Designing Low Carbon Electricity Futures for African and Other Developing Economies

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Policy Briefing Paper
October 2015

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Published October 2015

International Rivers
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Cover Photo: SolarReserve's 96 megawatt Jasper Solar PV Plant in South Africa

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Low Carbon Electricity Futures

Large-scale development of renewable energy technologies,[1] especially wind and solar, can enable African and other developing economies to meet their energy security and energy access goals and leapfrog into a low-carbon electricity future.

Coal and large hydroelectric power continue to be the dominant sources of electricity generation producing 40% and 17% of the world's electricity in 2014, respectively (IEA, 2015). Coal-based generation continues to expand, especially in China, India, and South Africa (IEA, 2014). Large hydroelectricity capacity is also expected to increase, with at least 3,700 dams with a capacity of more than 1 MW either planned or under construction, primarily in developing countries (Zarfl et al., 2014). Africa uses only 8% of its identified hydropower resources, and the World Bank has pledged US$5 billion for energy projects in Africa, with hydroelectricity being the key target of this investment (Darby, 2014).

The prevailing notion is that coal and large hydro can provide the least expensive electricity to meet the energy goals of developing economies. Yet, past experience and future trajectories point to underestimated and ever-increasing costs of these technologies, which often do not account for the costs of social impacts, global and local environmental pollution, and climate change risk that these technologies pose for society. Alternatively, utility-scale renewable energy technologies such as wind, solar, and geothermal not only have the potential to provide environmentally and socially sustainable energy, but are also increasingly cost-effective for consumers.

Although wind and solar resources are abundant throughout the world (Lu et al., 2009), their dependency on uncontrollable factors such as weather and cloud cover result in both variability and uncertainty in their generation patterns, which are the biggest impediments to their development from the perspective of electricity grid management. However, countries and regions with high shares of wind and solar in their energy mixes such as Denmark and Germany have pioneered and adopted strategies, planning tools, and technologies to cost-effectively and reliably manage these integration challenges. Some of these strategies include:

1) improved electricity grid operational practices using more precise forecasting;
2) building transmission interconnections between regions and countries to share resources;
3) using detailed studies and tools to support appropriate siting of renewable energy plants;
4) designing energy markets that will enable efficient buying and selling of electricity across regions; and
5) investing in supply-side and demand-side resources that enable a more "flexible" grid.

By leveraging these strategies, practices, and technologies early in the evolution of their electricity grid systems, African and other developing economies have the potential to leapfrog to clean, reliable, low-impact, and cost-efficient energy systems and avoid increasingly riskier investments in coal and large hydroelectric dam projects.

In this paper, we examine several recent studies to assess the prospects for renewable energy development in developing countries, with a particular emphasis on African countries. We first demonstrate that the changing economics of wind and solar technologies are making them increasingly cost-effective, while coal and large hydroelectric projects are becoming riskier investments due to significant cost overruns, uncertainty in future fuel costs, and climate change. We then present the evidence of large potential for wind and solar resources and discuss opportunities for their development with low social and environmental impacts. Finally, we highlight different emerging strategies that are being deployed around the world to efficiently manage the variability and uncertainty of large-scale grid-connected wind and solar energy generation.

HOW DO THE COSTS AND FINANCIAL RISKS OF RENEWABLE AND CONVENTIONAL GENERATION COMPARE?

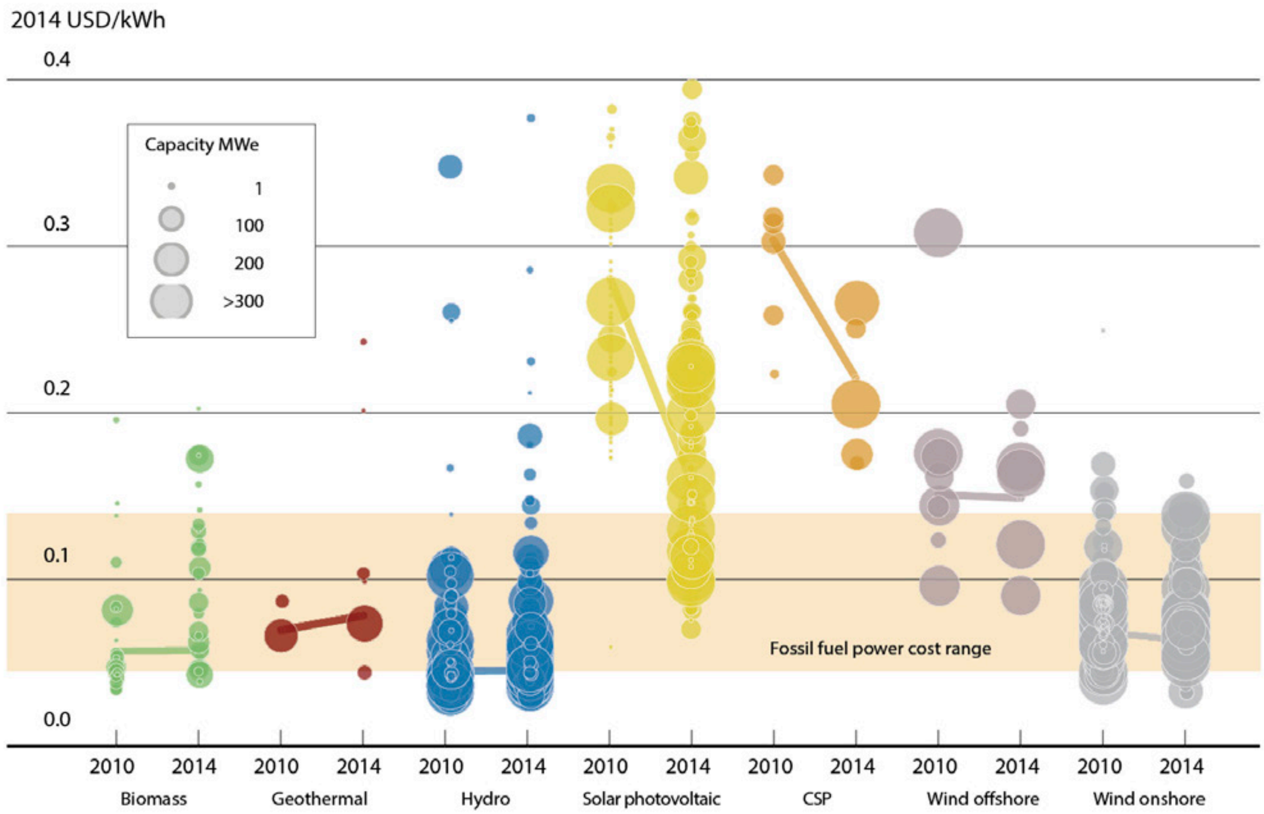
Wind and solar technologies are becoming increasingly cost-competitive

A comparison of the most recent data on the cost of energy projects, measured in levelized cost of electricity (LCOE),[2] across different generation technologies shows that the large majority of international wind projects and an increasing number of solar photovoltaic (PV) projects are cost-competitive with those of hydropower and fossil fuel technologies (Taylor et al. 2015), as shown in Figure 1. Solar PV's large declines in cost in just the last few years have brought it within the range of conventional generation. Even without subsidies, solar PV has achieved grid parity in at least 15 different markets globally—including China and Mexico—as of 2014, and with rising electricity prices across the world and declining prices of solar, it is likely that many more countries will join the list (Branker et al., 2011; Shah et al., 2014). For example, the average cost of solar PV in Kenya was estimated to be over €200 per MWh in 2010, but is expected to drop to €140 by 2020 (Schmidt et al., 2012), which would bring Kenyan solar PV within the current range of fossil fuel and hydropower costs. Current average wind costs, including those in emerging economies, are already highly competitive with hydropower costs, as shown in Figure 1. However, cost input assumptions could change the outcomes of these renewable versus conventional cost comparisons. For example, it is unclear whether the reported study-specific costs of conventional generation account for construction cost overruns, fossil fuel subsidies, or possible increasing inter-annual climate-change-induced variations in hydropower generation observed in recent years, which has led to reliance on expensive diesel-based emergency generation.

A renewable energy zoning study that estimated the total cost per unit of energy at sites suitable for wind and solar development in the Eastern and Southern African Power Pools (EAPP and SAPP) identified several countries with significant solar PV and wind potential that would cost less than US$130 and US$75 per MWh over their project lifetimes, respectively[3] (Wu et al., 2015), as shown in Figure 2. These cost estimates indicate increasing cost-competitiveness of wind and solar technologies.

Figure 1. Comparison of levelized cost of electricity (LCOE) for utility-scale renewable technologies and hydropower in 2010 and 2014.

The majority of wind projects and an increasing number of solar photovoltaic (PV) projects are cost-competitive with those of hydropower and fossil fuel technologies, with solar PV's large declines in cost in just the last few years bringing it within the range of conventional generation. This figure is reproduced from Taylor et al., 2015.

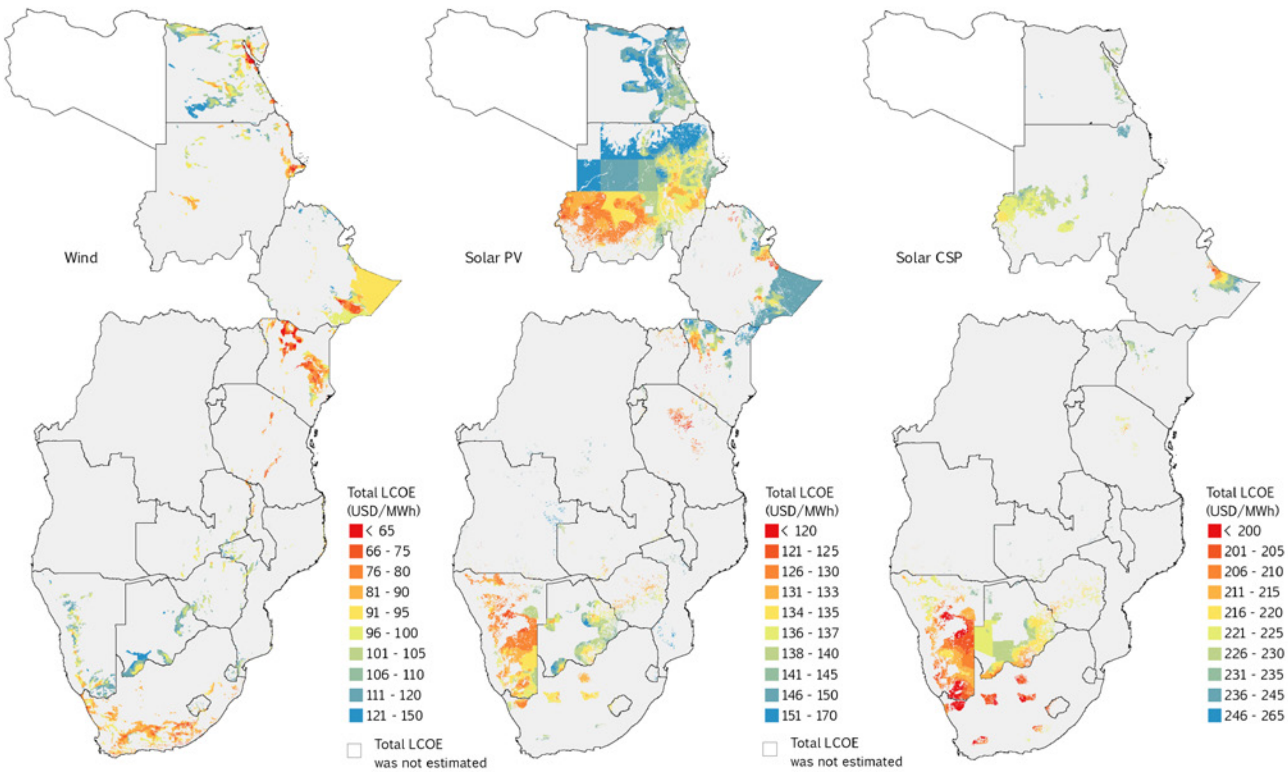


Source: IRENA Renewable Cost Database.

Note: Size of the diameter of the circle represents the size of the project. The centre of each circle is the value for the cost of each project on the Y axis. Real weighted average cost of capital is 7.5% in OECD countries and China; 10% in the rest of the world.

Figure 2. Total cost per unit of electricity for wind, solar PV, and solar CSP zones in the Southern and Eastern African Power Pools.

Several countries have significant solar PV[4] and wind potential that could cost less than US$130 and US$75/MWh, respectively. Total costs per unit of electricity over the project's lifetime include the cost of generation and estimated transmission and road connection costs. This figure is reproduced from Wu et al., 2015.



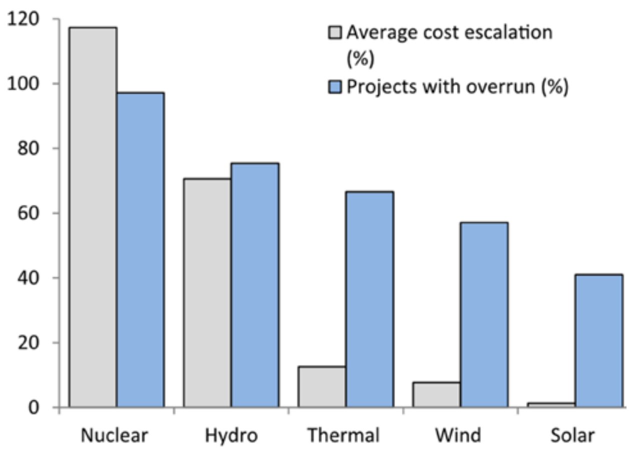
Wind and solar PV can scale up with limited financial risk and low cost overruns

Two recent groundbreaking studies comparing financial risk and cost overruns between generation technologies found that amongst low-carbon options, wind and solar are significantly less financially risky than hydroelectric dams (Sovacool et al., 2014a, 2014b). The authors tested six hypotheses about construction cost overruns and found statistically significant evidence that amongst five generation technologies (hydroelectric dams, nuclear, thermal, solar, wind), hydroelectricity was the only technology for which the larger the power plant was, the more likely and greater was the cost overrun (Sovacool et al., 2014a). Cost overruns, seen in over 70% of both hydroelectric dams and nuclear power projects in the study sample, resulted from longer times to project completion. While 40% and 60% of the solar and wind projects, respectively, in the study sample had cost overruns, the actual cost of overruns as a percentage of total investment was quite small, especially compared to hydro and nuclear projects (Sovacool et al., 2014a), as shown in Figure 3. It is worth mentioning the authors' following explanation for why cost overruns are highly problematic: "Cost overruns are bad for planners, who cannot adequately compare the costs of different options; bad for investors, who lose money on a project, or in the extreme, go bankrupt; and bad for environmentalists, who may be inadvertently supporting infrastructure that does not get built when, and at what cost, they thought it would" (Sovacool et al., 2014b).

These two complementary studies follow and largely agree with a recent study by Ansar et al. (2014) that used the largest reference dataset on large hydroelectricity dams to determine that on average, actual costs of large hydropower plants were double the budgeted costs (Ansar et al., 2014). Thus, lower financial risk and cost overruns make wind and solar projects financially more attractive than large hydro and nuclear technologies.

Figure 3. Amount and frequency of cost overruns by technology.

Figure reproduced from Sovacool et al., 2014a.



Overall financial benefits of wind and solar projects are significant

Wind and solar generation, with their fast deployment times, are well poised to address the severely resource-constrained power systems of many African countries, which have previously relied on expensive backup and emergency diesel generation (Foster and Steinbuks, 2009). Wind and solar have been able to alleviate the burden of high fossil fuel prices and the economic and social costs of curtailing demand.

A series of studies released by the South African Council for Scientific and Industrial Research (CSIR) found that electricity generated from 1.8 GW of competitively-bid wind and solar PV projects in South Africa created notable financial benefits in both 2014 and the first half of 2015 (Bischof-Niemz, 2015; Calitz et al., 2015). In 2014, the financial benefit specifically attributed to diesel and coal fuel cost savings was estimated at US$280 million, and those attributed to the delivery of 117 hours of otherwise "unserved energy" was US$130 million (Bischof-Niemz, 2015). Meanwhile, large hydropower and coal projects, many of which require many years to complete and often experience project delays (Sovacool et al., 2014a, 2014b), often fail to realize the social benefits of meeting existing unserved energy needs.

Policy incentives and market mechanisms can significantly alter costs

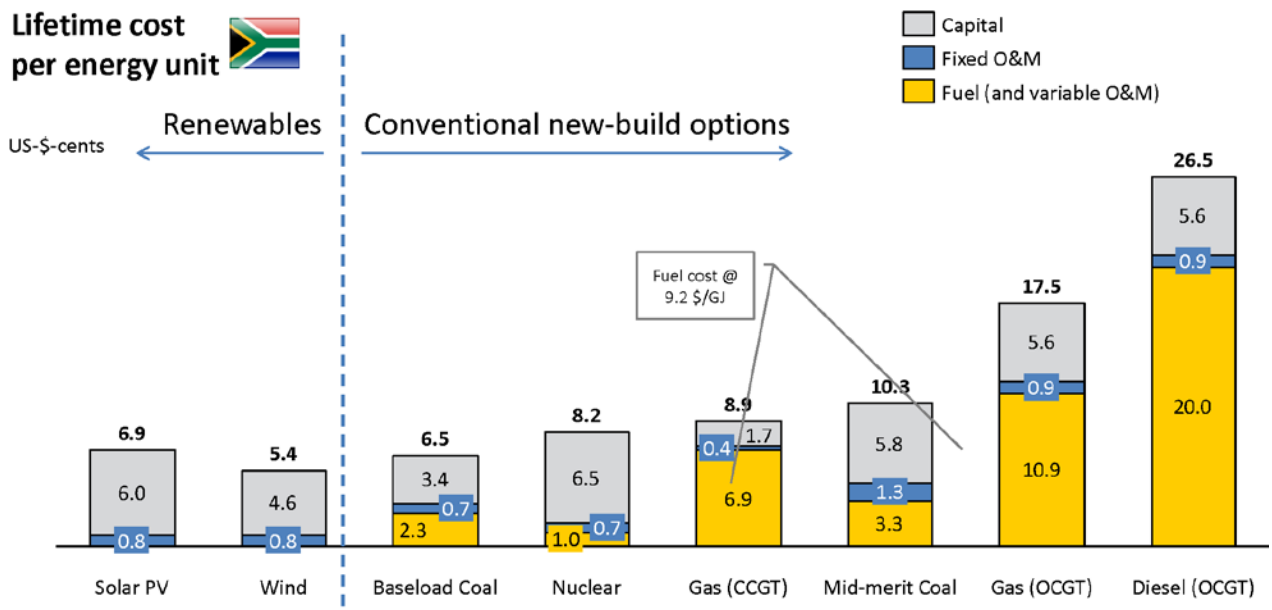
It is insufficient to simply examine the technically-informed differences in LCOEs of electricity generation technologies. Fossil fuel subsidies are a major hindrance to growth of renewable energy in developing countries (Schmidt et al., 2012; Wooders et al., 2014). Also, the choice of financial incentive mechanism for wind and solar energy significantly affects the cost to utilities and consumers (Mukasa et al., 2015).

A feed-in-tariff policy mechanism, where a generation facility is guaranteed a predetermined price from their utility for each unit of electricity generated and sold to the utility, may reduce the risk for a project developer and incentivize greater investments. However, such a mechanism, which has been implemented in four sub-Saharan African countries, may not promote price competition, especially if regulators have little information about actual costs to make informed decisions on setting the feed-in tariffs. Auction mechanisms or competitive bidding, where developers compete for a fixed renewable energy generation target by offering price bids, has proven to be a successful alternative.

As an example, South Africa's multi-round competitive bidding procurement process significantly reduced the solar PV and wind tariffs by 68% and 42%, respectively (Eberhard et al., 2014), effectively making solar and wind the lowest-cost options for new generation in South Africa (See Figure 4). Similarly, auctions for procuring solar energy capacity under India's National Solar Mission reduced the tariff offered to developers by up to 40% compared to the previously set feed-in tariff, allowing regulators to capture the sharp drops in solar PV prices (Azuela et al., 2014; Deshmukh et al., 2011). Appropriate policy incentives and market mechanisms can enable cost-effective deployment of renewable energy.

Figure 4. Solar and wind cheapest new build-out options per kWh in South Africa.

In the fourth and most recent bid-window of South Africa's competitive bidding program for wind and solar generation, costs fell below that of conventional generation options. Figure reproduced from Bofinger et al., 2015.



WHAT IS THE POTENTIAL OF WIND AND SOLAR ENERGY RESOURCES?

Many of the emerging economies observing the largest growth in large hydropower, namely China, India, and many Latin American countries such as Brazil, are also well endowed with plentiful wind and solar resources. The most recent estimates of wind energy potential in India are around 900 GW of installed capacity, with values ranging from 700 to 1500 GW, depending on the wind turbine height and land cover exclusions imposed (Hossain et al., 2011; Phadke et al., 2012).

China, with the largest electricity demand in the world, has the potential to generate about 70,000 TWh of solar PV electricity annually, more than ten times its electricity demand of 5,550 TWh in 2014 (He and Kammen, 2016). Another study determined that cost-effective wind potential in China could meet its entire demand in 2030, or roughly twice its demand in 2009 (McElroy et al., 2009); all "viable" wind potential has recently been estimated to be around 3,500 TWh (He and Kammen, 2014).

Brazil's wind resources are equally abundant relative to its demand, with more than 7,000 TWh of potential annual generation (Dutra and Szklo, 2008). A study simulating future wind conditions in Brazil suggests that wind potential will not be adversely affected under possible future climate change scenarios (Pereira de Lucena et al., 2010), unlike its large hydropower capacity (de Lucena et al., 2009).

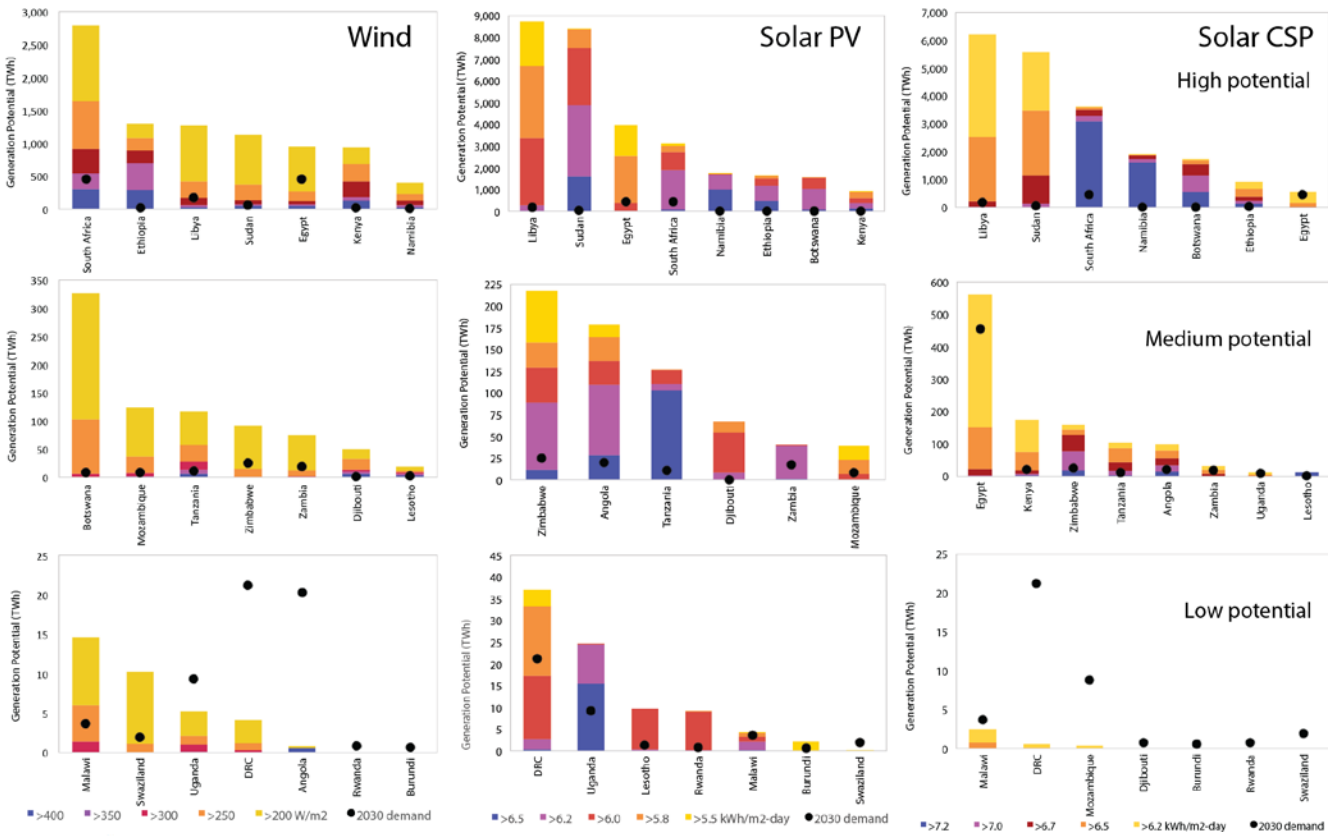
The few studies that have quantified renewable resources in African countries have also demonstrated large potential across the continent (Hermann et al., 2014; Wu et al., 2015). As shown in Figure 5, the potential electricity generation from wind, solar PV, and concentrating solar power (CSP) resources in the 22 member countries of the Southern and Eastern African Power Pools (SAPP and EAPP) varies significantly between countries, but resources of each technology are sufficient to meet projected 2030 demand in at least two-thirds of all countries (Wu et al., 2015).

High quality wind (>300 W/m^2) and CSP (>6.7 kWh/m^2/day) resources can meet 2030 demand in at least one-third of all countries, and this is true of solar PV (>6.0 kWh/m^2/day) for at least 15 countries (Figure 5) (Wu et al., 2015). Therefore, resource-sharing through regional transmission interconnections will be necessary to ensure that all countries within the region benefit from clean and cost-effective electricity.

Although a parallel study does not exist for West Africa (the ECOWAS electricity coordinating area), resource assessments indicate that solar and wind energy are plentiful, with 40,000 TWh of potential annual wind generation, 100,000 TWh of potential annual solar PV generation, 22,000 TWh of potential annual CSP generation in West Africa (Hermann et al., 2014). As is clear from available studies, resource abundance and quality are not barriers to wind and solar development in Africa.

Figure 5. Resource potential of wind, solar PV, and CSP and projected electricity demand in 2030 for 22 countries within the Southern and Eastern African Power Pools.

The projected 2030 demand for each country are provided as a reference to determine relative abundance of each resource (Eastern Africa Power Pool et al., 2011; Southern Africa Power Pool and Nexant, 2007). This figure is reproduced from Wu and Deshmukh et al. in prep.



Dual land use in Kenya for livestock and wind turbines

WHAT ARE THE OPPORTUNITIES TO MINIMIZE THE ENVIRONMENTAL AND SOCIAL IMPACTS OF WIND AND SOLAR ENERGY, AND CAN THEY IMPROVE DEPLOYMENT EFFICIENCIES?

Since wind and solar resources are spatially dispersed, with high quality solar resources being especially pervasive (Wu et al., 2014), many opportunities exist for socially and environmentally responsible solar and wind development. Recent studies have demonstrated the large potential for low-conflict wind (Kiesecker et al., 2011) and solar development (Cameron et al., 2012; Hernandez et al., 2015; Stoms et al., 2013) on marginal or disturbed lands in the United States, even in regions with multiple and tightly competing land use values such as California in the United States.

The only study to examine opportunities for cost-effective and low-impact wind and solar development at a regional scale in Africa did so by quantifying the trade-offs between direct capital and operational costs and more difficult to monetize environmental and construction costs associated with siting choices (Wu et al., 2015). Wu et al. (2015) quantified the distance to the nearest major load center, distance to the nearest transmission or substation, and human footprint score for every identified wind and solar energy zone in the Eastern and Southern Power Pools (EAPP and SAPP). These three criteria were selected to capture possible environmental impacts of power plant siting.[5]

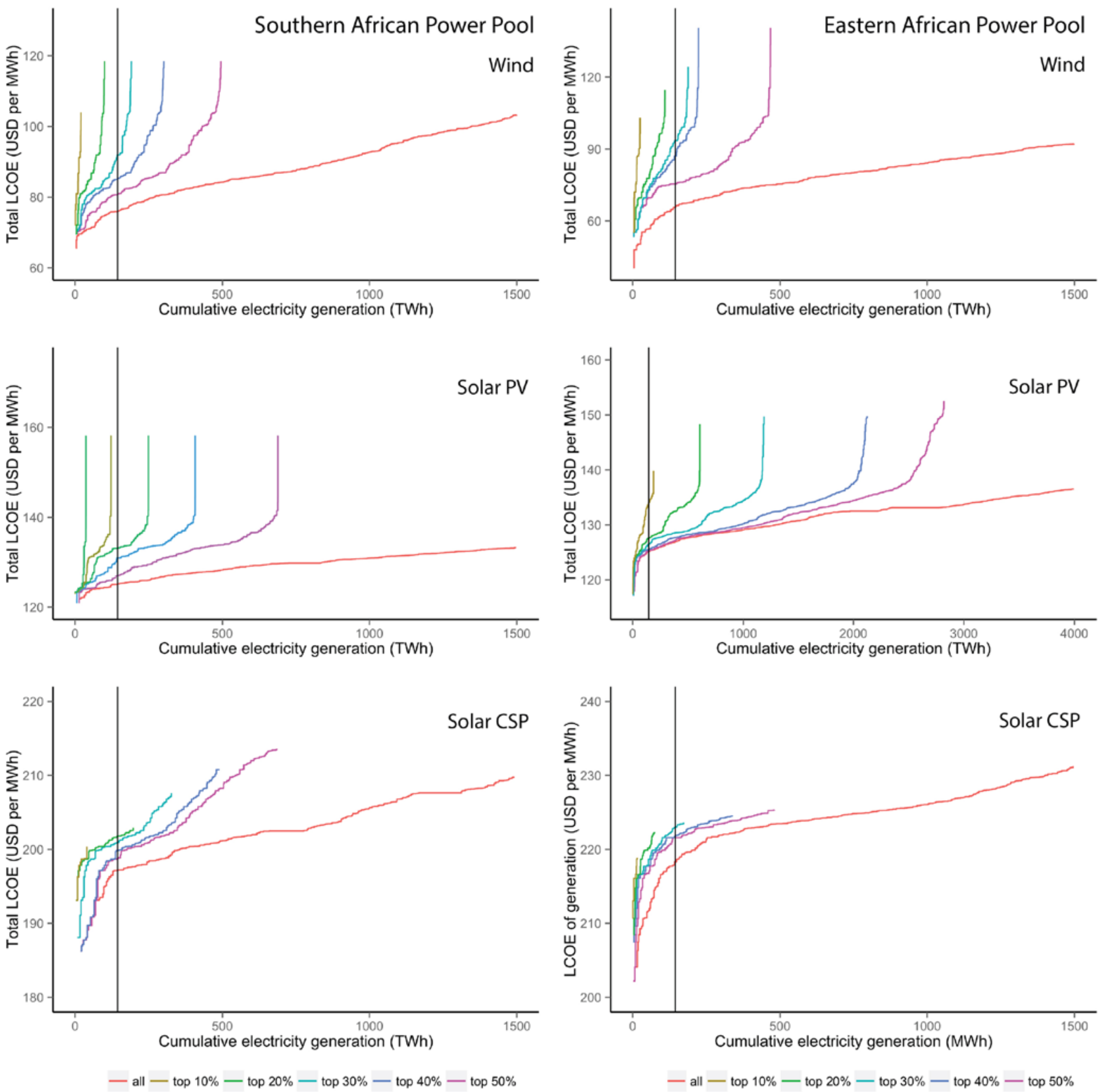
The authors examined multiple scenarios of increasing stringency in these three criteria. Generation supply curves show the total LCOE and available electricity generation of the wind and solar zones that are in the top 100%, 50%, 40%, 30%, 20%, and 10% of all three criteria values, depicting increasing stringency of those criteria (See Figure 6).

These results show the cost in terms of LCOE of a chosen level of environmental impact for each technology. For example in EAPP, to meet a solar PV target of 25% of electricity demand in 2030, selecting the best scoring 40% of solar PV zones negligibly (<1%) increases total LCOE, and selecting even the top 30% or 20% of zones increases total LCOE of the most expensive solar PV zone by only 1% (see Figure 6). In other words, solar PV zones that are close to load centers and transmission lines in already disturbed areas (quantified by human footprint scores) can be developed without large compromises on cost. These low-impact, low-cost development opportunities were also observed for solar PV and CSP in SAPP, where selecting amongst zones in the top 50% of criteria values would increase total LCOE of the most expensive zone by no more than 2% (see Figure 6).

Although the trade-offs between cost and environmental factors appear to be greater for wind power, particularly in EAPP, the generation cost is neither the only nor the most important determinant of wind resource quality. An examination of wind zones' time series generation profiles reveals that selecting sites based on only total levelized cost of electricity may not also optimally meet demand during the highest consumption hours, when electricity generation is most valuable (see Figure 7 in the section below on managing variability).

Figure 6. Supply curves for the Southern and Eastern African Power Pools showing all zones and zones scoring in the top 10%, 20%, 30%, 40%, and 50% of three environmental-impact siting criteria across each power pool.

Each plot shows the total LCOE of a chosen level of environmental impact and whether a highly environmentally-constrained scenario (e.g., top 10%) is able to meet a particular generation target (e.g., 25% of regional electricity demand in 2030). Overall, solar PV and CSP zones that are close to load centers and transmission lines in already disturbed areas can be developed without large compromises on cost. Criteria include distance to nearest transmission or substation, distance to nearest major load center, and human footprint score. The black vertical lines indicate 25% of the projected 2030 demand for the power pool. This figure has been created for this briefing paper using results from Wu and Deshmukh et al. in prep.



HOW CAN THE VARIABILITY AND UNCERTAINTY OF GRID-CONNECTED WIND AND SOLAR BE EFFICIENTLY MANAGED?

Site smarter: select wind and solar projects to better match demand

The value of wind and solar installations depends on how well their generation temporally matches peak demand. In other words, a renewable energy site that generates electricity when it is most needed during peak demand hours is considered more valuable (Milligan and Porter, 2005).

The metric that measures the temporal correlation of renewable energy generation with peak demand is called capacity value. More formally, capacity value can be defined as the amount of additional demand that can be served due to the addition of a generator while maintaining existing levels of reliability (Keane et al., 2011). As more and more variable RE capacity is installed, the capacity value of a new site is measured by the correlation of its generation with peak net demand, which is peak demand from consumers minus the generation from already installed solar and wind capacity. Prioritizing variable renewable energy sites that have a higher capacity value will result in larger offsets in conventional generation capacity investments required to meet peak net demand and maintain grid reliability.

Solar resources have a higher capacity value in electricity grids such as California's because their generation coincides with the peak demand hours that fall during the day due to cooling loads (Mills and Wiser, 2012). The capacity value of wind resources depends on the particular weather regime in the area, in addition to the demand profile of the electricity grid. Further, the capacity value of additional variable RE sites (marginal capacity value) changes with the amount of already installed capacity of variable RE because existing RE generation may or may not contribute to offsetting peak net demand (Mills and Wiser, 2012).

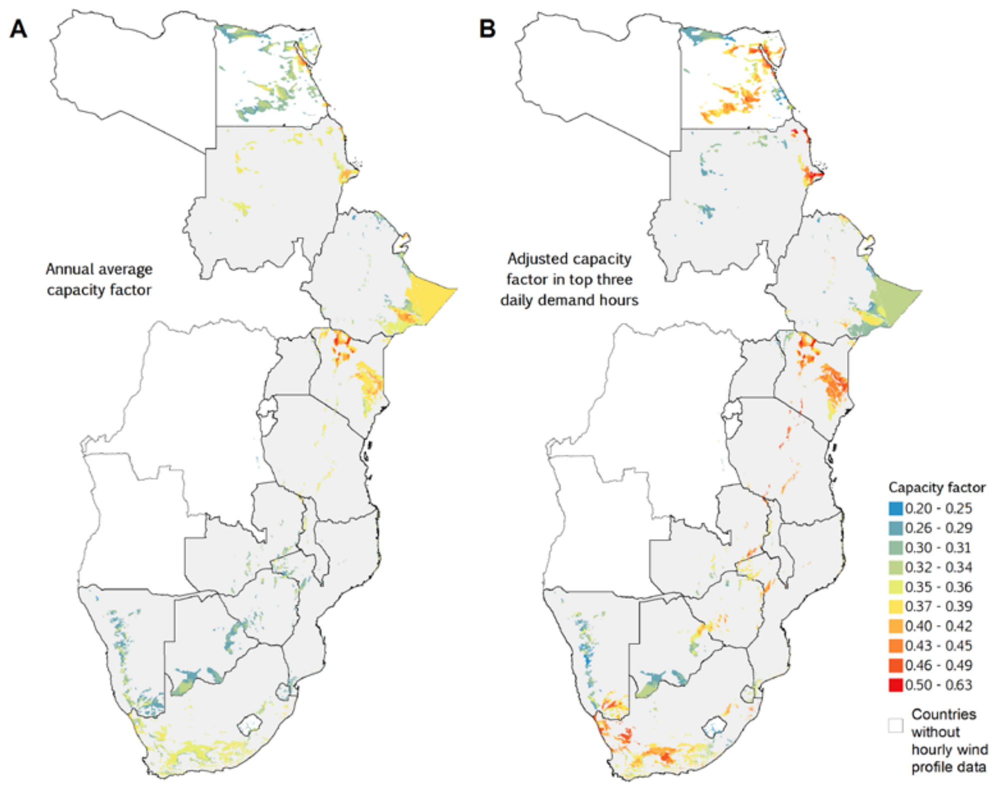
Selecting variable RE sites based on high average annual capacity factors may result in low LCOEs and higher annual energy production, but may not be optimal for the overall power system. As results from the renewable energy zones study for the Eastern and Southern African Power Pools revealed, wind resource areas with high annual average capacity factors may not also have high capacity factors during the top three (typically evening) peak demand hours during the day (a proxy measure for capacity value) (Wu et al., 2015). Figure 7 shows that some wind zones with high annual average capacity factors for wind generation (yellow to red colored areas in Figure 7A) have low capacity value (blue to yellow colored areas in Figure 7B), while some areas with relatively low annual average capacity factors (blue to yellow colored areas in Figure 7A) have high capacity value (yellow to red colors areas in Figure 7B) (Wu et al., 2015).

Incorporating capacity value in wind site selection will mitigate the effects of variability on the overall system reliability and cost. In other words, selecting wind sites with generation profiles more correlated to peak demand will save costs due to avoided investments in conventional generation.

Sere Wind Farm in South Africa

Figure 7. Comparison of annual average capacity factors (A) and adjusted capacity factors for the daily top three peak hours (i.e., capacity value) (B) for wind zones in the Eastern and Southern African Power Pools.

Some wind zones with high annual average capacity factors for wind generation (yellow to red) have low capacity value (blue to yellow), while some areas with relatively low annual average capacity factors (blue to yellow) have high capacity value (yellow to red). This figure is reproduced from Wu et al, 2015.



Increase transmission interconnections

Several studies and experiences, specifically from the United States and European Union, make a strong case for the need to develop grid interconnections between countries and regions to successfully and cost-effectively integrate high shares of variable renewable energy resources such as wind and solar (U.S. - (Enernex Corporation, 2011; GE Energy, 2010), EU - (Schaber et al., 2012; Trade Wind, 2009)). Interconnections reduce the system-wide variability of renewable energy generation, especially for wind, by enabling access to geographically diverse resources. Further, they enlarge the electricity grid balancing areas to enable sharing of conventional generation resources for balancing the net demand variability and maintain grid reliability (Cochran et al., 2012). In Africa, programs like the Programme for Infrastructure Development in Africa (PIDA) and the Africa Clean Energy Corridor (ACEC) initiative aim to develop a North-South transmission corridor extending from Egypt to South Africa, harnessing both conventional and renewable generation resources (IRENA, 2014). Significant international support and coordination will be needed for these infrastructure developments to be realized.

Improve grid operational strategies

Typically, electricity system operations were designed to schedule generators one day ahead of actual dispatch and at one hour intervals. Today's system operations, especially in developed economies, have evolved to incorporate sub-hourly scheduling and dispatch intervals (5-15 minutes) and the dispatch of generators closer to real time. This important operational change enables systems to respond to variability of not only demand, but also variable renewable energy (Cochran et al., 2012). Integrating advanced forecasting techniques in system operations helps predict the amount of renewable energy available to the system (Cochran et al., 2012). Frequent scheduling closer to actual dispatch also means that renewable energy generation and load forecasts will be more accurate, reducing scheduling errors and the need for idle, reserve capacity. Such improved operational strategies could enable electricity systems in developing economies to integrate large shares of wind and solar and generally reduce system-wide costs.

Increase flexibility in the system

Use existing flexible generators purposefully and efficiently

As variability in net demand increases with higher shares of wind and solar electricity, flexible generation plants that can ramp up and down quickly, have quick start capabilities, and can operate at low minimum generation levels will be more valuable.

Hydropower plants with storage can be very flexible, but other uses such as irrigation, water supply, and flood control can limit their flexibility. Open cycle gas turbine plants can quickly start and shut down, and have high ramp rates, but they also generate some of the most expensive electricity (Black & Veatch and NREL, 2012). Combined cycle gas turbine plants are more efficient but less flexible than gas turbine plants. Coal and nuclear plants are typically considered base load plants with little flexibility. Such inflexible plants have created barriers to integrating variable renewable energy in countries like China, India, and South Africa where the majority of electricity generation is from coal. However, coal plants can provide flexibility by cycling on and off, and by running at lower output (below 40% of capacity versus 60% in most coal plants) by modifications to operational practice and adequate compensation for impacts on heat rates during part-load operations and plant life expectancy (Cochran et al., 2014).

Demand response is a flexible and inexpensive resource

System flexibility can also be provided from the demand-side. Conventional demand response (DR) is a change in the normal electricity usage pattern by end-use customers in response to electricity price changes or some incentive payments designed to induce lower electricity consumption during high wholesale electricity prices or during critical system reliability periods (Federal Energy Regulatory Commission et al., 2009). Such DR programs are being implemented in emerging economies such as India and China (Deshmukh et al., 2015; Wang et al., 2010) However, DR can also be strategically used to integrate variable renewable energy such as wind and solar by providing both load reductions and increases (Watson et al., 2012).

Loads that can provide DR for integrating variable renewable energy include HVAC (heating, ventilation, and air conditioning) systems, lighting, those with storage capability such as refrigerated warehouses, municipal and agricultural water pumping, wastewater treatment plants, as well as industrial loads with batch and seasonal processes such as in the food processing industry (Kiliccote et al., 2010).

Depending on the type of loads, DR could provide regulation services (second-to-second balancing of load and generation), load following services (intra-hour balancing), ramping services (balancing over a few hours), and reserves (balancing when there is a sudden loss of generation). Early investments in infrastructure will enable new appliances and loads to be DR enabled (e.g. HVAC systems with telecommunications capability) and may avoid costly retrofits later when DR becomes essential to manage variability with high RE penetration.

Decreasing cost of storage will enable significantly more flexible grids

Electricity storage can significantly increase the flexibility of an electricity grid. With high shares of variable renewable energy, a storage system can store energy during period of oversupply, and supply electricity when renewable generation is low and demand is high. Pumped hydro storage (PHS), a two-reservoir hydropower station that can act as both generator and load, represents 99% of present electricity storage capacity worldwide (Gimeno-Gutierrez and Lacal-Arantegui, 2013). However, because PHS is terrain specific, since two reservoirs of sufficient size need to be built at two different elevations, it is limited in its potential capacity.

Other forms of storage such as batteries, compressed air energy storage, hydrogen storage, flywheels, and super-capacitors are being developed, but are still expensive for widespread deployment. However, the Australian Renewable Energy Agency has predicted a 40-60% drop in the prices of certain battery technologies such as lithium-ion and flow batteries by 2020 (AECOM, 2015). As other cost-effective flexibility options are exhausted and storage prices decline through technology innovations and economies of scale, electricity storage is expected to play a major role in providing flexibility to electricity systems.

Use integrated resource planning to make optimal long-term capacity investments

Even the smallest regions may have complex energy systems due to various options for generation and transmission investments, evolving costs of technology, region specific resource or financial constraints, region-specific social and environmental impacts, and multi-stakeholder participation. Long-term capacity expansion and integrated resource planning studies are essential to efficiently coordinate future investments for low carbon and low cost operation of the electricity system (Greacen et al., 2013).

The few studies modeling the optimal mix of solar, wind, geothermal, conventional, and hydropower in generation portfolios in hydro-dominated countries have demonstrated that it is possible to meet future projected demand using only existing hydropower and new sources of wind and solar PV. Schmidt et al. (2016) found that solar PV and wind alone can meet up to three times the 2013 demand of Brazil without the need for investments in new hydropower and thermal generation, although the study did not factor in the diurnal variation of load and generation.

Several countries in the EAPP and SAPP have significant capacity of large hydropower. Renewable energy integration studies that assess the balancing needs of increasing shares of variable RE are essential to inform the need for new hydropower, specifically for the purposes of managing variability and maintaining grid reliability.

Can distributed renewable energy rapidly increase access to basic electricity services?

1.3 billion people in the world do not have access to electricity; the majority of those without access live in sub-Saharan Africa and South Asia. While grid-connected large renewable energy development can lead to low carbon electricity grids, it cannot guarantee access to electricity unless the distribution grid is extended and electricity prices are affordable. Decentralized off-grid renewable energy has the potential to provide relatively quick access to basic electricity services such as lighting, mobile phone charging, television and others. With the invention of white LEDs (light emitting diodes), recent years have witnessed a surge in pico-lighting products that provide a clean alternative to dirty kerosene (Alstone et al., 2015).

Solar home lighting systems, which are small standalone off-grid systems usually with a single solar PV panel and battery storage, are already a major alternative to the central grid in many developing countries. In Bangladesh, more than 3 million systems have been installed, providing access to basic electricity services to almost 10 percent of the population (IDCOL, 2014). Market-based rural electrification using solar home lighting systems are widely prevalent in countries like Kenya (Jacobson, 2007). Off-grid renewable energy-based mini-grids, which are larger systems ranging from a few hundred watts to kilowatts, are able to provide electricity for productive uses beyond basic electricity services. Innovations in payment systems, business models, and efficient appliances are enabling such systems to be increasingly deployed across sub-Saharan Africa and South Asia (Deshmukh et al., 2013; Tenenbaum et al., 2014).

Continuing innovations in technology and significant international support can enable off-grid renewable energy solutions to make rapid progress towards providing basic electricity services in parallel with extending low-carbon electricity grids in developing economies.

Conclusions

Development of large-scale wind and solar generation can be a cost-effective, and environmentally and socially sustainable alternative to coal and large hydroelectric power for providing on-grid electricity. This will be increasingly important for energy planners as the costs of conventional generation are being better understood and accounted for, and given that wind and solar technologies are cost-competitive in an increasing number of markets and abundant in many regions. Unlike their conventional counterparts, however, wind and solar are comparatively resilient to climate change, and are more likely to be completed both on time and at cost, which are crucial considerations for rapidly developing economies.

With the right tools and planning, countries can effectively manage the variability of solar and wind technologies to make them an integral part of their on-grid energy strategy and increase the share of renewables in their energy make-up without sacrificing reliability. To achieve this shift toward renewable energy, some of the steps that countries will have to take include:

- using more precise forecasting of RE generation and assessing real-time demand for reliable and flexible grid operation;
- better integrating grids across borders by developing transmission corridors and designing energy markets that will enable efficient buying and selling of electricity across regions;
- undertaking resource assessments of renewable energy and incentivizing development on sites with low environmental and social impact, and where diurnal and seasonal generation trends better match demand; and
- investing in supply-side and demand-side resources that enable a more flexible grid.

However, such an energy transition demands a paradigm shift in energy planning and investment decisions in developing countries and regions. At the same time, it demands a willingness from the international community to invest its technical capacity and resources to support this shift toward smarter grids capable of sustaining a significantly higher share of renewable energy.

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Notes

1. The term "renewable energy technologies" in this paper does not include large hydropower.

2. The levelized cost of electricity (LCOE) is the ratio of the lifetime capital and variable costs to lifetime electricity generation, or the cost per unit of electricity over a project's lifetime (e.g., USD/kWh).

3. Total LCOEs in this study include the cost of generation, extending transmission connection from the nearest substation or transmission line to the generator, and road connection to the nearest existing road. Transmission cost estimates do not include costs of upgrading the line from point of interconnection to the delivery point or distribution network. See total LCOE cost input assumptions in Wu et al., 2015.

4. Note that solar PV and CSP zones in South Africa have been restricted to areas identified as "renewable energy development zones (REDZ)" by the Department of Environmental Affairs. The actual suitable area of solar PV resource in South Africa extends beyond REDZ.

5. Interviews with utilities in the United States reveal a preference for siting generation close to load centers to avoid the need for high-voltage transmission, which are difficult to develop in incremental phases, causing decadal delays in bringing new generation projects online (Schwartz et al., 2012). This preference exists even if sites closer to load centers are lower quality. Energy development on already disturbed or marginal land would reduce the overall land use impact, and siting close to existing transmission infrastructure would avoid landscape fragmentation. The human footprint score is a measure of degree of human influence on a unit of land, and it was used in this study as a proxy for degree of human "disturbance" from natural, unaltered states (Sanderson et al., 2002). This proxy was used due to the lack of detailed spatial ecological data (e.g., threatened or endangered species ranges, ecologically core or intact areas).

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