Economics of Renewable Energy Production

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Abstract

Renewable energy (RE) includes a diverse set of technologies that produce useful energy from nondepleting resources, emit little pollution, and involve no fuel costs. While RE comprises only about an eighth of world energy supply, it is growing quickly and could become a much larger share without approaching resource supply constraints. Valuation of the costs and benefits of RE has improved as studies have become more comprehensive in scope and more precise. Still valuation remains complicated and subject to wide bands of uncertainty for several reasons: heterogeneity among RE technologies; accounting for externalities, such as pollution, that are not always traded in markets; and benefits that depend on counterfactuals that vary substantially by time and location. Costs have to account for intermittency, which depends on many factors such as how thin a reserve margin to maintain, as well as technology dynamics, which over the long term may reduce costs. Experience with substantial shares of RE generation in real commercial settings has provided data and opportunities to analyze the integration of RE with the surrounding energy market. A key research challenge is to use this fuller accounting of costs and benefits to produce general insights about energy markets, without being limited by the technological, location, and temporal idiosyncrasies, which so far appear dominant. Future research questions revolve around whether costs are increasing or decreasing in deployment and include considerations of resource availability, temporal correlation in production across space and technologies, technological change in RE and complementary technologies, and emergent properties at large scale.

INTRODUCTION

Renewable energy (RE) encompasses a broad set of technologies that generally share several socially appealing characteristics. They involve low operating costs, produce minimal environmental impacts, and each accesses a large energy resource that does not deplete. While they account for a small portion of energy supply relative to fossil fuels, investment in RE has been growing at high rates for a decade, such that RE's effects on energy markets are no longer trivial. In some regions and time periods, RE supplies most of the electricity

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that is consumed. However, the potential benefits of RE—reduced climate change, avoided air pollution, and increased energy security—are generally public goods shared over large spatial scales with many of the benefits of RE only realized at very large deployment. Owing to internationally linked energy markets, global transport of pollution, and decadal-scale atmospheric lifetimes of greenhouses gases, the benefits from RE tend to disperse geographically and accrue over lengthy time periods. These features raise the stakes in assembling a more comprehensive accounting to avoid the risks of both the costs of excessive deployment and missed social benefits of insufficient investment.

For a variety of reasons, understanding and providing a comprehensive accounting of the true costs and benefits of RE has proven complicated and remains elusive. Owing to the public good nature of many of the benefits, they are not typically traded in markets. Some costs are also externalities, such as the need to backup intermittency. Further, in the longer term, costs are dynamic, owing to technological change. Difficulty in valuation also arises because of distinguishing characteristics of RE discussed below, as well as to the heterogeneous set of technologies that fall under the rubric of "renewables." The basic shared attribute that makes an energy source renewable is that it produces useful energy from a continuous flow of energy—such as sunlight, the orbit of the moon, or radioactive decay at the Earth's core—rather than from a stock of stored energy, such as buried biological material or radioactive isotopes near the Earth's surface. In descending order of their current contribution to world energy supply, the six main categories of RE are: bioenergy, hydropower, wind energy, direct solar energy, geothermal energy, and ocean energy. The technologies within these categories are diverse and have distinct features, for example, in terms of capital costs, dispatchability, and unit scale. This diversity increases as one considers the economics of RE technologies that are under development, or that are not yet even at that stage, but which could still play a role in energy markets over the time scales required in considering social issues such as energy security and climate change.

FOUNDATIONAL RESEARCH

Research on what makes renewables distinct from other energy technologies has enabled a more comprehensive accounting of the full costs and benefits of RE (renewable energy) production, particularly progress on valuing nonmarket goods, establishing counterfactuals, and characterizing innovation.

Distinctive Characteristics

Renewables are distinct from nonrenewables in several ways. First, costs are concentrated in up-front capital investment. In most cases fuel costs are zero and other operating costs small. The absence of fuel inputs makes them independent of both long-term cost, which increases because of resource depletion, and near-term price volatility.

Second, electricity production from RE is inherently tied to variation in the natural energy flux they use for input energy. While the renewable aspects of these fluxes make them generally constant over long periods, such as multiple years, they vary considerably on the shorter time scales that are relevant to energy markets and system reliability. In some cases this variation is precisely predictable, for example with tides. In other cases, built-in storage, such as in the accumulation of biomass for bioenergy power plants allows them to be as dispatchable as fossil fuel power plants. In others, the variation is very difficult to predict, such as in wind speeds and the location of clouds affecting solar power. For some, longer term variability, such as the chance of having a low wind year, is even more difficult to address even if more rare. These weakly predictable sources of variation impose external costs, which make valuing the full costs of RE difficult.

Third, even though the resource in a given location is inexhaustible over time, the total resource over space is limited. There is a fixed supply of adequate sites and a trend to lower quality sites—with lower resource intensity—as the best sites are used up. Even though the unit cost of energy from a given plant is constant, the average unit cost of plants over time is likely increasing. Moreover, these sites may have other uses that may compete with the land used for RE.

Fourth, RE's lack of combustion provides substantial environmental benefits over fossil fuels. Increasingly comprehensive studies of the "life cycle analysis" of RE generally show only small amounts of pollution in the manufacturing and decommissioning of RE plants, and close to zero in the use stage. The difficulty in valuing these avoided pollution benefits depends on the counterfactual of what energy source RE is displacing.

Grid Integration

Even though RE has historically promised to make consumers energy independent, this off-grid use is today limited to niche markets. RE is almost always more valuable when it is integrated into the larger energy system. Aggregation of supplies and loads, via transmission and distribution systems, allows for numerous efficiencies, such as in load factor and in economies of scale. Individual loads need not have their own storage capacity; they can use grid energy to supplement their RE when their load exceeds their RE supply; and conversely they can sell extra RE capacity to the grid when they do not consume all of it.

While it is clear that there are private benefits to integrating one's RE supply with the larger system, evidence is mixed about whether the energy system benefits from the addition of RE to it. Other than environmental externalities, which we cover separately, RE can confer benefits to the overall grid by providing zero-marginal cost power when the grid is near capacity. Because storage is practically infeasible owing to high costs, and because the supply of energy when it is near capacity is inelastic in the short term, additional power when it is needed most can be very valuable. The technology most applicable to this case is direct solar energy because peak output from solar plants, when sun is highest, tends to coincide reasonably well with demand, especially in warm areas and in seasons when peak demand is driven by use of air conditioning. Wind power can also provide output that coincides with peak demand, especially in situations in which wind is driven by diurnal thermal gradients, which often peak in the afternoon and are coincident with demand.

However, these benefits are only part of the story. The electric grid becomes unstable if instantaneous supply does not meet instantaneous demand within relatively narrow tolerances. Capacity for storage is small and expensive. Short-run demand is inelastic with respect to price. While typical fossil plants manage fluctuations owing to unforeseen outages and even variations imposed by weather or fuel quality, this variation is much smaller than that attributable to clouds and wind. As a result, deployment of RE creates a need for extra reserve capacity to provide backup generation that can be dispatched quickly in the event of reduced output from renewables. There are extra capital costs—in gas turbines, diesel generators, etc.—that need to be made as renewables are deployed on the grid. In addition costs also arise from fossil plants having to operate at lower capacity factors when RE plants are producing large amounts of electricity. This imposes long-term costs in terms of unused capacity investment. It also imposes near-term costs in that these plants typically run at lower efficiencies when they operate below capacity. Work has also shown that the ramping up and down of fossil capacity to match RE output results in additional efficiency losses. RE may also impose grid congestion and indeed one can observe negative locational marginal prices in wholesale electricity markets. For all these reasons, the variability in RE, especially that which is not predictable, imposes costs on the grid. Computer simulations, known as "dispatch models," in which demand is met by adding generation sources in order of increasing marginal costs while facing transmission constraints, have helped estimate some of these values, but they remain highly location and time specific.

Displaced Emissions

For related reasons, the potential for environmental benefits is another source of complexity in valuation. The key question here is: how much emissions do RE avoid? The answer depends on establishing the counterfactual of what combination of energy sources would be used if RE were not available. The mix also varies by location and time. In addition, over time, the mix of offset emissions sources can be very different as relative prices change. Studies have provided estimates assuming that renewables displace the highest marginal costs fuel sources, an average of the generation mix within a region area, or conditional on RE replacing all gas or all coal. Environmental benefits are highly sensitive to these assumptions and generally are much larger when RE displaces coal than gas and much larger if displacing gas than nuclear or other renewables. As in the discussion above, dispatch modeling is needed to provide precise estimates of anticipated savings, particularly as deployment of RE gets larger and displaced generation extends beyond what are currently the marginal fuels.

Technological Change

The valuation of RE is further complicated by the now robust set of findings that show their costs changing, and for the most part, improving over time. For example, the price of solar PV panels has fallen by two orders of magnitude. For the short time frames associated with dispatch and markets, technological change is not important. For the array of decisions in which years and decades are involved—for example in capacity planning, grid operation, long-term contracting, and policy decisions related to climate change—accounting for technological change is crucial. Owing to the stochastic aspects of the innovation process, technological change is also highly uncertain. However, we know from history that assuming "frozen technology," that the technology we have today will be similar to that we have in the future, is almost certainly wrong—especially at multiple year and decadal time horizons. Much work has helped to document the dynamism of renewable technologies and many models to inform energy and climate policy now explicitly characterize technological change.

Much of this improvement has been attributed to learning by doing, the notion that workers become more adept at performing manufacturing tasks as they repeat them. Studies have used experience curves to describe this aspect of technological change. Experience curves use a power function to describe the relationship between experience with a technology (typically measured as cumulative generation capacity produced) and performance of that technology (typically using data on costs). A primary justification for using experience curves is the very high goodness of fit of actual data to experience curves. Experience curves are also appealing because they collapse the complex process of technological change to a single parameter, which is useful for modeling. A serious criticism of experience curves is the possibility of omitted variable bias; that is, factors other than experience, such as changes in industry structure and input prices, also affect performance.

INCENTIVES AND DESIGN OF PUBLIC POLICY

RE involves multiple market failures. Pollution is certainly important, both the long-term effects of avoided climate change damages as well as avoiding pollution that creates benefits on shorter timelines, such as particulates, sulfur dioxide, and oxides of nitrogen. Emissions produce damages such as eco system quality, increased hospitalizations, and reduced crop yields. All of these are unpriced or at least underpriced without policy incentives in place. Technological change raises a second set of externalities. An innovation-related externality arises because firms are unable to capture the full value of their investments in innovation. For example, a new design for the gearbox on a wind turbine can be reverse-engineered and imitated. There may be strong incentives to avoid investment in risky new technologies and instead free ride on the investments of other firms. The outcome, if knowledge spillovers are present, is under-investment in innovation. Technological change itself is generally not a sufficient condition for justifying RE policy. It may be the case that firms are able to appropriate a sufficient amount of the return on their innovations, for example, because of patents or difficult to replicate manufacturing processes. It is these positive spillovers that can justify policies beyond pollution externalities. Because of the substantial, and potentially multiple, externalities involved, work on the economics of RE has to account for policies, which once implemented and affected by the policy making process, can become complicated. Work continues on how markets respond to various policies, including unintended consequences, and also on how better policies can be developed which directly focus on pricing positive and negative externalities and minimize unintended consequences.

CUTTING-EDGE RESEARCH

Recent research has taken advantage of the much richer opportunities for empirical research as the real world experience with RE (renewable energy) accumulates over time and now provides a substantial contribution to energy supply. The scale of deployment has led to new areas of research focus and to some reconsideration of how to evaluate the true costs and benefits of RE.

Emergent Issues from Large-Scale Deployment

Studies of electrical grid behavior and pricing in areas with high shares of renewables have allowed research to empirically study the effects of grid capacity among various mixes of RE and non-RE generation. It is now clear that the value of RE depends on a variety of properties, many of which are vary considerably across locations. These include typical issues with electric power systems, such as congestion, market power, and the flexibility of the generation mix to account for variable output from RE. They include the sophistication of grid operators in controlling the system as well as in accessing and responding to new information. They also include electricity market design, institutional rules, and the characteristics of demand. Some of these issues could be addressed more effectively than at present. A central issue is management of reserves. More precise anticipation of changes in load, through better data and state of the art forecasting, could enable grids to operate with less back up generation, thus lowering the extra costs for RE. Forecasting might also be improved by micrometeorological forecasting of near-term changes in RE generation, for example, clouds and wind speeds. The costs of grid integration are location specific and highly uncertain. In addition, similar to other aspects of RE, these costs are likely to change over time as because of improvements in technology, but also because of innovations in management and institutions.

Perhaps the most striking example of new economics emerging at scale is in biofuels. During the past decade, rising gasoline prices and policies designed to promote alternatives to oil produced dramatic expansions in the land area devoted to producing biofuel feedstocks, especially corn. The consequent rise in the demand for corn raised the cost of producing biofuels and the price of biofuels reflected that. However, the rather inelastic demand for food produced additional effects. High prices for corn and for substitutes led to expansion of agriculture to marginal lands with lower yields and created strong incentives to replace forested land with pasture and agriculture, most notably in tropical forests. The outcomes of this indirect land use change (ILUC) prompts equity concerns about demand for biofuels driving up the cost of food, which disproportionately affects the very poor. It also raises concerns about the release of carbon as tropical forests are cut down for agriculture. The latter affects how much greenhouse gas abatement biofuels actually provide and consequently the value of biofuels. Computable general equilibrium models, using detailed trade data, have been essential in assessing the magnitude of these effects. However, the effects of ILUC in reducing the value of a marginal gallon of biofuel remain highly uncertain and present a formidable challenge to policy makers trying to price externalities. This is an example of an emergent property at scale that was not anticipated even a few years prior. It may also be a harbinger of others as renewables attain scale sufficient to affect other sectors amidst a highly integrated global economy.

MECHANISMS BEHIND TECHNOLOGICAL CHANGE

Improved data in real settings has also improved understanding of the process of technological change. In contrast to the descriptive work that led to the widespread adoption of experience curves, more recent work has produced insights about the underlying mechanisms of technological change. These studies take advantage of modern analytical techniques and the substantially enlarged set of real world data that is available now that RE has been produced at large scale for decades. Instead of using a single explanatory variable, typically time or a proxy for experience, these studies consider the effects of a much broader set of factors affecting the performance of RE technologies. While learning by doing is still considered important to the process of technological changes, the intensity of its effects varies widely, by technology, by geography, and even by processes within a technology. Other factors play important roles simultaneously. For example, for some technologies, such as wind power, economies of scale in the size of each generating unit have led to tremendous reductions in cost, and consequently a drive to ever increasing scale. This is similar to the gains that have been observed in coal plants and nuclear plants, although wind has not yet shown evidence of hitting limits to scale economies as those have. Economies of scale are also available in the scale of production, for technologies that can be mass manufactured, such as solar cells. Efficiency improvements have also contributed to reducing the costs of RE. In some cases, efficiency has increased because of learning by doing, such as in concentrating solar thermal electricity, and in other cases efficiency improvements are more attributable to improvements in science and have resulted from R&D investments, both privately and publicly funded. This set of findings—of a much broader set of factors—has implications for both understanding technological change in RE and in the implications for the design of policy to address weak incentives. Most directly, the notion that creating incentives for deployment alone will drive down costs via learning effects is not a sufficient justification for policy.

While recent work has generally emphasized explanations of technological change other than experience, some work has also more clearly identified the characteristics of learning by doing by more carefully identifying those effects relative to the others. The effects are generally much smaller than if looking at experience alone, suggesting that the sum of these other factors is generally supporting technological change. However, work on learning by doing has also found direct evidence that knowledge spillovers exist. That is, when all factors are accounted for, learning by doing still plays a role, and firms can even learn from the experience of other firms. These effects tend to be quite small and they are also fragile, in that the knowledge produced from experience tends to depreciate over time. The findings of knowledge spillovers provide a much stronger justification for policy, even if the size of the effects is small relative to that found through simple learning curve explanations. Using trade data and the truly global nature of much of the RE supply chains, work along these lines, has found evidence of knowledge spillovers across countries. The results of this work have implications for intellectual property protection and even the cost of pollution abatement in developing countries. International knowledge spillovers can reduce these costs as long as incentives for investment remain high in developed countries. The continuing production of new data that the rapid expansion of RE generates will enable better identification of these effects.

A key challenge arising from these new research directions, which highlight the important roles of local and technological idiosyncrasies, is ascertaining general insights that hold across locations and across technologies. In any case, it has successfully broadened the scope of factors to consider in the valuation of RE.

KEY ISSUES FOR FUTURE RESEARCH

Key issues for future research revolve around more fully and more precisely characterizing the value and costs of energy produced from renewables. Costs need to account for the extra investment required to ensure grid stability while accommodating an intermittent resource. Benefits need to account for an array of public goods provided by RE (renewable energy) that are not traded in markets. We also know that multiple market failures are involved, requiring multiple policy instruments, even in a first-best context. The improved empirical basis with which to develop estimates, as the real world deployment goes well beyond niches in many places, provides grounds for optimism that work can move beyond acknowledging complexity toward more robust conclusions with normative implications.

Costs

A fundamental question in assessing the costs of RE is whether, in the long run, costs are increasing or decreasing in deployment.

Studies of resource availability—whether tidal, wind, solar, or geothermal—have shown that while these resources are large and nondepleting, they are still scarce; crucially, they are of heterogeneous quality across the Earth's surface. Satellite and other data have provided increasingly sophisticated analyses of the total resource potential for RE. However, there is a deficit in work that combines physically oriented assessment of energy potential with the economics of accounting for the varying costs associated with accessing that potential. Our improving understanding of how RE systems interact with the broader energy system provides a promising avenue for developing supply curves for RE in terms of prices rather than only in energy units.

Whether long-term costs are increasing or decreasing also depends on how, and whether, multiple renewable technologies are deployed simultaneously. Just as aggregation of individual loads provides social benefits by smoothing out overall demand over time, aggregation of diverse RE sources can smooth out energy production over time. We know that spatially dispersed renewables can reduce the effects of locally induced intermittency, for example, by clouds. A mix of different types of RE, reduces the correlation in output even further, thus reducing the need for storage and dispatchable back-up generation. Incorporating dispatchable renewables and storage would further reduce the need for reserves. Better information of the extent to which aggregation of diverse renewables can reduce costs can both inform characterization of overall costs and also strategies for deployment.

Technological change will also determine whether costs are ultimately increasing or decreasing. Costs may increase owing to resource limitations in the inputs to the capital stock of RE, such as metals, water, and land. Costs will depend on the extent to which innovation responds to the consequential changes in prices, as well as to competition for these resources from other sectors. The pace of improvement in RE itself will of course be crucial. Work will continue to be needed on the scope for and reasons for technological change, particularly in incremental improvement in existing technologies. Focus has already shifted to the components of costs that have not been reduced much already, for example, labor in installation. In the longer term, analysis will be fraught with the more difficult question of characterizing the potential for nonincremental technological change in RE, such as the adoption of new materials or radical new technologies that do not resemble existing ones but do compete with them. Perhaps even more fundamental to determining costs will be technological change in complementary technologies, such as storage devices and grid technologies. Current analyses of the costs of intermittency generally dismiss storing energy as far too expensive relative to producing back up generation from fossil fuels. However, batteries, flywheels, fuel cells, and other technologies are also dynamic technologies with improvements in costs and performance over time. The costs of grid integration could be lower depending on how much cheaper these and other forms of storage reduce their costs. Similarly, it is possibly that improvements in transmission technology could reduce the costs of intermittency. The use of direct current lines and efficient inversion to alternating current already are used for high-quality renewable resources to affordably serve distant loads. Other technologies, such as communication technologies that enable improved operating and stability in the transmission grid also have the potential to reduce the costs of RE. It is not only technological ones, but also human attitudes and preferences that affect these costs. While more transmission and higher-tech transmission can reduce costs, actual siting of transmission is often determined mainly by public acceptance. Understanding perceptions, and willingness to pay to avoid living near transmission corridors would help assess the extent to which linking uncorrelated resources via transmission is even a feasible avenue for reducing the costs of intermittency.

Finally, costs are subject to anticipating emergent issues that occur at scale. Work on technological change has shown that widespread adoption of technologies often brings unexpected negative consequences. These can increase costs or reduce value and they need also to be included. ILUC discussed above is an example. Other examples that have been studied include warming due to heat absorption by solar PV and the reduction in heat transfer from equator to poles at very large deployment of wind power. These may be impacts that society is willing to live with, but they also impose costs that need to be considered, and most importantly for research, to be anticipated. In addition, climate change itself may affect the resource available to RE, for example, through changes in wind, storms, temperatures, and water availability.

Benefits

Assessment of RE requires progress on understanding the magnitudes of the social damages it could potentially avoid, as well as the extent to which RE can avoid those damages. Damages depend in part on uncertain physical characteristics of the climate system, such as climate sensitivity and the magnitude of positive feedback mechanism. They also depend on society's ability to adapt to the consequences of a less stable climate. Because the ability to avoid those damages is delayed by the long residence time of greenhouse gases in the atmosphere, valuing those avoided damages depends crucially on the discounting methodology. Estimates of the social cost of carbon emissions differ by an order of magnitude across a narrow range of defensible discount rates and functions. Moreover, the benefits are not restricted to climate change; local air quality also improves with deployment of renewables. The value of the consequent avoided hospitalizations, lost workdays, and improved aesthetics also need to be taken into account. These co-benefits typically are more predictable, more local, and have much shorter time scales, so discounting is less crucial. The value of RE depends in part on estimating of many highly uncertain parameters, which depends on expertise from multiple areas, such as climate science, public health, sociology, and economics.

Even if avoided damages can be estimated with reasonable precision, we still need to know how much of those damages can be avoided per unit of energy produced. Our current estimates of avoided CO_2 from renewables include large error bars. They depend, in part, on improved lifecycle analysis that accounts for the hidden emissions in the construction and disposal of RE technologies. However, more important is what combination of energy sources is being displaced with an incremental unit of RE generation. This requires improved dispatch modeling, especially accounting for the potential for an expanded, improved, or at least different, transmission system than the one we have today. It also depends on accounting for the possibility of large changes in competing technologies, such as the adoption of hydraulic fracturing technology that has reduced gas prices substantially in the few countries in which it has been deployed so far. Similarly, the phase out of nuclear power in a few countries and the expansion of it in others affects the value of RE. As it is deployed to more substantial levels, valuation will be increasingly sensitive to RE's inducing changes in the generating mix it displaces, so models need to account for these endogenous changes as well. Since relevant time horizons are long, valuation will be forced to make assumptions about the configuration of the future energy systems. Among the most high impact, and uncertain, of these is the extent of electrification of transportation.

ANALYTICAL APPROACHES

While challenging, valuation of RE, can be enhanced with a few recent developments. First, better data are increasingly available allowing much more powerful estimation of the roles of various parameters in affecting both costs and benefits. We can now reliably measure important features, such as the level of correlation among wind power sites, actual grid congestion in real systems, and consequent effects on locational marginal prices. Improving access to data from real experience provides an important complement to modeling studies predicting effects. While data generation is expanding, these data are not always available for research because of privacy concerns and claims of proprietary ownership by firms. Second, some of the emerging data is novel in that it is remarkably disaggregated, allowing glimpses of individual behavior. Small-scale RE is qualitatively different from traditional energy supply in that consumers can own them. Consumer adoption behavior may affect its value. A third area of analytical work is to address the emergent uncertainties such as ILUC—parameters, technologies, or components that we do not yet even know to include. The long time scale needed for valuation puts analysts in a difficult position.

Costs and value need to be determined over decadal time periods, which allow for large changes in technology, markets, and human behavior that are impossible to predict with precision. Modeling needs to be robust to these developments, or at least adaptable to including improved information on them.

CONCLUSION

A main contribution of this research area is to provide analytical support for understanding the extent and ways in which RE can benefit society. The possibilities are such that RE can neither be dismissed because of the difficulties in integration nor assumed to be substantial because of the large nondepleting resource, and nonpolluting aspects. Work has improved to show that costs are real but not prohibitive, and that the resource is immense but that not all of it is necessarily available at a social cost that is below its value. The outcomes of the economics of RE have direct implications on public policy, not just on the balance of costs and benefits, but also on what market failures are actually affecting incentives. These depend not only on understanding climate change damages, but also co-benefits, and even energy security. They extend to innovation externalities, which exist not only in RE but also in complementary technologies such as storage and smart grid. There may even be interactions between positive knowledge externalities and negative pollution ones. Ultimately, these will need to be understood to know how best to arrange institutions and regulations so that decisions reflect a much fuller understanding of the true social costs and benefits of RE than currently exists.

FURTHER READING

Baker, E., Fowlie, M., Lemoine, D., & Reynolds, S. (2013). The economics of solar electricity. *Annual Review of Resource Economics*.

Borenstein, S. (2012). The private and public economics of renewable electricity generation. *Journal of Economic Perspectives*, *26*(1), 67–92.

Gowrisankaran, G., Reynolds S. S., *et al*. (2011). *Intermittency and the value of renewable energy*. National Bureau of Economic Research Working Paper Series No. 17086.

Heal, G. (2009). *Reflections—the economics of renewable energy in the United States*. Rev Environ Econ Policy: rep018.

IPCC (2011). *The IPCC special report on renewable energy sources and climate change mitigation*, Intergovernmental Panel on Climate Change (IPCC).

Joskow, P. L. (2011). Comparing the costs of intermittent and dispatchable electricity generating technologies. *The American Economic Review*, *101*(3), 238–241.

Lyon, T. P., & Yin, H. T. (2010). Why do states adopt renewable portfolio standards? An empirical investigation. *Energy Journal*, *31*(3), 133–157.

Mitchell, C. J., Sawin, G. R., *et al*. (2011 Chapter 11). Policy, financing and implementation. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, *et al*. (Eds.), *Intergovernmental panel on climate change (IPCC) special report on renewable energy sources and climate change mitigation*. Cambridge: Cambridge University Press.

Popp, D., Hascic, I., *et al*. (2011). Technology and the diffusion of renewable energy. *Energy Economics*, *33*(4), 648–662.

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