

*Annual Review of Resource Economics*  
**Faster Than You Think:  
 Renewable Energy and  
 Developing Countries**

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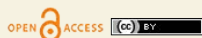
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**Keywords**

variable renewable energy, energy planning, development

**Abstract**

Since 2007, large and unexpected declines in generation costs for renewable energy systems, particularly solar but also wind, combined with policy measures designed to limit greenhouse gas emissions, have created a paradigm shift in energy systems. Variable renewable energy now dominates total investment in electricity power generation systems. This dominance of variable renewable energy in investment has thrust the systems integration task of matching electricity supply with demand to center stage, presenting new challenges for energy policy and planning as well as for the institutional organization of power systems. Despite these challenges, there is ample reason to believe that variable renewables will attain very high levels of penetration into energy systems, particularly in regions well endowed with solar and wind potential. Similar to their success with mobile phone telephony, many developing countries have a significant opportunity to leapfrog directly to more advanced energy technologies that are low cost, reliable, environmentally more benign, and well suited to serving dispersed rural populations.

## 1. INTRODUCTION

For more than a century, economic growth and development have been principally powered by fossil fuels. This strong dependence on fossil fuels is changing. Rapid advances in variable renewable energy (VRE) technologies along with country commitments to reduce emissions of greenhouse gases (GHGs) are leading to global shifts in energy production patterns, notably electricity production.

Developing countries are, in many ways, well positioned to benefit from these technological advances. They are frequently well endowed with naturally distributed renewable energy sources, notably sunshine; they frequently lack significant legacy energy systems; they are likely to experience rapid increases in energy demand; and they are often characterized by relatively large and dispersed rural populations with limited or no access to electricity or other modern forms of energy. For these reasons, many developing countries have a significant opportunity to leapfrog directly to more advanced energy technologies that are low cost, reliable, environmentally more benign, and well suited to serving dispersed rural populations.

VRE technologies, however, also pose new challenges. Solar and wind energy systems produce power when the sun shines and the wind blows. Hence, electricity supply does not necessarily correspond with demand. Matching supply with demand is known as the systems integration challenge. Partly as a consequence of this challenge and partly owing to other factors, fully benefiting from VRE also requires rethinking institutional arrangements shaping the energy system in general and electric power in particular.

This article is structured as follows. Section 2 reviews the rapid changes in electricity generation technologies that have taken place over the past 10–15 years. These cost declines were uniformly unanticipated by principal energy forecasters. Nevertheless, they have been major drivers behind a massive shift in investment patterns with VRE currently dominating investment in power generation. Section 3 considers the implications of the dramatic changes in costs and investment patterns discussed in Section 2 for energy planning and modeling, with a particular emphasis on systems integration. Section 4 looks forward with a focus on electricity systems. It includes a case study from South Africa that is emblematic of the changes that are in process and a discussion of energy security issues. Section 5 evaluates the particular implication of low-cost renewable energy for developing countries and development prospects. Section 6 provides discussion and conclusions.

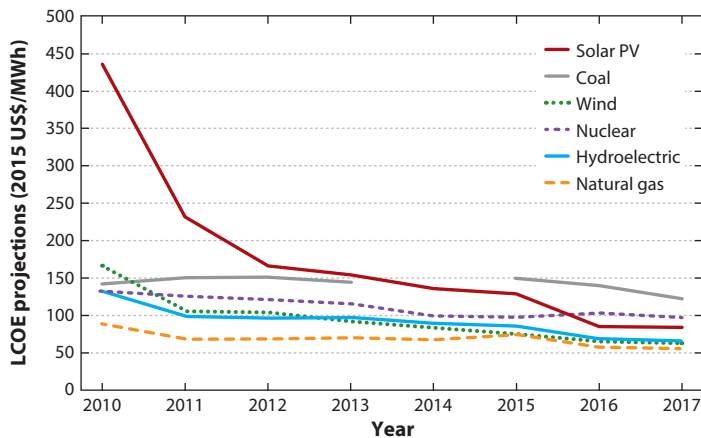
## 2. TRENDS FROM 2007 TO 2017

### 2.1. Energy Technologies and Costs

Over the past decade, improvements in technologies and changes in fuel costs have affected the cost of all electricity technology options. The pace of VRE development, however, has resulted in significantly larger cost declines in solar photovoltaic (PV) and wind technologies relative to others. Between 2010 and 2017, the levelized cost of electricity (LCOE) from solar PV and wind decreased by 81% and 62%, respectively, while coal and gas costs decreased by 15% and 37%, respectively, based on data from the US Energy Information Administration (EIA) from 2010 to 2017 ([https://www.eia.gov/outlooks/aeo/electricity\\_generation.php](https://www.eia.gov/outlooks/aeo/electricity_generation.php)).<sup>1</sup> VRE technologies are

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<sup>1</sup>The LCOE allows simple comparisons of costs of different methods of electricity generation. It is the average total cost per unit of electricity generated to build and operate a power-generating asset divided by the total energy output over the lifetime of that asset. The levelized cost can also be understood as the average minimum price at which electricity must be sold in order to break even. Limitations of levelized cost calculations are addressed in Section 2.3.



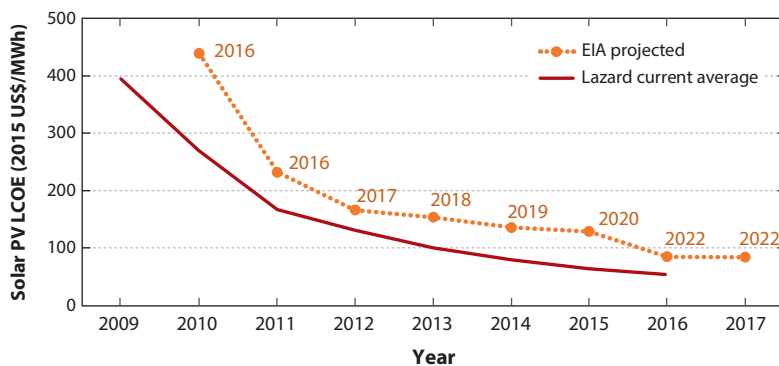
**Figure 1**

Annual energy outlook short-term technology LCOE projections. Figure based on data from the EIA from 2010 to 2017 ([https://www.eia.gov/outlooks/aeo/electricity\\_generation.php](https://www.eia.gov/outlooks/aeo/electricity_generation.php)). Abbreviations: EIA, US Energy Information Administration; LCOE, levelized cost of electricity; PV, photovoltaic.

now cost competitive with traditional technologies such as coal, oil, and gas in many circumstances.

**Figure 1** presents the evolution of the LCOE over the past decade for various technologies.

The decline in renewable energy technology costs was unexpected by most international forecasting agencies, leading to a continuous series of downward revisions in renewable LCOE projections. In 2009, for example, the LCOE for solar PV was forecasted by the EIA to be US\$439/MWh by 2016. The actual LCOE in 2016 was recorded at US\$84.7/MWh, less than one-fifth of the projected level ([https://www.eia.gov/outlooks/aeo/electricity\\_generation.php](https://www.eia.gov/outlooks/aeo/electricity_generation.php)). This phenomenon is shown graphically in **Figure 2**. The dashed line shows the EIA's projected LCOE for solar PV made in the year shown on the horizontal axis for the year shown on the label. For example, in 2010, EIA projected solar PV in 2016 to be more than \$400/MWh. At



**Figure 2**

Actual and projected solar photovoltaic (PV) levelized cost of electricity (LCOE), 2009–2017. Figure based on data from the US Energy Information Administration (EIA) from 2010 to 2017 ([https://www.eia.gov/outlooks/aeo/electricity\\_generation.php](https://www.eia.gov/outlooks/aeo/electricity_generation.php)), IEA (2016), IRENA (2017b), and Lazard (2016). EIA LCOE values are projections reported in each year on the horizontal axis for the labeled year (two projections were made for both 2016 and 2022).

the same time, the financial advisory and asset management firm Lazard estimated actual solar LCOE in 2010 at approximately \$250/MWh. Through 2017, actual costs, as reported by Lazard (2016), are less than EIA forecasted costs five or six years into the future for all data points.

The technical resource potential of renewables has also been underestimated historically. In 2000, for example, Nakicenovic & Swart (2000) estimated long-term wind potential to be greater than 130 exajoules (EJ) per annum (though presumably not so much greater as to make this lower bound estimate completely uninformative). Later studies by Cho (2010) and Tomabechi (2010) estimated annual usable wind potential to be 631 EJ and 700 EJ, respectively. Recently, Eureka et al. (2017) conducted a detailed assessment of exploitable wind resources for use in integrated assessment models (IAMs). They estimated high-quality wind resources to be approximately 10% of total wind resources. Furthermore, they estimated that global generation potential from high-quality wind resources alone, onshore and offshore, exceeds current global generation from all sources by a factor of about two.

The overestimation of costs in the past, along with underestimated renewable energy resource potential, resulted in projected electricity production mixes that did not include a significant role for VRE technologies. For example, in 2007, the core baseline scenarios underpinning the fourth Intergovernmental Panel on Climate Change (IPCC) assessment report (IPCC 2007), developed by Fujino et al. (2006), Van Vuuren et al. (2006, 2007), Riahi et al. (2007), and Clarke et al. (2007), projected that fossil fuels would remain the dominant fuel source globally, with renewable energy playing a very small role. Investment costs in these studies estimated the costs of solar PV to be almost three times larger than coal in baseline scenarios and almost double those of coal in the most optimistic renewable energy scenarios (e.g., Riahi et al. 2007).

The current cost of other electricity fuel sources also drastically differs from what was expected in 2007. In particular, natural gas prices were forecast to remain relatively flat in line with prices expected for 2008 (IEA 2008), but the widespread application of hydraulic fracturing in the United States led to a 41% expansion of US natural gas production despite a 70% decline in prices (IEA 2018a). While less markedly different from expectations, the use of nuclear in global power production decreased since 2007 due to safety concerns, ongoing high costs, and long lead times (Moriarty & Honnery 2012). Overnight construction costs for nuclear power plants have, in the main, not been reduced with increased experience (Loving et al. 2016). Overall, differences between actual and anticipated costs have resulted in marked differences between expected power generation from these sources and actual outcomes.

An interesting observation from the fourth IPCC assessment report is the important role of carbon capture and storage (CCS) as a mitigation measure. Across numerous studies, it was assumed that CCS would be a successful technology and therefore implementable as a significant mitigation measure (see, e.g., Clarke et al. 2007). The inclusion of CCS in emission reduction scenarios, along with the relatively low cost of coal versus renewable energy resources (according to costs around 2007), limited the inclusion of VRE in these scenarios.

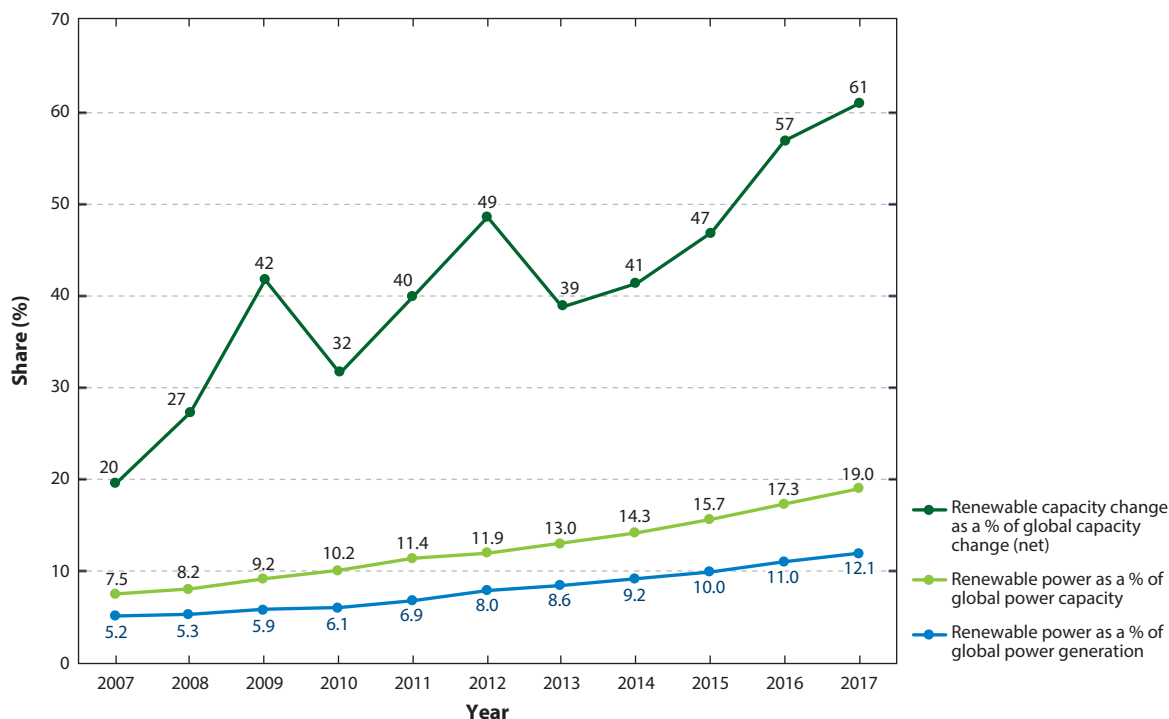
However, in contrast to VRE, developments in CCS technology since 2007 have been slow, relative to expectations, largely remaining in the piloting phase. Expansion of CCS has been dogged by poor economic viability (D'Aprile 2016, Global CCS Inst. 2016). The failure to substantially improve the economic viability of CCS has resulted in unpredictable government support for the advancement of CCS technology and few jurisdictions with a sufficient price on carbon to warrant investments. With low levels of new investment, deployment, and testing to improve efficiency and reduce costs, the expansion of CCS is currently expected to remain slow (D'Aprile 2016).

## 2.2. Investment Volumes and Capacity of Variable Renewable Energy

Due to these (unexpected) shifts in costs, combined with supportive policies, investment patterns in the electricity sector have shifted away from the historical dominance of thermal generation. Global investment in renewable power generation reached nearly \$US300 billion in 2017, or about two-thirds of total investment in power generation (IEA 2018b). From 2010 to 2017, cumulative renewable energy investment reached 2.2 trillion USD (Frankf. Sch. Finance Manag. 2018). With declines in the costs of renewable energy generation, generation capacity per dollar invested has risen rapidly over that same period.

Given these large investments, the power sector has been changing, especially at the margin. As shown in **Figure 3**, the contribution of renewables to net capacity growth more than tripled from 2007 to 2017, reaching 61% of net capacity additions on a global basis. Capacity additions are also increasingly concentrating in the developing world. In 2017, developing countries accounted for 63% of global investment in renewable energy. Developing country investment is mainly concentrated in China, India, and Brazil, who accounted for just over half of global investment in renewables (excluding large hydropower) in 2017, with China alone representing 45% (Frankf. Sch. Finance Manag. 2018). Finally, as shown in **Figure 3**, the proportion of world electricity generated from renewable sources, excluding large hydropower, more than doubled, reaching 12.1% in 2017.

This rise in the share of VRE in the total power mix introduces new challenges, especially if the rates of penetration of VRE continue.



**Figure 3**

Renewable power generation and capacity as a share of global power, 2007–2017, in percentages. Adapted with permission from Frankf. Sch. Finance Manag. (2018).

### 2.3. Systems Integration

The challenge of matching electricity supply with demand is referred to as systems integration and relates to the provision of power to customers on a smooth and continuous basis. When VRE comprises a very small share of the power system, the V in VRE is not particularly problematic. If VRE accounts for less than 10–20% (depending on system size and characteristics) of generating capacity, variation in power output is normally easily accommodated by the remainder of the system. However, concerns regarding the use of variable energy sources arise when integrating weather-dependent (e.g., wind and solar) generators that are nondispatchable (i.e., cannot be called upon when desired) to the power system at large volumes (see Cochran et al. 2012).

Effective systems integration is a nontrivial task when VRE represents a large share of total power generation. At these higher-generation proportions, it is quite possible for leveled costs of energy generation (the metrics depicted in **Figures 1** and **2**) to be misleading. If marginal additions to VRE generating capacity within a given system produce electricity when there is very little demand, then that investment mainly adds to total systems costs without contributing materially to the provision of the actual energy services. One cannot simply assume that the power generated from VRE systems (or some fraction thereof) will meet demand.

In 2007, the systems integration challenge was not of great concern because, as noted in Section 2.1, CCS technologies were anticipated to enable dispatchable generation technologies to predominate while achieving emissions reductions. With (a) the failure of CCS technologies to mature, (b) the reductions in the costs of VRE, and (c) the large global investment streams into VRE that have followed, the systems integration challenge has taken on much greater prominence.

The systems integration challenge also highlights how the technological changes that have characterized the past 10 years have changed the energy planning task, which is the subject of the next section.

## 3. ENERGY PLANNING AND MODELING

Due to the cost declines discussed in Section 2.1, mobilizing investment in renewable energy technologies has become a main mechanism for achieving low-carbon development pathways. A key component in this low-carbon energy transition is to develop coherent techno-economic analyses of how clean energy resources can be integrated into an energy system and the effects of generation from clean energy sources on other parts of the system.

Energy system models have historically played an important role in energy planning and decision making across governments, academia, and industry (Hall & Buckley 2016, Pfenninger et al. 2018); however, the growth of VRE is both shifting the nature of the modeling task and arguably increasing its importance (IRENA 2017a, Weijermars et al. 2012). There are two principal types of energy modeling approaches: (a) top-down approaches that evaluate the macroeconomic relationships between energy and economy (Nakata et al. 2011, Ossenbrink et al. 2018) and (b) bottom-up or structural approaches that represent the energy sector comprehensively to evaluate the technology selections with the best investment options to meet a set of energy demands (Krook-Riekkola et al. 2017). Bottom-up approaches rely on disaggregated data to present energy demands and technology options in detail.

Rapid declines in the costs of renewable generation technologies decidedly favor bottom-up or structural approaches. When CCS was regarded as the major route to emissions reductions on the energy supply side, the envisioned future system differed relatively little from the past. CCS was effectively an extra cost appended to traditional systems and, ideally, a relatively small cost. Hence, historical patterns of energy system responses to shocks or disturbances could be reasonably expected to provide information relevant for future decision making.

When considering a broad-scale transition to VRE, these historical relationships contain far less relevant information. VRE requires a new conception of energy endowments. Within the region being considered (e.g., a country), one needs answers to questions such as:

- Where and when is it windy and sunny?
- How far in advance can wind and sun and, hence, power output be accurately predicted?
- How do these wind and sun endowments vary over space and across time? For example, are there seasonal dimensions to the available endowments (e.g., less sun in the winter)?
- How should wind and solar assets be distributed across space to arrive at a more stable total power output across all generating assets?
- How does a favorable spatial distribution of wind and solar generation assets match up with existing and potential transmission infrastructure?
- How does the distribution of VRE system output, which is driven by weather conditions, match demand patterns, which are socially and economically driven?
- What dispatchable resources (hydropower, thermal generators, and storage) should be used to complement VRE to match electricity supply with demand?

Answers to these questions were nowhere near as pressing 10 years ago as they are today.

VRE is also driving a reconception of the role of hydropower in generation systems. Hydropower is a low marginal cost source of power. Unless the shadow price of releasing water by running turbines is very high, one would typically prefer to supply electricity via hydropower than to run a thermal generation plant, which requires purchase of fuel. Hence, hydropower has served principally as baseload power with the rest of the system adjusting to match supply with demand.

VRE from wind and solar produces power at even lower marginal cost than hydropower. As noted, with hydropower, there are shadow prices associated with the release of water from a dam. By turning turbines on and off, one renders hydropower dispatchable. Gebretsadik et al. (2016) and Rose et al. (2016) illustrate that linked hydropower and VRE systems can substantially increase the value of VRE investments by turning off turbines when it is windy/sunny and VRE output is high and turning on turbines when it is not windy/sunny and VRE output is low.

This opportunity for linking hydropower and VRE generation assets begets further questions, such as: What are the environmental and social impacts of varying hydropower output and, hence, downstream river flow? What are environmentally and socially tolerable anthropogenic contributions to river flow variance? How does staying within these tolerable levels affect the ability of a hydropower dam (or system of dams) to complement VRE output?

Prospects for very cheap power generated at occasional intervals also provoke questions (and modeling needs) on the demand side. Is it economic for electricity-intensive operations (such as smelting) to be designed to operate when power is cheap and be dormant when power is expensive? A predictable seasonal lull in wind or solar power output might be accommodated by temporarily shutting down all or part of an energy-intensive (smelting) operation.

It should be highlighted that, while VRE complicates the systems integration task on an instantaneous basis relative to coal-fired or nuclear energy generation, it simplifies the matching of supply with demand on a longer-term basis. Especially for developing countries, a single additional coal or nuclear facility usually represents a significant expansion of total generation capacity. VRE resources can be added at much smaller increments and potentially closer to demand, thus avoiding the need for additional transmission (while also recognizing that many of the best solar and wind resource areas may be far from demand centers and thus would require access to transmission). Furthermore, under the best of circumstances, construction of large thermal power

generation facilities takes years, thus requiring energy planners to forecast demand up to a decade into the future.

This demand forecasting task is particularly challenging in developing countries where economic growth and, by extension, electricity demand are both relatively rapid on average and highly variable, potentially opening large gaps between forecasted demand and actual demand within only a few years. Failure of supply to keep up with rapid demand growth, and consequent brown outs, carries a significant growth penalty, while excess capacity due to weaker-than-expected demand growth is a waste of scarce investment resources (Foster & Briceño-Garmendia 2009).

In contrast to coal and nuclear facilities, VRE generation is essentially modular. More solar panels and/or more wind turbines can be added to either existing or new solar/wind farms in relatively short order. Or, they can be added incrementally to rooftops or village-based “mini-grids.” Hence, if economic growth is rapid, generation capacity can be added in response. The benefits of the modularity of VRE for countries lacking other low-cost modular options, such as those countries without large and low-cost supplies of natural gas, are almost certainly under-researched and may well be underappreciated.

This is the new world of energy planning, modeling, and operations. It is at once more complex, as weather-dependent VRE elevates the challenge associated with the systems integration task, and simpler as VRE technologies, especially solar, are not particularly difficult to run or maintain. VRE technologies are also modular, allowing for the expansion of total systems capacity in response to growth in demand within months rather than years.

## 4. LOOKING FORWARD

This section first provides a discussion of broad prospects and then looks specifically at the case of South Africa. While South Africa has many features, such as a well-developed power sector, that distinguish it from other developing countries, it benefits from substantial renewable energy endowments, has been active in considering policies for VRE, and has conducted detailed technical and economic analysis. These attributes make it an attractive case study.

### 4.1. Broad Prospects

From a techno-economic perspective, the potential for renewable energy to contribute substantially to GHG reductions while providing reliable and reasonably priced power has increased significantly over the past decades as costs have been reduced, performance has increased, resource potentials have increased with changes in technologies (e.g., taller wind turbines access higher wind speed at higher altitudes), and model improvements have been realized (Edenhofer et al. 2012, GEA 2012, Luderer et al. 2017, Rogelj et al. 2018). Recent 2018 scenarios utilizing updated cost, performance, resource information, and model enhancements indicate significant contributions to potential attainment of the 1.5°C climate stabilization scenarios on the order of 60–80% of global electricity demand by 2050 and range from ~450 EJ/year to 1,000 EJ/year by 2100, including biomass with CCS.

This implies that economic analysis must continue to be updated in order to keep pace with technology advances; increased knowledge of design, operations, and optimization of energy systems; and advances in data science, modeling, and computational resources. As emphasized in Sections 2.3 and 3, a key element is meeting the systems integration challenge as VRE becomes an increasingly important part of the electricity generation mix in increasingly more countries.

There are three causes for optimism that the systems integration challenge will not significantly slow expansion of VRE on a global basis. First, numerous experiences over the past decade



have shown that systems integration concerns can be handled. For example, Denmark, Portugal, Ireland, and multiple additional locations regularly provide 50–100% of total power from VRE sources. Second, while penetration rates are high in some energy markets, in many energy markets, penetration of VRE remains relatively low, rendering systems integration relatively straightforward in the near term.

Finally, the systems integration challenge is practically made to order for modern information, communication, and computing technologies. Moreover, ongoing dramatic declines in the costs of energy storage are expanding the range of viable options for meeting the systems integration challenge. Over the longer term, advancing knowledge of system performance, technological advances in the techno-economics of storage, and institutional reforms such as improved market design (Cochran et al. 2013, Liebreich 2017) warrant increased optimism that power (and more broadly, energy) systems based predominantly on VRE will offer reliable, resilient, and affordable solutions in most locations of the globe (see REN21 2018).

## 4.2. The Case of South Africa

VRE costs in developing countries have declined in line with global developments (see Figure 4). In some developing nations, VRE has become cost comparable with new builds of traditional fossil fuel technologies. South Africa is a prime candidate for exploitation of VRE due to high-quality renewable energy endowments. Figure 5 compares estimated solar PV potential in South Africa with estimated PV potential in Germany. The key to reading Figure 5 is to note that not only are the scales in the German and South African maps different but they are nonoverlapping. Specifically, the lowest power output in South Africa is greater than the highest in Germany. South African wind resources, shown in comparison with the rest of sub-Saharan Africa in Figure 6, are also world class and reasonably well distributed throughout the country (Merven et al. 2018).

Despite these endowments, and like almost everywhere else, energy planning in South Africa a decade ago did not consider the potential for the substantial declines in VRE costs actually

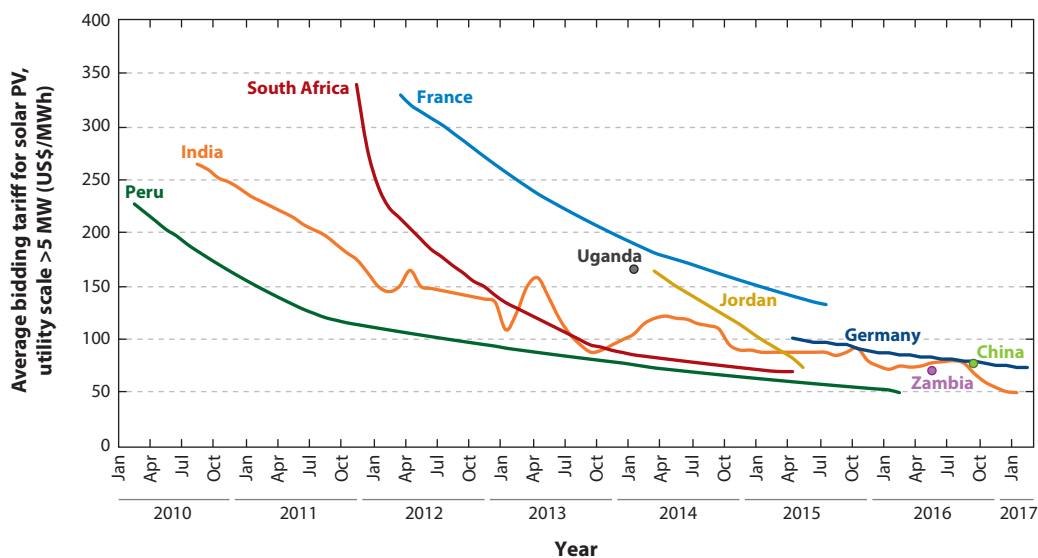
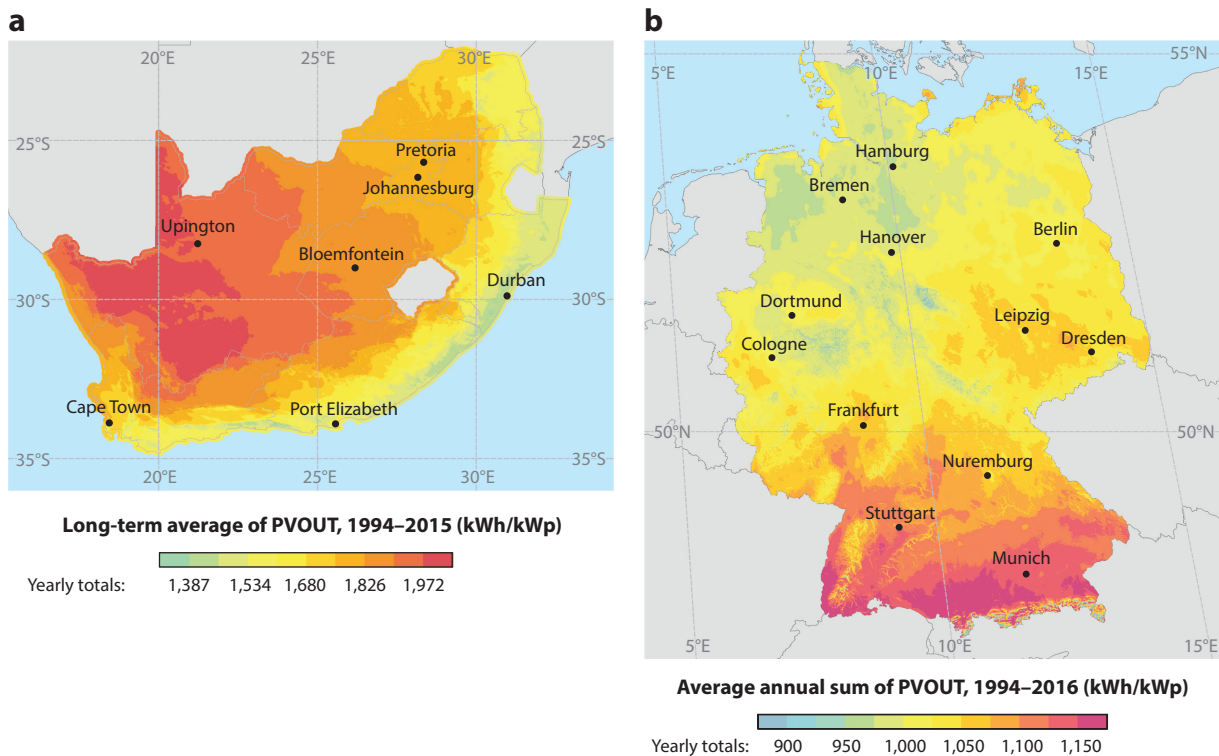


Figure 4

Average bidding tariff for solar photovoltaic (PV) with a utility scale > 5 MW. Based on data from IRENA (2018).



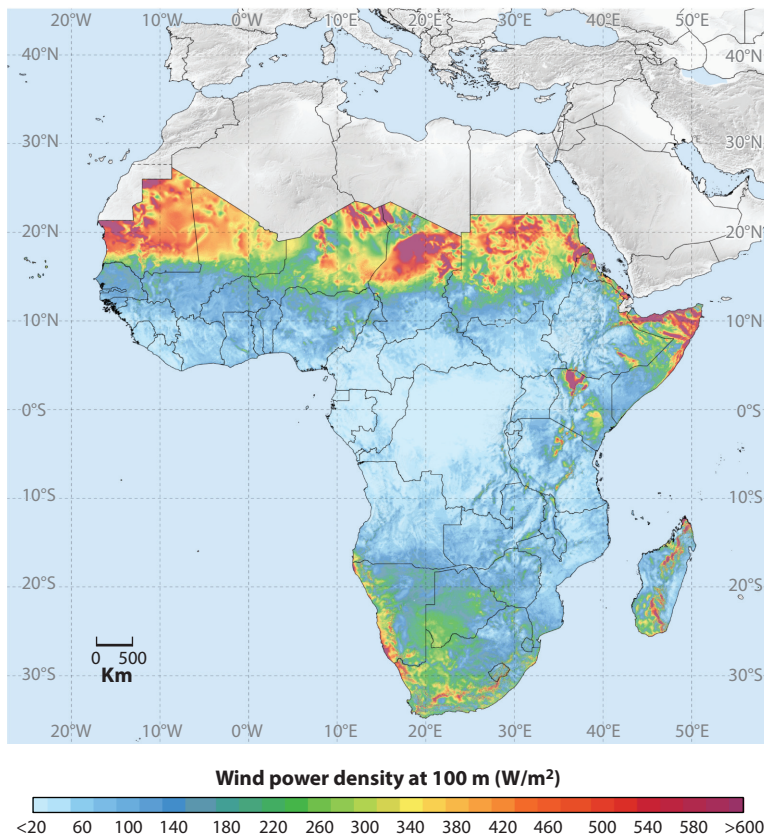
**Figure 5**

Photovoltaic (PV) power potential output in (a) South Africa and (b) Germany. Note that the legends differ and are in fact nonoverlapping. Panel a adapted with permission under the terms of the Creative Commons Attribution (CC BY 3.0 IGO) License, <http://creativecommons.org/licenses/by/3.0>. Copyright 2017, World Bank and Solargis (<https://solargis.com>). Panel b adapted with permission under the terms of the Creative Commons Attribution (CC BY-SA 4.0) License, <http://creativecommons.org/licenses/by/4.0>. Copyright 2019, Solargis (<https://solargis.com>).

experienced. In the 2007 South African Long-Term Mitigation Scenarios (LTMS), coal and nuclear power accounted for approximately 90% of total electricity production by 2050, with older retiring plants being replaced by more efficient plants (primarily integrated gasification combined cycle plants). VRE was not included in the baseline generation mix, and the only renewable energy resources included were hydropower and biomass (<1% of total capacity).

In the 2007 LTMS, VRE had to be forced into the electricity power mix as a mitigation measure. Due to high costs (e.g., solar PV was assumed to be five times more expensive than coal), this forcing resulted in negative estimated economic and welfare impacts (Scenar. Build. Team 2007).

In reality, VRE deployment in South Africa has been increasing since the implementation of the Renewable Energy Independent Power Producer Programme (REIPPP) in 2011. With these policies, South Africa occupied the leading edge of a global shift of financial support policies from subsidy-support schemes to competitive auctions. By the end of 2017, 3.2 GW of renewable capacity had already been installed in South Africa, with an additional 2.5 GW expected by 2020 (Eskom 2017). The experience in South Africa has been echoed elsewhere, with renewable power frequently winning technology-neutral auctions in multiple countries (Azuela et al. 2014, Lucas et al. 2013, SE4ALL 2016).



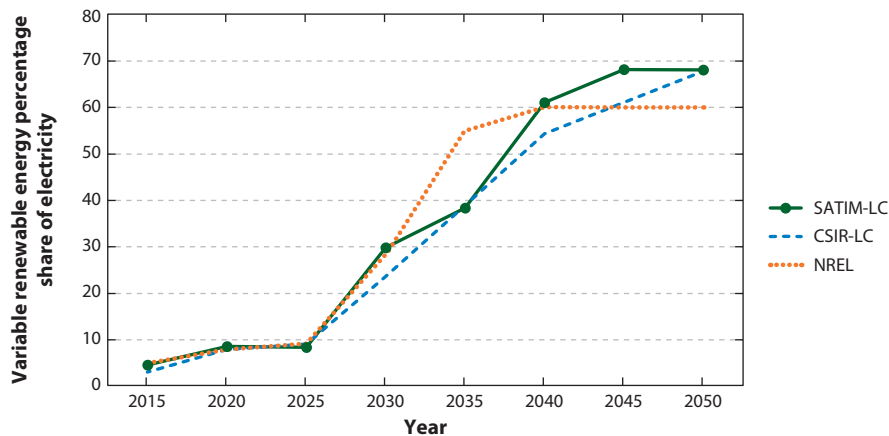
**Figure 6**

Africa wind power density potential. Data and map from Global Wind Atlas (<https://globalwindatlas.info/en/area/South%20Africa?print=true>). Adapted with permission under the terms of the Creative Commons Attribution (CC BY) License, <http://creativecommons.org/licenses/by/4.0>.

Looking forward, the 2018 Integrated Resource Plan (IRP), the most recently released electricity plan for South Africa, expects VRE to account for 21% of total electricity production by 2030, up from 14% and 10% in the 2016 and 2010 IRPs, respectively (DOE 2011, 2016, 2018).

However, in stark contrast to the energy planning model outcomes in 2007, the models underlying the 2018 IRP forced VRE out of the generation mix by capping annual new solar PV and wind capacities by 1 GW and 1.8 GW (DOE 2016), respectively, rather than into it as before. Least-cost optimization scenarios discussed by Merven et al. (2018), Reber et al. (2018), and Wright et al. (2017) show that if new VRE capacity is not constrained as in the IRPs, VRE could account for  $\pm 30\%$  of total electricity generation by 2030 and  $\pm 70\%$  by 2050 (see **Figure 7**).

In these approaches, the systems integration challenge is met principally by (a) distributing renewable generation assets throughout the country creating a portfolio effect on total power output, (b) transmission, and (c) natural gas-based generation that flexibly balances loads. An even more recent study by McCall et al. (2019) finds that with current and expected declines in battery costs, the role of natural gas is replaced by batteries. Hartley et al. (2019) further show that increased VRE deployment can be achieved without negatively affecting economic



**Figure 7**

Projected variable renewable energy percentage share (wind and solar) in South Africa from three recent analyses. Adapted from Merven et al. (2018).

growth and development. Rather, a growth boost, including a boost to manufacturing output and employment due to lower electricity costs, is more likely.

Appreciation of this positive long-run outlook is tempered by significant shorter-run concerns. Financial woes at the state-owned utility, Eskom, are being aggravated by defections from the grid to small-scale VRE systems, leading to concerns of a “death spiral,” as better customers are likely to have a higher propensity to defect. Prospects for a long-run contraction of coal output, reaching negligible levels before midcentury, are not broadly welcomed by mining companies, labor unions representing miners, and mining communities. These observations highlight the need for institutional and policy innovations to accompany the remarkable engineering triumphs that were presented in Section 2.

### 4.3. Energy and Security

The topic of energy security merits mentioning. Energy security is also being fundamentally rethought in this new era when renewable energies can contribute significant portions of a country’s energy use (see Global Comm. Geopolit. Energy Transform. & Van de Graaf 2019 for a recent and comprehensive review). Unlike conventional methods of producing electricity, renewable energy generators do not rely on fuel supply chains that can be disrupted intentionally or by natural events. Unlike combustible fuels and nuclear power, renewable energy does not pose a risk of dangerous leaks or explosions that threaten human health and public safety. VRE generation assets as a whole are also relatively difficult to destroy, due to their dispersion, and relatively easy to build. As noted toward the end of Section 3, renewable energy generation facilities can be constructed within short time frames (typically a few days for small distributed systems to a few months for larger-scale systems).

With growth in VRE, the nature of energy security concerns is likely to change. Concerns with access to fuels on international markets, such as coal and natural gas, may recede, but concerns with energy trade may well remain. For small countries in particular, the logic of distributing VRE-generating assets across space may put a higher premium on regional power pools, increasing regional interdependence. While geographic diversity of generation assets reduces their vulnerability to acts of terrorism, distribution networks will remain vulnerable. Locations with highly

favorable renewable energy endowments, such as strong and consistent wind velocities, may become somewhat akin to those with hydropower resources, whose power already frequently crosses national borders (Coester et al. 2018; Geels et al. 2017a,b).

These aspects add to an increasingly complex geopolitical landscape, where historical alliances, trade and domestic energy policies, and related economics are undergoing currents of change. Examples extend from Saudi Arabia where they have made significant commitments to develop—now highly competitive—renewables for domestic consumption while simultaneously reducing domestic petroleum consumption, to Denmark, which has committed to a 100% renewable power grid by 2050 as a combined commitment to address climate change and economic conditions. The decision paradigms for each country vary based on a complex set of factors, including energy access, development, domestic resource endowments, geopolitics, and macroeconomic factors.

## 5. RENEWABLE ENERGY AND DEVELOPMENT

In many developing countries, penetration of VRE began at small scales with small and medium enterprises focused on equipping households, health clinics, and/or schools with clean energy solutions. These typically involved the use of solar panels with batteries to provide a few hours of (a) nighttime power for lights, radio, and television; (b) water pumping and/or purification; (c) cell phone charging; and/or (d) other low electrical demand processes. Clean energy options were viewed as offering initial steps for improving education, providing clean water, reducing health impacts (e.g., reducing indoor air pollution), and increasing economic activity of small and medium enterprises (Kumar et al. 2017, McCollum et al. 2018, UNDP 2013, UNEP 2011, World Bank 2012).

These early clean energy applications provided clear lessons learned (Sovacool 2012). With the advance of clean energy technologies over the past decade, companies now offer a wide range of products and financing options, including village-level mini-grid systems and opportunities to leverage other infrastructure, such as cell phone communications (Bazilian et al. 2012a,b; Bhattacharya 2018; Cebraal et al. 2005; Dincer 2000; Yadoo & Cruickshank 2012), serving higher energy demands and supporting more advanced or extensive enterprise energy needs.

Advances have also been made in the pace of adoption. For example, in 2009–2010 in Myanmar, there were essentially no households reliant on solar power for lighting. By 2017, fully one-third of rural households relied on solar power for lighting (World Bank Group 2018).

For some time, observers have recognized that clean energy solutions, especially VRE, offer a pathway toward lower GHG emissions (Arent et al. 2011, Edenhofer et al. 2012, GEA 2012, World Bank 2012). The distributed nature of VRE, especially solar, has also long been recognized for its potential to serve dispersed rural populations. Because rural populations lacking access to electricity grids in developing countries are often poor, there are good arguments that clean energy solutions, such as those discussed in the immediately preceding paragraphs, have been particularly effective for inclusive growth for those near the bottom of the pyramid (Bhattacharya et al. 2016, GEA 2012, McCollum et al. 2018, World Bank 2012, Zinaman et al. 2015).

Increasingly, multiple factors suggest that VRE will be viewed and deployed as a force for economic transformation. These include:

- The rapid cost declines discussed in Section 2;
- The relatively large endowments of VRE, notably solar, in many developing regions;
- The developed world's growing experience with VRE, often with less favorable endowments (e.g., solar power in Germany), combined with positive experiences from other leapfrogging technologies such as cellular telephony; and
- The inherent advantages of VRE for rural electrification.

The case of South Africa, discussed in Section 4.2, points to this much broader conception of VRE as a key supplier of energy that integrates into a comprehensive strategy for inclusive, sustainable economic development.

In terms of realizing this broader conception of VRE, drawing from the experience of the past decade of integrating VRE into development plans is a good place to start. More than 175 countries have policies or goals in place (REN21 2018) that address development, sector-specific energy related goals, or goals that are economy wide. These span rural electrification policies and programs, specific deployment targets, finance mechanisms such as feed-in tariffs, carbon legislation or the establishment of regional taxes, cap and trade systems, and many combinations of these and other options. Additionally, the development and enforcement of technical standards, training certification, and education campaigns have proven to be critical elements of sustained impact (Doris 2012).

Cochran et al. (2012) assessed regulatory approaches for effectively integrating renewable energy into twenty-first-century power systems in a suite of case studies. They recommended:

- Engaging the public early, particularly for new transmission;
- Coordinating and integrating planning across supply and demand resources and across centralized and distributed resources;
- Developing market rules that encourage system flexibility; and
- Expanding access to diverse resources via expanded balancing areas.

Other work highlights the needs for flexibility in modern power systems (IEA 2018a, Lund et al. 2015, Mileva et al. 2016). Countries with aging infrastructure and slow capital stock turnover will likely need to address the issue of retiring old capacity that no longer meets modern standards for flexibility, resource utilization (e.g., water), or pollution. More generally, developing next-generation power systems will mean moving beyond specific renewable support policies and toward more general market-based solutions (IEA 2018a).

Electricity market rules play an increasingly central role in delivering sufficiently attractive returns for investors. Rules and institutions will likely need to be reformed as the sector moves to technologies with higher capital costs and low—often very low—operating costs (Blyth et al. 2012, Green & Vasilakos 2010, Obersteiner & Saguan 2010, Pöyry Energy Consult. 2009, Sáenz de Miera et al. 2008, Sensfuß et al. 2008).

Power system governance reflects a tension between the need to reliably meet current demand and simultaneously prepare for the future. Any proposed reforms to the architecture of power system governance must strike a “tenuous balance between the determination and efficiency needed to drive energy transitions with the flexibility and innovation necessary to deal with complexity and uncertainty” (Cherp et al. 2011, p. 75). Short-term operational challenges must be balanced with long-term power policy goals and interaction with other critical infrastructure, information systems, and social considerations (Bistline 2017, IEA 2018a). To this end, standards, policy, regulation, and institutional constructs must be set and markets designed to properly align electricity industry incentives with policy goals.

Early lessons from renewable energy policy formulation indicate that durable, adaptable policies that minimize policy-related risks are important to sustaining transformation and attracting the necessary capital through either public or private channels (GEA 2012, NRC 2011, REN21 2018). Further, well-formulated policy portfolios are likely more effective at enabling broader, sustained change (Doris 2012, Flues et al. 2014, GEA 2012, NRC 2011, World Bank 2012).

Incorporating past policy lessons, while simultaneously anticipating continued advances in technologies, consumer adoption, business/financing solutions, as well as infrastructure improvements and build-out, poses increasing policy complexities that demand new thinking and



policy insights. New tools, building on now-available data and modeling capabilities discussed in Section 4, offer options to inform policy and other decisions. These capabilities increasingly add value to integrated energy-economic decision making that crosses traditional sector boundaries such as transportation and power, power and industry, and the energy-water-food nexus (Kumar et al. 2017).

These more wholistic approaches are also at the core of Shared Socioeconomic Pathways and the 1.5-degree pathways that have recently been evaluated for consideration as countries contemplate actions to achieve local and Paris Agreement-related goals and ambitions (McCollum et al. 2018; Rogelj et al. 2015, 2018).

## 6. DISCUSSION AND CONCLUSIONS

Historically, energy has transitioned through two principle paradigms relative to availability, use, productivity, and economics. Before mechanization, energy resources were predominantly local—water- or wind-powered mills as well as crops and forests for heat and cooking. The advent of connected systems, such as the power grid and oil and gas networks, enabled a fundamental shift in paradigm to one of large-scale production (e.g., a coal-power-generating station or large refinery), with concomitant economies of scale on the production side. This paradigm of large-scale operations and extensive distribution was a fundamental component of development in many countries.

Today, energy systems, particularly power, are simultaneously trending toward even larger-scale integration of operations and returning to systems that again incorporate more local solutions. On the large-scale side, there are incentives to capture power where endowments of sun and wind are most favorable and rely on transmission across an array of generating locations to create a portfolio effect that produces a relatively stable volume of power at the system level. At the same time, solar power, microhydropower generators, hybrid systems (of many components), batteries, and smaller diesel “gensets” are part of a large suite of reliable, cost-effective energy sources that can enable the full suite of energy services—lighting, cooking, heating, and air conditioning as well as productive services for small, medium, and even large enterprises.

In short, today’s reliable, affordable, and resilient energy options are driving a new paradigm of heterogeneity. Distributed solutions today offer increasingly compelling economics for those without access to traditional energy carriers, suggesting a fundamental reconsideration of infrastructure policies, energy access solutions, and economics that do not rely on uniform—or old and outdated—assumptions of energy systems and embracing a portfolio of solutions versus singular approaches.

Smaller-scale renewable-based energy systems are becoming increasingly attractive economically, offering rapid scalability and applicability to serve growing energy demands and provide critical services (such as communications, lighting, and water pumping/purification). Utility-scale VRE offers the potential to substantially reduce local air pollution, drastically cut GHG emissions, and provide reliable energy at low cost. Application of the appropriate mix of these heterogeneous energy systems offers developing countries another opportunity for leapfrogging. Much as cell phones and wireless technologies have transformed communications in developing countries, distributed, affordable, and clean energy systems offer a compelling opportunity to leapfrog traditional energy paradigms.

Overall, these energy trends are potentially very good news for the world in general and developing countries in particular. VRE holds the prospect that developing countries can meet growing centralized power demands at low cost, using domestic (or regional) endowments while emitting very little pollution. At the same time, VRE systems offer unprecedented opportunities to provide energy at reasonable cost to dispersed rural populations. The challenges to realizing these

potentials are daily becoming less technical and more institutional. New best practices, market structures, financial tools, and exemplary policies will be identified as power systems around the developing world integrate new levels of variable renewables. Countries should strive to think creatively about the opportunities afforded by low-cost VRE and continue to share lessons learned.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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### Errata

An online log of corrections to *Annual Review of Resource Economics* articles may be found at <http://www.annualreviews.org/errata/resource>