joule June 16*.

t 40 82 Cole. Wesley. Et al. 2016. “*2016 Standard Scenarios Report: A U.S. Electricity Sector Outloo*k.” Golden. CO: National Renewable Energy Laboratory.

c 3 581 Committee to Assess Fuel Economy for Medium and Heavy Duty Vehicles. *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles.* National Research Council. 2010

e 1 368 Connolly D et al.. 2009. “A review of computer tools for analysing the integration of renewable energy into various energy systems.” *Appl Energy 87.*

a 2 292 Cooper. Mark. 2010 “Direct Testimony of Dr. Mark N Cooper in Re: Nuclear Plant Cost Recovery for the Southern Alliance for Clean Energy.” Before the *Florida Public Service Commission*. FPSC Docket No. 100009-EI. August.

d 2 339 Cooper. Mark. 2011a. “Nuclear liability: the post-Fukushima case for ending Price-Anderson.” *Bulletin of the Atomic Scientists.* October. 5.

c 1 426 Cooper. Mark. 2011b. “Prudent Resource Acquisition in a Complex Decision-Making Environment: Multidimensional Analysis Highlights the Superiority of Efficiency.” *Current Approaches to Integrated Resource Planning. 2011 ACEEE National Conference on Energy Efficiency as a Resource*. Denver. September 26.

c 1 427 Cooper. Mark. 2011c. *Least Cost Planning for 21st Century Electricity Supply: Meeting the Challenges of Complexity and Ambiguity in Decision Making.* MACRUC Annual Conference. June 5. 2011.

a 2 290 Cooper. Mark. 2011d. “Testimony of Dr. Mark Cooper on House File 9.” *Minnesota House of Representatives Committee on Commerce and Regulatory Reform*. February 9.

a 2 291 Cooper. Mark. 2011e. “Direct Testimony of Dr. Mark N Cooper in Re: Nuclear Plant Cost Recovery for the Southern Alliance for Clean Energy.” Before the *Florida Public Service Commission*. FPSC Docket No. 090009-EI. July 15.

j 1 423 Cooper. Mark. 2012a. “Nuclear Safety and Affordable Reactors: Can We Have Both?.” *Bulletin of the*

Atomic Scientists. 68.

d 2 338 Cooper. Mark. 2012b. "Nuclear Safety and Nuclear Economics. Fukushima Reignites the Never-ending Debate: Is Nuclear Power not worth the risk at any price?." *Symposium on the Future of Nuclear Power.* University of Pittsburgh. March 27-28.

c 1 425 Cooper. Mark. 2013. "Multi-Criteria Portfolio Analysis of Electricity Resources: An Empirical Framework for Valuing Resource in an Increasingly Complex Decision Making Environment". *Expert Workshop: System Approach to Assessing the Value of Wind Energy to Society. European Commission Joint Research Centre. Institute for Energy and Transport*. Petten. The Netherlands. November 13-14.

i 2 405 Cooper. Mark. 2013a "Nuclear Aging: Not so gracefully." *Bulletin of the Atomic Scientists.* 69.

i 2 403 Cooper. Mark. 2013b. *Renaissance in Reverse: Competition Pushes Aging U.S. Nuclear Reactors to the Brink of Economic Abandonment.* July.

b 1 299 Cooper. Mark. 2013c. "Why Growing Up is Hard to Do: Institutional Challenges for Internet Governance in the 'Quarterlife Crisis; of the Digital Revolution," *Journal on Telecommunications and High Technology Law,* 11.

c 3 582 Cooper. Mark. 2013d. *Energy Efficiency Performance Standards: The Cornerstone of Consumer-Friendly Energy Policy.* Comments of the Consumer Federation of America. October.

j 4 409 Cooper. Mark. 2014a. "Small modular reactors and the future of nuclear power in the United States." *Energy Research & Social Science.*.

d 2 353 Cooper. Mark. 2014b. *Energy Efficiency Performance Standards: Driving Consumer and Energy Savings in California.* California Energy Commission's Energy Academy. February 20.

j 1 412 Cooper. Mark. 2015. *Power Shift. The Nuclear War Against the Future: How Nuclear Advocates Are Thwarting the Deployment of a 21st Century Electricity Sector*. Institute for Energy and the Environment. Vermont Law School. May.

d 1 583 Cooper. Mark. 2015a, Comments of Dr. Mark Cooper." In the Matter of Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units. Environmental Protection Agency. RIN 2060-AR33. November 24.

b 2 319 Cooper. Mark. 2016. "Renewable and distributed resources in a post-Paris low carbon future: The key role and political economy of sustainable electricity." Energy Research & Social Science.

a 1 271 Cooper. Mark. *2017. The Political Economy of Electricity: Progressive Capitalism and the Struggle to Build a Sustainable Power Sector* (Santa Barbara. Praeger.

a 2 289 Cooper. Mark. 2017a. *The Failure of The Nuclear Gamble In South Carolina: Regulators can Save Consumers Billions by Pulling the Plug on Summer 2 & 3 Already Years behind Schedule and Billions Over Budget Things are Likely to Get Much Worse if the Project Continues*. for the Sierra Club of South Carolina. July.

b 2 318 Cooper. Mark. 2018. "Governing the Global Climate Commons: The Political Economy of State and Local Action. After the U.S. Flip-Flop on the Paris Agreement." *Energy Policy.*

a 4 287 Cooper. Mark. 2018a. *A Clean Slate for Vogtle. Clean Energy for Georgia: The Case for Ending Construction at the Vogtle Nuclear Power Plant and Reorienting Policy to Least-Cost. Clean Alternatives.* for the Sierra Club of Georgia. February.

a 2 288 Cooper. mark. 2018b. *Affidavit Of Mark Cooper. In the Matter of Hudson River Sloop Clearwater. Inc.. Goshen Green Farms. LLC. Nuclear Information and Resource Service. Indian Point Safe Energy Coalition. and Promoting Health and Sustainable Energy. Inc. before* the Supreme Court of the State Of New York County of Albany. December.

i 2 404 Cooper. Mark. 2018c. *The Green New Deal And Aging Reactors: Nuclear Power Has No Future Progressive Capitalism And The Struggle To Build A Clean. Sustainable Electricity Sector: New York's Zero Emission Credits for Nuclear Power Harm Consumers and the Environment and will slow the Transition to a Clean. Low Carbon Sector*. December..

i 1 584 Cooper. Mark. 2019. *Avoiding Nuclear and Fossil Fuel Potholes. a Green New Deal Has a Clear Path to a Clean. Low Cost. Low Carbon. Progressive. Capitalist Electricity Sector*. April. 2019.

i 1 402 Cooper Mark. 2019a. *The Green New Deal Can Build A Progressive. Capitalist. Low Cost. Low Carbon. Electricity Sector. If It Avoids The Nuclear Power And Fossil Fuel Potholes Along The Way.* April.

a 4 286 Cooper Mark. 2021. *Declaration Of Mark Cooper.* In the Matter of NextEra Energy Point Beach. LLC (Point Beach Nuclear Plant. Units 1 and 2) NRC–2021–0021. Docket Nos. 50-266 and 50-301. March 23. 2021. United States Of America Nuclear Regulatory Commission. March 3.

j 4 541 Cooper. Mark. And Amina Adbu. 2021. *Pragmatic, Progressive Capitalism at its Best: Network Neutrality, How an Entrepreneurial State Used Public Policy to Foster Experimental Entrepreneurialism and Create the Internet*, Consumer Federation of America, August.

t 31 250 Costello. Kenneth W. 2016. "Ways for utility regulation to grapple with new developments in the U.S. Electricity Industry." *The Electricity Journal.* 29.

t 30 330 Dale Hall, Nic Lutsey. 2017. *Emerging Best Practices for Electric Vehicle Charging Infrastructure.* ICCT. October.

d 3 354 Dale. Larry. et al.. 2009. "Retrospective Evaluation of Appliance Price Trends." *Energy Policy* 37.

g 1 389 Dalibor Petković et al.. "Adaptive Neuro-Fuzzy Maximal Power Extraction of Wind Turbine with Continuously Variable Transmission." *Energy* 64.

j 3 585 Daniels. Steve. 2014. "Exelon Puts an Opening Price Tag on Nuclear Rescue: $580 Million." Crains Chicago Business. September 24.

j 3 524 Daniels. Steve.2017. "How Exelon will keep getting bailout money in Illinois—whether it needs it or not." *Crain's Chicago Business.* August 2.

f 1 477 Das. H.S.. et al.. 2020 "Integration: A technological review." *Renewable and Sustainable Energy Reviews* 120.

j 1 489 Decommission Working Group. 2021. *Towards An Evidence-Based Nuclear Energy Policy*.. EESI Congressional Briefing. March 30.

a 1 258 Deep Decarbonization Pathways Project. 2015. *Pathways to Deep Decarbonization 2015 Report. Paris*: SDSN – IDDRI. 2015.

t 7 246 Deetjen. Thomas A. et al. 2016." Solar PV integration cost variation due to array orientation and geographic location in the Electric Reliability Council of Texas." *Applied Energy*. 180.

t 7 247 Deetjen. Thomas A. et al. 2017. "The impacts of wind and solar on grid flexibility requirements in the Electric Reliability Council of Texas." *Energy.* 12.

c 1 548 Deloite Insights. 2018. *Global Renewable Energy Trends: Solar and Wind Mover from Mainstream to Preferred,*

a 1 272 Delucchi. Mark A. and Mark Z. Jacobson. 2013. "Meeting the World's Energy Needs Entirely with Wind. Water. and Solar Power." *Bulletin of the Atomic Scientists* 69.

a 1 496 Delucchi. Mark A.. and Mark Z. Jacobson. 2011. "Providing All Global Energy with Wind. Water. and Solar Power. Part II: Reliability. System and Transmission Costs. and Policies." *Energy Policy* 39.

f 1 185 Denholm. Paul. Kara Clark. and Matt O'Connell. 2016. *On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System.* Golden. CO: National Renewable Energy Laboratory. NREL

g 1 93 Department of Energy Notice of Proposed Rulemaking. Docket No. RM17-3-000 "Grid Resiliency Pricing Rule" September 28. 2017. ("NOPR") published in the *Federal Register* Vol. 82 No. 194 Tuesday October 10. 2017 (82 FR 46.940).

d 1 455 Department of the Treasury. May 2021. *General Explanations of the Administration's Fiscal Year 2022. Revenue Proposals.*

f 1 205 Díaz-González. Francisco et al. 2012. "A Review of Energy Storage Technologies for Wind Power Applications." *Renewable and Sustainable Energy Reviews* 16.

g 1 384 Dincer. Ibrahim and Canan Acar. 2015. "A review on clean energy solutions for better. Sustainability." *Int. J. Energy Res*; 39.

j 3 526 DiSavino. Scott. "New Jersey governor signs nuclear power subsidy bill into law." *Reuters*. May 23.

a 2 497 Doluweera. Ganesh. et al.. 2018.. *A Comprehensive Guide To Electricity Generation Options In Canada*. Canadian Energy Research Institute. February.

b 2 309 Dorr. Adam and Tony Seba. 2021. *Rethinking Energy The Great Stranding: How Inaccurate Mainstream LCOE Estimates are Creating a Trillion-Dollar Bubble in Conventional Energy Assets.* A RethinkX Sector Disruption Report. February.

c 3 321 Doug Vine. 2021. *Power Infrastructure Needs For Economywide Decarbonization.* Center for Climate and Energy Solutions. April.

f 1 45 Droste-. Franke B. et al. 2012. *Balancing Renewable Electricity: Energy Storage. Demand Side Management. and Network Extension from an Interdisciplinary Perspective.* New York: Springer.

d 2 343 Dufour. Fritz. 2018. *The Costs and Implications of Our Demand for Energy: A Comparative and Comprehensive Analysis of the Available Energy Resources How Fossil Fuels Have Created an Energy Crisis Exploring Our Alternatives The Future of Energy.* June.

h 1 107 Dupont B. et al. 2014.” Demand response with locational dynamic pricing to support the integration of renewables.” *Energy Policy* 67.

t 31 172 Duthu. Ray C. and Thomas H. Bradley. 2015. “An Evaluation of Customer-Optimized Distributed Generation in New England Utility and Real-Time Markets.” *The Electricity Journal* 28

c 3 498 Dyson. Mark. and Becky Li. .2020. *Reimagining Grid Resilience.* Rocky Mountain Institute. 2020.

a 4 155 E3. 2015. *Higher Renewables Portfolio Standard. E3. Investigating a Higher Renewables Portfolio Standard in California. Energy and Environmental Economics.* Inc.. January.

b 2 532 Edison Foundation Institute for Electric Innovation. 2014. *Innovations across the grid: partnerships transforming the power sector*. Washington. DC.

a 3 331 EESI. 2021. *Background Information For The EESI Congressional Briefing: Towards An Evidence-Based Nuclear Energy Policy Gaps in Research, Regulation, Policy, and Practice in the U.S. Nuclear Industry, and What Policymakers Can Do to Bridge Them.* March 30.

j 1 490 EESI. 2021. Gaps in Research. Regulation. Policy. and Practice in the U.S. Nuclear. Industry. and What Policymakers Can Do to Bridge Them. EESI Congressional Briefing. March 30.

i 2 586 Eggers. Dan. Kevin Cole. and Matthew Davis. 2013. *Nuclear. The Middle Age Dilemma? Facing Declining Performance. Higher Costs. Inevitable Mortality.* Credit Suisse. 2013;

f 1 99 Eichman. Joshua D.. et al. 2013. Scott Samuelson. “Exploration of the Integration of Renewable Resources into California’s Electric System Using the Holistic Grid Resource Integration and Deployment (HiGRID) Tool.” *Energy* 50.

g 1 138 Ela E. et al. 2011. *Operating reserves and variable generation.* Report NREL/TP--5500--51978. Golden. CO: NREL

g 1 139 Ela E. et al. 2014a. *Active power controls from wind power: bridging the gaps.* Report NREL/TP--5D00--60574. Golden. CO: NREL

t 33 146 Ela E. et al. 2014b. *Evolution of wholesale electricity market design with increasing levels of renewable generation.* Report NREL/TP--5D00-- 61765. Golden. CO: NREL

t 36 252 Ela. E. et al.. 2016. “Wholesale electricity market design with increasing levels of renewable generation: Incentivizing flexibility in system operations.” *The Electricity Journal*. 29.

f 1 42 Electric Power Research Institute (EPRI). 2015. *The integrated grid: realizing the full value of central and distributed energy resources.* Palo Alto. CA.

c 3 456 Elfani. Maria. 2011. **“**The Impact Of Renewable Energy On Employment In Indonesia**.”** *International Journal of Technology* 1.

f 1 202 Elkind. Ethan M. 2010. *The Power of Energy Storage: How to Increase Deployment in California to Reduce Greenhouse Gas Emissions*. Center for Law and the Environment. Berkeley. and Environmental Law Center. UCLA. July.

d 1 366 Ellabban. Omar. Haitham Abu-Rub. and Frede Bltbjerg. 2014.. “Renewable energy resources: Current status. future prospects and their enabling technology.” *Renewable and Sustainable Energy Reviews* 39.

t 23 180 Elliston. MacGill. and Diesendorf. 2013. *Least Cost 100% Renewable Electricity Scenarios.* Australian Energy Management Organization.

c 3 587 ENE. *Energy Efficiency: Engine of Economic Growth: A Macroeconomic Modeling Assessment*. October 2008.

d 3 362 Energy Research Knowledge Centre. 2014. *Other alternative transport fuels.* European Commission. October.

j 4 333 Energy Strategies. 2019. *Analyzing the Cost of Small Modular Reactors and Alternative Power Portfolios.* Prepared for Healthy Environment Alliance of Utah. . May.

j 3 525 Energyzt Advisors. LLC. 2018. *Financial Assessment: Millstone Nuclear Power Plant”* April.

a 1 135 EPRI. 2012. *Integrating smart distributed energy resources with distribution management systems*. Palo Alto. CA.

a 1 270 Erickson. Peter. Chelsea Chandler and Michael Lazarus. 2012. *Reducing Greenhouse Gas Emissions Associated with Consumption: A Methodology for Scenario Analysis.* Stockholm Environment Institute. Working Paper No. 2012-05.

d 2 350 Ernst Worrell. et al.. 2003. “Productivity Benefits of Industrial Energy Efficiency Measures.” *Energy Journal*. 11.

f 1 249 Eryilmaz. Derya. and Sanem Sergici. 2016. “Integration of residential PV and its implications for current and future residential electricity demand in the United States.” *The Electricity Journal. 29*.

a 4 68 Eurelectric. 2010. *Power choices: pathways to carbon-neutral electricity in Europe by 2050*. Brussels.

a 4 67 European Network of Transmission System Operators for Electricity (ENTSO--E). 2014. *Ten- year network development plan and regional investment plan*. Brussels.

t 23 119 EWE AG and e--Energy. 2014. *eTelligence final report.* Oldenburg. Germany.

t 23 175 Falsafi. Hananeh. Alireza Zakariazadeh. and Shahram Jadid. 2014. “The Role of Demand Response in Single and Multi-Objective Wind-Thermal Generation Scheduling: A Stochastic Programming.” *Energy* 64.

t 41 50 Fang. Tingting and Risto Lahdelma. 2016. “Optimization of combined heat and power production with heat storage based on sliding time window method”. *Applied Energy* 162.

t 36 235 Faruqui. Ahmad. and Kirby Leyshon. 2017. Fixed charges in electric rate design: A survey.” *The Electricity Journal.* 30.

t 36 234 Faruqui. Ahmad. Sanem Sergici and Cody Warner. “Arcturus 2.0: A meta-analysis of time-varying rates for electricity.” *The Electricity Journal* 30.

h 1 105 Federal Energy Regulatory Commission (FERC). 2014. *Demand response and advanced metering*. Staff Report. Washington. DC.

j 3 520 Federal Energy Regulatory Commission. 2015. *Order Instituting Section 206 Proceeding and Directing Filing to Establish Reliability Must Run Tariff Provisions (*Docket No. EL15-37-000). February 19.

c 3 336 Federal Treade Commission Staff Report. *Internet of Things, Privacy & Security in a Connected World*. January 2015.

d 2 217 Feldman. David. and Mark Bolinger. 2016. *On the Path to SunShot: Emerging Opportunities and Challenges in Financing Sola*r. Golden. CO: National Renewable Energy Laboratory. NREL.

t 23 117 Findlay C. 2011. Strength in numbers: merging small generators as virtual power plants. January.

a 4 62 Fine. S. Patricia D’Costa and Kiran Kumararswamy. 2014. “Policies for Accommodating Higher Penetration of Variable Energy Resources: U.S. Outlook and Perspectives.” *Renewable Energy Integration,* Chapter 2.

j 4 410 Flyvbjerg1. Bent. 2021. *Four Ways to Scale Up: Smart. Dumb. Forced. and Fumbled.* Saïd Business School Working Papers. January.

t 35 143 Foley AM. Et al. 2012. “Current methods and advances in forecasting of wind power generation.” *Renewable Energy* 37.

t 27 39 Forsberg. Charles W.. et al. 2017. “Converting Excess Low-Price Electricity into High-Temperature Stored Heat for Industry and High-Value Electricity Production.” *The Electricity Journal* 30.

t 7 245 Fowler. Luke and Autumn T. Johnson. 2017. “Overlapping authorities in U.S. energy policy.” *The Electricity Journal*. 30.

t 40 11 Fox--Penner P. 2010. *Smart Power: Climate Change. the Smart Grid and the Future of Electric Utilities.* Washington DC: Island Press.

t 31 334 Frew, Bethany, et al. 2019. “Sunny with a Chance of Curtailment: Operating the US Grid with Very High Levels of Solar Photovoltaics.” *iScience* 21, November 22.

c 3 457 Garcia-Casals1. Xavier. Rabia Ferroukhi1 and Bishal Parajuli1. 2019. “Measuring the socio-economic footprint of the energy transition.” *Energy Transitions* 3:

t 42 297 Gellings, Clark W. 2009. *The Smart Grid: Enabling Energy Efficiency and Demand Respons*e. CRC Press.

f 1 141 General Electric International. Inc. 2014. *PJM Renewable Integration Study*. March 31.

a 4 56 German Federal Ministry for Economic Affairs and Energy. 2015. *An electricity market for Germany’s energy transition*. White Paper. Berlin.

b 2 499 Gielen. Dolf. et al.. 2019. “The role of renewable energy in the global energy transformation.” *Energy Strategy Reviews* 24.

t 36 83 Gifford. Raymond L. and Matthew S. Larson. 2016. *State Actions in Organized Markets States Strive to ‘Fix’ Markets and Retain Base Load Generation.* Wilkinson. Barker. Nauer. LLC. September 7.

b 2 308 Giglio. Stefano. 2015. “Climate Change And Long-Run Discount Rates: Evidence From Real Estate.” *Centre for Economic Policy Research.* Discussion Paper No. 10958. November.

d 2 346 Gilleo. Annie. 2017. *New data. same results – Saving energy is still cheaper than making energy. American Counsel for and Energy Efficient* Economy. December 1.

j 1 482 Gilmore. Donna. 2021. *Spent Nuclear Fuel Dry Storage: Urgent Problems and Solution*. NRC

Commission Meeting. February 11.

t 36 30 Gimon. Eric. 2017a. *Flexibility. Not Resilience. is the Key to Wholesale Electricity Market Reform.*

a 3 9 Gimon. Eric. 2017b. *On Market Designs for a Future with a High Penetration of Variable Renewable Generation*. Submitted to the U.S. Department of Energy Future Markets Workshop. September 8. Energy Innovation LLC.

d 2 212 Gireesh. Shrimali. Melissa Lynes. and Joe Indvik. 2015. “Wind Energy Deployment in the U.S.: An Empirical Analysis of the Role of Federal and State Policies.” *Renewable and Sustainable Energy Reviews* 43.

c 3 588 Gold. Rachel. et al.. 2009. Energy *Efficiency in the American Clean Energy and Security Act of 2009: Impact of Current Provisions and Opportunities to Enhance the Legislation.* American Council for an Energy Efficient Economy. September.

c 3 601 Gold. Rachel. et al. 2011. *Appliance and Equipment Efficiency Standards: A Money Maker and Job Creator.* American Council for an Energy-Efficient Economy. January.

j 1 414 Goldberg. Marshall. *Federal Energy Subsidies: Not All Technologies Are Created Equal*. Washington. DC: Renewable Energy Policy Project. 2000;

a 1 458 Goldman School of Public Policy. 2020. *Report 2035. Plummeting Solar. Wind. And Battery Costs Can Accelerate Our Clean Electricity Future.*

h 1 480 Gowdy. John Malcolm. 2008. “Behavioral Economics and Climate Change Policy." *Journal of Economic Behavior & Organization.* December.

j 4 381 Green. Jim. 2019. “Obituary for small modular reactors.” *Ecologist.* March.

d 2 213 Greene. David L Judith M. Greenwald and Rebecca E.Ciez. 2020. “U.S. fuel economy and greenhouse gas standards: What have they achieved and what have we learned?” *Energy Policy. 116.*. November.

d 2 182 Greene. David. and Jilleah G. Welch. *The Impact of Increased Fuel Economy for Light-Duty Vehicles on the Distribution of Income in the United States*. Oak Ridge National Laboratory and the Energy Foundation. September 2016.

a 1 19 Greenpeace. 2015. *Energy [R]evolution: A Sustainable world energy outlook*. Amsterdam.

c 3 329 Greenpeace. 2020. *Toxic Air: The Price Of Fossil Fuels*. February.

t 8 429 Grossmann. Wolf D.. Iris Grosssman. and Karl W. Seininger. 2014.“Solar Electricity Generation Across Large Geographic Areas. Part II: A Pan-American Energy System Based on Solar.” Renewable and Sustainable Energy Reviews 32.

t 40 226 Guido. Pepermans. 2014. “Valuing Smart Meters.” *Energy Economics* 45

j 1 486 Gunter. Paul. *Decommissioning's Critical Link to Reactor Safety & Operating License Extensions.* EESI Congressional Briefing. March 30 2021.

d 4 113 Hahn T. et al. 2013.” Model-based quantification of load shift potentials and optimized charging of electric vehicles. Smart Grid and Renewable,” *Energy* 4.

d 3 365 Hall. Dale and Nic Lutsey. 2017. *Literature Review 0n Power Utility Best Practices Regarding Electric Vehicles.* ICCT.

t 30 550 Hall. Dale, Nic Lutsey. 2017. *Emerging Best Practices for Electric Vehicle Charging Infrastructure*. ICCT, October.

a 1 21 Hand MM. et al. 2012. *Renewable electricity futures study*. Report NREL/TP--6A20–52409. vol. 1–4. Golden. CO: NREL.

f 1 371 Hannele Holttinen. 2009. *Design and Operation of Power Systems with Large Amounts of Wind Power*. Final Report. IEA Wind Task 25.

g 1 419 Hansen. Kenneth. Chrisitan Breyer and Henrik Lund. 2019. “Status and perspectives on 100% renewable energy systems,” *Energy.* 175.

a 5 293 Harrington. Winston. 2006. *Grading Estimates of the Benefits and Costs of Federal Regulation: A Review of Reviews.* Resources for the Future. September.

f 1 424 Hartsfield. Tom. 2017. *Fleeing the Paris Accord Makes Scientific Sense.* Realclearscience.com.

f 1 203 Hasan. Nor Shahida. et al. 2013 “Review of Storage Schemes for Wind Energy Systems.” *Renewable and Sustainable Energy Reviews* 21.

c 3 589 Heintz. James. Robert Pollin . and Heidi Garrett-Peltier. 2009. *How Infrastructure Investments Support the U.S. Economy: Employment. Productivity and Growth.* Political Economy Research Institute. January.

t 34 123 Henriot. A. 2015. "Economic curtailment of intermittent renewable energy sources." *Energy Economics* 49.

d 4 220 Heymans. Catherine. et al. 2014. "Economic Analysis of Second Use Electric Vehicle Batteries for Residential Energy Storage and Load-Levelling." *Energy Policy* 71.

t 36 420 Hibbard. Paul. Susan Tierney. and Katherine Franklin. 2017. *Electricity Markets, Reliability and the Evolving U.S. Power System.* Analysis Group. June.

f 1 75 Hirth L. F. Ueckerdt and O. Edenhofer. 2015." Integration costs revisited—An economic framework for wind and solar variability". *Renewable Energy* 74.

f 1 140 Hirth L. Ziegenhagen I. 2013. *Control power and variable renewables: a glimpse at German data.* Milan. Italy: Fondazione Eni Enrico Mattei.

a 3 15 Hirth. Lion. 2016. "The benefits of flexibility: The value of wind energy with hydropower". *Applied Energy*. 181.

c 2 17 Hirth. Lion. 2018. "What Caused the Drop in Euripean Electricity Prices? A Factor Decomposition analysis." *The Energy Journal. 39.*

d 3 494 Hischier. Roland and Patrick A. Wäger. 2014. *The Transition from Desktop Computers to Tablets: A Model for Increasing Resource Efficiency?* Research gate. January.

c 3 387 Hoffert. Martin I.. 2010. "Farewell to Fossil Fuels?" *Science* 329..

f 1 66 Hogan M. Weston F. Gottstein M. 2015. *Power market operations and system reliability in the transition to a low-carbon power system: a contribution to the market design debate*. Regulatory Assistance Project.

t 36 33 Hogan. Mike. 2012. *Aligning Power Markets to Deliver Value.* Regulatory Analysis Project.

t 36 95 Hogan. William W. and Susan L. Pope. 2017. *Priorities for the Evolution of Energy Only Electricity Market Design in ERCOT.* FTI Consulting. May 9.

f 1 34 Holttinen H. 2013. *Expert Group Report on Recommended Practices: Wind Integration Studies. International Energy Agency Wind Task 25*. Paris: IEA.

t 31 162 Holttinen. H. et al. 2013. "The Flexibility Workout: Managing Variable Resources and Assessing the Need for Power System Modification." *IEEE Power & Energy*. 11.

d 2 163 Holttinen. H. et al. 2013a. *Design and Operation of Power Systems with Large Amounts of Wind Power. Final summary report.* IEA WIND Task 25.

b 2 316 Honeywell. 2021. *How 4Gg LTE And 5G Will Transform Utility Operations..*

a 5 298 Hwang. Roland and Matt Peak. 2006. *Innovation and Regulation in the Automobiles Sector: Lessons Learned and Implicit on for California CO_2 Standards.* April..

j 4 421 Idaho Power. *2019 IRP.*

g 1 390 Ilham. Nur Iqtiyani. M. Hasanuzzaman ad M.A.A. Mamun. 2020. 'World energy policies. "Chapter 8 in MD. Hasanuzzaman. Nasrudin Abd Rahim. *Energy for Sustainable Development.*

j 3 561 Illinois Commerce Commission, Illinois Power Agency, Illinois Environmental Protection Agency, and Illinois Department of Commerce and Economic Opportunity. *Response To The Illinois General Assembly Concerning House Resolution 1146*. January 5, 2015,

f 1 170 Imperial College. 2014. *Integration of Renewable Energy*. June 12.

t 40 80 International Energy Agency. 2011. *Technology roadmap: smart grids*. Paris.

d 3 576 International Energy Administration. 2013.*From hidden fuel to world's first fuel?:* 16 October

t 27 100 International Energy Agency. 2014a. Technology roadmap: energy storage. Paris.

a 1 26 International Energy Agency. 2014b. *The Power of Transformation: Wind. Sun and the Economics of Flexible Power Systems*. Paris.

d 2 352 International Energy Agenc*y. 2016. Energy Efficiency Market Report 2016*. October.

a 1 517 International Energy Agency. 2019. *Global EV Outlook 2019.*

f 1 28 International Energy Agency-RETD (Renewable Energy Technology Deployment). 2014. *RE--integration: integration of variable renewable electricity sources in electricity systems—lessons learnt and guidelines*. Paris: OECD.

t 23 116 International Energy Agency-RETD. 2014. *Residential prosumers – drivers and policy options.* Paris.

f 1 206 Ippolito. M. G.. et al. 2014. "Multi-Objective Optimized Management of Electrical Energy Storage Systems in an Islanded Network with Renewable Energy Sources under Different Design Scenarios." *Energy* 64.

d 1 216 IREN21. 2018a. *renewables 2018: Global Status Report.*

c 3 324 IRENA. *2013. Renewable Energy and Jobs.* December.

t 36 88 IRENA. 2015. *From baseload to peak: renewables provide a reliable solution.* Abu Dhabi,

e 1 126 IRENA. 2015a. Grid investments for renewables. Abu Dhabi,

a 5 40 IRENA. 2015.b *The age of renewable power: designing national roadmaps for a successful transformation.* Bonn.

d 1 369 IRENA. 2017. *Synergies between renewable energy and energy efficiency. a working paper based on REmap.* International Renewable Energy Agency (IRENA). Abu Dhabi.

d 1 382 IRENA. 2018. *Renewable Energy Policies in a Time of Transition* April..

g 1 122 Jacobsen. Henrik Klinge. And Sascha Thorsten Schroeder. 2012. Curtailment of renewable generation: economic optimality and incentives. *Energy Policy* 49.

a 1 267 Jacobson. Mark Z. 2009. "Review of solutions to global warming. air pollution and energy security." *Energy Environmental Science.* 2.

i 1 443 Jacobson. Mark .Z. 2019. Evaluation of Nuclear Power as a Proposed Solution to Global: Warming, Air Pollution, and Energy Security. In Jacobson. M.Z. 2019. 100% Clean, Renewable Energy and Storage for Everything, Cambridge University Press. New York. , December 22

a 1 531 Jacobson. Mark Z. 2021. *CEE 176B/276B:100% Clean. Renewable Energy and Storage for Everything***. course slides.**

a 4 266 Jacobson. Mark Z. et al. 2013. "Examining the Feasibility of Converting New York State's All-Purpose Energy Infrastructure to One Using Wind. Water and Sunlight." *Energy Policy* 57.

a 1 269 Jacobson. Mark Z.. et al. 2015. "100% Clean and Renewable Wind. Water. and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States." *Energy and Environmental Science* 8.

a 1 257 Jacobson. Mark Z.. et al. 2015. *100% Clean and Renewable Wind. Water. and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries.* December 13.

a 1 501 Jacobson. Mark. Z. and Mark A. Delucchi. 2011. "Providing All Global Energy with Wind. Water. and Solar Power. Part I: Technologies. Energy Resources. Quantities and Areas of Infrastructure. and Materials." *Energy Policy* 39.

t 36 248 Janko. Samantha A. Michael R .Arnold and Nathan G. Johnson. 2016. "Implications of high-penetration renewables for ratepayers and utilities in the residential solar photovoltaic (PV) market" *Applied Energy.* 180.

d 2 98 Jason Rauch. 2014. "Price and Risk Reduction Opportunities in the New England Electricity Generation Portfolio." *Electricity Journal* 27.

a 1 263 Jebaraja. S. Iniyan. 2006. "A review of energy models." *Renewable and Sustainable Energy Reviews.* 10.

d 2 97 Jing Wu et al.. 2015, "Integrating Solar PV (Photovoltaics) in Utility System Operations: Analytical Framework and Arizona Case Study." *Energy* 85 (2015);

d 3 446 Johannes Kester. et al. 2018. "Policy mechanisms to accelerate electric vehicle adoption: A qualitative review from the Nordic region." *Renewable and Sustainable Energy Reviews* 94.

d 3 449 Johannes Kester. et al.. 2018b. "Promoting Vehicle to Grid (V2G) in the Nordic region: Expert advice on policy mechanisms for accelerated diffusion." *Energy Policy* 116.

d 3 450 Johannes Kester. et al.. 2019. "Public perceptions of electric vehicles and vehicle-to-grid (V2G): Insights from a Nordic focus group study." *Transportation Research Part D* 74.

h 1 394 John Chambers. et al.. 2015. "Psychology. Behavioural Economists and Climate Change." *Energy & Environment* 26.

a 4 279 Johnson. Erik Paul. 2014. "The Cost of Carbon Dioxide Abatement from State Renewable Portfolio Standards." *Resource and Energy Economics* 36.

f 1 376 Johnson. *et al.*. 2017. "A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system." *Energy Economics* 64.

f 1 25 Jones L. 2014. *Renewable Energy Integration: Practical Management of Variability. Uncertainty. and Flexibility in Power Grids.* London: Elsevier.

a 4 273 Jones. Christopher M. Stephen M. Wheeler and Daniel M. Kammen. 2018. "Carbon Footprint Planning: Quantifying Local and State Mitigation Opportunities for 700 California Cities.' *Urban Planning* 3.

j 3 518 Judson. Tim. 2016. *Too Big to Bail Out: The Economic Costs of a National Nuclear Power Subsidy.*

Nuclear Information and Resource Service. November.

j 3 523 Judson. Tim. 2018. *Nuclear Reactor Closures Practical. Cost-Effective Solutions for Communities and the Climate*. Nuclear Information Research Service. November.

i 1 399 Judson. Tim. 2018. *Nuclear Power And Climate Action: An Assessment for the Future.* Rosa Luxemburg Stiftung. New York Office. November.

j 1 488 Judson. Tim. 2021. *Nuclear Decommissioning: Dangers & Opportunities*: *An Overview of Failed Policies. State & Local Impacts. and Proactive Solutions.* EESI Congressional Briefing. March 30.

d 3 254 Kaatz. Joe.2017. "Resolving the conflict between new and old: A comparison of New York. California and other state DER proceedings." *The Electricity Journal*. 29.

a 5 295 Kahn. Alred. 1988. *The Economics of Regulation: Principles and Institutions* (MIT).

d 2 341 Kammen, Daniel M., Kamal Kapadia, and Matthias Fripp. 2004. *Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate?* RAEL Report. University of California, Berkeley.

t 34 124 Kane L. Ault G. 2014. A" review and analysis of renewable energy curtailment schemes and principles of access: transitioning towards business as usual." Energy Policy 72.

b 2 568 Kanger. et al. 2019. "Technological diffusion as a process of societal embedding: Lessons from historical automobile transitions for future electric mobility." *Transportation Research Part D: Transport and Environment,* 71.

b 2 453 Kanger. Laura. et al.. 2019.. "Technological diffusion as a process of societal embedding: Lessons from historical automobile transitions for future electric mobility." *Transportation Research Part D* 71.

d 1 38 Karier. T.. Fazio. J.. 2017. "How hydropower enhances the capacity value of renewables and energy efficiency.". *Electricity Journal*. 30.

c 2 242 Kästel. Peter and Bryce-Gilroy Scott. 2015. "Economics of pooling small local electricity prosumers—LCOE & self-consumption." *Renewable and Sustainable Energy Reviews* 51.

t 24 495 Kejriwal. Surabhi and Saurabh Mahajan, 2016. *Smart buildings: How IoT technology aims to add value for real estate companies: The Internet of Things in the CRE industry. Deloite University Press.*

b 1 386 Kelly-Detwiler. Peter. 2021. *The Energy Switch: How Companies and Consumers are Transforming the Electric Grid and the Future of Power.* Promethues.

a 1 261 Kemfert. Claudia and Mark Z. Jacobson. 2020. Mediocrity Is The Enemy Of The Solution

t 36 567 Kentucky Before the Public Service Commission. 2021. *Order,* Commonwealth of Kentucky Before the Public Service Commission In The Matter of Electronic Application of Kentucky Power Company for (1) A General Adjustment of Its Rates For Electric Service; (2) Approval of Tariffs and Riders; (3) Approval of Accounting Practices to Establish Regulatory Assets and Liabilities; (4) Approval of a Certificate of Public Convenience and Necessity; and (5) All Other Required Approvals and Relief Case No.2020-00174. May 14.

b 2 313 Khan. N. et al.. 2018. "Energy transition from molecules to atoms and photons." *Engineering Science and Technology.*

h 1 108 Kiliccote S. et al. 2010. *Integrating renewable resources in California and the role of automated demand response.* Report LBNL--4189E. Berkeley. CA: Lawrence Berkeley National Laboratory.

j 1 275 Kitson. Lucy. Peter Wooders. and Tom Moerenhout.2011. *Subsidies and External Costs in Electric Power Generation: A Comparative Review of Estimates.* Geneva. Switzerland.

g 1 572 Kiviluoma. Juha. 2013. *Managing wind power variability and uncertainty through increased power system flexibility.* VTT.

h 1 396 Kok. G.. et al..2011. "Changing energy-related behavior: An Intervention Mapping approach." *Energy Policy* 39.

j 1 565 Komanoff. C. 1981. *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics.* Van Nostrand.

f 1 201 Komiyama. Ryoichi and Yasamusa Fuji. 2014. "Assessment of Massive Integration of Photovoltaic System Considering Rechargeable Battery in Japan with High Time-Resolution Optimal Power Generation Mix Model." *Energy Policy* 66.

t 40 81 Komor P. A. Hoke. And R. Kempener R. 2014. "Seven steps to a smarter grid." *The Electricity Journal* 27.

f 1 204 Koohi. Kamali. et al. 2013. "Emergence of Energy Storage Technologies as the Solution for Reliable

Operatoin of Smart Power Systems: A Review." *Renewable and Sustainable Energy Reviews* 25.

b 2 307 Kopnina. Helen. 2017. "European Renewable Energy. Applying Circular Economy Thinking to Policy-Making." *Visions for Sustainability* 8.

j 1 528 Kopolow. Douglas. 2011. *Nuclear Power: Still Not Viable Without Subsidies.* Union of Concerned Scientists. February.

d 3 357 Kotilainen1. Kirsi. et al. 2019. From path dependence to policy mixes for Nordic electric mobility: Lessons for accelerating future transport transitions." *Policy Sciences* 52.

f 1 210 Kucsera. Dénes and Margarethe Rammerstorfer. 2014. "Regulation and Grid Expansion Investment with Increased Penetration of Renewable Generation." *Resource and Energy Economics* 37.

j 3 481 Kuperman. Alan J.. 2021. *Proposed U.S. Army Mobile Nuclear Reactors:* Costs *and Risks Outweigh Benefits*. NPPP Working Paper #4. April 22.

j 3 522 LaCount. Robert. 2016. *Joint Proposal for the Orderly Replacement of Diablo Canyon Power Plant with Energy Efficiency and Renewables.* M.J. Bradley & Associates. LLC. June 21.

d 2 459 Laitner. John A. "Skip." et al.. 2021. *Investing in US Energy Efficiency and Infrastructure Creates More Nationally-Distributed Jobs while Saving Money and Protecting the Climate.* IGSD, Economic and Human Dimensions Research.

J 3 169 Larsen. et al.2021. *Pathways to Building Back Better: Investing in 100% Clean Electricity,* Rhodium Group, April.

j 3 192 Larsen. et al.2021. *Pathways to Building Back Better:Maximizing Clean Energy Tax Credits,* Rhodium Group, July 8.

g 1 383 Larson. E.. et al.. 2020. *Net-Zero America: Potential Pathways. Infrastructure. and Impacts. interim repor*t. Princeton University. December.

t 27 570 Lazar, Jim. 2014. *Teaching the "Duck" to Fly*, Regulatory Assistance Project, January.

f 1 27 Lazar. Jim. 2016. *Teaching the "Duck" to Fly.* Regulatory Analysis Assistance Project. January.

c 1 332 Lazard. *Lazard's Levelized Cost of Energy Analysis* – Versions 1.0 to 14.0. October 2020.

c 1 434 Lazard. Lazard's Levelized Cost of Energy Storage – Versions 1.0 to 6.0. October 2020.

d 2 342 Leal-Arcas et al.. 2020. "Towards a carbon-free. decentralized. and democratized system of energy generation." *Connecticut Journal of International Law*. 35.

a 1 460 Leal-Arcas. Rafael. Nelson Akondo. and Juan Alemany Rios. 2019. "Energy Decentralization In The European Union. *Georgetown Environmental Law Review*. 32.

t 36 149 Lehr RL. 2013. "New utility business models: utility and regulatory models for the modern era." *The Electricity Journal* 26.

j 1 447 Leiserowitz. Anthony. et al.. 2020. "*Politics & Global Warming.*": Yale Program on Climate Change Communication. December.

j 4 534 Levitan. David. 2020. "First U.S. Small Nuclear Reactor Design Is Approved Concerns about costs and safety remain, however." *Scientific American.com*. September 9,

g 1 120 Lew D. et al. 2013. *Wind and solar curtailment.* Report NREL/CP--5500--60245. Golden. CO: NREL.

a 4 52 Lew D. Schroder M. Miller N. Lecar M. 2015. *Integrating high levels of variable energy resources in California.* Report prepared for Large--Scale Solar Association. Schenectady. NY: GE Energy Consulting.

d 1 35 Lew. Deborah. 2017. The Power of Small: The Effects of Distributed Energy Resources on System Reliability. *IEEE Power and Energy Magazine.* 6.

g 1 121 Li C. Shi H. Cao Y. Wang J. Kuang Y et al. 2014. Comprehensive review of renewable energy curtailment and avoidance: a specific example of China. *Renewable and Sustainable Energy Reviews* 41.

t 36 181 Liebreich. Michael . 2017. "Six Design Principles for the Power Markets of the Future" *Bloomberg New Energy Finance.* May 24

t 27 215 Liu. Y. and C.K. Woo. 2017. "California's renewable generation and pumped hydro storage's profitability." *The Electricity Journal* 30.

d 4 222 Loisel. Rodica. Guzay Pasaoglu. and Christian Thiel. 2014. "Large-Scale Deployment of Electric Vehicles in Germany by 2030: An Analysis of Grid-To-Vehicle and Vehicle-To-Grid Concepts." *Energy Policy* 65.

b 2 317 Loorbach. Derk. 2010. "Transition Management for Sustainable Development: A Prescriptive.

Complexity-Based Governance Framework. *Governance: An International Journal of Policy. Administration. and Institutions*. 23.

h 1 72 Lopes. Marta A.R. et al. 2015. "Towards more effective behavioural energy policy: An integrative modelling approach to residential energy consumption in Europe." *Energy Policy* 39.

d 1 590 Lopez. Anthony. et al. 2012. *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*. NREL. July.

f 1 10 Loutan. Clyde and Vahan Gevogian. 2017. *Using Renewables to Operate a Low-Carbon Grid: Demonstration of Advanced Reliability Services from a Utility-Scale Solar PV Plant.* CAISO. NREL

a 1 22 Lovins A and Rocky Mountain Institute. 2011. *Reinventing Fire: Bold Business Solutions for the New Energy Era*. White River. VT: Chelsea Green.

a 3 569 Lovins, Amory. 2014. *An Initial Critique of Dr. Charles R. Frank, Jr.'s Working Paper "The Net Benefits of Low and No-Carbon Electricity Technologies," Summarized in the Economist as "Free Exchange: Sun, Wind and Drain."* Boulder, CO: Rocky Mountain Institute, August 7.

j 2 274 Lovins. Amory. 2017. "Do coal and nuclear generation deserve above-market prices?" *The Electricity Journal*, 30.

f 1 36 Lovins. Amory. 2017a. " Reliably integrating variable renewables: Moving grid flexibility resources from models to results." *The Electricity Journal.* 30.

b 2 230 Lovins. Amory. 2019**. "**Does Nuclear Power Slow Or Speed Climate Change?" *Forbes*. Nov 18.

d 3 535 Lovins, A. 2020. "Reframing Automotive Fuel Efficiency." *SAE Int. J. Sust. Trans. Energy, Env., & Policy* 1.

j 1 461 Lovins. Amory. 2021. *Nuclear power and climate protection*. EESI Briefing. March 30.

h 1 462 Lovins. Amory. 2021a.*The Texas Power Freeze: First Impressions Demand. renewables. interdependencies. and institutions.* EESI Briefing. March 30.

f 1 207 Lu. Xi. et al. 2013. "Optimal Integration of Offshore Wind Power for a Steadier. Environmentally Friendlier. Supply of Electricity in China." *Energy Policy* 62.

d 3 89 Lund H. et al. 2010. The role of district heating in future renewable energy systems. *Energy* 35.

d 3 505 Lutsey. Nic et al.. 20`7. *Efficiency Technology and Cost Assessment of U.S. 2025-2030 Light Duty Vehicles.* March.

j 4 411 Lyman. Edward. 2021. *"Advanced" Isn't Always Better: Assessing the Safety. Security. and Environmental Impacts of Non-Light-Water Nuclear Reactors.* Union of Concerned Scientists. March.

g 1 536 M.J. Bradley and Associates. 2017. Powering into the Future: Renewable Energy & Grid Reliability.

a 4 63 MacDonald. Alexander E.. et al. 2016. "Future Cost-Competitive Electricity Systems and Their Impact on US CO2 Emissions." *Nature Climate. Change* 6.

t 31 31 Madrigal M. Porter K. 2013. *Operating and planning electricity grids with variable renewable generation: review of emerging lessons from selected operational experiences and desktop studies*. Washington. DC: World Bank.

a 5 296 Mai. Trieu et al. 2014. "Envisioning a Renewable Electricity Future for the United States." *Energy* 65.

d 2 96 Makovich. Lawrence and James Richards. 2017. *Ensuring Resilient and Efficient Electricity Generation The value of the current diverse US power supply portfolio.* IHS Market September.

b 2 310 Manson. Neil A. .Formulating the Precautionary Principle. *Environmental Ethics.* 24.

c 3 322 Maradin. D.. Cerović. L. and Mjeda. T. 2017. Economic Effects of Renewable Energy Technologies. *Naše gospodarstvo/Our Economy*. 63.

d 3 577 Marszal. A.J. et al. 2011. " Zero Energy Building – A review of definitions and calculation methodologies." *Energy and Buildings,* 43, April.

d 1 464 Marta Victoria. et al.. 2021. "Solar photovoltaics is ready to power a sustainable future." *Joule* 5. May.

t 23 173 Martínez Ceseña. Eduardo A.. et al.. 2015. "Electrical Network Capacity Support from Demand Side Response: Techno-Economic Assessment of Potential Business Cases for Small Commercial and Residential End-Users." *Energy Policy* 82

f 1 53 Martinot E. 2015. *Grid integration of renewables in China: learning from the cases of California. Germany. and Denmark*. A White Paper for the China Variable--Generation Integration Group. Beijing: China Energy Research Institute.

d 2 131 Martinot E. Kristov L. and Erickson JD. 2015. "Distribution system planning and innovation for distributed energy futures." *Current Sustainable and Renewable Energy Reports* 2.

f 1 1 Martinot. E. 2016. “Grid Integration of Renewable Energy: Flexibility. Innovation. Experience.*"* *Annual Review of Environment and Resources.* 41

g 1 165 Martinot. E. et al. 2013. *RES-E-NEXT: Next Generation of RES-E Policy Instruments. International Energy Agency’s Implementing Agreement on Renewable Energy Technology Deployment.* (IEA-RETD).

a 2 2 Martinot. E. et al. 2015. *Status report on power system transformation.* Report NREL/TP--6A20--63366. A report of the 21st Century Power Partnership. Golden. CO: National Renewable Energy Laboratory.

t 27 502 Maurer. Lui. et al.. 2020. *Creating a Level Playing Field for Battery Energy Storage Systems Through Policies. Regulations. and Renewable Energy Auctions.* Washington. DC: Crown Agents USA and Abt Associates. Prepared for USAID.

t 9 240 May. Nils. 2017. “The impact of wind power support schemes on technology choices.” *Energy Economics.* 65.

c 3 591 McKinsey. 2009. *Global Energy and Material. Unlocking Energy Efficiency in the U.S. Economy.* January.

g 3 111 McPherson. Madeleine. and Brady Stoll. 2020. *Demand Response for Variable Renewable Energy Integration: A Proposed Approach and its Impacts*. *Energy* Volume 19..

j 1 537 Metcalf. Gilbert E. 2017. *Ending Fossil Fuel Tax Subsidies: Removing Tax Preferences For Domestic Oil And Gas Production.* Kleinman Center for Economic Policy. April 27.

f 1 129 Milligan M. et al. 2010. *Advancing wind integration study methodologies: implications of higher levels of wind*. In Proceedings of American Wind Energy Association. Wind power 2010. Dallas. TX.

f 1 76 Milligan M. et al. 2011. Integration of variable generation. .cost--causation. and integration costs. *Electricity Journal* 24.

f 1 166 Milligan. M. et al. 2012. *Markets to Facilitate Wind and Solar Energy Integration in the Bulk Power Supply:* An IEA Task 25 Collaboration. Golden. CO: National Renewable Energy Laboratory.

t 36 253 Milligan. Michael et al. 2016. “Wholesale electricity market design with increasing levels of renewable generation: Revenue sufficiency and long-term reliability.” *The Electricity Journal.* 29.

f 1 592 Milligan. Michael. et al. 2009. *The Impact of Electric Industry Structure on High Wind Penetration Potential*. Technical Report NREL/TP-550-43273. NREL. July.

e 1 367 Mills. Andrew. and Ryan Wiser. 2012. *Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California. La*wrence Berkeley National Laboratory.

c 2 159 Mills. Andrew. and Ryan Wiser. 2013. *Solar Valuation in Utility Planning Studies. Clean Energy States Alliance: RPS Webinar*. January.

a 1 151 Mills. Andrew. and Ryan Wiser. 2014. *Strategies for Mitigating the Reduction in Economic Value of Variable Generation with Increasing Penetration Levels.* Environmental Energy Technologies Division. Lawrence Berkeley National Laboratory.

e 1 125 Mills. Andrew. and Ryan Wiser. 2015." Strategies to mitigate declines in the economic value of wind and solar at high penetration in California." *Applied Energy* 147.

a 2 560 Millward-Hopkins. Joel,. et al. 2021, ”Providing decent living with minimum energy: A global scenario.” *Global Environmental Change* 65.

a 1 3 MIT Energy Initiative. 2011. *The future of the electric grid: an interdisciplinary MIT study.* Cambridge. MA.

j 1 465 MIT Energy Initiative. 2018. *The Future of Nuclear Energy in a Carbon-Constrained World.* Cambridge. MA.

c 3 593 MIT. 2008. *Laboratory of Energy and the Environment. On the Road in 2035: Reducing Transportation’s Petroleum Consumption and GHG Emissions* Cambridge: July. 2008).

d 3 355 MIT Study On The Future Of The Electric Grid. 2011. *Chapter 5: The Impact of Distributed Generation and Electric Vehicles.* MIT Energy Initiative..

d 2 340 Molina. M. (2014). *The Best Value for America’s Energy Dollar: A National Review of the Cost of Utility Energy Efficiency Programs.* American Council for an Energy-Efficient Economy (ACEEE). March.

d 1 503 Moomaw. W.. F.. et al. 2011. *Renewable Energy and Climate Change*. Cambridge University Press.

b 2 304 Moore. Jason W.. 2017. “The Capitalocene. Part I: on the nature and origins of our ecological crisis. Capitalocene Part II: accumulation by appropriation and the centrality of unpaid work/energy." *The Journal of Peasant Studies*. 44.

c 1 147 Morales JM. et al. 2015. Integrating Renewables in Electricity Markets. Operational Problems. New York: Springer.

j 1 485 Morgan. Leona. 2021. *CIS is Nuclear Colonia*lism. Nuclear Issues Study Group (NISG). EESI Congressional Briefing. March 30.

j 1 529 Morgan. M. Granger. et al.. 2018. “US nuclear power: The vanishing low-carbon wedge.” *Proceedings of the National Academy of Sciences of the United States of America.* July 10.

g 1 431 Mousazadeh. Houssain. et al. 2009. "A review of principle and sun-tracking methods for maximizing solar systems output." *Renewable and Sustainable Energy Reviews* 13.

t 20 571 Nadel. Steve. 2014. “Conquering the Evening Peak,” *ACEEE Blog*, November 24.

d 2 351 Nadel. Steve and Lowel Unger. 2019. *Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half*. ACEEE. September.

c 3 594 Nadel. Steve. Neal Elliott. and Therese Langer. 2015. *Energy Efficiency in the United States:35 Years and Counting.* June

d 3 361 Nadel. Steven and Andrew Delaski. 2013. *Appliance Standards: Comparing Predicted and Observed Prices.* American Council for an Energy Efficient Economy and Appliance Standards Awareness Project. July.

j 3 527 Nash. James. and Nicholas Pugliese. 2018. “Nuclear plants are profitable. Should NJ electric customers be asked to pay more?” *Bergen Record.* February 21.

f 1 128 National Renewable Energy Laboratory (NREL). 2011. *Eastern wind integration and transmission study.* Report NREL/SR--5500--47078. Golden. CO.

f 1 127 National Renewable Energy Laboratory. 2013. *The Western wind and solar integration study*. Report NREL/TP--5500--55588. Golden. CO.

g 1 24 National Renewable Energy Laboratory. 2014. *Flexibility in 21st century power systems*. Report 61721. A report of the 21st Century Power Partnership. Golden. CO

f 1 4 National Renewable Energy Laboratory. 2015. *Power systems of the future*. Report NREL/TP--6A20--62611. A report of the 21st Century Power Partnership. Golden. CO.

g 1 37 National Renewable Energy Laboratory. 2016. *Forecasting Wind and Solar Generation: Improving System Operations.*

f 1 198 National Renewable Energy Laboratory. 2017. *Wind-to-Hydrogen Project. Hydrogen and Fuel Cells Research..*

b 2 595 National Research Council of the National Academies. 2009. *America's Energy Future: Technology and Transformation*. Summary Edition. Washington. D.C.

c 3 504 National Research Council 2010. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use.* Washington. DC: The National Academies Press.

j 3 596 Naureen. S. Malik and Jim Poulson. 2015.“New York Reactors Survival Tests Pricey Nuclear.” *Bloomberg.* January 5.

t 40 224 Naus. Joeri. et al.. 2014. “Smart Grids. Information Flows and Emerging Domestic Energy Practices.” *Energy Policy* 68.

f 1 109 Navigant Consulting. 2012. *Potential role of demand response resources in maintaining grid stability and integrating variable renewable energy under California's 33 percent renewable portfolio standard.* San Francisco. CA.

t 23 118 Navigant Research. 2016. *Virtual Power Plants: Demand Response. Supply--Side. and Mixed Asset VPPs.*

t 31 13 Navigant. 2017. *2017 Utiity Demand Response Snapshot.* Smart Electric Power Alliance.

a 4 48 Nelson J and Wisland L. 2015. *Achieving 50 percent renewable electricity in California.* Oakland. CA: Union of Concerned Scientists.

c 3 466 Neumann. Fabian and Tom Brown. 2021, “The near-optimal feasible space of a renewable power system mode,” *Electric Power Systems Research* 190.

j 3 516 New York Independent System Operator. 2016. *Generator Deactivation Assessment: James A. Fitzpatrick Nuclear Generating Facility*. April 22.

a 4 132 New York State Department of Public Service. 2014. *Reforming the energy vision*. Albany. NY: New York State Department of Public Service.

d 1 255 Newcomb. James. et al. 2013. "Distributed Energy Resources: Policy Implications of Decentralization." *The Electricity Journal.* 26.

t 36 553 Newman. Jonathan. and Pamela MacDougall. 2021. "Increasing DER integration through discrete intraday settlements." *The Electricity Journal* 34.

d 2 137 Nivad Navid. 2012. *Reserve Requirement Identification with the Presence of Variable Generation.* UVIG Spring Technical Meeting. April 26.

d 3 360 Noel. Lance. et al.. 2019. "Fear and loathing of electric vehicles: The reactionary rhetoric of range Anxiety." *Energy Research & Social Science* 48.

c 3 597 Northeast States Center for a Clear Air Future. International Council on Clean Transportation and Southwest Research Institute. *Reducing Heavy Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions.* October *2009;*

i 2 598 Nuclear Energy Institute. 2014. NEI Operating Cost. February.

i 2 599 Nuclear Energy Institute. 2020. *Nuclear Costs in Context.* October. 2020;

i 2 600 Nuclear Street News Team. 2014. "NEI Lays Out the State of Nuclear Power." *Nuclearstreetcom*. February 26.

j 4 538 Nuscale. 2021. *Carbon Free Power Project Resource "Option" Update.* County Council Meeting February 16.

a 4 539 NYC, 2021,*The New York City Internet of Thing Strategy,* March.

t 23 179 O'Connell. Niamh. et al. 2014. "Benefits and Challenges of Electrical Demand Response: A Critical Review." *Renewable and Sustainable Energy Reviews 39*.

c 1 87 Oates. David Luke and Paulina Jaramillo. 2013. "Production cost and air emissions impacts of coal cycling in power systems with large-scale wind penetration." *Environ. Res. Lett.* 8.

t 23 115 Obi M. Bass R. 2016. Trends and challenges of grid--connected photovoltaic systems—a review. *Renewable and Sustainable Energy Reviews* 58.

a 1 507 Oei. Pao-Yu. et al. 2020. "Lessons from Modeling 100% Renewable Scenarios Using GENeSYS-MOD, l." *Journal Economics of Energy & Environmental Policy (EEEP*) 9.

f 1 150 Oggioni. Giorgia. F. H. Murphy. and Yves Smeers. 2014. "Evaluating the Impacts of Priority Dispatch in the European Electricity Market" *Energy Economics* 42.

t 30 554 Olivella-Rosell. Pol. Et al. 2015. "Probabilistic Agent-Based Model of Electric Vehicle Charging demand to Analyse the Impact on Distribution Networks." *Energies* 8.

d 3 448 Olivella-Rosell. Pol. et al.. 2015. "Probabilistic Agent-Based Model of Electric Vehicle Charging Demand to Analyse the Impact on Distribution Networks.´ *Energies* 8.

j 3 521 Omaha Public Power District. 2016. "Resource Planning Update." May 12.

a 2 8 Orvis. Robbie and Sonia Aggarwal. 2017. "A Roadmap for Finding Flexibility in Wholesale Markets: Best Practices for Market Design and Operations in a High Renewables Future." *Energy Innovation. Policy and Technology*. October.

t 31 64 Ott A. 2017. Case study: demand response and alternative technologies in (PJM) electricity markets. Reprinted as Chapter 19 in Lawrence Jones (Ed.). *Renewable Energy Integration: Practical Management of Variability, Uncertainty, and Flexibility in Power Grids: Second Edition.*

b 1 301 Owen Poindexter. "The Internet of Things Will Thrive on Energy Efficiency." *Government Technology*. July 29.

t 40 79 Palensky P. Kupzog F. 2013. Smart grids. *Annual Review of Environment and Resources* 38.

t 32 194 Palmintier. Bryan. et al. 2016. *On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System*. Golden. CO: National Renewable Energy Laboratory.

d 1 506 Pandey. Rita. and Meeta Keswani Mehra. 2015. *Role of Fiscal Instruments in Promoting Low-carbon Technology Innovation.* National Institute of Public Finance and Policy. New Delhi. Working Paper No. 2015-147. May.

t 40 225 Park. Chan-Kook.Kim Hyun-Jae. and Kim. Yang-Soo. 2014. "A Study of Factors Enhancing Smart Grid Consumer Engagement." *Energy Policy* 72.

d 4 223 Parsons. George R.. et al. 2014."Willingness to Pay for Vehicle-To-Grid (V2G) Electric Vehicles and Their Contract Terms." *Energy Economics* 42.

b 2 508 Perez. Carlota. 2010. "Technological Dynamism and Social Inclusion in Latin America: A Resource-Based Production Development Strategy." *CEPAL Review* 100..

b 2 509 Perez. Carlota. *Technological Revolutions and Techno-Economic Paradigms.* Working Papers in Technology Governance and Economic Dynamics. January 2009.

b 2 510 Pérez. Carlota. *The Advance of Technology and Major Bubble Collapses: Historical Regularities and Lessons for Today.* Engelsberg Seminar on "The Future of Capitalism." Axson Foundation. Sweden. June. 2010.

t 9 156 Pfenninger. Stefan. et al. 2014. "Potential for Concentrating Solar Power to Provide Baseload and Dispatchable Power." *Nature Climate Change* 4.

j 1 415 Pfund. Nancy. and Ben Healey. 2011. *What Would Jefferson Do? The Historical Role of Federal Subsidies in Shaping America's Energy Future*. San Francisco. CA: DBL Investors.

f 1 380 Phuangpornpitak. N. and S. Tia. 2013. "Opportunities and Challenges of Integrating Renewable Energy in Smart Grid System." *Energy Procedia* 34.

t 36 183 Pierpont. Brendan and David Nelson. 2017. *Markets for Low-carbon. Low-cost Electricity Systems*. Climate Policy Initiative. September.

f 1 184 Pierpont. Brendan. et al. 2017. *The Flexibility: Path Markets for Low-carbon. Low-cost Electricity Systems.* Climate Policy Initiative. April.

e 1 236 Pietzcker. Robert C. et al. 2017. "System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches." *Energy Economics* 64.

j 3 519 PJM Interconnection. 2018. *Generation Deactivation Notification Update*. Presentation to PJM Transmission Expansion Advisory Committee. May 3.

f 1 200 Pleßmann. Guido. et al. 2014. "Global Energy Storage Demand for a 100% Renewable Electricity Supply." *Energy Procedia* 46.

j 4 540 Portland Electric. *2019 IRP.*

t 32 152 Power Partnership. 2014. *Flexibility in 21st Century Power Systems.* NREL. May .1

t 42 408 Pratt. RG. et al. *The Smart Grid: An Estimation of the Energy and CO2 Benefits (Revision 1).* U.S. Department of Energy. January.

t 42 385 Prem. Eric. 2009. *Electronics enabling efficient energy usage: Results from the E4U project*. E4u. December.

f 1 77 Pudjianto D. P. Djapic. J. Dragovic. And G. Strbac 2013. *Grid integration cost of photovoltaic power generation*. Report prepared for PVParity.eu. London: Imperial College Energy Futures Lab.

c 3 327 Rafael Leal-Arcas. et a. l2019. "Decarbonizing the Energy Sector." *J. Animal & Nat. Resource L.* 15.

e 1 474 Rafique. Zimran. et al.. 2020. "Communication Systems in Distributed Generation: A Bibliographical Review and Frameworks." *IEEE Access*. November.

t 30 551 Rahman. Mohammad Mominur. et al. 2019, *Technical Assessment of Plug-In Hybrid Electric Vehicle Charging Scheduling for Peak Reduction.* IEEE.

d 3 445 Ramalingam. K. and C.S. Indulkar. 2015. *Overview of Plug-in Electric Vehicle Technology in Plug In Electric Vehicles in Smart Grids*. Springer Singapore.

j 4 406 Ramana. M. V.. 2020. *Eyes Wide Shut: Problems with the Utah Associated Municipal Power Systems Proposal to Construct NuScale Small Modular Nuclear Reactors*. Oregon Physicians for Social Responsibility. September.

j 4 407 Ramana. M.V.. 2021. "Small Modular and Advanced Nuclear Reactors: A Reality Check." *IEEE Access.* March.

f 1 191 Rasmussen. Morten Grud Gorm Bruun Andresen. and Martin Greiner. 2012. "Storage and Balancing Synergies in a Fully or Highly Renewable Pan-European Power System." *Energy Policy* 51.

f 1 188 Rasmussen. Morton Grud. et al. 2011."Optimal Combination of Storage and Balancing in a 100% Renewable European Power System." in *Proceedings of the 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants.* Energynautics.

a 4 285 Rauch. Jason. 2014. "Price and Risk Reduction Opportunities in the New England Electricity Generation Portfolio." *Electricity Journal* 27.

d 3 228 Ravindranath. Mohana. 2014. "At GSA. an 'Internet of Things' Experiment." *Washington Post.* August 31.

c 3 325 Raymenta. Matt. et al.. 2009. *The economic benefits of environmental policy.* Institute for Environmental Studies. November.

d 4 221 Reber. Timothy J.. Koenraad F. Beckers. and Jefferson W. Tester. 2014. "The Transformative Potential of Geothermal Heating in the U.S. Energy Market: A Regional Study of New York and

Pennsylvania." *Energy Policy* 70.

b 2 467 Rechsteiner. Rudolf. 2021."German energy transition (Energiewende) and what politicians can learn for environmental and climate policy." *Clean Technologies and Environmental Policy* 23.

d 3 227 Ren. Guizhou. Guoqing Ma. and Ning Cong. 2015. "Review of Electrical Energy Storage System for Vehicular Applications." *Renewable and Sustainable Energy Reviews* 41.

a 1 20 REN21. 2013. *Renewables global futures report.* Paris

t 27 157 Renewables International. 2012. *Little Power Storage or Coal Power Needed for 40% Green Power Supply*. Renewables international.net Imperial College. August 10.

i 1 256 Richards. James and Wesley J. Cole. 2017. "Assessing the impact of nuclear retirements on the U.S. power sector." *The Electricity Journal*. 30.

j 1 168 Richards. James. Piyush Sabharwall and Matthew Memmott. 2017. "Economic comparison of current electricity generating technologies and advanced nuclear options." *The Electricity Journal 30.*

a 4 16 Riva. Alberto Dalls. Janos Hethey and Aisma Vitina. 2017. *Impact of Wind Turbine Technology on the System Value of Wind in Europe.* Energy Analyses.

f 1 190 Rodriguez. Rolando A. 2014. "Transmission Needs Across a Fully Renewable. European Power System." *Renewable Energy* 63.

c 3 602 Roland-Holst. David. 2016. *Revised Standardized Regulatory Impact Assessment: Computers. Computer Monitors. and Signage Displays.* prepared for the California Energy Commission. June.

j 3 603 Rosner. Robert and Stephen Goldberg. 2011. *Small Modular Reactors – Potentially Key Contributors to Future Nuclear Power Generation in the U.S.* Center for Strategic and International Studies. December 1;

i 1 604 Rosner. Robert. et al. 2011a. *Analysis of GW-Scale Overnight Capital Costs.* EPIC. University of Chicago. Technical Paper November.

d 3 363 Royal Academy of Engineering. 2010. *Electric Vehicles: charged with potential.* May.

c 3 326 Rydge. J.. Jacobs. M. and Granoff. I.. 2015. *Ensuring New Infrastructure is Climate-Smart.* Contributing paper for *Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. New Climate Economy. London and Washington. DC.

t 43 573 Sadineni. Suresh B. Srikath Madala and Robert F. Boehm. 2011. "Passive building energy savings: a review of building envelope compnents." *Renewable and Sustainable Energy Reviews* 15

t 27 43 Safaei. H.. Keith. D.. 2015. How much bulk energy storage is needed to decarbonize electricity? *Energy Environ. Sci. 12.*

t 30 549 Saliba. Chad. 2020. "The geography of EV charging: How regional climates impact charging and driving behavior." *Geotab*. July 28.

d 1 469 Samadi. Sascha. 2017. "The Social Costs of Electricity Generation—Categorising Different Types of Costs and Evaluating Their Respective Relevance." *energies.* March 13.

d 4 114 San Roman TG. Et al. 2011. "Regulatory framework and business models for charging plug--in electric vehicles: infrastructure. agents. and commercial relationships." *Energy Policy* 39.

d 3 359 Sandén. Björn. 2013. *Systems Perspectives on Electromobility. 2013*. Chalmers University of Technology.

d 4 555 Sandénand. Björn. and Pontus Wallgren. 2014. *Systems Perspectives On Electromobility*, Chalmers University of Technology.

j 1 282 Santiago. Katerina. et al. 2014. "A Strong Argument for Using Non-Commodities to Generate Electricity." *Energy Economics* 43.

t 25 102 Sarah Becker et al. 2014. "Features of a Fully Renewable US Electricity System: Optimized Mixes of Wind and Solar PV and Transmission Grid Extensions." *Energy* 72.

d 2 103 Sarah Becker et al. 2014a. "Transmission Grid Extensions During the Build-Up of a Fully Renewable Pan-European Electricity Supply." *Energy 72*.

c 2 130 Sarah Becker et al.. 2015. "Renewable Build-Up Pathways for the US: Generation Costs Are Not System Costs." E*nergy* 81.

c 3 468 Saria. Arif and Murat Akkaya. 2016. *Contribution of Renewable Energy Potential to Sustainable Employment*. 5th International Conference on Leadership. Technology. Innovation and Business Management. Procedia - Social and Behavioral Sciences 229.

f 1 189 Schaber. Katrin . Florian Steinke. and Thomas Hamacher. 2013. *Managing Temporary Oversupply from Renewables Efficiently: Electricity Storage Versus Energy Sector Coupling in German*y. International Energy Workshop. Paris. July.

c 2 544 Schleifer. Anna H. et al. 2021. “The evolving energy and capacity values of utility-scale PV-plus-battery hybrid system architectures.” *Advances in Applied Energy* 2.

j 1 482 Schneider. Mycle and Antony Froggatt. 2020. *The World Nuclear Industry Status.* September.

b 2 511 Scholten. Daniel and Rick Bosman. 2013. *The Geopolitics of Renewable Energy; a Mere Shift or Landslide in Energy Dependencies?* Conference: Politicologenetmaal At: Ghent. May.

t 7 44 Scholz. Yvonne. Hans Christian Gils. and Robert C. Pietzcker. 2017. “Application of a High-Detail Energy System Model to Derive Power Sector Characteristics at High Wind and Solar Shares.” *Energy Economics* 64.

f 1 167 Schwartz. L. ed. 2012. *Meeting Renewable Energy Targets in the West at Least Cost: The Integration Challenge.* Western Governors’ Association.

j 3 575 Senator Cardin and Representative Pascrell. 2021. *S.2291/HR. 4024 The Zero-Emission Nuclear Power Production Credit Act of 2021*. July

f 1 186 Shallenberger. Krysti. 2017. “How utility pilot programs are driving renewable energy integration.” *Utility Dive.* September 18.

g 1 110 Shariatzadeh F. P. Mandal. and A. Srivastava. 2015. "Demand response for sustainable energy systems: a review. application and implementation strategy". *Renewable and Sustainable Energy Reviews* 45.

h 1 442 Shaukata. N. et al.. 2018. “A survey on consumers empowerment. communication technologies. and renewable generation penetration within Smart Grid.” *Renewable and Sustainable Energy Reviews* 81.

t 42 259 Shaukata , N. et al.,, 2019, “A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid,” *Renewable and Sustainable Energy Reviews* 81.

t 42 303 Shaukata , N. et al. 2019a. “A survey on electric vehicle transportation within smart grid system, *Renewable and Sustainable Energy Reviews* 81.

d 1 335 Shrimali. Gireesh. Melissa Lynes and JoeIndvik. 2015. “Wind energy deployment in the U.S.: An empirical analysis of the role of federal and state policies.” *Renewable and Sustainable Energy Reviews* 43 March.

d 3 364 Silvester. Sacha. et al.. 2010. *Electric Mobility & the Urban Environment; the Schiphol Case.* ERSCP-EMSU conference. Delft. The Netherlands. October 25-29.

d 3 451 Silvester. Sacha. et al.. 2010. *Schiphol: The Grounds 2030 a Scenario For Integration of Electric Mobility into the Built Environment*. Delft University of Technology.

t 37 92 Sioshansi FP. 2012. Why the time has arrived to rethink the electric business model. *The Electricity Journal* 25.

d 2 104 Sioshansi FP. 2014. *Distributed Generation and Its Implications for the Utility Industry*. London: Academic

j 1 413 Slavin. Matthew. 2009. “The Federal Energy Subsidy Scorecard: How Renewables Stack Up.” *Renewable Energy World.com*. November 3.

b 2 311 Smith. M. 2015. *Doubling Energy & Resource Productivity by 2030 – Transitioning to a Low Carbon Future through Sustainable Energy and Resource Management*. ANU Discussion Paper.

f 1 196 Sobotka. Katarzyna. 2009. *A Wind-Power Fuel Cell Hybrid System Study: Model of Energy Conversion for Wind Energy System with Hydrogen Storage.* Master’s thesis. The School for Renewable Energy Science. Akureyri. Iceland.

a 2 430 Solangib. K.H.. st al.. 2011. “A review on global solar energy policy.” *Renewable and Sustainable Energy Reviews* 15

h 1 395 Sonenshein. Scott. Katherine A. Decelles and Jane E. Dutton. 2014. It’s Not Easy Being Green: The Role of Self-Evaluations in Explaining Support of Environmental Issues. *Academy of Management Journal* 57.

d 4 556 Sorrentino. Marco. Gianfranco. Rizzo and, Luca Sorrentino. 2014. ‘A study aimed at assessing the potential impact of vehicle electrification on grid infrastructure and road-traffic greenhouse emissions. *Applied Energy* 120.

i 1 400 Sovacool. Benjamin K.. Matthew Kryman and Emily Laine. 2015. “Profiling technological failure and disaster in the energy sector: A comparative analysis of historical energy accidents.” *Energy*. 90.

d 3 454 Sovacool. Benjamin K et al.. . 2018. “The neglected social dimensions to a vehicle-to-grid(V2G) transition: a critical and systematic review." *Environmental Research Letters.*13.

i 1 401 Sovacool. Benjamin K. And Christopher Cooper. 2008. Nuclear Nonsense: Why Nuclear Power Is No Answer To Climate Change And The World's Post-Kyoto Energy Challenges." *Wm. & Mary Envtl. L. & Pol'y Rev.* 33(1)

t 30 557 Sovacool. Benjamin K. and Richard F. Hirsh, 2009. "Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy* 37.

d 4 545 Sovacool. Benjamin K. et al.,2019. "Income, political affiliation, urbanism and geography in stated preferences for electric vehicles (EVs) and vehicle-to-grid (V2G) technologies in Northern Europe, Journal of Transport Geography 78.

d 3 358 Sovacool.. Benjamin K. et al.. 2019a. "Pleasure or profit? Surveying the purchasing intentions of potential electric vehicle adopters in China." *Transportation Research Part A*. 124.

d 2 347 Sperling. Dan et al.. 2004. *Analysis of Auto Industry and Consumer Responses to Regulation and Technological Change and Customization of Consumer Response Models in Support of AB 1493 Rule*making. Institute of Transportation Studies. UC Davis. June 1

b 2 312 Sprinkle . Geoffrey B. and Laureen A. Maines. 2010 "The benefits and costs of corporate social Responsibility. *Business Horizons* 53.

d 2 348 Staffell. Iain. *2009. A Review of Domestic Heat Pump Coefficient of Performance.* April.

j 1 530 Stanford Bulletin. *Explore Courses*. 2020-2021.

g 1 512 Stanton. Tom. 2020. "Solar Energy that Pays for Low-Income Customers and Communities. *NRRI Insights."* December.

f 1 46 Stark. Greg. 2015."*A Systematic Approach to Better Understanding Integration Costs*. Golden. CO: National Renewable Energy Laboratory.

b 2 305 Steffen. Will. 2015. "Planetary boundaries: Guiding human development on a changing planet" *Science Express.* 15 January.

h 1 398 Steg. Linda. et al.. 2014 "An Integrated Framework for Encouraging Pro-environmental Behaviour: The role of values. situational factors and goals." *Journal of Environmental Psychology* 38 .

h 1 391 Steg. Linda. Goda Perlaviciute and Ellen van der Werff. 2015. "Understanding the human dimensions of a sustainable energy transition." *Frontiers of Psychology. 6.*

b 2 542 Steinberger. Kevin and Miles Farmer. 2017. Debunking Three Myths About "Baseload." NRDC. July 10.

f 1 208 Steinke. Florian. Philipp Wolfrum. and Clemens Hoffman. 2013. "Grid vs. Storage in a 100% Renewable Europe." *Renewable Energy* 50.

t 27 49 Stenclik. Derek. Paul Denholm and Babu Chalamala. 2017. "Maintaining Balance: The Increasing Role of Energy Storage for Renewable Integration." *IEEE Power and Energy Magazine.* 6.

d 3 229 Stephenson. W. David. 2014. "Internet of Things Could Offset Government Inaction on Climate." *Greenbiz.com*. November 17.

d 2 134 Sterling J. et al. 2015. T*he flexible solar utility: preparing for Solar's impacts to utility planning and operations.* Report NREL/TP--6A20--64586. Golden. CO: NREL

b 2 158 Steve Propper. *Evolution of the Grid Edge: Pathways to Transformation.* GTM Research.

b 2 514 Stolten. Detlef and Viktor Scherer. 2013. *Transition to Renewable Energy Systems.* Wiley.

a 4 60 Strøm S. and AN Andersen. 2017. "The Danish case: Taking advantage of flexible power in an energy system with high wind penetration." In Lawrence E. Jones (Ed.) *Renewable Energy Integration Practical Management of Variability, Uncertainty, and Flexibility in Power Grids* (Second Edition).

j 2 276 Sueyoshi. Toshiyuki and Mika Goto. 2014. "Photovoltaic Power Stations in Germany and the United States: A Comparative Study by Data Envelopment Analysis." *Energy Economics* 42.

j 4 543 Surina. Jay and Mike McGough. 2015. *The NuScale Value Proposition: Simple. Safe. Economic. NuScale Power. LLC.* February 18.

a 1 479 Sustainable Development Solutions Network *2020. Zero Carbon Action Plan*. New York:

d 2 344 Takahashi. Kenji and David Nichols. *2008. Sustainability and Cost of Increasing Efficiency Impacts: Evidence from Experience to Date*. ACEEE Summer Study on Energy Efficiency in Buildings.

f 1 373 Tascikaraoglu. A.. and M. Uzunoglu. 2014. "A Review of Combined Approaches for Prediction of Short-Term Wind Speed and Power." *Renewable and Sustainable Energy Reviews* 34.

f 1 428 The Center for Climate Strategies. 2016. *Enhancing Transatlantic Collaboration to Expand*

Renewable Energy Market Penetration. February.

j 1 566 Tomain, J, 1987, *Nuclear Power Transformation,* Bloomington: Indiana University.

d 4 174 Traut, Elizabeth J. 2013. *Life Cycle Cost and Environmental Implications of U.S. Electric Vehicle and Charging Infrastructure Scenarios.* Dissertation.

t 7 471 Trondle. Tim. et al.. 2020. “Trade-Offs between Geographic Scale. Cost. and Infrastructure Requirements for Fully Renewable Electricity in Europe.” *Joule 4.*

j 3 239 Tsai. Chen-Hao and Gürcan Gülen. 2017. “Are zero emission credits the right rationale for saving economically challenged U.S. nuclear plants?” *The Electricity Journal.* 30.

a 1 515 Tsiropoulos I. D. Tarvydas. and A. Zucker. 2017. *Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050*. EUR 29034 EN. Publications Office of the European Union. Luxembourg.

t 43 7 U.S. Department of Energy, 2015. *Increasing the Efficiency of Building Systems and Technologies.* September.

d 2 219 U.S. Department of Energy. 2015. *Wind Vision: A New Era for Wind Power in the United States.* March 12

t 27 435 U.S. Department of Energy. *2020. Energy Storage Grand Challenge: Energy Storage Market Report.* December.

c 2 244 U.S. Energy Information Administration. 2013. *Assessing the Economic Value of New Utility-Scale Electricity Generation Projects. Workshop Discussion Paper: LCOE and LACE.* July.

c 2 29 U.S. Energy Information Administration. 2017. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2017.*

t 27 436 U.S. Energy Information Administration. 2020. *Battery Storage in the United States: An Update on Market Trends.* July.

c 1 337 U.S. Energy Information Administration. 2021. *Cost of Generation,* various.

c 1 605 U.S. Energy Information Administration. *Monthly Energy Review.* various

d 3 606 U.S. Environmental Protection Agency. Department of Transportation. 2010. In the Matter of Notice of Upcoming Joint Rulemaking to Establish 2017 and Later Model Year Light Duty Vehicle GHG Emissions and CAFE Standards. Docket ID No. EPA-HQ-OAR-0799 Docket ID No. NHTSA-2010-0131.

f 1 65 U.S. Federal Energy Regulatory Commission (FERC). *Order No. 1000 -- Transmission Planning and Cost Allocation*. Washington DC

j 3 277 U.S. GAO. 2007. *Federal Electricity Subsidies: Information on Research Funding. Tax Expenditures. and Other Activities That Support Electricity Production.* GAO-08-102. Washington. DC: U.S. Government Printing Office.

f 1 209 U.S. GAO. Dan. et al. 2014. “An Integrated Energy Storage System Based on Hydrogen Storage: Process Configuration and Case Studies with Wind Power.” *Energy* 66.

d 3 607 U.S. National Highway Traffic Safety Administration. 2010. *Corporate Average Fuel Economy for MY2012-MY 2016 Passenger Cars and Light Trucks*. *Preliminary Regulatory Impact Analysis*.

j 3 574 U.S. Treasury Department. 2021. *General Explanations of the Administration's Fiscal Year 2022 Revenue Proposals. May*

a 2 278 UCal Berkeley. *Bending The Curve.* 2015

f 1 232 Ueckerdt. Falko et al.. 2017. “Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model.” E*nergy Economics*. 64.

f 1 71 UKERC. 2017. *The Costs and Impacts of Intermittency – 2016 Update.* UK Energy Research Centre.

c 3 320 UN Environment Programme. 2008. *Green Jobs: Towards decent work in a sustainable, low-carbon world.*

d 3 90 UN Environment Programme. 2015. *District energy in cities: unlocking the potential of energy efficiency and renewable energy*. Paris.

c 3 328 UN Environment Programme. 2017. *The Emissions Gap Report 2017*. United Nations Environment Programme (UNEP). Nairobi

a 1 136 Union of Concerned Scientists. 2015. *Renewables and reliability: grid management solutions to support California's clean energy future.* Cambridge. MA

f 1 133 Union of the Electricity Industry. 2013. *Active distribution system management: a key tool for the* *smooth integration of distributed generation.* Brussels: Eurelectric.

d 2 349 van Hulst. Noel. 2017. Hydrogen Envoy at the Ministry of Economic Affairs & Climate Policy of the Netherlands. *The Untapped Potential of Energy Efficiency.* 11 May.

d 2 492 Varnäs. et al.. 2012. *Driving Technological Innovation for a Low-Carbon Society: Case Studies for Solar Photovoltaics and Carbon Capture and Storage. Stockholm Environment Institute.*

f 1 379 Veena. P.. et al.. 2014. "Review of Grid Integration Schemes for Renewable Power Generation System." *Renewable and Sustainable Energy Reviews* 34.

t 36 241 Vergados. Dimitrios J. et al. 2016. "Prosumer clustering into virtual microgrids for cost reduction in renewable energy trading markets." Sustainable Energy. Grids and Networks. 7 241

d 3 444 Vergis. Sidney. et al.. 2014. *Plug-In Electric Vehicles A Case Study of Seven Markets.* Institute of Transportation Studies. University of California. Davis. October.

t 31 438 Villalón. Ariel. et al.. 2020 "Predictive Control for Microgrid Applications: A Review Study." ***energies. 13.***

c 1 472 Vine. Doug and Timothy Juliani. 2014. *Climate Solutions: The Role Of Nuclear Power*. *Center for Climate and Energy Solution*s. April.

h 1 397 Vlek. Charles and Linda Steg. 2009. "Encouraging pro-environmental behaviour: An integrative review and research Agenda." *Journal of Environmental Psychology* 29.

j 1 487 von Hippel. Frank N. 2021. "Biden can rescue the Nuclear Regulatory Commission from industry capture." *Bulletin of the Atomic Scientists* January 27.

b 2 164 VTT Technology. IEA. 2014. *The Power of Transformation: Wind. Sun and the Economics of Flexible Power System.* OECD. IEA www.ieawind.org/task. Paris.

g 1 432 Vyas. Khyati. Sudhir Jain. and Sunil Joshi. 2014. "A Review On An Automatic Solar Tracking System." *International Journal of Computer Applications.*

t 35 441 Wang. Huaizhi. et al.. 2019. "A review of deep learning for renewable energy forecasting." *Energy Conversion and Management.*198.

j 1 484 Wealer. Dr. Ben. 2021. *Toward an Evidence-Based Nuclear Energy Policy; What Congress Needs to Know About Nuclear Decommissioning. Radioactive Waste. and Nuclear Energy as a Climate Strategy.* EESI Congressional Briefing. March 30.

t 36 70 Weidman. Joseph and Tom Beach. 2013. "Distributed Generation Policy: Generation on Both Sides of the Meter." *The Electricity Journal.* 26.

j 3 463 Weimar. Mark R. et al. 2021. *Techno-economic Assessment for Generation III+ Small Modular Reactor Deployments in the Pacific Northwest.* Pacific Northwest National Laboratory April.

d 4 233 Weiss. Jürgen. et al. 2017. "The electrification accelerator: Understanding the implications of autonomous vehicles for electric utilities." *The Electricity Journal.* 30.

c 3 608 Wie. Max. Shana Patadia. and Daniel Kammen. 2010. "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?. *Energy Policy.* 38.

h 1 393 Williamson. K. et al. 2018. *Climate Change Needs Behavior Change: Making the Case For Behavioral Solutions to Reduce Global Warming.* Arlington. VA.

c 1 5 Wiser. Ryan. Andrew Mills and Joachim Seel. 2017. *Impact of Variable Renewable Energy on Bulk Power System Assets. Pricing and Costs.* Argonne and Lawrence Berkeley National Laboratories.

t 36 69 Wiser. Ryan. Galen Barbose. and Mark Bolinger. 2017a. *Retail Rate Impacts of Renewable Electricity: Some First Thoughts*. Berkeley. CA: Lawrence Berkeley National Laboratory.

t 27 214 Woo. C.K. and J. Zarnikau. 2017. "A solar rate option for the development of behind-the-meter photovoltaic systems." *The Electricity Journal* 30.

d 2 218 Woodhouse. Michael. et al. 2016. *On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency. Reliability. and Costs* . Golden. CO: National Renewable Energy Laboratory.

d 3 558 Woolf. Tim.. et al. 2016, *Aiming Higher Realizing the Full Potential of Cost-Effective Energy Efficiency in New York.* Prepared for Natural Resources Defense Council, E4TheFuture, CLEAResult, Lime Energy, Association for Energy Affordability, and Alliance for Clean Energy New York. Synapse. April 22.

d 2 345 Worrell. 2003. "Productivity Benefits of Industrial Energy Efficiency Measures." *Energy*. 28.

b 1 32 Wu. Tim. 2010. *The Master Switch.: The Rise and Fall of Information Empires.* Knopf.

f 1 374 Wu. Jung et al. 2015. "Integrating Solar PV (Photovoltaics) in Utility System Operations: Analytical Framework and Arizona Case Study." *Energy* 85.

t 37 91 Würtenberger L. et al. 2012. *Business models for renewable energy in the built environment.* Prepared for IEA--RETD. Petten: Energy Research Center of the Netherlands

f 1 375 Xi Lu et al.. 2013. "Optimal Integration of Offshore Wind Power for a Steadier. Environmentally Friendlier. Supply of Electricity in China." *Energy Policy* 62.

f 1 231 Yoram Krozer. 2013"Cost and Benefit of Renewable Energy in the European Union*." Renewable Energy* 50.

t 8 237 Yue-wei Wu. Tiffany. and Varun Rai. 2017. "Quantifying diversity of electricity generation in the U.S." *The Electricity Journal*. 30.

t 27 559 Zangs. Maximilian J. et al. 2016. "Distributed Energy Storage Control for Dynamic Load Impact Mitigation." e*nergies* August.

j 1 283 Zelenika-Zovk and J.M. Pearce._2011. "Diverting indirect subsidies from the nuclear industry to the photovoltaic industry: Energy and financial returns." *Energy Policy* 39.

b 2 314 Zheng and Daniel M. Kammen. 2014. "Innovation-Focused Roadmap for a sustainable global photovoltaic industry." *Energy Policy* 67.

c 3 323 Zuckerman. J. et al. 2016. *Investing at Least a Trillion Dollars a Year in Clean Energy*. Contributing paper for *Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. New Climate Economy. London and Washington. DC.

d 3 475 Zulkarnain. et al. 2014. "The Electric Vehicles Ecosystem Model: Construct. Analysis and Identification of Key Challenges." *Managing Global Transitions*. 12.

ENDNOTES

[1] Illinois Commerce Commission et al., 561, pp. 130-131.
[2] As suggested by Figure 2.2 in Cooper, 271.
[3] Cooper, 271.
[4] Acemolgue and Robinson, 334, use this phrase; Perez, 302, calls it a "turning point."
[5] Lazard, 332, 14.0.
[6] The energy and communications resource systems are two of the most important, "focal core resource" systems of any society, that determine its ability to function and exploit opportunities (Cooper, citing Ostrom).
[7] Energy Information Administration (hereafter, EIA), 436.
[8] Lazard, 434, 2.0.
[9] Id., p. 7.
[10] Id., p. 9.
[11] Id., pp. 11-12.
[12] Id., pp. 13-16.
[13] Id., p. 23.
[14] Id., 3.0, press release, p. 2.
[15] Id.,, 6.0, Additional Highlights.
[16] EIA, 436.
[17] United States Department of Energy (hereafter U.S. DOE), 435.
[18] Lazard, 332.
[19] van Hulst, 349.
[20] Liu et al. 334.
[21] van Hulst, 349, p. 1.
[22] Cooper, 427, 582.
[23] Cooper, 271, pp. 98, 101, 152-179.
[24] For example, Lovins, 535, idenfities lightweighting of vehicles as an important efficiency measure that dramatically lowers consumption, whatever the power source.
[25] Cooper, 353, pp. 30-31, and the underlying studies.
[26] I have prepared analyses on individual states, including California and Illinois. See Cooper, 271, pp. 169-201, New York (288), South Carolina (289), Wisconsin (286), and Georgia (287).
[27] Takahashi and Nichols, 344.
[28] Hwang and Peak, 228.
[29] Harrington, 253, p. 3.
[30] Worrell et al., 348, p. 1081.
[31] Nadel and Delaski, 361.
[32] Worrell et al., 348. This examination shows that including productivity benefits explicitly in the modeling parameters would double the cost-effective potential for energy efficiency improvement, compared to an analysis excluding those benefits. (p. 1)
[33] Dale et al., 354.
[34] A multivariate analysis confirms these results. Stricter standards as set by DOE lead to measurable improvements in appliance efficiency. This finding is highly statistically significant, with a probability level less than .0001. There is a very high probability that the effect observed is real. The underlying trend is also statistically significant, suggesting that the efficiency of these consumer durables was improving at the rate of 1.35% per year. Given that the engineering-economic analysis had justified the adoption of standards and that standards were effective in lowering energy consumption, this means the market trend was not sufficient to drive investment in efficiency to the optimal level.
[35] I have built this analysis in the typical way that multivariate regression analysis is conducted. The dependent variable is energy consumption with the base year set equal to 1. Later years had lower values. We introduce a variable to represent the adoption of a standard. This variable (known as a dummy variable) takes the value of 1 in every year when the standard was in place and a value of zero when it was not. A negative number means that the years in which the standard was in force had lower levels of energy consumption. Similarly, the difference between appliances is handled with dummy variables. We include each appliance except furnaces, which shows how the other appliance performed compared to furnaces. Again, a negative number means that the other appliances had lower levels of energy consumption.

[36] Nadel and Delaski, 361.
[37] Sperling et al., 347, emphasized the adaptation of producers in the analysis of auto fuel economy standards.
[38] Kahn, 295, p. 11.
[39] Lovins, 274.
[40] Cooper, 541; Perez, 510, p. 2. "The digital mode of production is based on a powerful cluster of interdependent new and dynamic industries and infrastructures. These result in explosive growth and structural change ... new multipurpose technologies, infrastructures and organisational principles that are capable of modernising all the existing industries, transforming the opportunity space and the ways of living, working, and communicating."
[41] Perez, 508, p. 135.
[42] Perez, 508. p. 124.
[43] Perez, 509, pp. 155-156.
[44] Kanger et al., 474, p. 47.
[45] Rafique et al., p. 207226. The parallel and interconnected nature of the technological transformations in the important core resource systems of the 21st century economy is capture in the titles of two works, Wu's *Mater Switch* (32) and Kelly-Detwiler's *The Energy Switch* (386). The fact that the former was written ten year before the latter reflects the fact that the communications revolution was antecedent, but the two have now merged because innovator are using the revolutionary communications and computer technologies to transform the energy sector.
[46] Illinois Commerce Commission, 561, p. 128.
[47] Id., pp. 130-131.
[48] Id., p. 128.
[49] Id., p. 150.
[50] Berkman and Murphy, 284.
[51] Lovins, 274, p. 24, notes that decommissioning jobs will be the same whenever the reactors are shut down and do not affect the employment picture in the long term.
[52] Nadel and Unger, 351.
[53] Jacobson, et al., 269.
[54] Even the Kentucky Commission recognized these values (567): "The Kentucky Power had \$.03553 for residential consumers, and \$.03778 for commercial consumers. In the final order, the compensation rate is approximately \$0,097/kWh, with additions of the value of ancillary services, generation, transmission, and distribution capacity, avoided carbon costs, and avoided criteria pollutant costs: Residential NMS II Export Rate
Energy \$0.03893
Ancillary Services \$0.00063
Generation Capacity \$0.02816
Transmission Capacity \$0.01245
Distribution Capacity \$0.01046
Carbon Cost \$0.00578
Environmental Compliance Cost \$0.00105
[55] Lazard, 332, Version 13.0..
[56] Bhandari, 564.
[57] Id.
[58] Judson, 523.
[59] Issues t7-t42.
[60] Cooper, 402.
[61] Mills and Wiser, 367, p. 24. "A portfolio with high geographic diversity leads to a higher value of wind due to a reduction in extremes: Fewer hours have significant amounts of wind from all wind sites in the portfolio (reducing overgeneration and curtailment), and more hours have at least a small amount of wind generation from some sites. The benefit of increased geographic diversity is more pronounced with high wind penetration levels since wind is more likely to affect wholesale prices at high penetration levels." Issue t7.
[62] Ibid., 25. "The increase in the capacity value of wind with 10% PV is due to PV shifting the timing of the peak prices into the early evening, when wind generation is somewhat stronger." p. 27: "As PV penetrations increase, adding 10% wind increases the marginal value of PV substantially relative to the Reference scenario. ... The increase in the capacity value is tied in part to wind generation occurring." Issue t8.
[63] Ibid., 33. "The increase in the value of PV with low-cost storage is almost entirely due to the increase in the energy value of PV relative to the Reference scenario. ... The energy value of PV increases in part due to a reduction in PV curtailment from 2.9% with 30% PV in the Reference scenario to less than 0.1% in the Low-cost

Storage scenario. The strong negative correlation between PV generation and generation from storage (existing and new) at high PV penetrations indicates storage is consistently charging when PV is generating and discharging otherwise." Issues t27-t30.

[64] Ibid., 32, 33. Issues t21-t22.

[65] Ibid., 33. Issue t23.

[66] Ibid., 35. " ... since reductions in demand relative to historical levels at time of system need enable a balance between demand and generation rather than relying on new conventional capacity." Issues t18-120

[67] Mills and Wiser, 151. The issue enters implicitly through the frequent attention to forecasting error. The other major studies give sub-hourly scheduling prominent, explicit attention.

[68] Id., 43. Issues t10-t11.

[69] Id., 30, "In addition, the impact of more-flexible generation will depend on the degree of flexibility in the existing generation mix. California has significant amounts of CTs, PHS capacity, and hydropower. In comparison, we found in an earlier analysis of highly concentrated wind in the Rocky Mountain Power Area [Andrew Mills and Ryan Wiser, Solar Valuation in Utility Planning Studies. Clean Energy States Alliance: RPS Webinar, January 2013] that assuming all new CCGTs had quick-start capability increased the value of wind by up to $6/MWh at 30% wind penetration. The Rocky Mountain Power Area has much less flexible incumbent generation relative to California." Issue t8.

[70] Id., 39. Issues t8-t13, t24.

[71] The four "least regrets" opportunities identified in this study include "1. Increase regional coordination. ... 2. Pursue a diverse portfolio of renewable resources. ... 3. Implement a long-term, sustainable solution to address overgeneration before the issue becomes more challenging. ... 4. Implement distributed generation solutions. ... 5. Promising technologies, storage (Solar thermal with energy storage, Pumped storage, Other forms of energy storage including battery storage, Electric vehicle charging, Thermal energy storage). ... 6. Flexible loads that can increase energy demand during daylight hours (Advanced demand response and flexible loads). ... 7. Sub-five-minute operations. ... 8. Size of potential export markets for excess energy from California. ... 9. Transmission constraints. ... 10. Changing profile of daily energy demand. ... 11. Future business model for thermal generation and market design. ... 12. Optimal thermal generation fleet under high RPS." (pp. 31–35) E3, 155.

[72] Id., 155, pp. 31–35.

[73] Holttinen, 163; Wu et al., 374; Rauch, 285.

[74] U.S. Doe, 219, p. xxiii.

[75] Id., xlii.

[76] Shrimali and Indvik, 335, p. 454; Bouzid et al., 187, p. 753.

[77] For academic studies on system integration, generally the citations in issues e-1, f-1, t-27 thru t-33); on geographic diversity, see issue f-1, t-7, t-8.

[78] See, for example, on general scenarios and their evaluation, issues a-4 thru a-4; on resources, see issues c1 thru c-3, and on sustainability, see issue h-1.

[79] U.S. Department of Energy, 333, p. xv.

[80] Id., p. xxxvi.

[81] EIA, 244, p. 1.

[82] EIA, 29, p.3.

[83] EIA, 244, p. 1.

[84] Johnson, et al., 376, *Energy Economics* 64 estimate the system cost of ramping various resources as an "efficiency waste." The concept of "inflexibility waste" would include that cost plus the cost of larger reserves made necessary by the need to be able to replace the largest unit on the grid.

[85] Agora, 74.

[86] Wiser, Mills, and Seel, 5, pp. 81-82.

[87] This is consistent with Karier and Fazio, 38. Table 3 shows efficiency with much higher capacity values than natural gas. Karier and Fazio show efficiency with a 50% capacity advantage over gas and an 11% standalone advantage over gas. Johnson et al., 376, show gas with a 14% efficiency penalty. Resources available on-peak without ramping have capacity values of 1 and efficiency penalties of zero. All of these value suggest efficiency is a 1 on capacity and a zero on efficiency penalty.

[88] A study by researchers at the Columbia University Center on Global Energy Policy applied this approach to the underlying EIA LCOE, Benes. and Augustin, 243. Since the earlier EIA costs were out of touch with reality, the analysis leads to erroneous conclusions, although the impact of other system costs points to the same conclusions as in the above analysis.

[89] See Issues j1, j2.
[90] BWE, German Wind Energy Association, 417; Kitson, Wooders, and Moerenhout, 275; Berwick, 281; U.S. GAO, 277; Goldberg, 414; Pfund and Healey, 415.
[91] Branker and Pearce, 422; Badcock and Lenzen, 416.
[92] Id.
[93] Zelenika-Zovk and Pearce, 283, p. 2626,
[94] Id., p. 2.
[95] Lovins and Rocky Mountain Institute, 22. p. 216.
[96] Oei et al., 507, p.116.
[97] Lovins, 274.
[98] Ramana, 406.
[99] Cooper, 271.
[100] Bupp and Denton, 562, p. 154–155. See Also Bupp, 563; Komanoff, 565; Tomain, 566.
[101] Id., p. 27.
[102] Neumann, 466.
[103] Tomain, 566, argued that the political element is central to the analysis of nuclear safety and regulation from the broad perspective of public safety and public subsidy and the narrow perspective of the limitation on liability that was conferred on the nuclear industry by the government.