THE ECONOMIC AND INSTITUTIONAL FOUNDATIONS OF THE PARIS AGREEMENT ON CLIMATE CHANGE:

THE POLITICAL ECONOMY OF ROADMAPS TO A SUSTAINABLE ELECTRICITY FUTURE

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Abstract

Three recent "roadmap" analyses outline routes to a low-carbon economy that model the decarbonization of the electricity sector and the pervasive electrification of the transportation and industrial sectors. Two of these also impose a pollution constraint on electricity resources that rejects the use of nuclear power and fossil fuels with carbon capture and storage. Using independent cost estimates and sequentially "relaxing" the constraints on resource selection, this paper compares the resource costs of the resulting portfolios of assets needed to meet the need for electricity. Reflecting the continuing decline of the cost of renewable resources, the paper supports the claim that the long run costs of the 100% renewable portfolios are not only less than business-as-usual portfolios, but that the "environmental merit order" of asset selection is quite close to the "economic merit order." Neither fossil fuels with carbon capture and storage nor nuclear power enters the least-cost, low-carbon portfolio. As long as a rigorous least-cost constraint is imposed on decarbonization, the pollution constraint is superfluous. The paper evaluates the Paris Agreement on climate change in light of these findings. The Agreement is described as a progressive, mixed market economic model with a governance structure based on a polycentric, multi-stakeholder approach for management of a common pool resource. The paper argues that this approach reflects the underlying techno-economic conditions and the fact that national governments have authority over local energy policy. It also notes that the political economy of the Agreement is consistent with current academic analysis of policy responses to the challenges of climate change and management of a large, focal core resource system.

January 2016

TABLE OF CONTENTS

I. INTRODUCTION

PURPOSE

In the run up to the Paris Conference on climate change,[1] several major studies were released with strong, positive messages for the economics of dealing with climate change:

- Three "roadmap" studies of the route to decarbonizing the global economy were released. Two of these excluded all fossil fuels and nuclear power, relying solely on renewables (Jacobson et al.[2] for 139 countries and a Greenpeace study of climate change[3]). One of them focused only on decarbonization, allowing the use of fossil fuels with carbon capture and storage and nuclear power.[4]
- Two independent cost projections of various energy technologies were released – Lazard's annual estimate of the *Levelized Cost of Energy Analysis 9.0*[5] and the *Australian Power Generation Technology Report*[6] – both of which found that the costs of low-carbon, low-pollution resources continue to fall dramatically.

All of the roadmap studies project a sustainable path to a low-carbon future.[7] Using long-term price projections,[8] all three studies conclude that, as a result of the technological revolution in the electricity sector, the economy, in general, and the electricity sector, in particular, can be decarbonized with at most a very modest increase in the cost of energy services. All three studies envision continued, sustainable economic development, while delivering significant environmental and public health benefits.

This paper uses three lenses to examine these conclusions.

- It places the studies in the context of the Paris Agreement.
- It uses the independent cost estimates to examine the robustness of the price assumptions that played a key role in the roadmap analyses.
- It uses a strictly economic lens to evaluate the roadmaps by asking how closely the portfolios of resources selected based on the environmental constraints resemble a portfolio of assets that would be assembled without those constraints.

The paper begins with a discussion of the Paris Agreement because it sets the context for the economic analysis. Policy choices are the essence of political economy and in this case, their impact is indisputable.[9] The political commitment to decarbonization is intended to and, if pursued, will certainly be the dominant driver for energy resource development and selection. It is also critically important to recognize the techno-economic reality that underlies and is expressed in the Agreement.

OUTLINE

Section II presents a brief discussion of the political economy of the Paris Agreement to underscore the profound relevance of the techno-economic basis of the response to the challenge of climate change. The remainder of the paper deals with the evaluation of the techno-economic paradigms embodied in the three roadmap studies.

Section III describes our approach to the economic analysis and the key features of the decarbonization road map studies that define the structure of this analysis. It focuses on the Jacobson et al. analysis, since it provides the greatest detail.

Section IV reviews the current estimates of resource costs. It uses those costs to demonstrate the methodology for assessing the impact of placing constraints on the selection of assets for the electricity portfolio. It then reviews projections of future costs and applies the "merit order" methodology to those projections.

Section V provides summary estimates of the impact of the resource constraints on the cost of electricity. It adds a scenario that assumes a higher level of efficiency. It also examines how the consideration of other factors, e.g. non-carbon externalities, timing, affects the attractiveness of resources. It also offers some concluding observations.

II. THE POLITICAL ECONOMY OF THE PARIS AGREEMENT

This paper argues that the techno-economic revolution underlying the road maps had a profound impact on the Paris Agreement that went beyond the simple question of cost. The impact was existential. Without that technological revolution, it would not have been possible to reconcile the two great challenges of the 21st century: the aspiration of billions of people for economic development and the need to eliminate carbon emissions from the global economy

For political reasons, the Paris Agreement hammered out in December 2015 was carefully framed as enhanced action under the United Nations Framework Convention on Climate Change negotiated nearly 25 years earlier. The ability to arrive at the Agreement was the result of the technological revolution that had taken place in the intervening quarter century. Balancing the dual goals of decarbonization and development was a necessary condition for reaching political consensus.

The techno-economic context also had a profound impact on the political structure created by the Agreement to guide the response to climate change. The governance structure defined the challenge as a commons problem and recognized the array of technology choices and vast difference in energy resources endowments and levels of development between nations, as well as the need to respect the autonomy of nations.[10] The governance solution had to be geographically polycentric and vertically coherent, affording flexibility to the Parties. This required collaborative solutions and reciprocity around shared goals. The success of the Paris Agreement, as with any multi-stakeholder approach that delegates responsibility (relies on the principle of subsidiarity), will be determined by the ability to build trust and the development of social norms through reciprocity and the transparency of a vigorous information/evaluation framework.

THE TECHNOLOGICAL UNDERPINNING

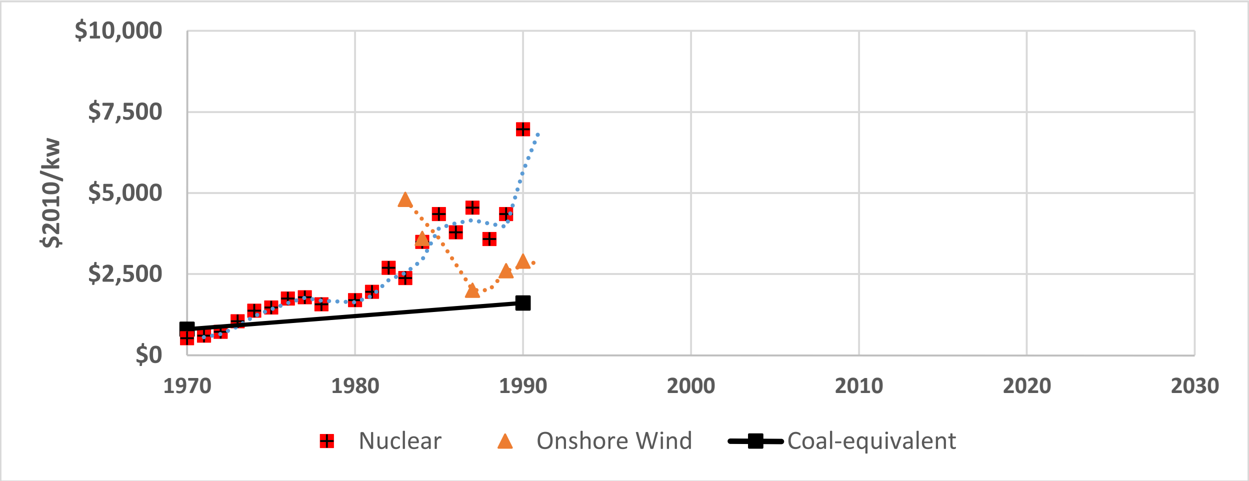
As shown in the upper graph of Figure II-1, in 1991, when the United Nations Framework Convention on Climate Change (UNFCCC) was negotiated, prospects for building a low-carbon electricity sector and, therefore, a low-carbon economy were bleak. This is captured by the comparison of the cost of the low-carbon resources generally available at the time (nuclear and onshore wind) and the cost of the dominant resource at the time (coal-fired generation, which is presented as the equivalent of overnight costs). Nuclear and offshore wind were much more costly than the fossil fuels that drove the economy and not exhibiting declining cost trends.[11]

As shown in the lower graph of Figure II-1, in the next two decades, economic fundamentals of the supply-side options changed. A technological revolution in generation dramatically lowered the cost of some low carbon technologies. It was built on the combination of public policies to set the direction of socially responsible economic growth with support for basic research and programs to create markets.[12] The private sector responded with investment in innovation and clean energy patents proliferated, followed by rapid deployment as costs fell. [13]

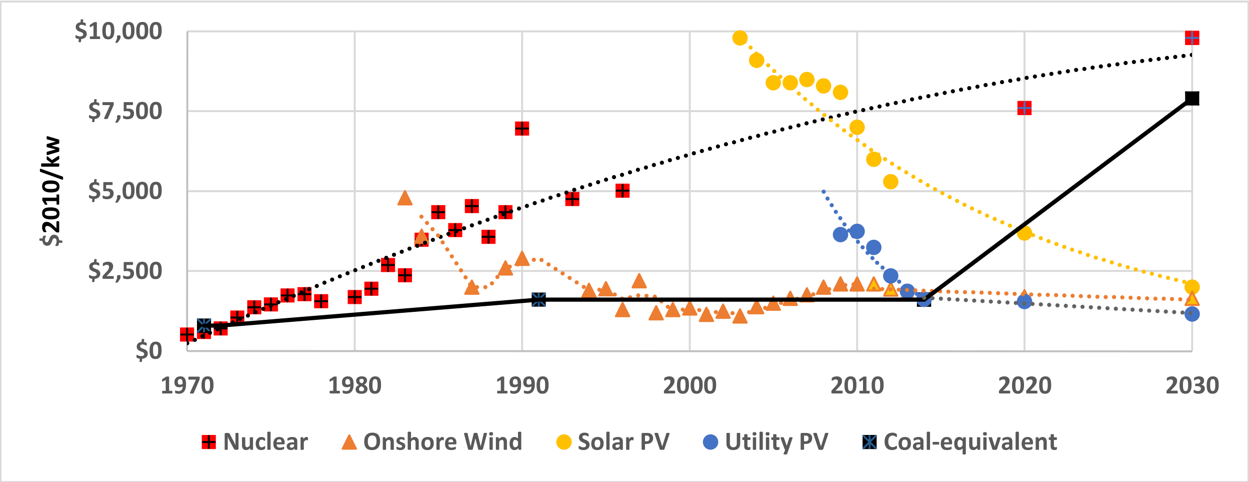
While the cost of nuclear power remained high and appeared to be rising, the cost of wind and other low-carbon alternatives plummeted. The current cost of coal, expressed as an overnight cost equivalent, reflects both changes in fuel prices and new technologies to deal with non-carbon pollutants, while the long-term price for coal includes the cost of carbon capture and storage. The long-term cost of natural gas generation with carbon capture storage is generally slightly below that of coal with carbon capture and storage.

FIGURE II-1: PROSPECTS FOR DECARBONIZATION UNDER THE FRAMEWORK CONVENTION

Generation Options at the Negotiation of the Framework Convention on Climate Change (1991)



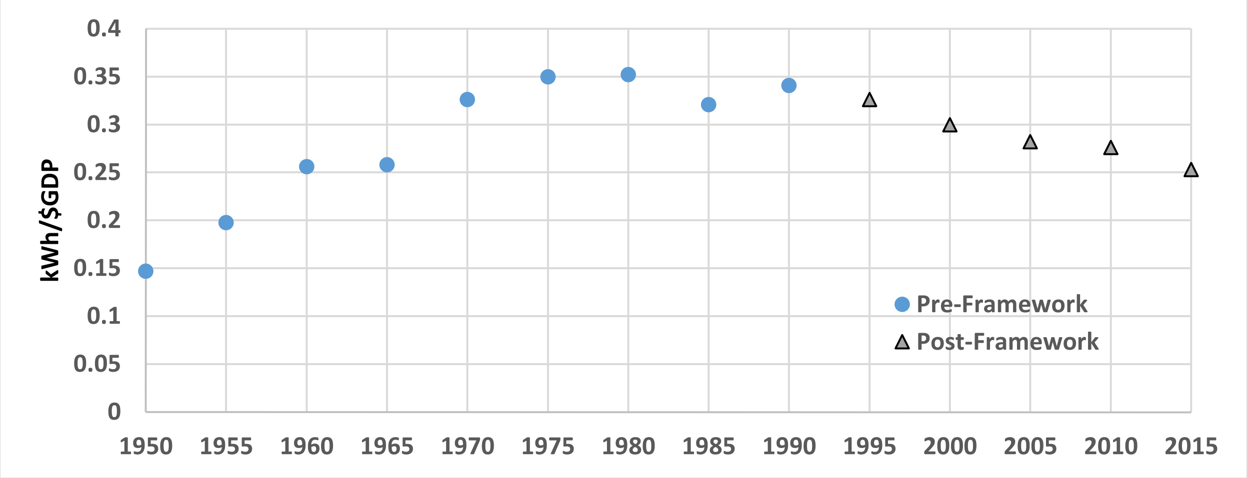
Generation Options at the Negotiation of the Paris Agreement (2015)



Sources: Mark Cooper, "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, 2012; Charles Komanoff,** ***Power Plant Cost Escalation, Nuclear and Coal Capital Costs, Regulation and Economics*** **(1981); James McNerney, J. Doyne Farmer and Jessika E. Trancik, "Historical costs of coal-fired electricity and implications for the future,"** ***Energy Policy, 39 (6), 2011;*** **Lazard,** ***Lazard's Levelized Cost of Energy Analysis – Version 9.0,*** **November 2015; Galen Barbose, Naïm Darghouth, Samantha Weaver, and Ryan Wiser,** ***Tracking the Sun VI: An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2012,*** **Lawrence Berkeley National Laboratory, July 2013; Ryan Wiser and Mark Bolinger,** ***2012 Wind Technologies Market Report,*** **U.S. Department of Energy, August 2013; Mark Cooper, "Small Modular Reactors and the Future of Nuclear Power in the United States,"** ***Energy Research & Social Science,*** **3, 2014; Greenpeace International, Global Wind Energy Council, and Solar Power Europe,** ***energy [r]evolution: A Sustainable World Energy Outlook, A 100% Renewable Option for All,*** **September 2015.**

At the time of the 1991 negotiations, the link between economic growth and energy consumption was strong, as it had been throughout the history of the Industrial Revolution. A technological revolution took place on the demand side over the period. New, more energy efficient technologies in capital equipment and consumer durables first weakened and then severed the tie between energy consumption and economic growth. In Figure II-2, we use the U.S. to make this point, since it is the largest energy consumer among the developed nations in both absolute level and electricity consumed per dollar of GDP.

FIGURE II-2: U.S ELECTRICITY GENERATION (KWH) PER DOLLAR OF GDP (REAL)



Source: U.S. Energy Information Administration, *Monthly Energy Review December 2015*, http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_5.pdf; *US Real GDP by Year*, http://www.multpl.com/us-gdp-inflation-adjusted/table.

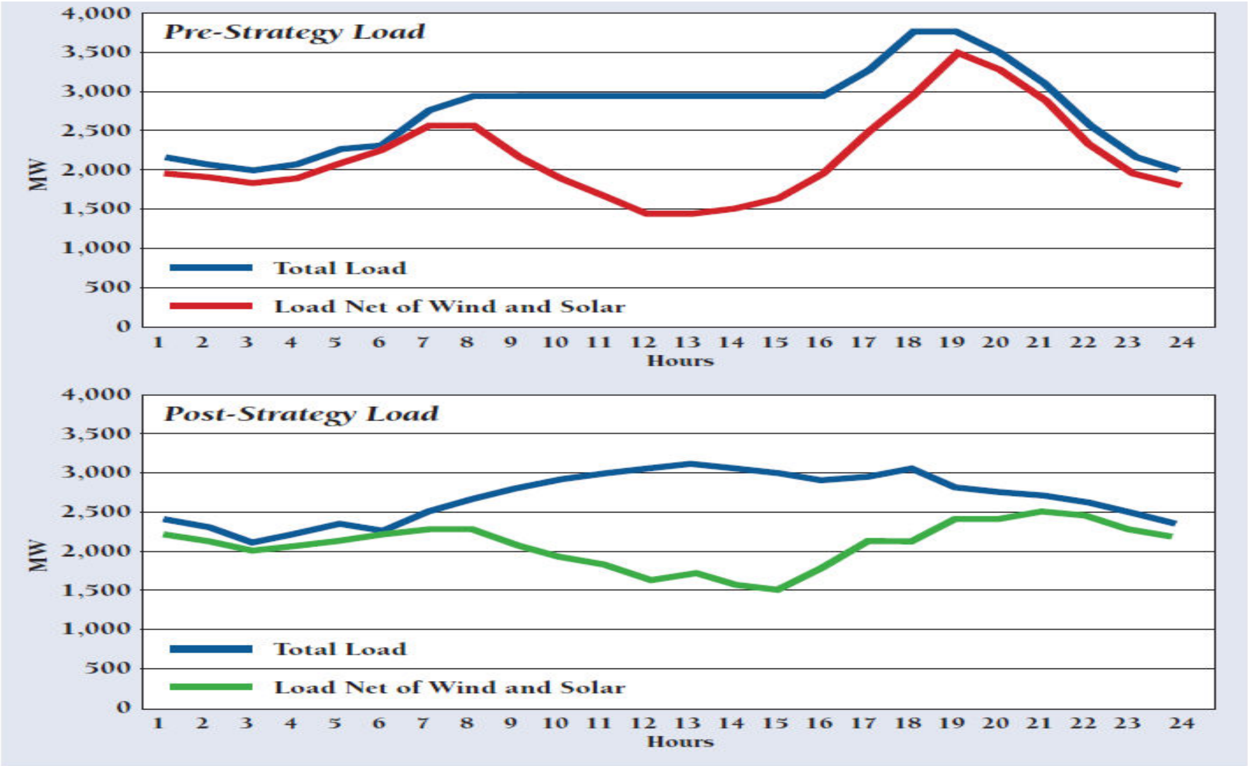
Another technological revolution is taking place between energy supply and demand, powered by information, computing, communications and control technologies. It is transforming the ability to manage a dynamic electricity system that integrates decentralized and variable clean renewable supply with demand. Lowering peak demand reduces that system size significantly, by 17% in the model depicted in Figure II-3. It also brings supply into closer coordination with demand. The results in Figure II-3 are based on only 10 of the numerous potential measures identified in Table II-1. In the long-term, the ICT revolution will play a dramatic role in meeting the need for low-carbon electricity at affordable costs.

THE ECONOMIC FRAMEWORK

These techno-economic fundamentals are reflected in the Paris Agreement in several important ways. Cost are a critical concern.

The Agreement affirms the urgent need to reduce carbon emissions (using the word "urgent" 6 times). It makes repeated reference to near-term timeframes (referencing "2020" a total of twenty times, "2025" four times and "2030" four times). It draws a direct link between rapid action and the ultimate cost of meeting the challenge by "*Emphasizing* the enduring benefits of ambitious and early action, including major reductions in the cost of future mitigation and adaptation efforts" (p. 2).

FIGURE II-3: THE BENEFIT OF MATCHING SUPPLY AND DEMAND WITH INTELLIGENT LOAD MANAGEMENT



Source: Jim Lazar, *Teaching the "Duck" to Fly*, Regulatory Analysis Project, January 2014, p.3.

TABLE II-1: MEASURES TO MANAGE A MORE DYNAMIC GRID

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**
- **Deploy fast-ramp generation**

Grid management
- **Expand balance area**
- **Improve forecasting**
- **Integrated power transactions**
- **Import/export**

Dispatchable storage
- **Solar thermal with storage**
- **Utility storage in strategic locations**

Distributed storage
- **Community & individual storage**
- **Large air conditioning water heating with storage subject to grid control**
- **Electric vehicles**

Sources and Notes: The "Peaking Duck" graph is from Jim Lazar, *Teaching the "Duck" to Fly*, Regulatory Analysis Project, January 2014, based on only the ten underlined the measures. The longer list, which includes additional measures from the U.S. Department of Energy, *Wind Vision: A New Era for Wind Power in the United States,* 2015, p. 90, citing M. Milligan, et al., *Impact of Electric Industry Structure on High Wind Penetration Potential*, NREL, July 2009 (p. 23). E3, *investigating a Higher Renewables Portfolio Standard in California,* January 2014; 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,"* Rocky Mountain Institute, August 7, 2014. Steve Nadel, *Conquering the Evening Peak,* ACEEE, 2014.

This urgent call to action reflects the conclusion that current commitments are inadequate, which leads to "the concern that the estimated aggregate greenhouse gas emission levels in 2025 and 2030 resulting from the intended nationally determined contributions do not fall within least-cost 2˚C" (p. 3). It also reflects the fact that, in the long-term, "greater levels of mitigation can reduce the need for additional adaptation efforts, and that greater adaptation needs can involve greater adaptation costs" (p. 24). Thus, near-term mitigation reduces long-term adaptation and total costs.

The Paris Agreement is progressive in a number of ways,[14] including

- vigorous policies to achieve the goals of access to and local control of electricity for developing nations,
- differential contributions from Parties to reflect the capabilities,
- transfer of resources from developed to developing nations, and
- a mixed public and private approach.

Timing and technology also must interact with capacity-building (mentioned 49 times) to achieve the benefits of near-term action. The agreement focuses on rapid development and deployment of carbon-reducing technologies and practices (mentioned 44 times). It stresses the early period noting "the urgent need to enhance the provision of finance, technology and capacity-building support by developed country Parties, in a predictable manner, to enable enhanced pre-2020 action by developing country Parties" (p. 2).

The Agreement requires individual and shared responsibility that reflects the role of economics in other ways. The important role of economics arises in the desire to achieve sustainable development (mentioned 16 times), based on nationally determined contributions (mentioned 61 times). The framework for these contributions recognizes "the differentiated responsibilities and respective capabilities, in the light of different national circumstances" (mentioned 4 times).

It encourages the parties to stimulate broad public participation (mentioned 7 times) in the local and global decision making process, encouraging "the Parties to the Paris Agreement at its first session to explore ways of enhancing the implementation of training, public awareness, public participation and public access to information so as to enhance actions under the Agreement" (p. 10).

The goal of sustainable development is balanced and progressive in the Agreement: "Developing countries... are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances" (p. 21). Developed countries not only take the lead in financing and enhancing technology transfer, they "shall continue taking the lead by undertaking economy-wide absolute emission reduction targets" (p. 21). As larger emitters with more resources, they have a higher standard.

The lower the cost, the greater the ability to achieve the sustainable development goal. The only generation technologies specifically mentioned in the Agreement are those that are currently being widely deployed – renewables. The Agreement points to the "need to promote universal access to sustainable energy in developing countries, in particular in Africa, through the enhanced deployment of renewables" (p. 2).

The focus on renewables, which use local resources, also furthers other goals of the Agreement, including a desire to promote the "development and enhancement of endogenous capacities and technologies… Exploring how developing country Parties can take ownership of building and maintaining capacity over time and space" (pp. 9… 10).

The idea of promoting local ownership, capacity and resources is embedded in an approach that recognizes the need for flexibility in resources and technology, but also the need to promote a mixed model of public and private involvement in meeting the challenge of climate change. Treating climate change as a commons/externality challenge generally supports an active role for public policy. An important task highlighted in the Agreement is to develop and integrate non-market approaches

> To incentivize and facilitate participation in the mitigation of greenhouse gas emissions by public and private entities authorized by a Party… [and] …recognize the importance of integrated, holistic and balanced non-market approaches being available to assist in the implementation of their nationally determined contributions, in the context of sustainable development and poverty eradication, in a coordinated and effective manner… These approaches shall aim to… (b) Enhance public and private sector participation in the implementation of nationally determined contributions; and (c) Enable opportunities for coordination across instruments and relevant institutional arrangements. (p. 23)

The academic literature on climate change strongly supports the general approach and economic principles embodied in the Paris Agreement:

- least-cost measures should take precedence,[15]
- mitigation costs are smaller than adaptation costs,[16]
- early action lowers the transitional and total economic cost of decarbonization dramatically,[17]
- early action that lowers costs requires targeted and induced technological change,[18]
- institutional capacity is crucial to effective, least-cost implementation,[19]
- technology transfer and learning play a vital role in meeting the challenge in a cost effective manner,[20]
- need for flexibility in policy to recognize both localism[21] and complexity that requires overlapping policies,[22] and
- making sustainable development the cornerstone of the response to climate change. [23]

GOVERNING THE CLIMATE COMMONS

A brief description of the political governance structure of the Agreement rounds out the description of its political economy. The governance structure establishes how resources will be selected and judged in the effort to meet the challenge of climate change. We view the governance structure of the Paris Agreement as a commons governance model based on a multi-stakeholder approach that delegates responsibility to local authorities (i.e., applies the principle of subsidiarity).[24] The Agreement defines the challenge of climate change as a common problem (used 7 times) in need of a collaborative/coordinated solution (used 14 times). It intends to elicit the appropriate responses with intensive exchange of information (mentioned 43 times).

The Agreement's approach to governance can best be described in terms of the elements of a successful common pool resource management model. Just as we have argued that the current state of academic research is well-reflected in the economic structure of the Agreement, so too it can be argued that the governance structure reflects the current state of the academic research.

Over the course of the past half century, the viability and in some circumstances the superiority of the collaborative approach to common pool resource management has been widely recognized, culminating in the award of a Nobel prize in economics to Elinor Ostrom, one of its leading practitioners. The following are key elements of the common pool resource management model derived from Ostrom's analysis, framed as challenges or questions to which the management system must respond.[25] The Paris Agreement is described in terms of the answers it provides.

<u>Constitutional rules</u> govern the way the overall resources system is constituted, particularly how collective choice rules are defined. How does the resource system come into existence? **Paris Agreement:** The governance of the common pool resource system is created by the United Nations Framework Convention on Climate Change.

<u>Collective choice</u> rules embody the procedures by which the operational rules are changed. How can the operation of the system adapt? **Paris Agreement**: The Parties acting through a summit and meeting process have the authority to adapt and improve the operational rules (as happened in Paris).

<u>Operational rules</u> govern the activities that take place within the borders of the resource system. How does the system work? **Paris Agreement**: Being based on a convention, it has the trappings of a traditional, international agreement, but the dynamics of its governance – the operational rules – resemble the institutions of a traditional common pool resource system.

<u>Boundary rules</u> specify how participants enter or leave their positions. How are users awarded rights? **Paris Agreement**: The set of commoners is defined as the Parties to the convention, which is the province of nations. Nations also have primary responsibility for local energy policy.

<u>Position rules</u> associate participants with an authorized set of actions. Who gets to use the resource and who oversees it? **Paris Agreement**: Contributions to decarbonization are required, with the strategies defined by individual Parties That must be consistent with the shared goal.

Aggregation rules specify the transformation function to map actions into outcomes. How is the resource measured and controlled? **Paris Agreement:** The responsibility attaching to each commoner is both individual and shared. The nations define their contributions, subject to a collaborative review of the appropriateness of the contribution from the point of view of the capabilities of the individual nation and the likelihood that the combined effect of the individual contributions will achieve the shared goal.

Authority rules specify which sets of actions are assigned to positions and how those actions will be overseen. How are users allowed to exploit the resource? **Paris Agreement:** The Agreement follows the principle of subsidiarity, delegating responsibility to self-organized, self-governing policy sectors, i.e., nation states.

Payoff rules specify how benefits and costs are required, permitted, or forbidden in relation to players, based on the full set of actions taken and outcomes reached, as well as how the provisioning and maintenance of the resource system will be provided. What are the incentives, taxes and fines that elicit proper behaviors? **Paris Agreement:** At a high level, the principles for the distribution of both burdens and rewards is laid out. The Paris Agreement is aggressively progressive, in both laying a heavier burden on developed Parties to reduce emissions and to assist developing parties to achieve the dual goals of development and decarbonization.

Scope rules specify the set of outcomes that may be affected. How do actions impact the resources and other users? **Paris Agreement:** The Agreement adopts a more aggressive target for holding down temperature increases, which drives the steps necessary to achieve the outcome.

Information rules specify the Information available to each position for purposes of monitoring and enforcing compliance with rules. What flow of information best encourages, manages, and distributes the resources? **Paris Agreement:** The Paris Agreement seeks to hold accountable the sectors and powerful actors by establishing effective monitoring and accountability. A great deal of reporting and information exchange on a continuous basis is outlined to promote transparency and facilitate the application of social pressures to elicit compliance. In this regard, the Agreement calls for immediate and ongoing efforts to continually assess and refine the goals and relationships.

Given the central policy role of the state, the great diversity of capabilities and differences in resource endowment, a flexible, collaborative approach was necessary. While concerns have been expressed about a lack of force, it is difficult to see how that force would have been mobilized in the absence of a single overarching authority. It is also the case that common pool resource systems frequently rely on reciprocity in commitment and graduated sanctions. Much work on these resource systems has been done to document the ability of individuals to work out effective management without the imposition of traditional property relations and governmental authority at the level of fairly small, local resources systems. More recent work and Ostrom's Nobel speech engaged the much larger scale resource problems as a nested set of authorities.

The policy challenges that Ostrom derives from her work on common pool resource systems are the challenges that the Parties to the Paris Agreement face.

> Extensive empirical research leads me to argue.... a core goal of public policy should be to facilitate the development of institutions that bring out the best in humans. We need to ask how diverse polycentric institutions help or hinder the innovativeness, learning, adapting, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales.[26]

The goal is to find polycentric modes of governance that fall between the market and the state where a community self-organizes to build institutions based on trust, legitimacy, and transparency. One aspect of the problem of scale that is important to successful management of the commons to which the Agreement devotes a great deal of attention is information.[27] Supportive, large-scale institutions can play a key role.[28] The effort to coordinate across vertical governance levels and horizontal policy centers is central to the success of the management of a large commons. The Paris agreement is a response to these challenges. The theory is correct; it remains to be seen if the practice develops.

III. ROAD MAPS TO A LOW-CARBON ECONOMY

APPROACH TO THE ECONOMIC ANALYSIS

Focusing on the electricity sector is important for several reasons. It is the heart of the long-term response to climate change and sustainable development, not only because the electricity sector is an important source of emission, but also because decarbonization of the transportation and industrial sectors (which combined are a larger source of emissions) requires a great deal of electrification of those end-uses. If electrification is central to decarbonization and development, the ability to deploy sufficient resources at affordable costs becomes the central challenges for delivering energy services in 21st century economy. Given the dramatic technological developments of the past quarter century, the focal point of the challenge in the electricity sector is institutional – to deploy the physical and institutional infrastructure of a low carbon sector.

In this paper, we take a long-term perspective, assuming that all costs are variable. This means that every generation asset online today must be replaced, so the analysis must focus on the cost of new "builds."[29] We extend the concept of "economic merit order"[30] to the long-term. "merit order" is usually applied in the electricity system to the decision about which resources to use in the short-term, based on their variable cost. We compare the "economic merit order" of long-term resource acquisition based on total levelized cost with relaxed constraints, to the "environmental merit order" of long-term low-carbon resources acquisition based on total levelized cost within a constrained set of choices.[31]

The analysis focuses on the Jacobson et al. report because it provides the greatest detail across time, analyzes individual nations, and includes a comprehensive set of technologies from which to choose. Jacobson et al. impose two environmental constraints on resource acquisition – a carbon constraint and a constraint on other pollutants. The authors add renewable resources to the generation portfolio for each nation based on the cost of those resources, which varies depending on the richness of the local resources.

Reflecting this structure, we ask how different the costs would be if the individual constraints were lifted. We assess the road maps in two steps. We relax the pollution constraint first; then we relax the carbon constraint.

This paper, therefore, focuses on and "isolates" the direct economic cost of the technologies. Excluding the indirect costs and benefits of the carbon and other pollutant constraints is justified in part because the Paris Agreement is based on the decision to decarbonize the global economy. All of the deep decarbonization scenarios will reap the same carbon external benefits, but different mixes of decarbonizing technologies will have different costs and benefits in terms of other pollutants.

This study concludes, however, that once the decision is made to decarbonize the economy, the impacts of other pollutants are of secondary importance for two reasons.

- First, the application of a rigorous least-cost approach to decarbonization accomplishes other pollution reduction goals as well. The lowest cost low-carbon resources are also the lowest in terms of the release of other pollutants, making the benefits of the reduction of these other pollutants "free."

- Second, even on the basis of a standalone analysis, the set of alternatives that are least-cost with respect to other pollutants are also least-cost with respect to decarbonization.

While the purpose of this paper is not to dissect the complex technological and infrastructural assumptions and mechanics of the road map studies, a brief review of their key elements is necessary to locate the focal point of this analysis.

COMMONALITIES IN THE STUDIES

The analysis of the response to climate change has moved well beyond the simple proposition of decarbonizing the electricity sector. The road map studies involve not only the transformation of the electricity resource mix, they also model the elimination of fossil fuel use in the transportation and industrial sectors. While a dramatic increase in the reliance on renewables is a striking feature of all of the studies, the total transformation of all three sectors – electricity, transportation and industry – is even more striking. Regardless of how far, or fast, the electrification of transportation and industrial processes proceeds, low-carbon resources will be necessary in the electricity sector.

In taking on these very broad goals of total transformation, these studies are forced to construct a portfolio of electricity resources that is huge compared to the current portfolio of electricity resources. Total electricity generation increases dramatically because fossil fuels are backed out of the transportation and industrial sectors by the use of electricity. Renewables must expand to meet those needs because of the carbon constraint. For example, in the Jacobson et al. road map, the current levels of low-carbon/low-pollution electricity resources are less than 4% of the total resources that would be needed at the end point (i.e., 2050) in the 100% transformation.[32] In the Deep Decarbonization in Australia analysis, current deployment of the technologies that make up the final portfolio equals less than 1% of the total needed to be deployed in 2050.[33]

Here is it important to note that this transformational challenge afflicts any resource that claims to be the solution to the problem. Advocates who claim that nuclear is critical to a viable decarbonization policy estimate that it would "only" require building 115 new nuclear reactors every year for 35 years.[34] The current nuclear fleet represents just 5% of the future fleet that would be needed to implement such a strategy. Total new nuclear builds would be just as large as total new renewable builds. The highly centralized, complex technology involved in nuclear power and the troubling past of the industry suggests the task would not only be much more costly, it would be much more difficult.[35]

Needless to say, such a transformation involves a huge amount of investment in new electricity generation technologies and in the transformation of the capital equipment that consumes energy. All of the studies devote a great deal of attention to demonstrating the feasibility of achieving the goal of total transformation in terms of the availability of the resource base, complementary assets (e.g., land, capital equipment), magnitude of the total investment necessary, macroeconomic impacts, etc.

Studies of the cost of electricity tend to hold the cost of capital equipment that consumes electricity separate, except in the case of efficiency, which is occasionally included as the levelized cost of saved energy. These studies of the transformation of the economy do the same. They estimate the cost of generation independent of the cost of electricity-consuming equipment, but they do not ignore those equipment costs. The cost of the capital equipment and durables that consume electricity is dealt with separately in these analyses. For example, in the case of Deep Decarbonization in Australia, household personal transportation costs decline by 13% from current levels.[36] In the U.S., total energy service costs (i.e., the cost of the supply of electricity and the cost of the capital equipment that consumes electricity) increase by a net of about 1% of GDP.[37]

At the same time, the environmental and public health benefits of the transformation do not enter directly into the analysis of the selection of resources. These benefits are huge. In the Jacobson et al. analysis, the benefits are almost $5,000 per person per year. The environmental benefits are overwhelming compared to the benefit of fossil fuel cost savings ($170/year).[38] The benefits that are held outside of the analysis vastly exceed the costs that are held outside.

Moreover, focusing on the direct economic cost of generation is justified for several other reasons.

- First, given the long-term nature of the transformation, a large part of the investment in energy-consuming equipment and durable involves substitution for investments that would have been made in supply and demand technologies that emit carbon or release other pollutants. The net increase in investment is much smaller than the total.
- Second, the direct economic benefits of reducing consumption of fossil fuels, whose price is expected to rise, with fuel switching and increased efficiency cushion the blow of the cost of the transformation and help to fund the transition.
- Third, choosing the least-cost electricity options can lower aggregate household expenditures on energy services (i.e., the combination of more efficient capital equipment and lower energy consumption levels).

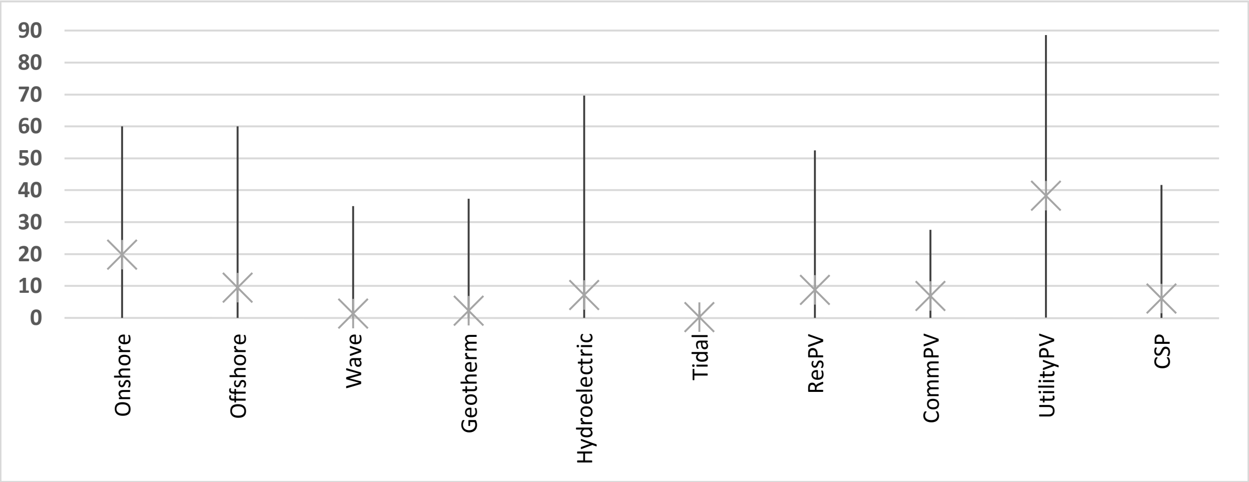
100% Renewables (Jacobson et al.)

The 100% renewable road map in the Jacobson et al. study assumes a robust 5.7% per year growth in the business-as-usual demand for energy. It assumes that this level of economic growth could be achieved in the 100% renewable scenario with a substantial reduction in energy consumption due to the superior efficiency of electricity in transportation and industrial uses. The amount of efficiency improvement in the electricity sector itself (i.e., end use efficiency) beyond the business-as-usual case is described by the authors as “modest,” only 6.9% of total demand.[39]

The authors evaluate the economic costs of the renewable resources available in each of 139 nations and build a portfolio of resources for each nation to meet the assumed need. The constraint is that only low-carbon/low-pollution resources are considered. Fossil fuels, nuclear, and biomass are excluded because they are either carbon emitters, release other pollutants, or both. Having excluded the high-carbon and polluting resources, the study then includes resources in the "merit order" of their costs.

As shown in Figure III-1, across the 139 nations there is a wide range of utilization projected for each of the major resources. This variability supports the approach of applying merit order principles within countries, once the high-carbon and high-polluting resources are eliminated. It also supports the approach taken by the Paris Agreement to rely on national contributions to carbon reduction. Jacobson et al. identify a handful of nations that already derive between one-fifth and two-thirds of their energy from the resources included in the environmentally constrained portfolios,[40] which suggests the feasibility of the long-term goal.

FIGURE III-1: RESOURCE PERCENTAGE IN 100% RENEWABLE PORTFOLIO FOR ALL 139 COUNTRIES, WITH HIGH, LOW, MEAN, STANDARD DEVIATION IN % of Resources



Mean	**20**	**9**	**1**	**2**	**7**	**0**	**9**	**7**	**38**	**6**
St. Dev.	**13**	**13**	**3**	**6**	**11**	**0**	**8**	**4**	**21**	**8**

Source: Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries,* December 13, 2015; Onshore = onshore wind, Offshore = offshore wind; Geotherm = geothermal; ResPV = residential photovoltaics; CommPV = commercial photovoltaics; UtilityPV = utility-scale PV; CSP = Concentrating Solar Power.

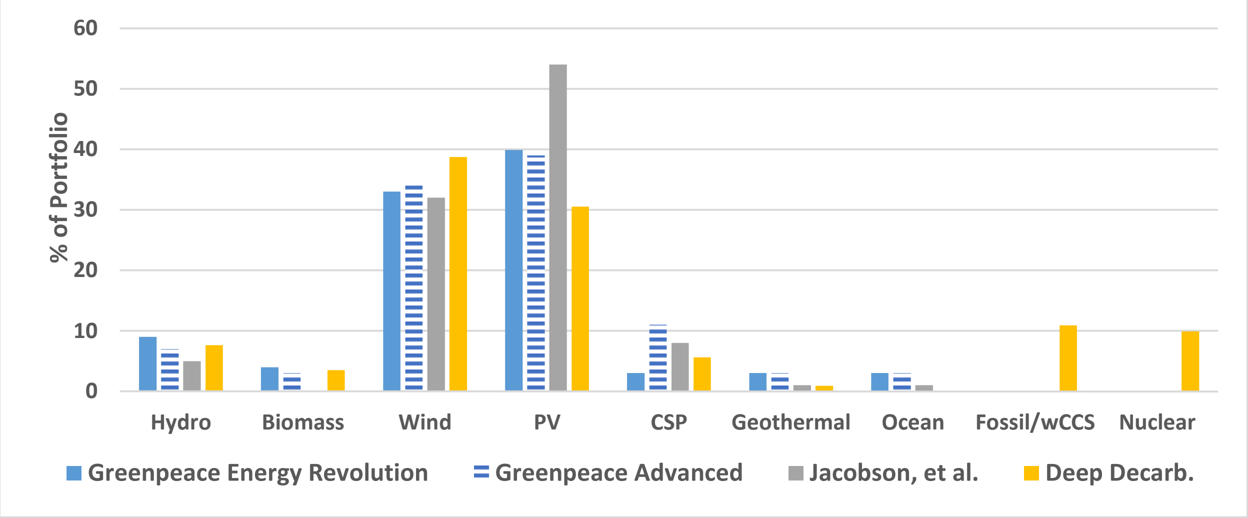
As shown in Figure III-2, however, combining the different solar technologies and applications makes solar the dominant resource by far in the 2050 resource mix. Wind and solar account for between two-thirds and three-quarters of the resources in all of the scenarios. Moreover, it is important to keep in mind that in each of the studies, efficiency is assumed to be the least-cost resource and its contribution substantial, but it is not reflected in the analysis of the acquisition of the resources to meet the need for electricity. Efficiency decreases the need exogenously.

energy [r]evolution (Greenpeace)

The Greenpeace study is similar to the Jacobson et al. study in excluding both high-carbon and high-pollution resources. There are two scenarios (cases) identified in Figure II-2. The energy revolution base case assumes 83% reliance on renewables. The advanced case assumes 100% renewables. As shown in Figure II-2, the mix of generation resources in the Jacobson et al. and the Greenpeace studies is similar. There are some significant differences between the studies, however.

Greenpeace assumes a much higher rate of efficiency improvement. Although the Greenpeace analysis treats sectors separately, which makes it difficult to compare directly to the Jacobson et al. study, it appears that Greenpeace assumes a much larger role for efficiency improvement in end-uses – over 40%. Combining the base-case efficiency improvement with the "modest" end-use efficiency improvement in the Jacobson, et al. analysis yields an overall improvement in efficiency about half as large as the Greenpeace assumption. The Greenpeace assumption of a higher level of efficiency gain is consistent with current estimates of what is already economically justified.[41] In the long-term, the technical potential is much higher. While the assumption of a higher level of efficiency gain is not central to the conclusions of this paper, it provides an important focal point of analysis in Section V.

FIGURE III-2: RESOURCE MIX OF LOW-CARBON, GLOBAL PORTFOLIOS



Sources: Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries,* December 13, 2015; Greenpeace International, Global Wind Energy Council, and Solar Power Europe, *energy [r]evolution: A Sustainable World Energy Outlook 2015, A 100% Renewable Option for All*, September 2015; Deep Decarbonization Pathways Project, *Pathways to Deep Decarbonization,* September 2015.

Deep Decarbonization Pathway Project

While the Deep Decarbonization study shares many of the key attributes with the other two studies about carbon reduction and the electrification of the broader economy, including the transportation and industrial sectors, there is a major difference. It limits the constraint of acquisition of resources to decarbonization and does not impose the pollution constraint. As shown in Figure III-2, this results in a substantial role for carbon capture and storage and nuclear power. Our analysis below shows that the inclusion of carbon capture and storage and nuclear is not economically justified because their costs are much higher than renewables.

Because the Deep Decarbonization study builds up from multiple country studies, it is difficult to ascertain why these resources end up in the generation portfolio. However, the Australian case provides a clear possible explanation. That analysis points to a cost study from several years ago that had an unjustifiably low estimate of the cost of nuclear power from new reactors.[42] The most recent updated estimate from essentially the same author in Australia more than doubles the projected cost of nuclear, a subject that will be addressed in the next two sections. At the current cost, it would not be included in the *Pathway* portfolio. Empirical evidence from the current construction of new reactors around the world shows that the real cost of new nuclear is several times higher than the artificially low industry cost estimates that may have affected the Deep Decarbonization Project estimates. The Jacobson, et al., analysis which also uses artificially low projection for nuclear costs avoids making the mistake of including nuclear power in the portfolio by disallowing nuclear because of its high level of other pollutants.

While renewables are clearly the core of a decarbonized electricity sector, the seeds of the ongoing debate between advocates of renewables and advocates of the adaptation of 20th century central-station generation can be seen in the side-by-side scenarios. That debate continues to be intense, not only because of the economics, as discussed below, but also because there is a fundamental difference and incompatibility between the two in the nature of the electricity system that is necessary to optimize the performance of the technologies.[43]

IV. THE COST OF ELECTRICITY IN A LOW-CARBON FUTURE

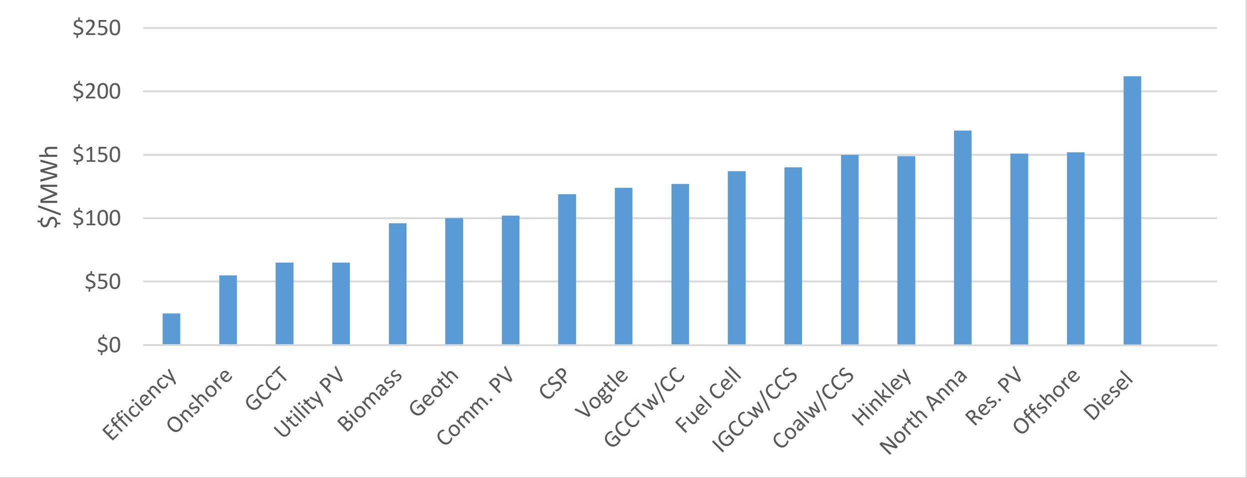
A CURRENT COST VIEW OF RESOURCE ACQUISITION

Current Costs

Figure IV-1 shows the mid-points for the levelized costs of the technologies analyzed by Lazard in 2015. For the projected cost for natural gas with carbon capture and storage and battery storage, this review uses Lazard data from 2013 because these technologies were not included in the 2015 analysis.[44]

Here we use Lazard's estimate for the cost of the Vogtle reactors under construction in the U.S. as the midpoint Lazard nuclear cost since it is quite close to the average of Lazard's range for nuclear. However, the Vogtle construction schedule continues to slip and the cost estimate continues to rise.[45] Therefore, we also show the cost of the proposed Hinkley reactor in the UK, which is estimated to be 20% higher than Lazard's Vogtle estimate. In fact, a more recent estimate would put Vogtle at 93% of the cost of Hinkley.[46] Finally, we include a cost estimate for the proposed North Anna reactor in the U.S. from a recent regulatory proceeding, which is about 33% higher than Lazard's Vogtle estimate,[47] but still 10% below the recent estimate from Australia.

FIGURE IV-1: LAZARD LEVELIZED COST OF ENERGY TECHNOLOGIES: 2015



Sources: Lazard, *Lazard's Levelized Cost of Energy Analysis – Version 9.0,* November 2015.For Natural Gas Combined Cycle, Lazard, *Lazard's Levelized Cost of Energy Analysis – Version* 7.0, August 2013, average of high and low estimates except for point estimates for carbon capture (CC) technologies. For Hinkley, Cooper, Mark, "Small Modular Reactors and the Future of Nuclear Power in the United States," *Energy Research & Social Science,* 3 2014. North Anna calculated based on "official" utility estimates (Sean Farrell and Terry Macalister, "Work to begin on Hinkley Point Reactor within weeks after China deal signed," *The Guardian,* October 13, 2015; North Anna, Direct Testimony of Scott Norwood on Behalf of the Office of the Attorney General, Division of Consumer Counsel, Virginia Electric and Power Company, Integrated Resource Plan Filing Pursuant to Va. Code § 56-597 et. Seq., Case No. PUE-2015-00035, September 15, 2015, p. 5). Onshore = onshore wind; Utility PV = utility-scale PV; GCCT = Natural Gas Combined Cycle; Geoth = geothermal; CommPV = commercial PV; CSP = concentrating solar power; Vogtle = Vogtle nuclear reactor; GCCTw/CC = Natural Gas Combined Cycle with Carbon Capture; IGCCw/CCS = Integrated Gasification Combined Cycle with Carbon Capture; Hinkley = Hinkley reactor (UK), North Anna = North Anna 3 reactor (US); Res PV = residential PV; Offshore = offshore wind.

While these are current costs and this analysis focuses on future costs, we use Lazard's estimates as an anchor point. Our previous analyses have generally relied on Lazard price projections more than others for a variety of reasons.[48]

- 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.
- 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.

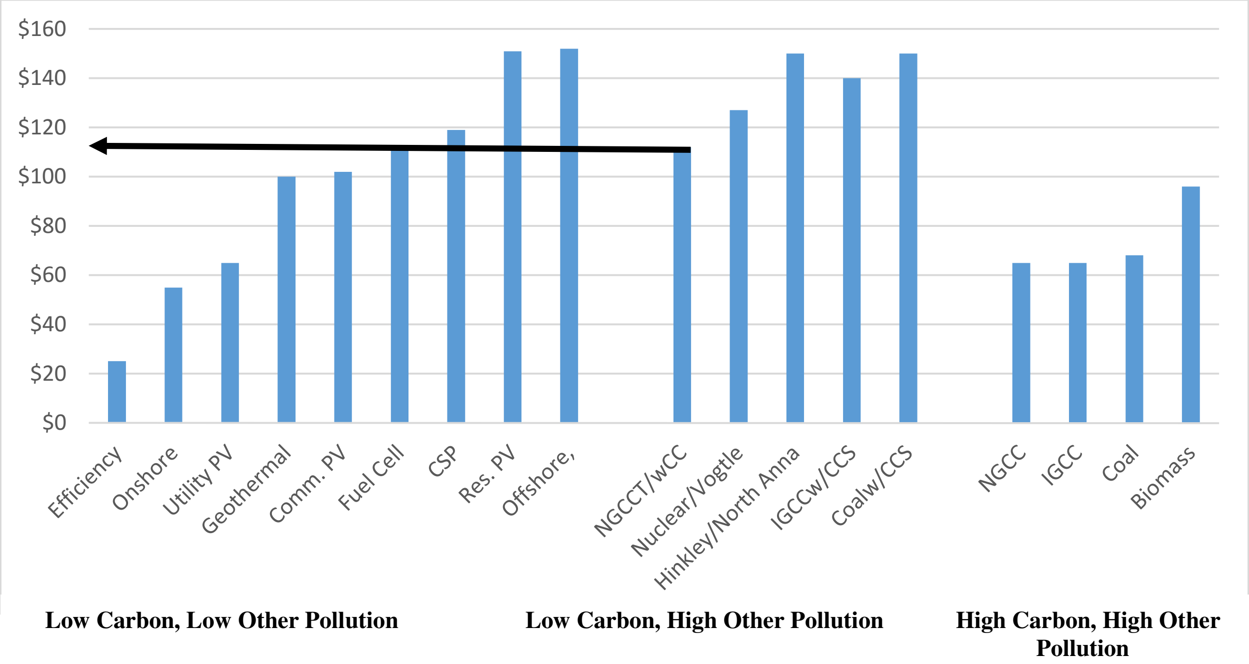
Although Lazard estimates current or near-term costs, these data make an important point for the analysis of decarbonization. Three important resources – efficiency, wind, and utility-scale solar – are cost competitive now with the dominant central-station fossil fuels (natural gas and coal). These three resources account for over 60 percent of the need in the Jacobson et al. analysis. Under an assumption of more aggressive utilization of efficiency that our review supports below, reaches almost three-quarters of the total need. These three resources are also less than half of the cost of new nuclear reactors or fossil fuels with carbon capture. These resources are not only less costly, they are widely available. Thus, based on current costs, the renewable resources that are the cornerstone of the 100% renewable scenarios should be the resources chosen today. There is no conflict between the assets that are preferable in the short term and the long term. This means that the immediate effort should also entail building the physical and institutional infrastructure to support the long-term goal.

"Merit Order" Analysis

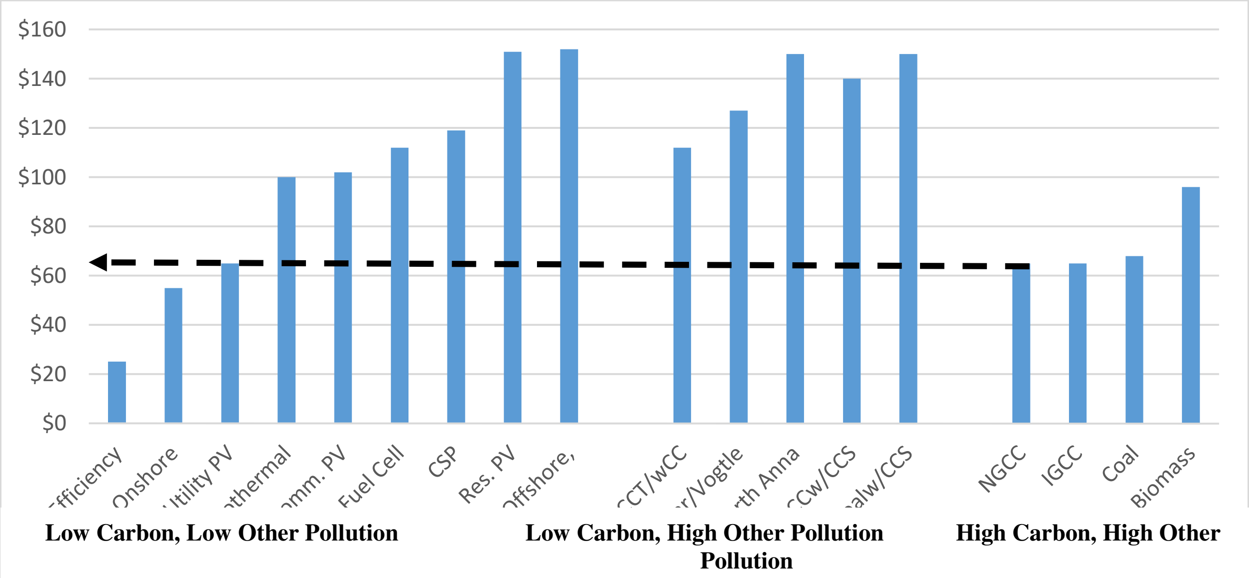
Figure IV-2 reorganizes the Lazard costs according to the "environmental merit order" to frame the issues analyzed in this paper. We divide the resources into three groups: resources that are low in carbon and other pollutants (low-carbon, low-polluting); those that are low-carbon, but high in other pollutants (low-carbon, high-polluting); and those that are high in carbon and high in other pollutants (high-carbon, high-polluting). The horizontal arrows show the resource that would complete the portfolio as constraints are lifted.

FIGURE IV-2: ENVIRONMENTAL AND ECONOMIC MERIT ORDER AT LAZARD CURRENT COSTS

Relaxing the Pollution Constraint
LCOE ($/MWh)



Relaxing the Pollution and Carbon Constraint



Sources: See Figure II-1.

In the upper graph of Figure IV-2, we can see that relaxing the pollution constraint, but keeping the carbon constraint, suggests that gas with carbon capture and storage could enter the portfolio, depending on how much the lower-cost resources could expand. However, because the cost of gas with carbon capture is high, other renewable and distributed resources are cost competitive and also enter the portfolio. Therefore, other low-carbon resources would meet part of the need, pushing their share to about 85%, even without considering the expansion of the cost-effective resources beyond their original share. It also suggests that "forcing" Concentrating Solar Power (CSP) into the portfolio would have little impact on the total cost compared to natural gas with carbon capture and storage. At current costs, new nuclear does not enter the portfolio.

The lower graph shows that at current costs, although efficiency, onshore wind and utility-scale PV are competitive, allowing unabated fossil fuels into the portfolio squeezes the headroom for their expansion and makes the cost impact of keeping unabated fossil fuels out higher. However, this is at current prices. The future cost analysis in the next section paints a markedly different picture. Moreover, carbon capture and storage is not widely available at present or in the near-term.

The other clear conclusion from these graphs involves nuclear. It never enters the least-cost portfolio when economic cost is a criterion and costs are at the level of the U.S. Vogtle reactors. At the cost of the U.K. Hinkley reactor, nuclear barely competes with coal with carbon capture and storage. At the cost projected for the North Anna reactor and in the recent Australian analysis, nuclear is the most costly technology by far.

COST TRENDS AND THE FUTURE VIEW OF ECONOMIC MERIT ORDER

Cost Trends

Figure II-1 above showed that the capital costs of wind, solar and nuclear have been headed in opposite directions since the negotiation of the United Nations Framework on Climate change and are expected to continue to do so.[49] Overnight costs represent the economic cost of constructing these generation assets, without financing costs taken into account.[50] Because fuel costs are relatively unimportant for these three resources, overnight costs are a good indicator of the relative levelized costs, with capital costs accounting for about 80% of wind and nuclear and 90% of solar levelized costs.[51]

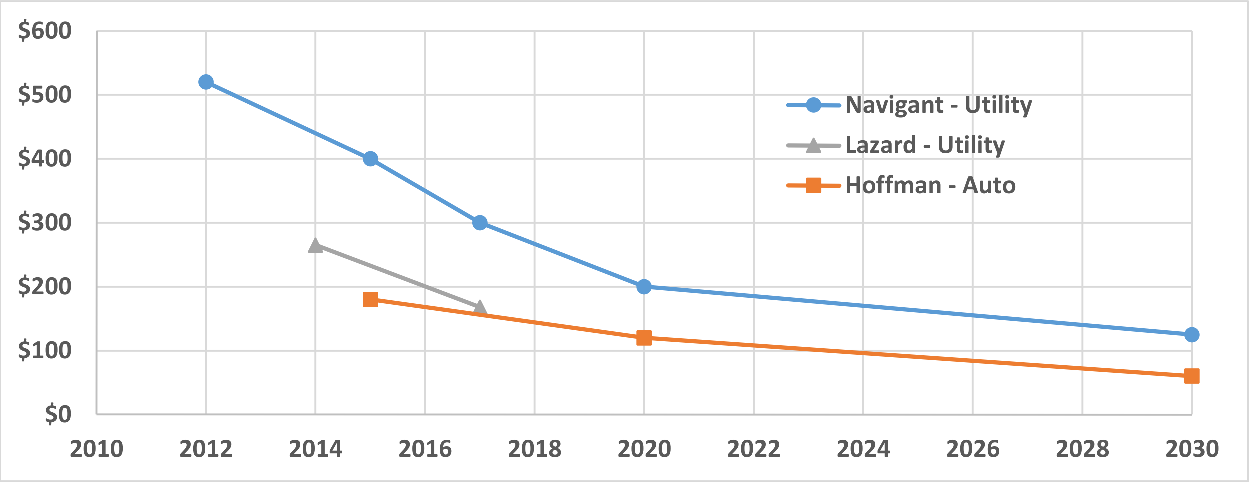
In the past decade, solar technology has experienced a dramatic decline from a high level. Wind costs have been declining moderately from a relatively low level. Onshore wind costs are projected to be about half of offshore wind costs. Utility-scale PV costs have declined from a moderate level to be competitive with wind. Nuclear costs have shown a continuous increase. By 2030, overnight costs of onshore wind and solar are projected to be less than one-fifth of nuclear. By 2030, offshore wind is projected to be somewhat below the current Hinkley and recent Vogtle cost estimates and well below the North Anna and Australia estimates.

As shown in Figure IV-3, another technology cost that has been declining sharply, but does not play an important part in the Jacobson et al. analysis, is the cost of battery storage. Battery costs have recently exhibited a dramatic decline that is expected to continue. Both Lazard and the Australian analyses reflect this dramatic development,[52] as do others.[53]

Figure IV-3 shows trends for utility-scale and residential battery storage costs. In the 2025-2030 timeframe, and perhaps sooner, battery power will be the least-cost source of peaking power.[54] Battery power can interact forcefully with renewables to increase their load factor and/or make their output more attractive to grid operators. In fact, some argue that when all of their potential values to the operation of the grid are taken into account, batteries are beneficial at today’s costs and will be very attractive at future costs.[55] However, since careful planning of the acquisition of renewable resources (geographic deployment and technology selection) and active integration of supply and demand yields reliability that is equal to or exceeds the current reliability without batteries,[56] the 100% renewable roadmaps do not rely a lot on storage, except in the case of CSP with thermal energy storage. Others who advocate for the transformation of the energy sector see storage playing a larger role.[57] In any case, storage represents a potential resource that could reduce the cost of the 100% renewable scenario and/or ensure its viability.

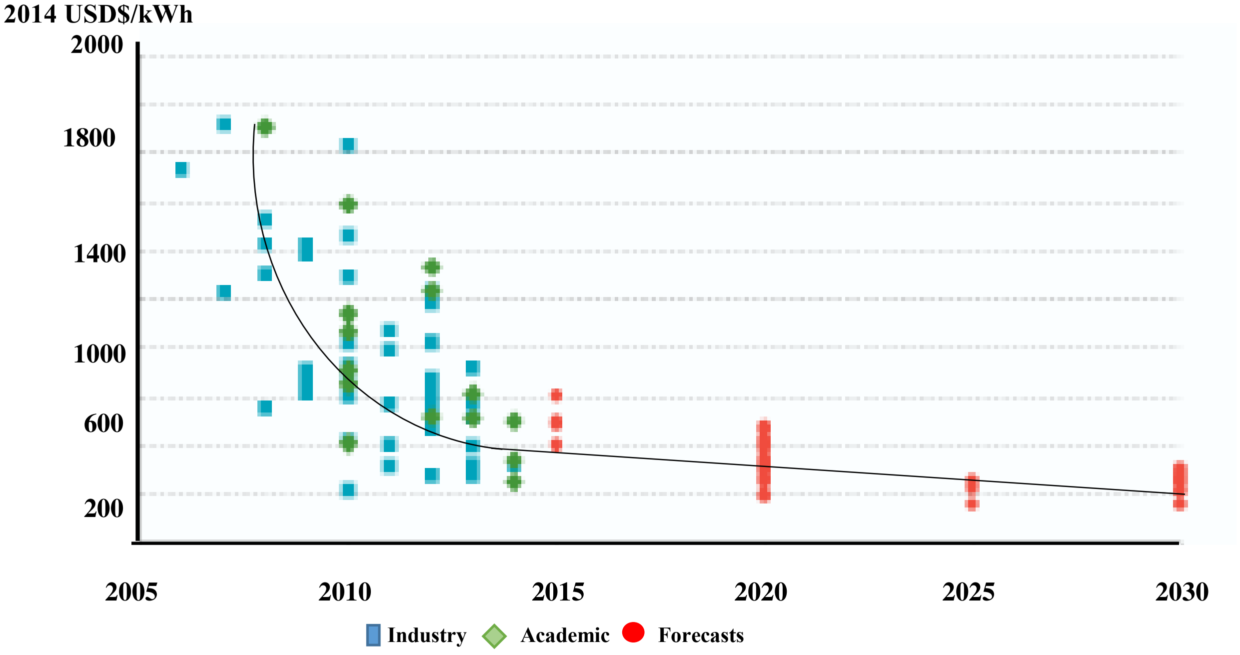
FIGURE IV-3: BATTERY COST TRENDS ($/MWH)

Trade Analysts



Sources: Lazard, *Lazard’s Levelized Cost of Energy Analysis,* November 2015; Jaffe, S. and Adamson, K.A., *Advanced Batteries for Utility-Scale Energy Storage*, Navigant Consulting, Boulder, CO, 2014.

Multiple Estimates: Australian Cost



Source: *Australian Power Generation Technology Report*, November 2015.

Disagreements on Nuclear Costs

As shown in the upper graph of Figure IV-4, there is a sharp divergence between some nuclear cost estimates and reality. Nuclear costs were severely underestimated about a decade ago amid the hype of a so-called "nuclear renaissance." The problem is evident in the future projections, as shown in the lower graph of Figure IV-4 and in Figure IV-5. The International Energy Agency (IEA) cost projections, done in conjunction with the Nuclear Energy Association are quite low, as are the projections from the U.S. Energy Information Administration (EIA). Jacobson et al.'s cost projections are quite close to those of the IEA.

As shown in Figure IV-5, the IEA and EIA track records on nuclear cost projections have been poor. The unfolding costs for Vogtle, Hinkley and North Anna seem to be where costs are headed. Even the high cost estimate from Australia does not seem out of line. Figure IV-5 also shows the extremely low prior estimate of nuclear cost in the previous Australian study, which may have led the deep decarbonization pathway analysis (among others) astray.

As noted, Lazard has steadily increased the estimate of nuclear costs so that the midpoint of their range is approximately the same as the current cost projection for the Vogtle reactors in the U.S and cost increases are far from done. The proposed Hinkley reactor in the U.K and the North Anna reactor in the U.S. have much higher projected costs.

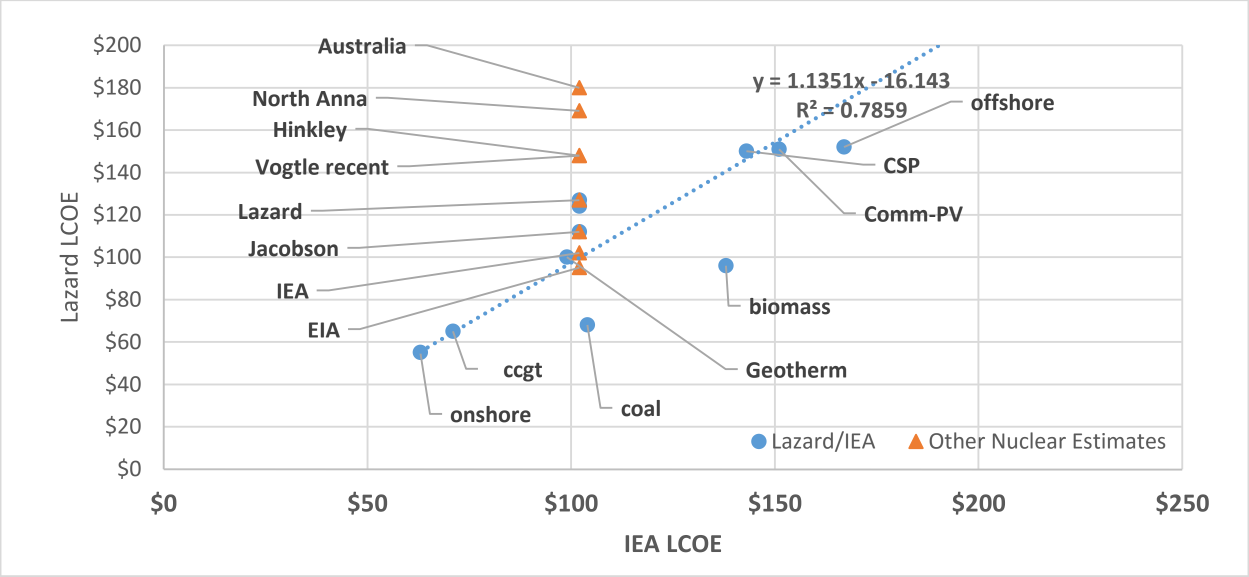
Merit Order Analysis Based on Future Costs

Figures IV-6 and IV-7 apply the "merit order" framework to two sets of future costs – Jacobson et al. and the Australian study. As one would expect from the cost trends over time, in the analysis using future costs the economics of renewables improve in an absolute sense and even more dramatically relative to the fossil alternatives. More technologies are below the cost of low-carbon, high-polluting generation and the headroom for additional renewables to be pulled into the portfolio is greater. Even allowing unabated fossil fuels to compete to enter the portfolio, efficiency, wind, and solar resources enter the portfolio first. In the Jacobson et al. analysis, even in the unabated case, between 80% and 90% of the "environmental merit order" is also the "economic merit order." At the Australian costs, all of the major renewable resources enter under both the environmental and economic "merit orders."

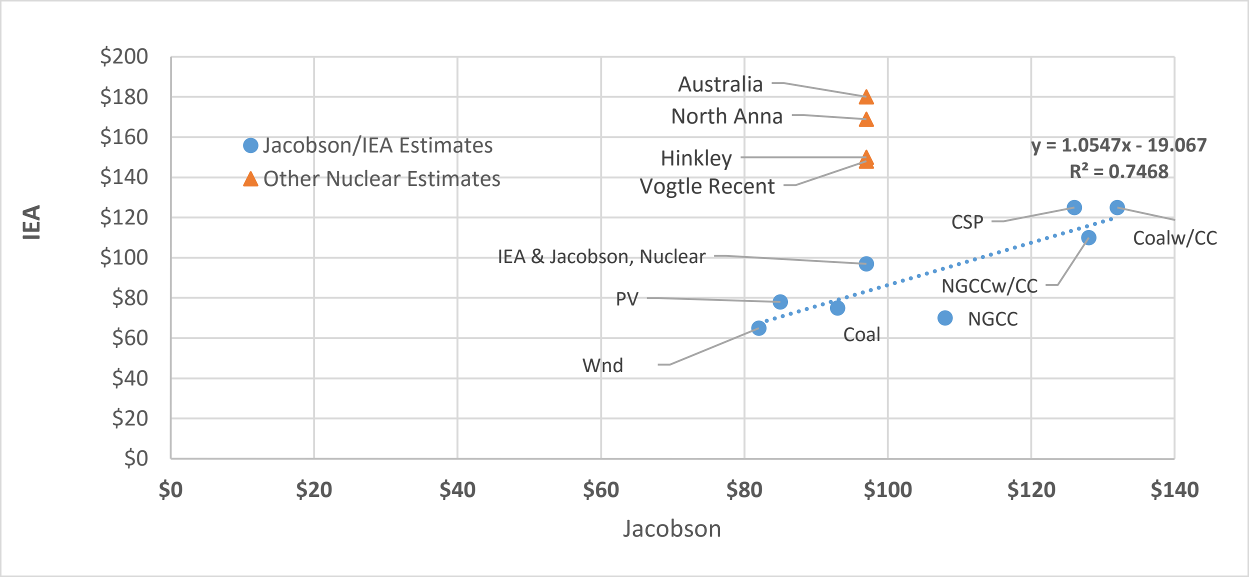
These findings are consistent with the strong consensus that has emerged in the financial and trade literatures that the mid-term need for electricity will be met entirely without new coal or nuclear assets.[58] These analyses also see natural gas being backed out of the resource mix on economic terms.

FIGURE IV-4: LEVELIZED COST ($/MWH) HIGHLIGHTING DISAGREEMENT ON NUCLEAR (Lazard, IEA and Jacobson Compared to Other Cost Estimates)

Current Costs



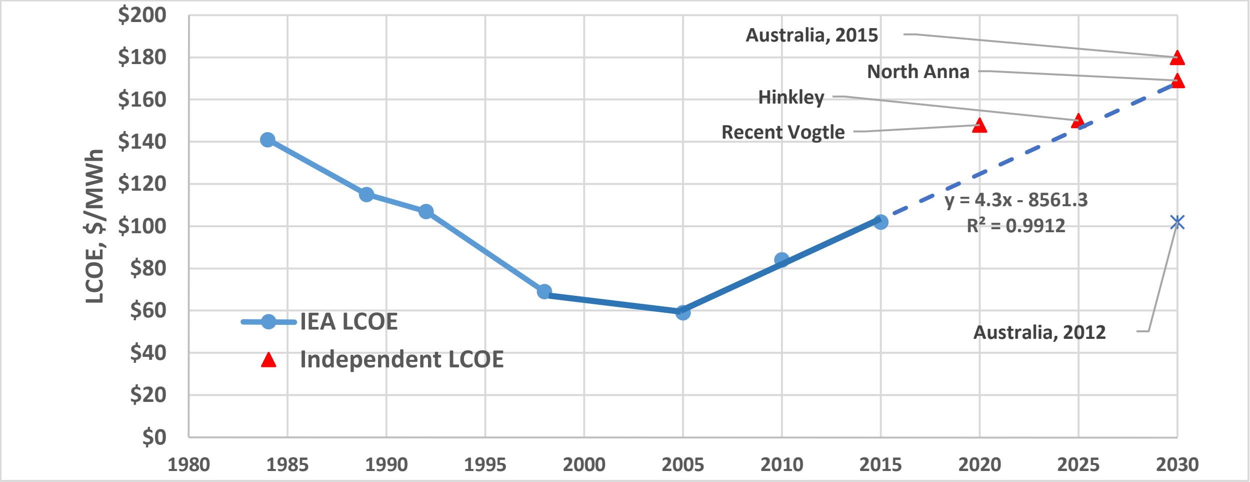
Future Costs



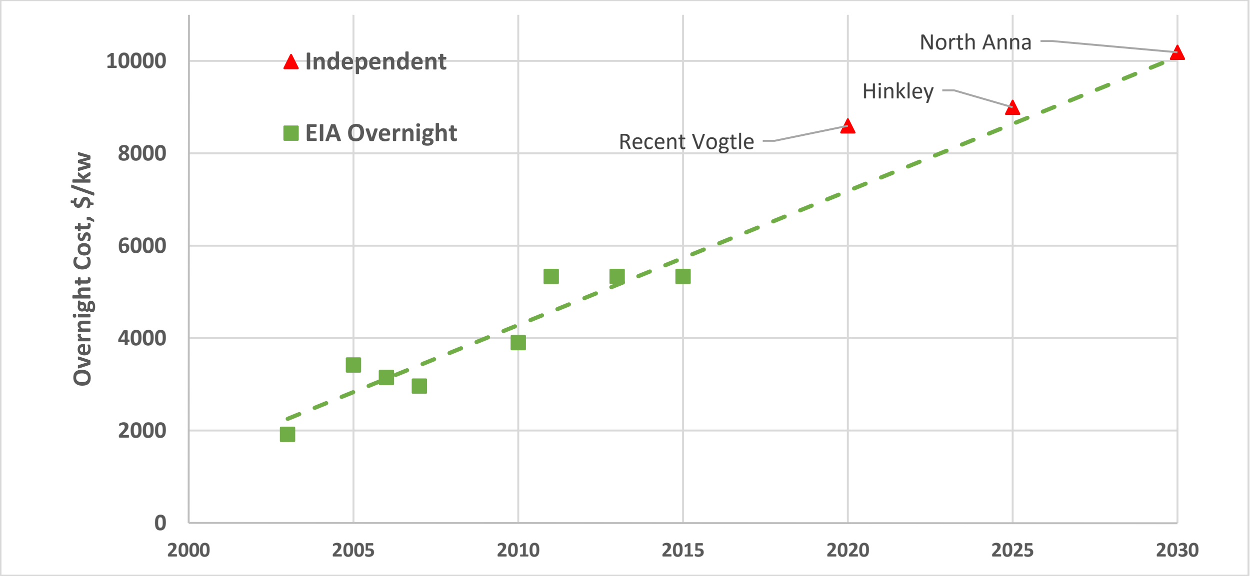
Sources: International Energy Agency and Nuclear Energy Association, *Projected Costs of Generating Electricity: 2015 Edition*, September 2015; Mark Z. Jacobson et al., 100% *Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries,* November 20, 2015; Figure II-1 and associated text for Vogtle and Hinkley reactors.

FIGURE IV-5: TRENDS IN RECENT NUCLEAR COST PROJECTIONS

Levelized Cost Estimates



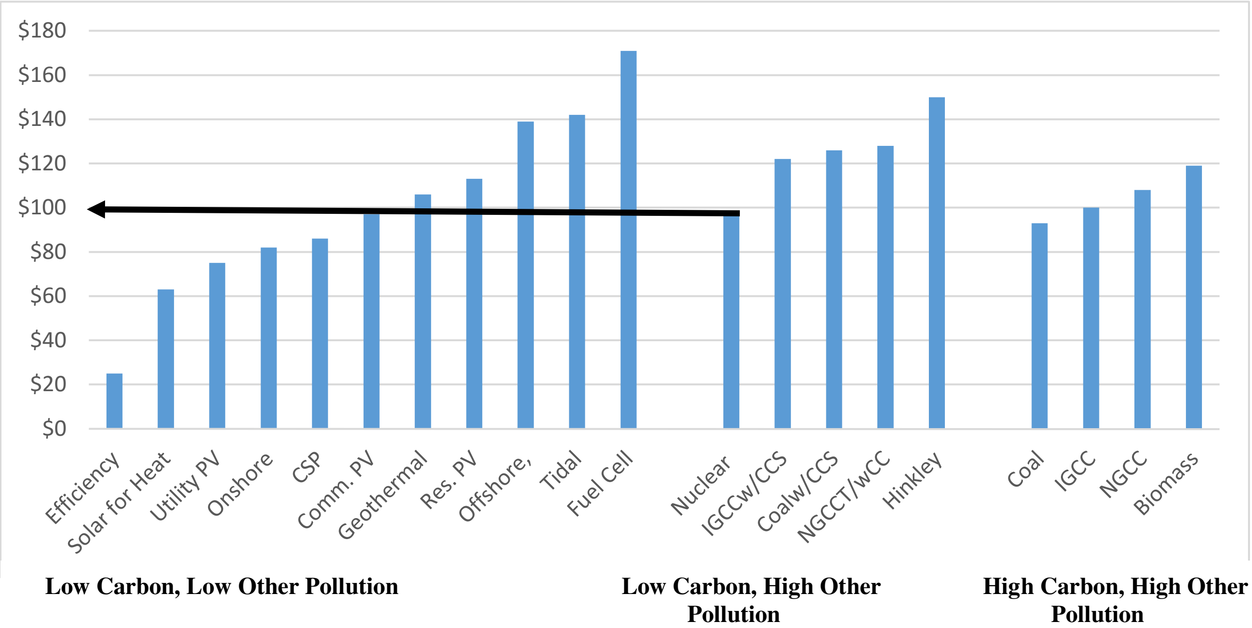
Overnight Cost Estimates



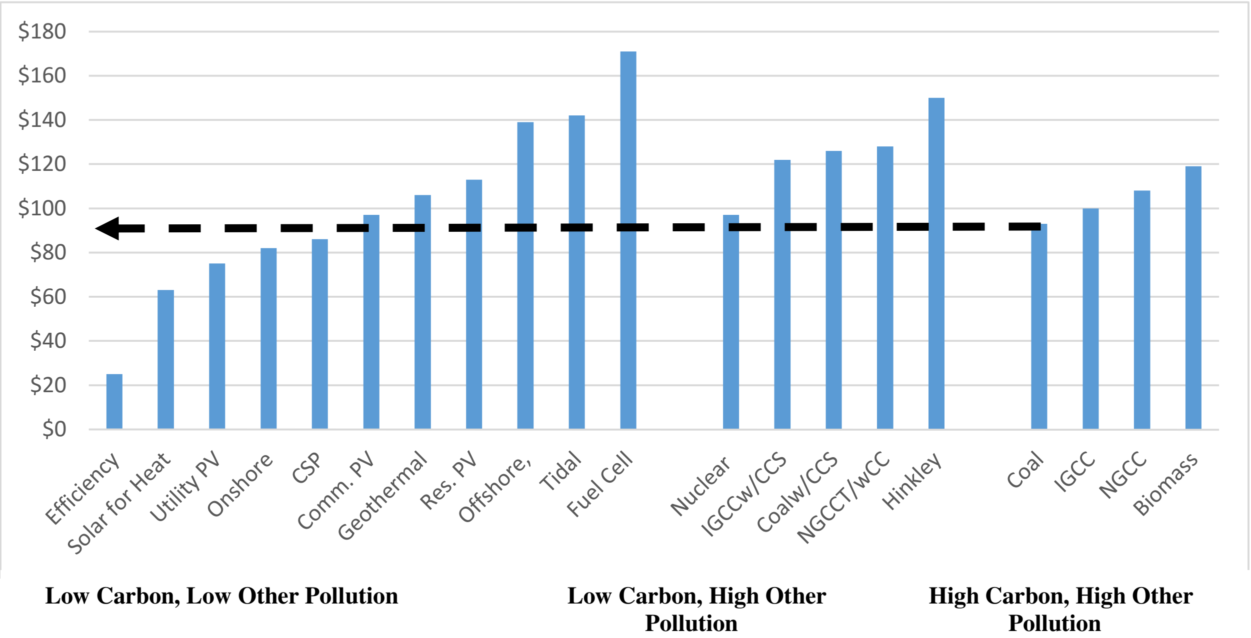
Sources: International Energy Agency (IEA) and Nuclear Energy Association (NEA), Projected *Costs of Generating Electricity: 2015 Edition,* September 2015; Energy Information Administration (EIA), *Updated Capital Costs for Electricity Generation Plants, 2010 and 2013*; Vogtle and Hinkley/North Anna, see Figure II-1 and associated text; *Australian Power Generation Technology Report,* November 2015; Bureau of Resources and Energy Economics, *Australian Energy Technology Assessment*, 2012.

FIGURE IV-6: ENVIRONMENTAL AND ECONOMIC MERIT ORDER, JACOBSON FUTURE COSTS

Relaxing the Pollution Constraint
LCOE ($/MWh)



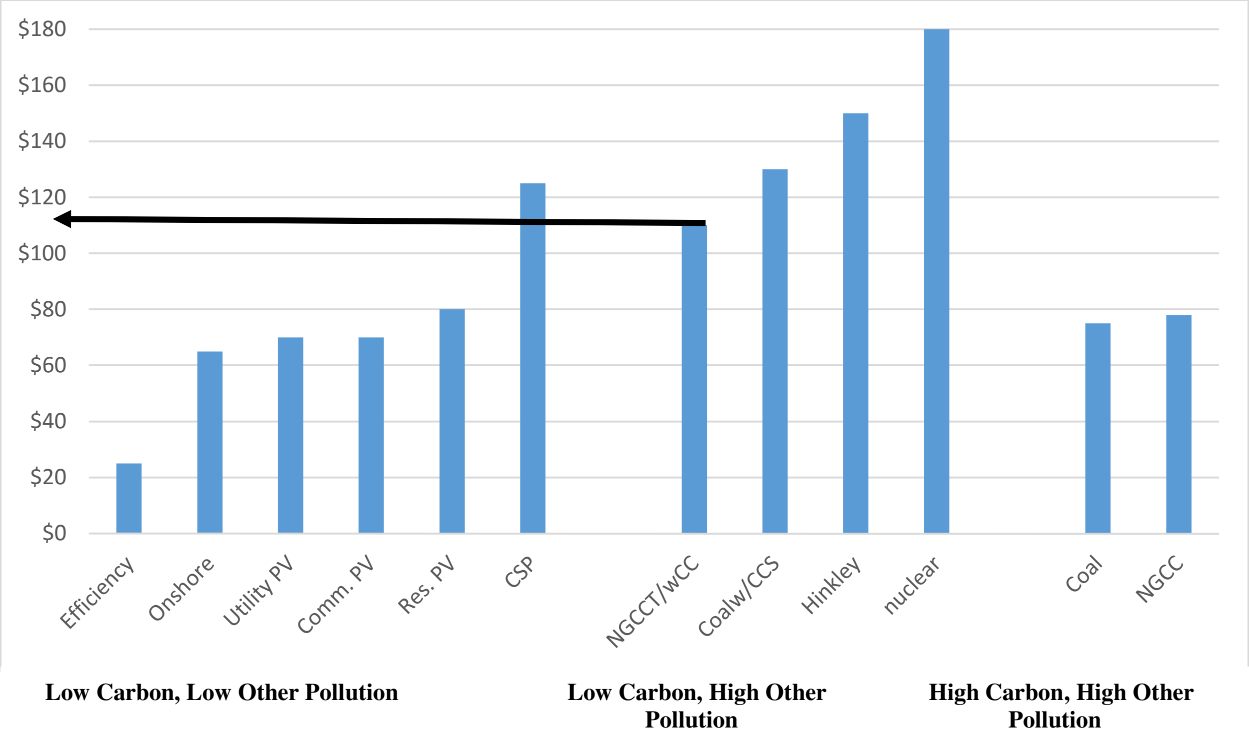
Relaxing the Carbon and Other Pollution Constraints



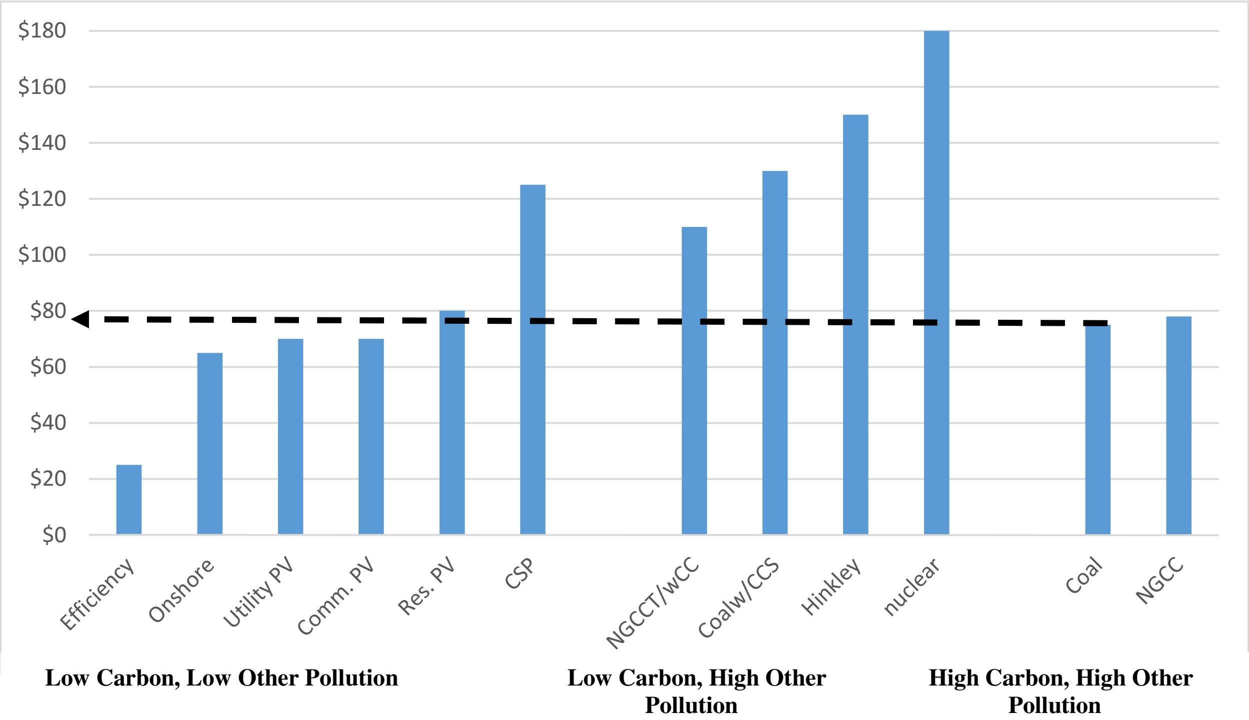
Source: Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries,* November 20, 2015.

FIGURE IV-7: ENVIRONMENTAL AND ECONOMIC MERIT ORDER, AUSTRALIA FUTURE COSTS

Relaxing the Pollution Constraint



Relaxing the Carbon and Constraints



Source: All costs are from *Australian Power Generation Technology Report,* November 2015, except for Hinkley.

V. CHARTING THE ROUTE TO A DECARBONIZED ELECTRICITY SECTOR

REFINING THE ROUTE TO DEEP DECARBONIZATION

Minimal Cost Saving from Relaxing Environmental Constraints

In the above analysis, when we indicate that there could be competition at the margin for the final spots in the resource portfolio if either of the environmental constraints are relaxed, that does not mean that the "environmental merit order" would be more costly than a business-as-usual approach. Quite the opposite is the case because the cost of the resources that make up the first three-quarters to nine-tenths of the "environmental merit order" are so much lower. In every case, building the resource portfolio with the renewable building blocks – efficiency, wind, solar (overwhelmingly CSP) – would be less costly. The competition at the margin is only about how large the cost savings will be.

The outcome is uncertain because it depends on how much the low-cost resources could expand, if one or both of the constraints is lifted. At one extreme, it can be argued that the environmental and economic "merit orders" are so close and leave such a small amount of competition at the margin that one or more of the lower cost resources will expand to occupy the space left. Cost might go up, but not very much.

At the other extreme, one can argue that there would be no expansion, as shown in Figure V-1. In the Jacobson et al. analysis for the U.S., the marginal resource needed would be nuclear, which would increase the cost savings by 10% because of the extremely low assumed cost of nuclear and the relatively large role of offshore wind. At Vogtle costs, the marginal resource would be coal with carbon capture and the cost savings would be 5%. The result is similar with the higher costs of Hinkley or North Anna. If both the carbon and pollution constraints were relaxed, the marginal resource would be coal and the marginal savings would be about 11%.

In the global analysis, the relaxation of the pollution constraint would lower costs about 5%, again because of the unjustifiably low nuclear cost projected, while eliminating the carbon constraint would lower costs by 10%, because of the smaller role of offshore wind. At the Vogtle cost of nuclear, the marginal resource is coal with carbon capture and storage and the additional savings are even smaller. Thus, relaxing the constraint on other pollutants results in minimal cost savings.

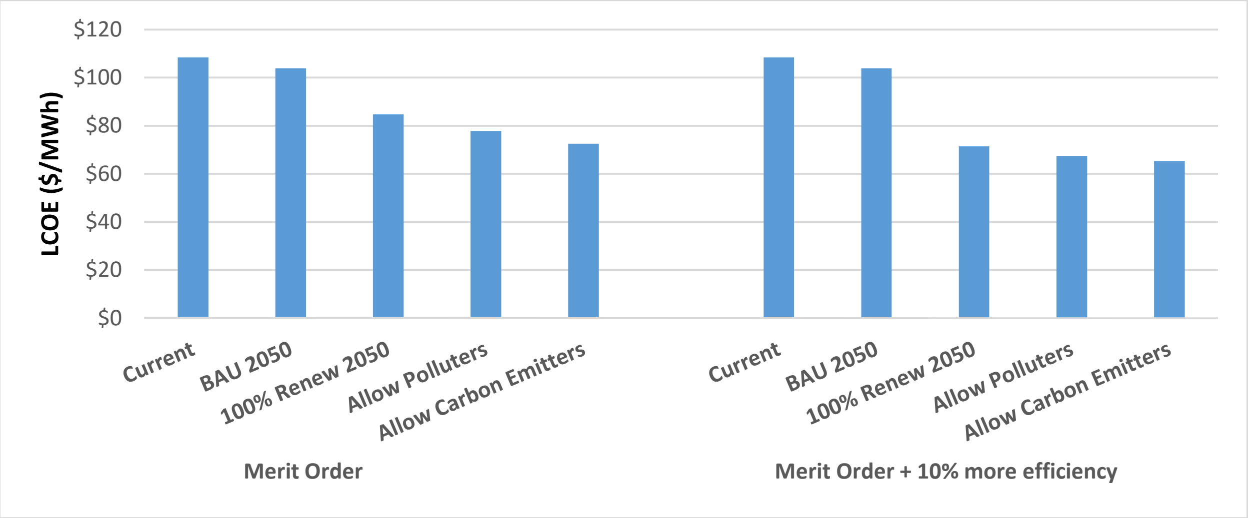
Cost Savings from Increased Energy Efficiency

While we will not explore the space between the extremes of assuming that other resources would fill the gap of relaxing the constraints entirely, or not at all in detail, one area between the extremes that is compelling and worthy of comment is the amount of efficiency that is assumed. Given the way efficiency is treated in the larger Jacobson et al. analysis and the fact that only modest gains in end use efficiency are assumed, it seems reasonable to project a larger contribution from efficiency, not only in the analysis of the lifting of constraints, but even in the base renewable case. Combining the business-as-usual and the transformation scenario, the total improvement in end use efficiency is about 20%. The economic potential is larger than that today and the technical potential is much larger. Moreover, the active management of demand in the transformation of the system has a dividend in reduced demand in the range of 10% to 20%.[59]

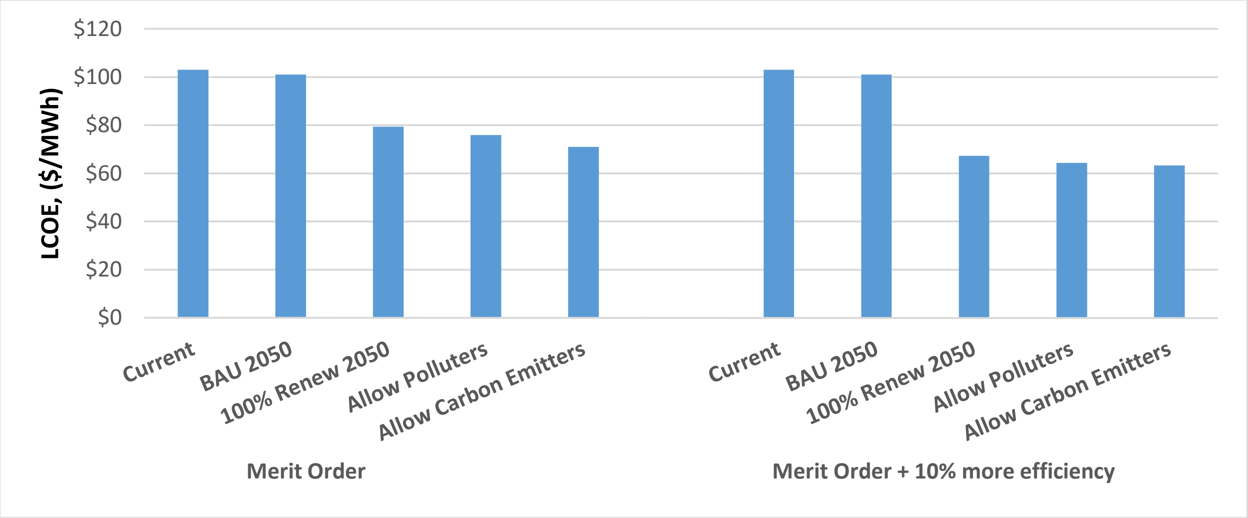
Therefore, it can be argued that higher end use efficiency savings should be assumed and priced into the overall analysis. Although assuming an additional 10% of efficiency and pricing it into the analysis is conservative, as shown in Figure V-1, it has a large impact on the cost of the portfolio of assets.

FIGURE V-1: IMPACT OF MERIT ORDER CHANGES ON COST OF ELECTRICITY, JACOBSON ET AL. AVERAGE LEVELIZED COSTS

United States



Global



Source: Based on Mark Z. Jacobson, et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries,* November 20, 2015. See text for a discussion of the data and methodologies. BAU = Business as Usual; Renew = Renewables

Figure V-1 compares estimates for the impact of assuming a relatively modest ten percentage point increase in efficiency from the base case. We find that it not only fills a large part of the gap created by removing the carbon or pollution constraints, it also more than offsets any cost increase associated with the constraint, compared to savings that would result from lifting the constraint. Of course, one can argue that policy could achieve efficiency independently of the constraints, so that the overall price would be even lower, but the difference is extremely small.

Thus, contrary to loud complaints that dealing with climate change will cause a disastrous increase in electricity costs, a rigorous, least-cost approach prevents such an outcome and may even result in a reduction in the total cost of energy services, taking into account the cost of more efficient capital equipment powered by electricity and the very large potential for passive approaches to energy services.

OTHER FACTORS AND CONSIDERATIONS

Environmental and System Factors

Having reached this conclusion on the basis of the direct cost of the resources, we would be remiss in not mentioning other costs and factors that have economic implications. Jacobson et al. have quantified the large public health and environmental benefits of shifting to low-carbon, low-polluting resources. There have been quantitative and qualitative efforts to assess and rank the resources in terms of their environmental impacts and sustainability.

Figure V-2 combines qualitative and quantitative approaches to demonstrate the nature of these considerations. The upper graph shows two quantitative assessments. The lower graph correlates these with Jacobson et al.'s ranking of environmental impacts. The quantitative and qualitative ranks yield similar results that support a clear set of conclusions:

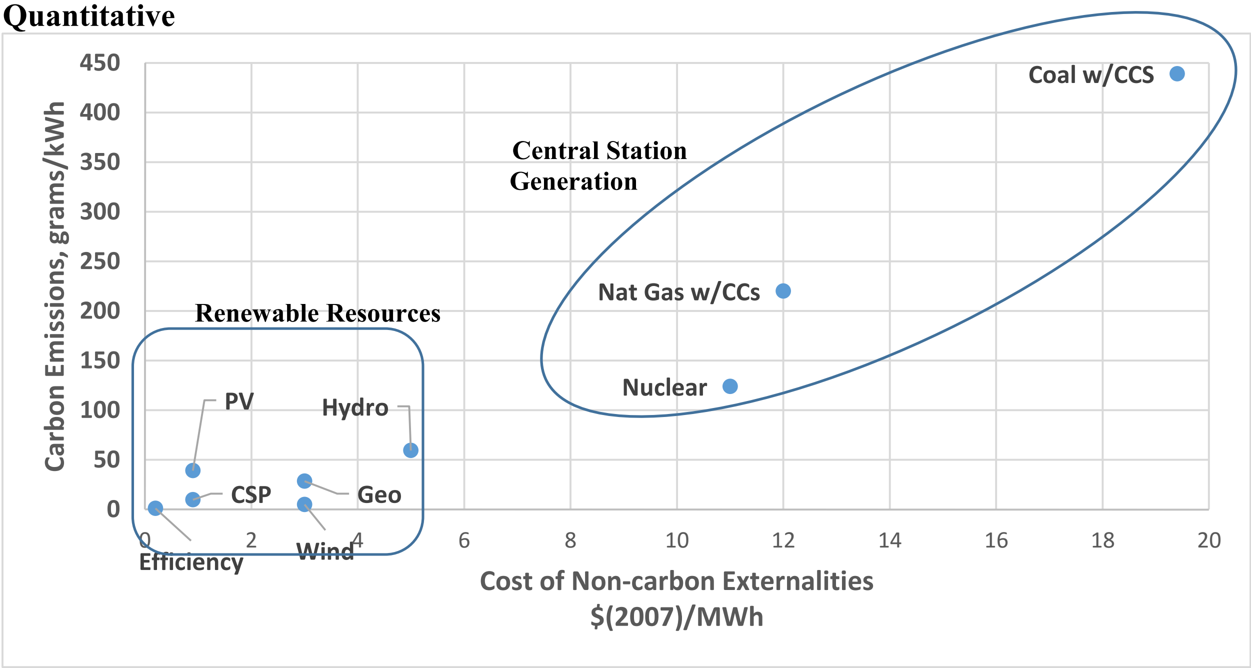
- The selection of resources on the basis of their environmental and sustainability characteristics would be almost identical to a selection based on their economic cost.
- Renewables have much smaller impacts.
- Nuclear and natural gas are quite close to one another.

Simply put, the environmental and economic "merit orders" fit hand in glove based on these considerations. In fact, the recent Australian cost study included a qualitative assessment of many of the factors considered by Jacobson et al.

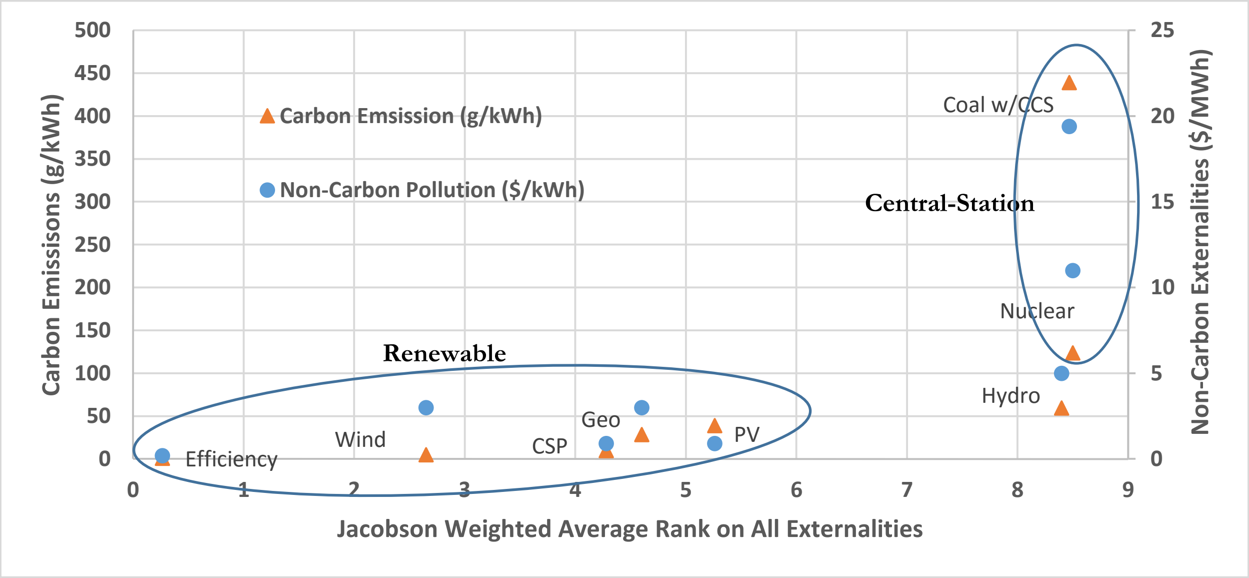
One other impact of the transition to a low-carbon economy that deserves special attention is the energy-water nexus. Water is an essential need for human life, a critical input to agriculture and has been an important input for electricity generation. The electricity sector is a huge consumer of water.[60] Electricity generating technologies have impacts on water from both the consumption and contamination points of view, which have been recognized in the broader environmental evaluations of resources.[61] Climate change and the response to it are also likely to magnify the importance of the energy-water nexus.[62] As shown in Figure V-3, the examination of water reinforces the earlier conclusions.

FIGURE V-2: EVALUATION OF EXTERNALITY IMPACTS OF RESOURCES

Quantitative

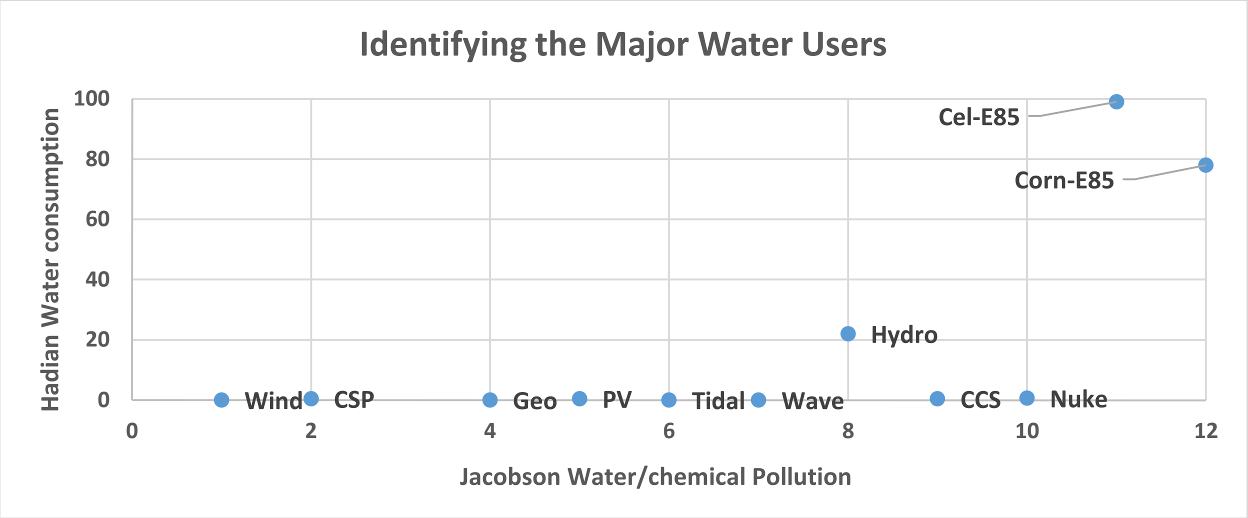


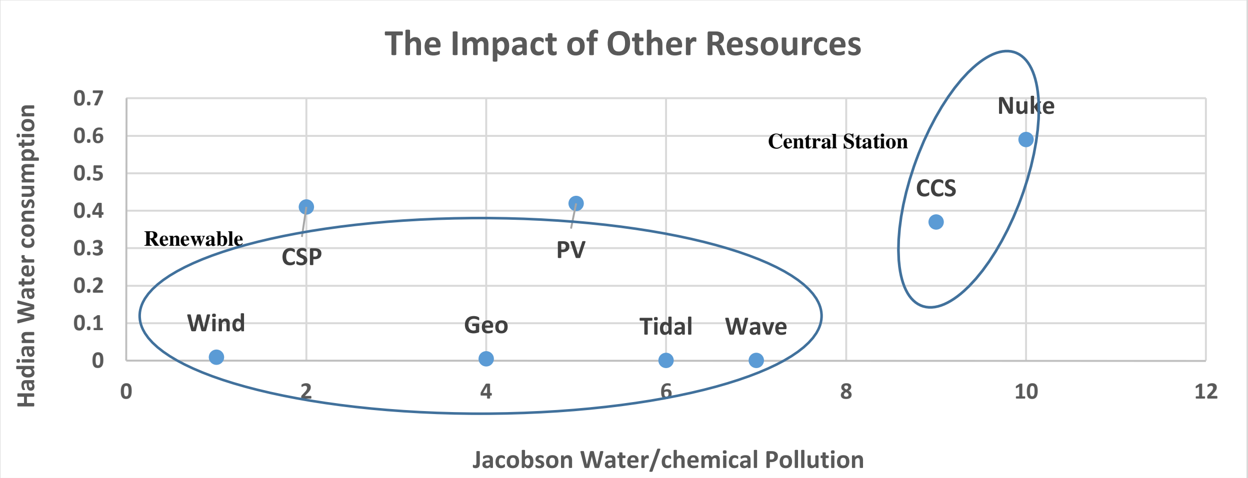
Jacobson Qualitative Ranking Compared to Quantitative Measures



Sources: Benjamin K. Sovacool and Michael Dworkin, *Global Energy Justice,* Cambridge University Press, 2014 (Non-GHG, p. 149; GHG, p. 108); Benjamin K Sovacool, "Exposing the Paradoxes of Climate Change Governance," *International Studies Review,* 16 (2), 2014; Mark Z. Jacobson, "Review of solutions to global warming, air pollution and energy security," *Energy Environ. Sci*., 2, p. 165, 2009.

FIGURE V-3: WATER IMPACT OF GENERATION TECHNOLOGIES





Sources: Jacobson, Mark Z., "Review of solutions to global warming, air pollution, and energy security," ***Energy and Environmental Science*****, 2009; Hadian, Saeed and Kaveh Madani, "A system of systems approach to energy sustainability assessment: Are all renewables really green?"** ***Ecological Indicators*** **52, 2015.**

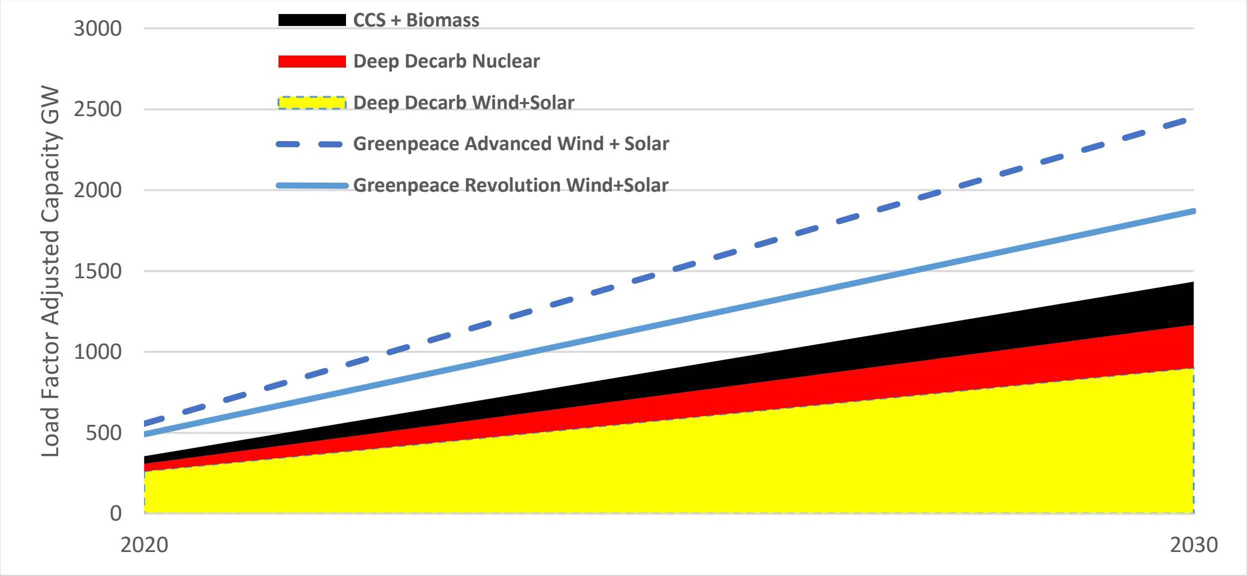
Bioenergy (represented in the upper graph of Figure V-3 as ethanol) and hydro power are very large consumers of water. This supports the Jacobson approach, which excludes biomass on environmental grounds and includes no increase in hydro generation. Comparing the remaining resources, we find that the renewable alternatives are clearly preferable.

The Timing and the Task

A final factor that must be taken into account is time. Indeed, the urgency expressed in the Paris Agreement suggests it should be the first factor. Although we have shown similar "merit order" results in the short- and long-term analyses, there is an urgent need to reduce carbon emissions and pollution as quickly as possible. All of these road maps require significant change in the technologies used to produce and consume energy, essentially a transition to intelligent energy services that includes active management and passive design to meet the much greater need for electricity required by the electrification of the industrial and transportation sectors. Given the current state of technological developments, some technologies can deliver much sooner than others in response to the urgency of the challenge.

As shown in Figure V-4, wind and solar, which will be the core technologies of the future global energy system, can deliver the needed power in large quantities more quickly. The capacity projections in Figure V-4 are adjusted for load factors, using current experience. The variable nature of wind and solar is reflected in an assumed 35% factor for wind, 25% factor for solar and 70% for CSP with thermal energy storage. Nuclear is assumed at 90% and fossil fuels at 85%. Over the course of the next decade and a half, the load factors for wind and solar are likely to go up as the technologies improve and they are combined with increasingly economic storage. Indeed, there are many deployments of these technologies that already exceed the load factor levels assumed above. This is all the more likely since, according to the economic "merit order" approach, much of the global deployment of renewable resources would be in virgin territories with rich resources. Since the Deep Decarbonization Project covers nations that emit three-quarters of global carbon, their projected resource mix, which includes nuclear and carbon capture, is scaled up in Figure V-4 to represent the decarbonization of 100% of the global electricity system.

FIGURE V-4: PATHS TO SUSTAINABLE GLOBAL DEVELOPMENT: LOAD FACTOR ADJUSTED CAPACITY IN A DECARBONIZED ELECTRICITY SECTOR



Sources: Greenpeace International, Global Wind Energy Council, and Solar Power Europe, *Energy [r]evolution: A Sustainable World Energy Outlook 2015, A 100% Renewable Option for All*, September 2015, Table 6.1.1; Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), *Pathways to Deep Decarbonization,* Deep Decarbonization Project, September 2015, Table 4.

The analysis of Deep Decarbonization without the environmental constraint ends up claiming a significant contribution from fossil fuels and nuclear. However, that contribution comes much later and results in electricity costs that are much higher. Though 2030, there is little contribution for new nuclear reactors and fossil fuels with carbon capture and storage. The Deep Decarbonization Pathways assume increasing contributions from nuclear and carbon capture in later years.

Both fossil fuel-based technologies and nuclear power, however, are much more costly and would require long research, development and deployment processes to get those costs down. Both would also have to solve significant environmental problems. The analysis of cost trends presented above suggests that an economic revolution in the traditional technologies is not likely in the near- or mid-term. The real world experience of nuclear reactor construction does not support a claim that it can be brought online quickly. Construction periods in the U.S. increased throughout the history of the industry and average a decade. Current nuclear construction is well behind schedule throughout the world. Globally, nuclear construction periods are not quite as long as the U.S., but they are far longer than other technologies. Globally and in the U.S., nuclear construction periods are six times as long as renewable construction periods. The extreme urgency of climate change means that nuclear will miss the critical period of the next decade, particularly if new nuclear technologies that are still on the drawing board are needed.

The comparison in Figure IV-4 also challenges the claim that technologies based on fossil-fuels with carbon capture or nuclear power are necessary to deal with climate change. The Greenpeace "revolution scenario" projects a level of low-carbon generation that equals the Deep Decarbonization Project projection with carbon capture but without nuclear. Both the Greenpeace "advanced scenario" and Jacobson et al. projects a level of carbon reduction that exceeds the Deep Decarbonization Projection without either fossil fuels or nuclear.

CONCLUSION

Resource Economics of a Low-Carbon Electricity Sector

This paper demonstrates that the "economic merit order" of resource acquisition is quite close to the "environmental merit order." Applying least-cost criteria in the context of a carbon constraint achieves the goal of pollution reduction.

- In the long-term, the economic and environmental "merit orders" are almost identical. Because the cost of the low-carbon, low-pollution technologies has plummeted and their cost is expected to continue to decline, the shift away from baseload resources (fossil fuels and nuclear power) to reliance on flexible renewable resources – linked with active management of supply and demand – will lower the cost of electricity.
- Even in the mid-term, the "economic merit order" follows the "environmental merit order" to a large extent (75%-90%, depending on costs used). Because the deviation of the "environmental merit order" is so small and the economic benefit of pursuing a 100% renewable electricity sector is so large, it does not seem worthwhile to relax the carbon or the other pollutant constraints.
- In the short-term, the main resources of the 100% renewable approach are currently less costly and widely available. Therefore, there is no reason to hesitate in pursuing the low-carbon, low-pollution path.

Given that this analysis assumes the massive electrification of the whole economy, the much smaller task of decarbonizing the electricity sector to meet the "traditional" need for electricity would be quite manageable. The technologies are in hand; we “merely” need to deploy them. The constraints are in the transportation and industrial sectors, where the necessary technologies are not as far along. The economic resource savings achieved by utilizing lower cost low-carbon, low-pollution resources largely “pays for” the transformation of the other sectors. The environmental and public health benefits of the transformation are surplus savings.

The Paris Agreement

This paper concludes that the political economy chosen for responding to climate change in the Paris Agreement fits the underlying techno-economic nature of the available resources. It is also consistent with the terrain of political authority and responsibility of the Parties to the underlying United Nations Framework Convention on Climate Change. The political economy of the Agreement reflects the combination of techno-economic conditions and environmental goals.

- The progressive, mixed market economic model is driven by the need for a rapid, least-cost decarbonization that supports sustainable development of the global economy.
- It also recognizes vast differences in resource endowments and the dramatic differences in level of economic development between the Parties.
- The multi-stakeholder, commons approach to governance reflect the diversity of circumstances and the authority of nations over local energy policy.

The Final Word on Nuclear Power

At this moment, nuclear power demands attention as a subtheme of the analysis because its advocates claim it must be a part of the solution. Indeed, some go so far as to call for a 100% nuclear future. Because these claims are made in spite of nuclear power’s extremely high cost, abysmal and continuing record of cost overruns and construction delays, serious environmental and public health impacts, and fundamental incompatibility with renewable resources, it merits at most a footnote in the analysis, a footnote that merely explains why nuclear power should not be included as an asset in the long-term, low-carbon portfolio.

- To match the economic cost of renewables, nuclear power would need a technological revolution that has eluded it in its half century of commercial deployment.
- Such an improbable revolution is very unlikely to take place in the time frame deemed critical to the fight against climate change.
- Nuclear power is equally unlikely to overcome its other severe environmental problems.

Once the direction of a least-cost route to a decarbonized economy is set by the superiority of renewables, it becomes impossible for nuclear power to participate in the ultimate portfolio. The idea of pursuing an “all-of-the-above” scenario runs afoul of the fundamental differences between the 20th century, baseload fossil fuelapproach and 21st century, renewable energy approach. The two technologies simply do not mix very well because nuclear is not flexible. The vigorous attack on the renewables launched by advocates of nuclear power in their effort to secure favorable treatment of aging reactors is testimony to the incompatibility between the two.[63] Gas has also fought renewables over market share. Much the same can be said of fossil fuels with carbon capture.

The structure of the Paris Agreement gives individual nations the authority and responsibility to develop local decarbonization strategies within the parameters endorsed by the Parties. The Parties cannot be ordered not to pursue nuclear, but the goal of rapidly developing and deploying a least-cost, economically and environmentally sustainable decarbonized electricity sector argues strongly against nuclear power. To the extent that collaborative and coordinated actions are necessary and undertaken to accomplish the goals of the Agreement, they should be devoted to promoting progress along the 100% renewable route to a decbarbonized economy. The reference to renewables in the Agreement in the context of promoting access to affordable, sustainable electricity and building local capabilities, suggest that, here too, the Agreement got it right.

ENDNOTES

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[1] United Nations Framework Convention on Climate Change, *Adoption of the Paris Agreement,* Conference of the Parties, Twenty-First Session, December 12, 2015.

[2] Jacobson, Mark Z. et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) all-Sector energy Roadmaps for 139 Countries*, November 20, 2015.

[3] Greenpeace International, Global Wind Energy Council, and Solar Power Europe, *energy [r]evolution, A Sustainable World Energy Outlook, A 100% Renewable Option for All*, September 2015.

[4] Deep Decarbonization Pathways Project, *Pathways to Deep Decarbonization*, September. 2015.

[5] Lazard, *Lazard's Levelized Cost of Energy Analysis – Version 9.0,* November 2015.

[6] November 2015, hereafter Australian LCOE Report.

[7] Needless to say, examination of 100% renewable approaches to climate change have been appearing in the research literature for some time. See, for example, Ghisetti, Claudia and Francesco Quatraro, "Beyond inducement in climate change: Does environmental performance spur environmental technologies? A regional analysis of cross-sectoral differences," *Ecological Economics*, 96. 2010. Krajac, Goran, Neven Duic and Maria da Graca Carvalho, "How to achieve a 100% RES electricity supply for Portugal?," *Applied Energy,* 88, 2011; D. Connolly et al., "The first step towards a 100% renewable energy-system for Ireland," *Applied Energy*, 88, 2011; Jacobson, Mark. Z. and Mark A. Delucchi, "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, 2011; Delucchi, Mark A. and Mark Z. Jacobson, "Providing all global energy with wind, water, and solar power, Part II: reliability, system and transmission costs, and policies," *Energy Policy* 39, 2011. Elliston, Ben, Iain MacGill and Mark Diesendorf, "Least cost 100% renewable electricity scenarios in the Australian National Electricity Market" *Energy Policy,* 59, 2013, identifies studies prior to 2013; Cochran, Jacquelin, Trieu Mai and Morgan Bazilian, "Meta-Analysis of high penetration renewable energy scenarios," *Renewable and Sustainable Energy Reviews,* 29, 2014, compare a dozen studies. Jacobson et al., provide more recent examples. There is a second professional trade literature, particularly from financial analysts that has demonstrated the economics of deep decarbonization, both in comprehensive reviews (for example, Jason Chanell, *Energy Darwinism II: Why a Low Carbon Future Doesn't Have to Cost the Earth,* Citi GPS: Global Perspectives & Solutions, August 2015) and, in particular, assessments of the economics of renewables (Eggers, Dan*, A Thought... Energy Efficiency: The Reality of Slower Power Demand Growth*, Credit Suisse, February 11, 2013; Eggers, Dan et al*., A Thought... The Transformational Impact of Renewables,* Credit Suisse, December 20, 2014); Frankel, David, Kenneth Ostrowski, and Dickon Pinner, "The disruptive potential of solar power: As costs fall, the importance of solar power to senior executives is rising," *McKinsey Quarterly,* April 2014; Bloomberg New Energy Finance, *New Energy Outlook, 2015.* June 2015).

[8] Throughout this analysis we use long-term and long run interchangeably: "In microeconomics, the ""long run"" is the conceptual time period in which there are no fixed factors of production, so that there are no constraints preventing changing the output level by changing the capital stock or by entering or leaving an industry. The long run contrasts with the short run, in which some factors are variable and others are fixed, constraining entry or exit from an industry," https://en.wikipedia.org/wiki/Long_run_and_short_run

[9] I use the term political economy in the traditional, positive sense and say comeback because, by some accounts, political economy was the traditional approach to economic analysis at the beginning of the science. As David W. Pearce (*The dictionary of Modern Economics,* MIT,1984, p. 342) put it in defining the term: "Until recent times the common name for the study of the economic process. The term has connotations of the interrelationship between the practical aspects of political action and the pure theory of economics. It is sometimes argued that classical political economy was concerned more with this aspect of the economy and that modern economists have tended to be more restricted in the range of their studies." Three decades later in urging social scientists to engage in the "old-fashioned" practice of political economy, Thomas Piketty (*Capitalism in the 21st Century,* 2014, p. 574.) took an even more striking stance, arguing that economics is set apart from the others social sciences "by its political, normative and pragmatic purpose… and asked… What public policies and institutions bring us closer to the ideal society?"

[10] The international governance literature is vast. Our interpretation builds on analysis of the transnational governance of the Internet (Cooper, Mark, "Why Growing Up is Hard to Do: Institutional Challenges for Internet Governance in the "Quarter Life Crisis of the Digital Revolution," *Journal on Telecommunications and High Technology Law*, 2013. 11(1). Three examples from the literature on international energy policy lead us to believe our analysis it applicable. Florini, Ann and Benjamin K. Sovacool, "Who governs energy? The challenges facing global energy governance,"

Energy Policy 37, 2009, describe the weaknesses of various international institutions and the severe challenges that climate change poses including, urgency, geopolitical tensions, and economic vulnerabilities and call for collaboration between energy policy researchers and global governance scholars. The description of the Paris Agreement indicates a vigorous effort to confront these challenges that is consistent with the research literature. Goldthau, Andreas, A Public Policy Perspective on Global Energy Security," International Studies Perspectives (2012), identifies four classic sources of market failure that need to be addressed, lack of competition, externalities, public goods and lack of information. The Paris Agreement is long on all of these. Wilson, Jeffrey D., "Multilateral Organizations and the Limits to International Energy Cooperation," *New Political Economy,* Jan 2014) citing Ravenhill, (J. 'Resource Insecurity and International Institutions in the Asia-Pacific Region," *The Pacific Review,* 26,2013) identifies five levels of institutionalization: Dialogue/Information Sharing, Coordination (Non-binding Principles), Negotiation of Monitored Targets, Legally binding treaty, Governance though Joint Institutions. These activities are not mutually exclusive; they are all ongoing. The Agreement did not bind parties to specific goals and the joint institutions do not have enforcement authority. In this sense it is soft, but, given the complexity of the economic terrain and the authority of nations, it went a long way.

[11] The adjustment is necessary because of differences in the structure of costs between the resources. The low-carbon resources – wind, solar and nuclear – are capital intensive, with capital costs and fixed O&M costs equal to 85 % to 95% of total costs. Coal's capital and O&M costs are about two-thirds of total costs.

[12] The recognition of the technological revolution came first in the academic literature, then in the popular press. See, for example, Avent, Roger, "Creating the Clean Economy," The Economist, June 11, 2011; Leonhardt, David, "There's Still Hope for the Planet," New York Times, July 21, 2012.

[13] Goldberg, Marshall, *Federal Energy Subsidies: Not All Technologies are Created Equal*, Renewable Energy Policy Project, July 2000; Pfund, Nancy 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; Bettencourt, Luıs M.A., Jessika E. Trancik, and Jasleen Kaur, "Determinants of the pace of global innovation in energy technologies," *PLoS ONE,* October 8, 2013, p. 10.

[14] I use the term progressive in the traditional economic and political sense of seeking to obtain desires outcomes through policies applied to markets. Scherer, F.M. and David Ross (*Industrial Market Structure and Economic Performance,* Houghton Mifflin, 1990, 3rd Ed., p. 4)*)* argue that for markets "good performance" should entail "efficiency" and be "responsive… to consumer demand… be progressive, taking advantage of opportunities opened by science and technology to increase output… and to provide consumers with superior new products." They should endeavor to "facilitate stable full employment of resources, especially human resources." "The distribution of income should be equitable." At the same time (p.7) they recognize that "for a variety of reasons markets may fail… Then government agencies may choose to intervene and attempt to improve performance by applying policy measures that affect either market structure or conduct."

[15] Least cost principles have long been the central pillar of regulatory economics (see, e.g., Cooper, Mark "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, 2011; Cooper, Mark "Least Cost Planning for 21st Century Electricity Supply: Meeting the Challenges of Complexity and Ambiguity in Decision Making*," Mid-America Regulatory Utility Conference,* June 5, 2011). In climate change analysis they were given intense, practical voice in studies by energy consultants (e.g., McKinsey Global Energy and Material, *Unlocking Energy Efficiency in the U.S. Economy*, 2009 (McKinsey & Company); McKinsey and Company, *Energy Efficiency: A Compelling Global Resource*, 2010*)* and utility executives (e.g., Rowe, John, *Fixing the Carbon Problem Without Breaking the Economy,* Resources for the Future Policy Leadership Forum Lunch, May 12, 2010; Rowe, John, *Energy Policy: Above All, Do No Harm,* American Enterprise Institute, March 8, 2010).

[16] Mitigation is the master strategy, but as significant impacts appear to be unavoidable, adaptation is recognized as a strong complementary strategy both to alleviate harms and to capture synergies that can lower total costs. Klein, R.J.T., S. Huq, F. Denton, T.E. Downing, R.G. Richels, J.B. Robinson, and F.L. Toth, Inter-relationships between adaptation and mitigation, *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 745-777, 2007; Illman, Julia et al., "Scoping study on financing adaptation-mitigation synergy activities," Nordic Council of Ministers, Nordic Working Paper, 2013; Landauer, , Sirkku Juhola and Maria Söderholm, "Inter-relationships between adaptation and mitigation: a systematic literature review," *Climatic* Change*,* 131, 2015.

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[17] Grubb, Michael, Thierry Chapuis and Minh Ha Duong,, *The Economics of Changing Course: Implications of Adaptability and Inertia for Optimal Climate Policy*, 1995; Popp, David, Richard G. Newell and Adam B. Jaffee, "Energy, the Environment, and Technological Change," in Bronwyn H. Holland and Nathan Rosenberg (Eds.), *Economics of Innovation* Burlington: Academic Press, 2010; Dechezleperte, Antoine et al., *Climate Change & Directed Innovation: Evidence from the Auto Industry, London School of Economics and Political Science*, 2011*;* Johnstone, Nick and Ivan Hascic, *Directing Technological Change while Reducing the Risk of (not) Picking Winners: The Case of Renewable Energy,* November 2010; Luderer, Gunnar, "Economic mitigation challenges: how further delay closes the door for achieving climate targets," *Environmental Research Letters*, 8, 2013.

[18]Gerlagh, Reyer, "Measuring the Value of Induced Technological Change," *Energy Policy,* 35:2007,;Gerlagh, Reyer, Snorre Kverndokk, and Knut Einar Rosendhal, "Optimal Timing of Climate change Policy: Interaction between Carbon Taxes and Innovation Externalities," *Environmental Resource Economics,* 43, 2009; Kalkuhl, Matthias, Ottmar Edenhofer, Kai Lessmann, "Learning or Lock-in: Optimal Technology Policies to Support Mitigation, *Resource and Energy Economics,* 34, 2012; Acemoglu, Daron, et al., *"The Environment and Dedicated Technical Change," American Economic Review, 102(1*), 2012; Gross, Robert et al., *On Picking Winners: The Need for Targeted Support for Renewable Energy,* Imperial College, October 2012; Nordhaus, Ted, Michael Shellenberger and Alex Trembath, "Carbon Taxes and Energy Subsidies: A Comparison of the Incentives and Costs of Zero-Carbon Deployment, *Breakthrough Institute,* September 12, 2012. This observation has crossed over to the popular press: Leonhardt, David, "There's Still Hope for the Planet," *New York Times,* July 21, 2012; Avent, Ryan, "Creating the Clean Economy," *The Economist,* June 11, 2011.

[19] Kobos, Peter, H, Jon D. Erickson and Thomas E. Drennen, "Technological Learning and Renewable Energy Costs: Implications for US Renewable Energy Policy," Energy Policy, 34:2006; Horbach, Jon, "Determinants of Environmental Innovations -- New Evidence from German Panel Data Source," Research Policy, 37:2008; Ahlborg, Helene, "Provision of electricity to African households: The importance of democracy and institutional quality," *Energy Policy,* 87, 2015; Boschma, Ron and Gianluca Capone, "Institutions and diversification: Related versus unrelated diversification in a varieties of capitalism framework," Research Policy, 44, 2015; Heubaum, Harald and Frank Biermann, "Integrating global energy and climate governance: The changing role of the International Energy Agency," *Energy Policy*, 87, 2015.

[20] Bosetti, Valentina and Enrica De Cian, "A Good Opening: The Key to Make the Most of Unilateral Climate Action," *Environ Resource Economics,* 56, 2013; Ek, Kristina and Patrik Soderholm, "Technology Learning in the Present of Public R&D: The Case of European Wind Power," *Ecological Economics,* 69, 2010; Kahouli Brahmi, Sondes, "Technological Learning in Energy-Environment-Economy Modeling: A Survey," *Energy Policy,* 2008:36; Kalkuhl, Matthias, Ottmar Edenhofer, Kai Lessmann, "Learning or Lock-in: Optimal Technology Policies to Support Mitigation, *Resource and Energy Economics,* 34, 2012; Lindman, Asa and Patrik Soderholm, "Wind Power Learning Rates: a conceptual Review and Meta-Analysis," *Energy Economics,* 34, 2012; Rubin, Edward S., "A review of learning rates for electricity supply technologies," *Energy Policy,* 86, 2015; Lindahl, Theres, Örjan Bodin and Maria Tengö, "Governing complex commons — The role of communication for experimental learning and coordinated management," *Ecological Economics,* 111, 2015.

[21] Qui, Yeuming and Laura D. Anadon, "The Price of Wind in China During its Expansion: Technology Adoption, Learning-by-doing, Economies of Scale, and Manufacturing Localization," *Energy Economics*, 34*,* 2012*;* Toke, David, Sylvia Breukers and Maarten Wolsnik, "Wind Power Deployment Outcomes: How Can We Account for the Differences?," *Renewable and Sustainable Energy Review,* 2008:12; Lízal, Lubomír M, Sherzod and N. Tashpulatov, "Do producers apply a capacity cutting strategy to increase prices? The case of the England and Wales electricity market," *Energy Economics,* 43, 2012; Baek, Chulwoo Euy-Young Jung, and Jeong-Dong Lee, "Effects of regulation and economic environment on the electricity industry's competitiveness: A study based on OECD countries," *Energy Policy*, 72, 2014; Gonseth, Camille, "Energy-tax changes and competitiveness: The role of adaptive capacity," *Energy Economics, 48,* 2015.

[22] Grimaudi, André and Gilles Laffrougue, *Climate Change Mitigation Policies: Are R&D Subsidies Preferable to a Carbon Tax,* Tolouse School of Economics, November 21, 2008; de La Rue du Can, Stephane et al., "Design of incentive programs for accelerating penetration of energy-efficient appliances," *Energy Policy,* 72, 2014; Zheng, Cheng and Daniel M. Kammen, "An innovation-focused roadmap for a sustainable global photovoltaic industry," *Energy Policy*, 67, 2015; Shrimali, Gireesh, Melissa Lynes and Joe Indvik, "Wind energy deployment in the U.S.: An empirical analysis of the role of federal and state policies," *Renewable and Sustainable Energy Reviews*, 43, 2015; Shiell, Leslie and Nikita Lyssenko, "Climate policy and induced R&D: How great is the effect?," *Energy Economics*, 46, 2014; Sahu, Bikash Kumar, "A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries," *Renewable and Sustainable*

Energy Reviews, 43, 2015; Duan, Hong-Bo, Lei Zhu and Ying Fan, "Modelling the Evolutionary Paths of Multiple Carbon-Free Energy Technologies with Policy Incentives," *Environ Model Assess,* 20, 2015.

[23] The debate over sustainable growth is huge. The Paris Agreement seems to embrace the proposition that development and decarbonization goals can be reconciled, which finds support among some economists (e.g., Sachs, Jeffrey, D., *The Age of Sustainable Development* (Columbia University Press, 2015) and some environmentalists (e.g., Rockstrom, Johan and Mattias Klum, *Big World, Small Planet* (Yale University Press, 2014).

[24] Cooper, Mark, "Why Growing Up is Hard to Do: Institutional Challenges for Internet Governance in the "Quarter Life Crisis of the Digital Revolution," *Journal on Telecommunications and High Technology Law,* 11(1). 2013, presents a discussion of the structure of commons governance applied to the Internet as a focal core resource system and the challenge of multinational governance. Mark Cooper, "Governing the Spectrum Commons," *Telecommunications Policy Research Conference,* October 2006, demonstrates the core concept of rules with respect to the management of radio spectrum.

[25] Ostrom, Elinor, *Understanding Institutional Diversity*, Chapters 7 and 9, 2005.

[26] Ostrom, Elinor, Prize Lecture: Beyond Markets and States: Polycentric Governance of Complex Economic Systems, December, 8, 2009, p. 435-36.

[27] Ostrom, *Institutional Diversity*, p. 278, (citation and footnotes omitted). Obtaining reliable information about the effects of different uses of resource systems and resource conditions is an activity that is essential to long-term sustainability. If all local communities were to have to develop all of their own scientific information about the physical settings in which they were located, few would have the resources to accomplish this.

[28] Ostrom, *Institutional Diversity*, p. 278, (citation and footnotes omitted). While smaller-scale, community-governed resource institutions may be more effective than centralized government in achieving many aspects of sustainable development, the absence of supportive, large-scale institutional arrangements may be just as much a threat to long-term sustenance as the presence of preemptive large-scale governmental agencies. Ostrom, Elinor, "A General Framework for Analyzing Sustainability of Social-Ecological Systems," 325 *Science*, 422, 2009. Furthermore, the long-term stability of rules devised at a focal… level depends on monitoring and enforcement as well as their not being overruled by larger government policies.... Larger scale governance systems may either facilitate or destroy governance systems at a focal… level.

[29] Very long-lived hydro facilities might be an exception, although refurbishing and updating of these projects would be necessary.

[30] https://en.wikipedia.org/wiki/Merit_order, The merit order is a way of ranking available sources of energy, especially electrical generation, based on ascending order of price (which may reflect the order of their short-run marginal costs of production) together with the amount of energy that will be generated. In a centralized management, the ranking is so that those with the lowest marginal costs are the first ones to be brought online to meet demand, and the plants with the highest marginal costs are the last to be brought on line. Dispatching generation in this way minimizes the cost of production of electricity. Sometimes generating units must be started out of merit order, due to transmission congestion, system reliability or other reasons.

[31] In analyses that impose environmental constraints on resource selection this is sometimes referred to as the "funding order" (see Baker, Erin, et al., 2007, *Uncertainty, Technical change and Policy Models, U Mass Boston, College of Management, July.*

[32] Jacobson et al., Table 2.

[33] Deep Decarbonization, Table 4.

[34] For the 115 reactors per year, see Hansen, James, Kerry Emanuel, Ken Caldeira and Tom Wigley, "Nuclear power paves the only viable path forward on climate change," *The Guardian,* December 3, 2015. http://www.theguardian.com/environment/2015/dec/03/nuclear-power-paves-the-only-viable-path-forward-on-climate-change, For the current capacity, see http://www.world-nuclear.org/info/current-and-future-generation/nuclear-power-in-the-world-today/. To compare this to the earlier estimate of needed capacity, we calculate that building reactors that deliver the same capacity as the deep decarbonization scenarios in Figure IV-3 suggests that current capacity is only 4% of what would be needed, which is identical to the Jacobson et al. estimate of the need for the 100% renewable new builds compared to the current base.

[35] Cooper, Mark, "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, 2012, reviews the U.S. history with a comprehensive data set on completed and abandoned reactors.

[36] Deep Decarbonization, Executive Summary, Figure 7.

[37] Deep Decarbonization, Executive Summary, Figure 6.

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[38] Jacobson et al., p. 35. Two-fifths of the environmental and public health benefits are the result of carbon reduction.

[39] Jacobson et al., p. 1.

[40] Jacobson, et al., p. 13.

[41] Cooper, Mark, 2014, Energy Efficiency Performance Standards: Driving Consumer and Energy Savings in California, California Energy Commission's Energy Academy, February 20, presents a review of the efficiency literature. Recent analyses that support the large potential include Sreedharan, Priya, "Recent estimates of energy efficiency potential in the USA," Energy Efficiency, 6, 2013; Letschert, Virginie, E. et al., *Energy Efficiency Appliance Standards: Where do we stand and how far can we go and how do we get there? An analysis across several economies, Lawrence Berkeley National Laboratory*, 2013*;* Mishra, Gouri Shankar, et al., Mitigating climate change: Decomposing the relative roles of energy conservation, technological change, and structural shift," *Energy Economics*, 44, 2014.

[42] Bureau of Resources and Energy Economics, *Australian Energy Technology Assessment,* 2012. Cooper, Mark, Submission of Dr. Mark Cooper to the Electricity Generation from Nuclear Fuels, Nuclear Fuel Cycle Royal Commission: Nuclear Power is an Expensive, Inferior Resource That Has No Place in a Least-Cost, Low-Carbon Portfolio, August 3, 2015, demonstrates the general relevance of the global analysis to Australia.

[43] Cooper, 2015.

[44] The levelized cost is adjusted to reflect the decline in gas costs between 2013 and 2015 used by Lazard.

[45] In the case of Vogtle, additional potential cost estimates of another 50% have surfaced. This would put Vogtle costs close to Hinkley http://www.cleanenergy.org/2015/12/11/plant-vogtles-price-tag-climbs-to-21-billion-as-commission-experts-predict-further-delays-and-cost-increases-for-southern-companys-proposed-reactors/#.VmrwbDOP-x8.twitter; Jones, Walter C., "Georgia Power adding up costs of Vogtle delay," Athens Banner Herald, February 14, 2015; Weekly Round Up, "Vogtle Costs May Have Reached $21 Billion," Nuclear Intelligence Weekly, December 11, 2015.

[46] The cost increase in Nuclear Intelligence Weekly puts overnight cost of Vogtle at $1,000 above Lazard's high estimate, which adds about $13/MWh, to put Vogtle at $140/MWh.

[47] For the purposes of this analysis to maintain consistency with the underlying Lazard cost projections, I use estimates of the overnight cost (Farrell, Sean and Terry Macalister, "Work to begin on Hinkley Point Reactor within weeks after China deal signed," *The Guardian*, October 13, 2015; North Anna, Direct Testimony of Scott Norwood on Behalf of the Office of the Attorney General, Division of Consumer Counsel, Virginia Electric and Power Company, Integrated Resource Plan Filing Pursuant to Va. Code § 56-597 et. Seq., Case No. PUE-2015-00035, September 15, 2015, p. 5) to calculate the capital cost per kW, and then derive the levelized cost by multiplying the high end of the Lazard nuclear range: LCOE = (Project $/kW/Lazard High $/kW) * Lazard high LCOE. 1 British £ to U.S. $ at 1.6. Hinkley overnight costs are $9,000/kW (although cost escalation to $10,000 is already being mentioned). North Anna overnight costs are $10,186/kW.

[48] Cooper, Mark, Small Modular Reactors and the Future of Nuclear Power in the United States," *Energy Research & Social Science,* 3, 2014.

[49] Cooper, 2012; Cooper, Mark, "Small Modular Reactors and the Future of Nuclear Power in the United States," *Energy Research & Social Science,* 3, 2014, discusses the long-term trend in relation to the recent release and analysis of the French nuclear cost data.

[50] https://en.wikipedia.org/wiki/Overnight_cost, Overnight cost is the cost of a construction project if no interest was incurred during construction, as if the project was completed "overnight." The overnight cost is frequently used when describing power plants. The unit of measure typically used when citing the overnight cost of a power plant is $/kW. For example, the overnight cost of a nuclear plant might be $5,000/kW, so a 1000 MW plant would have an overnight cost $5 billion. (Interest on the $5 billion spent during construction would be extra.)

[51] Lazard, Version 9.0, pp. 13, 14.

[52] Lazard, *Lazard's Levelized Cost of Energy Analysis*, November 2015; *Australian Power Generation Technology Report*, November 2015.

[53] Jaffe, S. and Adamson, K.A., *Advanced Batteries for Utility-Scale Energy Storage*, Navigant Consulting, Boulder, CO, 2014.

[54] Eckhouse, Brian, "Batteries Gaining Favor Over Gas Peaker Plants in California," *Bloomberg*, December 22, 2015.

[55] International Renewable Energy Agency, *Battery Storage for Renewables: Market Status and Technology Report*, January 2015; Rocky Mountain Institute (RMI), Homer Energy, CohnReznick Think Energy, *The Economics of Grid Defection: When and Where Distributed Solar Generation Plus Storage Competes with Traditional Utility Service*, RMI, Boulder, CO, 2014; Parkinson, G., Citigroup: solar + battery storage "socket" parity in years,

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RenewEconomy, 3 October 2014; Fitzgerald, Garrett, et al., *The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid*, Rocky Mountain Institute, September 2015; Dyson, Mark, James Mandel, et al., *The Economics of Demand Flexibility: How "flexwattts" create quantifiable value for customers and the grid*, Rocky Mountain Institute, August 2015.

[56] Cooper, Mark, "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, 2014.

[57] Dumoulin-Smith, Jullien, et al., US Solar & Alternative Energy The Real Battery Storage Opportunity, UBS, Global Research, 11 May 2015; Ayodele, T.R. and A.S.O. Ogunjuyigbe,, "Mitigation of wind power intermittency: Storage technology approach," Renewable and Sustainable, *Energy Reviews,* 44, 2015; Bronski, Peter, et al., *The Economics of Load Defection How Grid-Connected Solar-Plus battery Systems Will Compete With Traditional Electric Service, Why It Matters, and Possible Paths Forward,* Rocky Mountain Institute, April 2015; Garrett Fitzgerald et al.,, *The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid,* Rocky Mountain Institute, September 2015.

[58] Cooper, 2015, Power Shift.

[59] Cooper, 2014.

[60] Fthenakis, Vasilis and Hyung Chul Kim, "Life-cycle uses of water in U.S. electricity generation," *Renewable and Sustainable Energy Review,* 14, 2010; Macknick, Jordan et al., *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*, NREL, 2011.

[61] Jacobson, Mark Z., "Review of solutions to global warming, air pollution, and energy security," *Energy and* Environmental *Science*, 2009; Hadian, Saeed and Kaveh Madani, "A system of systems approach to energy sustainability assessment: Are all renewables really green*?," Ecological Indicators* 52, 2015.

[62] Chandel, Munish K., Lincoln F. Pratson and Robert B. Jackson, "The potential impacts of climate-change policy on freshwater use in thermoelectric power generation**,"** *Sustainability of biofuels,* 39, 2011; Pechan Anna and Klaus Eisenack, "The impact of heat waves on electricity spot markets," *Energy Economics* 43 (2014) 63–71.

[63] Cooper, 2015.