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Southern Africa –Towards Inclusive Economic Development (SA-TIED)

The SA-TIED programme looks at ways to support policy-making for inclusive growth and economic transformation in the southern Africa region, through original research conceived and produced in collaboration between United Nations University World Institute for Development Economics Research (UNU-WIDER), National Treasury, International Food Policy Research Institute (IFPRI), and many other governmental and research organizations in South Africa and its sub-region. A key aspect of the programme is to encourage networking and discussion amongst people involved in policy processes across the participating organizations and civil society aiming to bridge the gap between research and policy-making.

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Developments in variable renewable energy and implications for developing countries

Authors: Arndt, C., Hartley, F., Ireland, G., Mahrt, K., Merven, B. and Wright, J.

Abstract: This technical report provides an overview of the developments in variable renewable energy technologies globally and in South Africa. It highlights the significant advances made in these technologies, which are already resulting in structural shifts in energy systems globally. With the costs of wind and solar beginning to dip below that of their non-renewable competitors, system integration, policy, and institutional arrangements become increasingly important in removing barriers to variable renewable energy adoption. Developing country markets, where electricity demand is growing, are well poised to develop policy, institutions, and systems to efficiently and effectively incorporate solar and wind resources in large shares. Understanding the complex interactions of the numerous interconnected factors involved, and the implications of various planning choices for the environment and national objectives are essential to prepare adequate national transition plans, roadmaps and policies in these countries. Transparent, flexible and integrated energy systems models are therefore essential tools for providing credible evidence-based knowledge for future energy infrastructure planning.

Keywords: Variable renewable energy, solar PV, wind, levelized cost of energy, South Africa

1. Introduction

The global energy landscape has changed significantly in recent years and a transition to a decarbonised energy system appears to be underway. The International Energy Agency's (IEA) most recent report, *Renewables 2017*, indicates that in 2016 all renewables accounted for nearly two-thirds of new electricity capacity additions (IEA 2017b). Solar photovoltaic (PV) capacity increased by 50% in 2016 and for the first time solar PV additions increased faster than any other fuel.

The shift toward renewables has been driven by plummeting variable renewable energy (VRE - a collective term for solar and wind energy) generation costs, which have now become cost competitive with conventional fossil fuel technologies in many contexts. Technology costs reductions have been most significant for solar PV and lithium-ion battery storage. The International Renewable Energy Agency (IRENA) estimates that between 2010 and 2016 average solar prices fell by a factor of five, while the unitized capital cost of lithium-ion batteries (per kWh) fell by 50% between 2014 and 2016 (IRENA 2016b; 2017d). Wind generation costs have also decreased over the past 5 years with wind auction prices falling by a factor of about two (IRENA 2017b). Continued cost declines are widely expected (BNEF 2017a; CSIRO 2015; IRENA 2017b). As will be detailed in section 2, rates of cost decline of VREs, and by extension investment volumes and increments to generation capacity, have been (and most likely remain) difficult to predict.

Falling VRE and storage costs combined with increasing technological know-how have improved the possibilities for both utility-scale and off-grid renewable electricity generation. This has created an opportunity to rapidly transition to a low-carbon global energy system with significantly fewer or no economic compromises. Due to their naturally distributed nature, VREs also have the potential to increase electrification in remote rural areas where the costs of grid extension have been prohibitively high. This is particularly important for developing countries. IRENA (2015c) estimates that in 2015 renewable solutions, including solar lighting kits, solar home systems (SHS), small wind turbines, and renewable mini-grids provided power to nearly 26 million households or an estimated 100 million people. They estimate that nearly 60% of the additional generation needed to achieve universal electrification by 2030 will come from off-grid solutions with renewable energy likely to supply most of this share (IRENA 2017c). Furthermore, as solar and wind costs decline, there is great potential for VRE to replace diesel generators or to form hybrid mini-grids made up of VRE, storage and diesel. In many remote areas, hybrids became cheaper than diesel alone a few years ago (IRENA 2017c).

This paper seeks to synthesize a wide variety of work assessing the future of VRE and their potential for revolutionizing electricity generation, particularly in developing countries. As VRE technology matures and costs fall, focus shifts from installation costs to integration costs and institutional barriers of adopting VRE electricity generation. The second part of this paper discusses deliberate actions that must be taken to optimize the future ability to incorporate both utility-scale and off-grid VRE capacity into developing countries' generation mix. A case study of South Africa is specifically considered in this paper.

2. Global VRE trends

In recent years, the EIA and the IEA's projected contributions of wind and solar to the electric power sector have greatly missed the mark. Both agencies have been subject to criticism for their inability to anticipate falling costs as well as mounting political and social momentum which have bolstered growth in solar, and to a lesser degree wind (e.g. Hoekstra 2017; AAE Institute 2015; MIT 2015; Osmundsen 2014; Metayer et al. 2015; Creutzig 2017). Over the past 10 years, each agency's annual reports have repeatedly failed to predict the extent of solar and wind growth. Historically, annual reports appear to merely react to the growth in previous years while ultimately not incorporating fundamental changes occurring in VRE markets.

a. Costs

Solar costs have fallen at a spectacular rate. Policies such as Germany's Feed-in-Tariff and California's Renewable Portfolio have fuelled solar uptake at a rate beyond expectation. This rapid uptake resulted in significant reductions in solar costs through technology learning. Since 1979, solar PV has followed a learning curve characterized by module costs decreasing by 22.5% with each doubling of installed capacity. This is considerably greater than the median rate for other technologies (Creutzig 2017, ITRPV 2017). Relatedly, expansion of PV production in China further contributed to falling costs. The rapid and difficult to anticipate cost reductions in recent years, has meant that cost assumptions fell behind actual trends. This is illustrated in Figure 1 by the sharp adjustments made in the levelized cost of energy (LCOE) projections for solar PV by the EIA from year to year.[1] Between 2010 and 2017, solar PV and wind cost projections decreased by 81 and 62% compared to 37 and 15% for natural gas and coal.

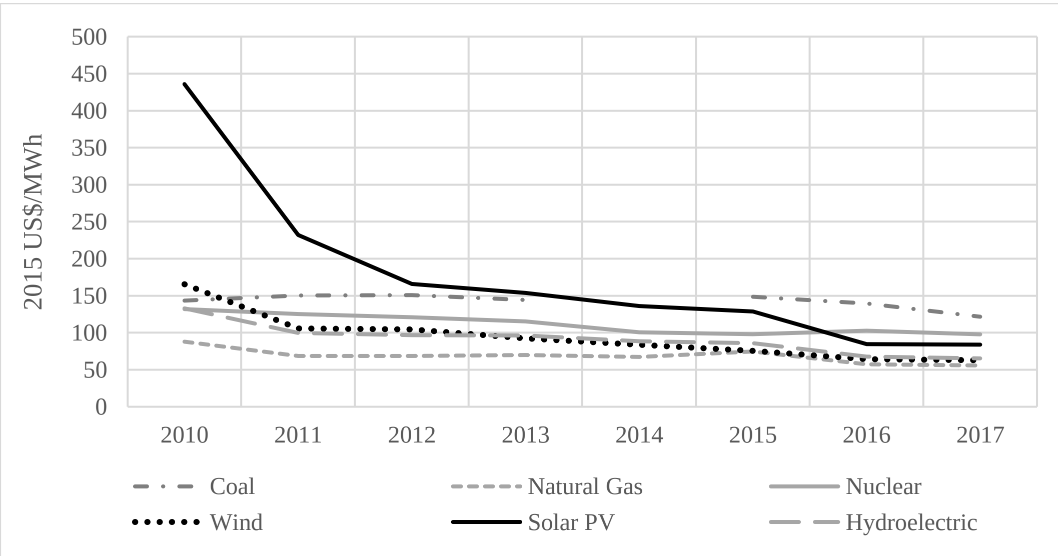

Figure 1 Annual Energy Outlook short-term LCOE projections for various technologies, 2010-2017 (2015 $/MWh) Source: EIA 2010c, 2012b, 2012c, 2013c, 2014b, 2015b, 2016c, 2017c

In 2017, the EIA expects that, on average, the LCOE for plants coming online in 2022 will be lowest for natural gas plants followed by wind and hydroelectric. Utility-scale solar PV generation is only cheaper than coal and nuclear. This contrasts with 2016 estimates put forth by Lazard (Figure 2).

Figure 2 shows EIA and Lazard high and low range estimates. Lazard's low range coal LCOE estimate is only slightly lower than its high range estimates for wind and solar. Moreover, most of the range of gas estimates lies above that of solar and gas. In contrast, EIA 2022 upper end solar costs overlap with the entire range of coal costs

[1] LCOE estimates the average total cost per total energy output of constructing and operating an electricity generating facility over its lifetime. For the purposes of this study, LCOE provides a useful means of comparing the relative cost of different generating technologies. However, it is important to note that LCOE is not always the most useful or accurate tool for comparison particularly when comparing technologies with very different characteristics. To fully understand the implications of the advances in energy technologies on future electricity generation, a fully integrated energy systems assessment is required. LCOE values also reflect numerous parameter choices and assumptions across various technologies. As such these levels are not strictly comparable between studies, but nonetheless provide a tool for assessing patterns and trends.

and the average solar cost is greater than the entire natural gas cost range. With solar and wind costs expected to continue their decline, the EIA appears to overstate the future costs of VRE relative to coal and gas.

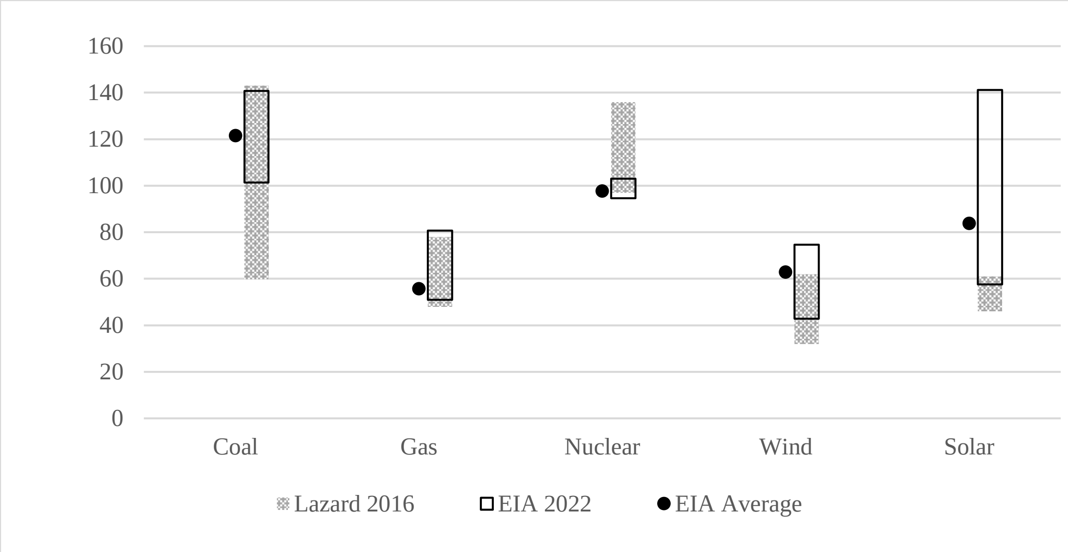

Figure 2 Recent actual and projected LCOE for various technologies (2015 $/MWh)
Source Lazard 2016, EIA 2017c
Notes: EIA estimates are regional ranges and, therefore, low and high estimates across technologies are not necessarily comparable. Lazard ranges correspond to technology variations. The EIA makes assumptions regarding emissions control costs for coal whereas Lazard does not.

Figure 3 displays actual and projected utility-scale solar PV LCOE estimates. The EIA line displays the projections for the labelled year which are reported in the horizontal axis. For example, the first 2016 point on the solid black line reflects the EIA projected LCOE for 2016 in 2010. EIA projected LCOEs are reported alongside Lazard, IEA and IRENA current year estimates to illustrate trends in expected costs relative to the current cost environment. EIA projections five or so years into the future have been roughly in line with current costs and consistently substantially above the realized. This remains the case with the most recent projections to 2022, which essentially posit no further declines from observed cost levels.

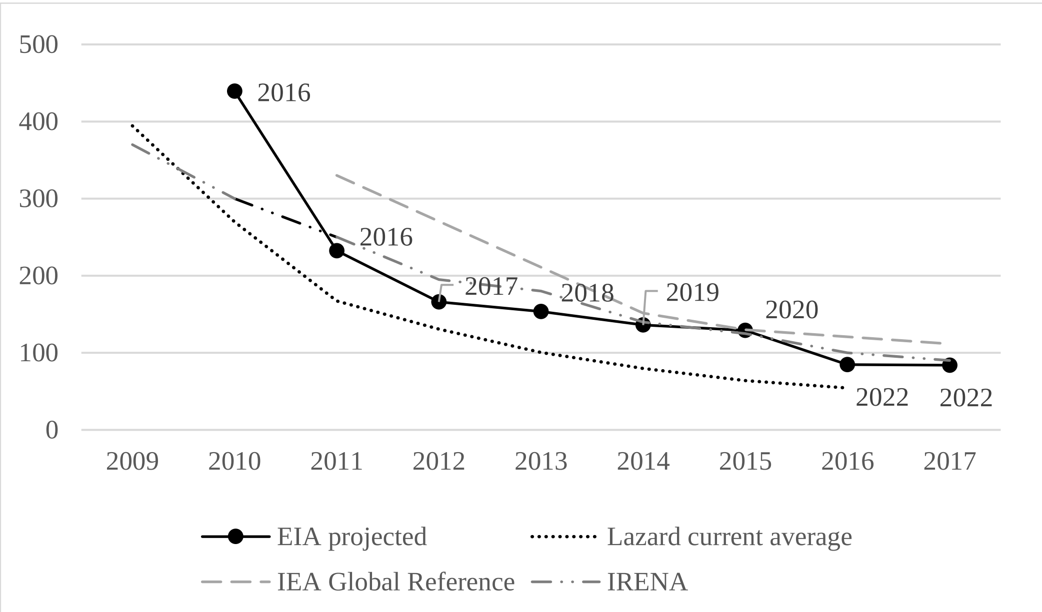

Figure 3 Actual and projected solar PV LCOE, 2009-2017 (2015 $/MWh)
Sources: EIA 2010c, 2012b, 2012c, 2013c, 2014b, 2015b, 2016c, 2017c; Lazard 2016; IEA 2016b; IRENA 2017c
Note IEA (AEO) LCOE values are projections reported in each year on the horizontal axis for the labelled year.

The EIA (2016d) evaluates whether its cost assumptions differ greatly from those used in other studies. It compares its estimates of the capital costs of utility-scale PV technologies, a key assumption underpinning LCOE projections, with values reported by LBNL, Lazard, and NREL. Costs are not necessarily reported for the same projects and therefore levels are not necessarily comparable. Though EIA costs are 14% higher than those reported by LBNL, the EIA estimates follow the same rate decline.

Despite lessons learned in the last decade, VRE costs projections continue to be revised downward in what appears to be reaction to rather than anticipation of the changing market. For instance, in 2015 BNEF expected wind costs to drop by 32% and solar costs by 48% between 2015 and 2040 (BNEF 2015). In addition to significant cost reductions between 2015 and 2017, BNEF's 2017 projections expect wind and solar LCOEs to drop another 47 and 66% by 2040 (BNEF 2017a). As equipment costs fall, balance of system costs; operations and management; and capital costs become relatively more important (IRENA 2016c).

b. Capacity

Installed PV capacity has increased significantly since 2005. Utility-scale capacity installed increased from 0.03GW in 2005 to 19.4GW in 2016 and end-use capacity (e.g. grid-connected residential and commercial installations) from 0.5GW to 11.6GW. The rapid increases in PV capacity have been consistently under captured in projections. This is illustrated in Figure 4 which compares actual US capacity outcomes to the EIAs *Annual Energy Outlook* (AEO) projections. The sharp kink in the 2015 capacity projection reflects the scheduled termination of the 30% solar investment tax credit (ITC) in the United States. The Consolidated Appropriations Act of 2016 extended the ITC to solar construction initiated through 2021, with the credit phasing out in 2020 and 2021. This phase out period is apparent in the 2016 and 2017 forecasts. The large increase in projected end-use capacity in AEO reports published after 2008 reflects the inclusion of the residential sector in the ITC (2007 Energy Independence Security Act) and the removal of residential caps (2008 Emergency Economic Stabilization Act) (EIA 2016d). The EIA attributes its greater difficulty in projecting utility-scale capacity compared to end-use capacity to two factors: (1) the complexity and volume of local and state level policies directed toward utility-scale production; and (2) unanticipated falling PV module prices which have a lesser influence on end-use systems where installation costs comprise a more significant portion of total costs (EIA 2016d).

a) Utility-scale ***b) End-use***

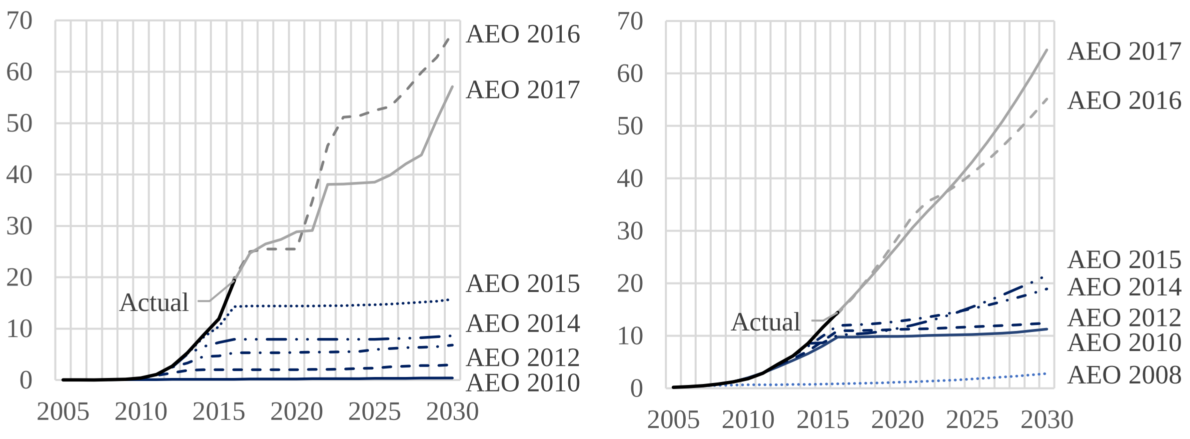

Figure 4 Actual and Projected Utility-Scale and End-Use PV capacity, 2005-2030 (GW)
Source: EIA 2008, 2009, 2010a-2017a

The continuation of the ITC, remarkable drops in the cost of solar PV, and continued effort to update models have resulted in a dramatic change in the trajectory of EIA's projected PV generating capacity in 2016 and 2017. The 2017 AEO expects solar PV capacity to grow 50% between 2016 and 2021 compared to the 2015 AEO which sees no growth over the same period. While the 2015 AEO expected capacity to grow only 55% by 2040, remarkably, the 2017 AEO puts 2040 capacity at five times 2016 levels. Figure 5 shows a similar shift in projections reported in the EIA's 2017 *International Energy Outlook* (IEO).

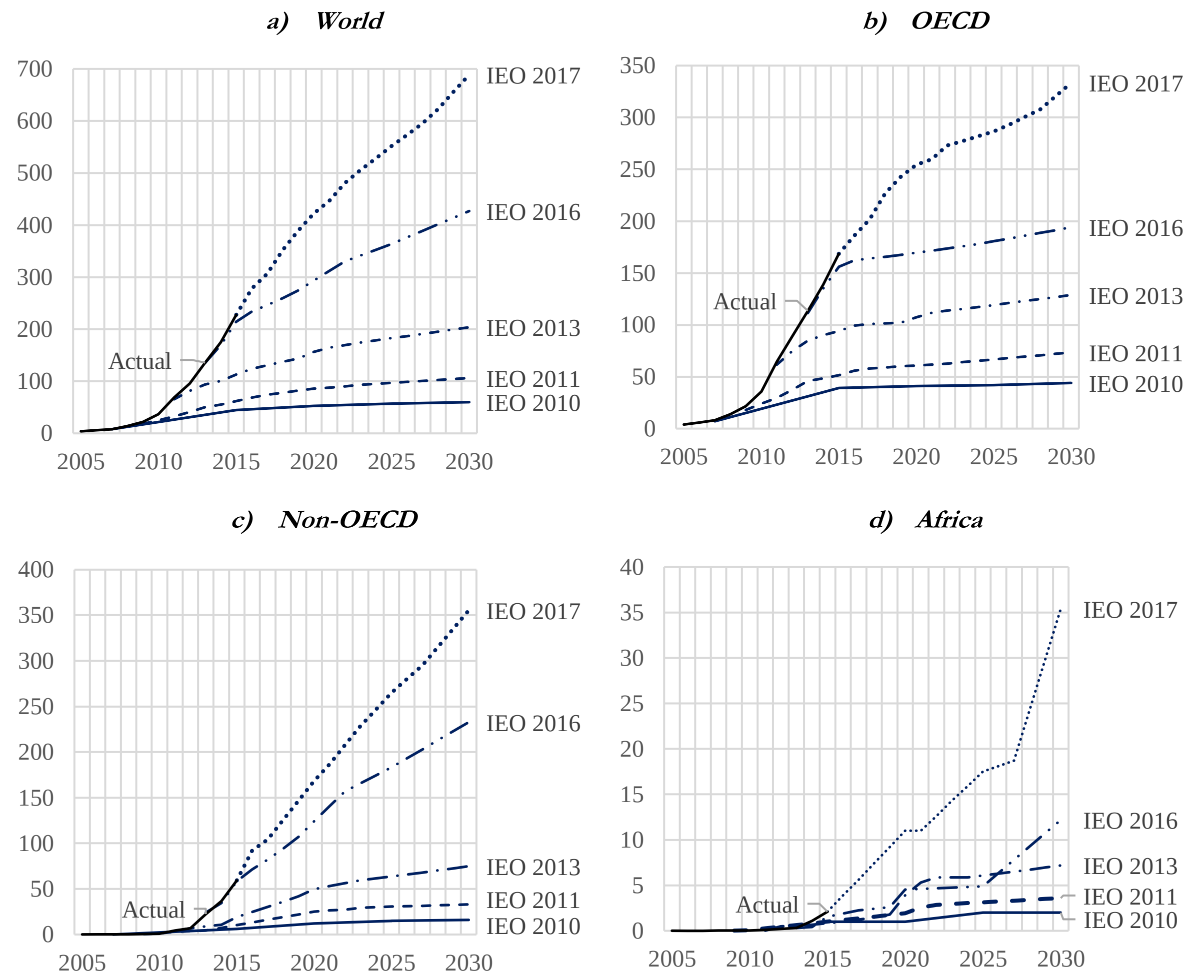

Figure 5 Actual and IEO Projected Solar Capacity by Region, 2005-2030 (GW)
Source: EIA 2010b, 2011b, 2013b, 2016b, 2017b

The actual and projected rise in installed capacity in non-OECD countries and in Africa highlights the spill over effects of lower solar PV costs to developing countries. This is more evident in Figure 6 which provides greater regional detail for 2017 projections. While solar PV capacity additions in the US are expected to dominate growth in coming years, increased installation in China and India are expected to increase markedly as well. Significant PV capacity additions are expected in Africa through to 2030, although its contribution to global capacity is quite small.

The most recent analysis by the IEA at time of writing was the Renewables 2017 (IEA 2017b) report which presents an even more optimistic outlook than presented here. This report includes 2016 data and projects global solar capacity will reach 740 GW by 2022 - more than triple the 2015 level (IEA 2017b). The EIA projects capacity to slightly more than double by 2022 and not reach 740 GW until 2033 (EIA 2017b). BNEF's 2017 New Energy Outlook sees solar and wind accounting for 48% of installed capacity by 2040 up 8 percentage points from its 2015 report (BNEF 2015, 2017a). This is more optimistic than IEO estimates, of 42% by 2040 (EIA 2017b). Wind and solar comprised only 4% of installed capacity in 2010 and an estimated 12% in 2017 (EIA 2017b).

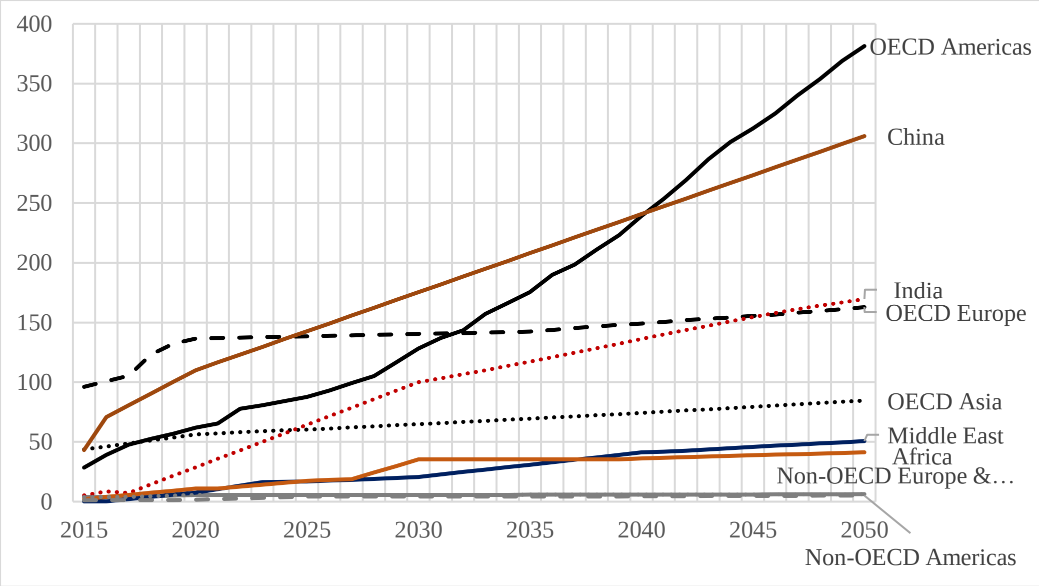

Figure 62017 IEO Projected PV Capacity by Detailed Region, 2015-2030 (GW)
Source: EIA 2017b

The EIA and IEA are not the only organizations who have fallen short in its forecasts. Creutzig et al. (2017) present data showing that even Greenpeace estimates fall short and according to REN21, even the solar industry's own early projections have been surpassed by the actual uptake (REN21 2017). In a recent Bloomberg blog post, Bullard (2017) acknowledges that Bloomberg has also had the tendency to be "always undershooting".

Creutzig et al. (2017) illustrates the impact of model design in systematically underestimating solar growth. They adjust number of modelling features involving system integration and growth constraints, endogeneity of technology learning, and cost assumptions. The resulting forecasts illustrate the potential for considerably greater solar growth. Estimates are sensitive to the rate of technology learning and suggest that PV could represent between 30 and 50% of the global generation mix by 2050 with the potential for as much as 30% of generation supplied by PV by 2035. This compares 2040 projections by BNEF, where 34% of global electricity is generated by wind and solar combined, and the EIA, where 31% is generated by all renewables.

3. VRE trends in developing countries: The case of South Africa

The implications of rapidly falling VRE prices are significant particularly for developing countries like South Africa, China and India where new renewable capacity is now competitive with new coal. Higher projections for coal costs and further VRE learning imply that by 2030, many markets will also have reached the point where the unitised costs of new renewable capacity are lower than even the short run marginal costs of existing coal plants (Liebrich 2017). This would result in the potential of significant stranded coal assets. In countries with a large amount of older stations, such as South Africa, this may happen sooner as the cost of coal increases and legislation changes to account for externalities not currently priced into the cost of coal for power generation.

The South African electricity system relies heavily on coal. In 2016, coal accounted for 74% of total generation capacity with the balance comprising of hydro and pumped storage, peaking plants such as Open Cycle Gas Turbines (OCGTs), nuclear and renewables - total capacity is reported to have been 49.8GW in 2016 (Wright et al. 2017). Since 2011, 6,328MW of renewable capacity has been procured through the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) with construction underway for a large proportion of this capacity (Eberhard & Naude 2016). While South Africa's prices were relatively high at the start of the REIPPPP programme, prices fell dramatically over the competitive bid rounds, particularly for solar PV (see Figure 7). This is in line with international technology trends and the competitive nature of the auctions, but also highlights how capital costs fell substantially in South Africa over the bid rounds. The cost of solar PV decreased by more than 80% between 2011 and 2015 while the cost of wind decreased by almost 60%. These advances have resulted in renewable technologies being cost competitive with new coal IPPs as well as new builds identified in the 2016 Draft IRP (see Figure 8).

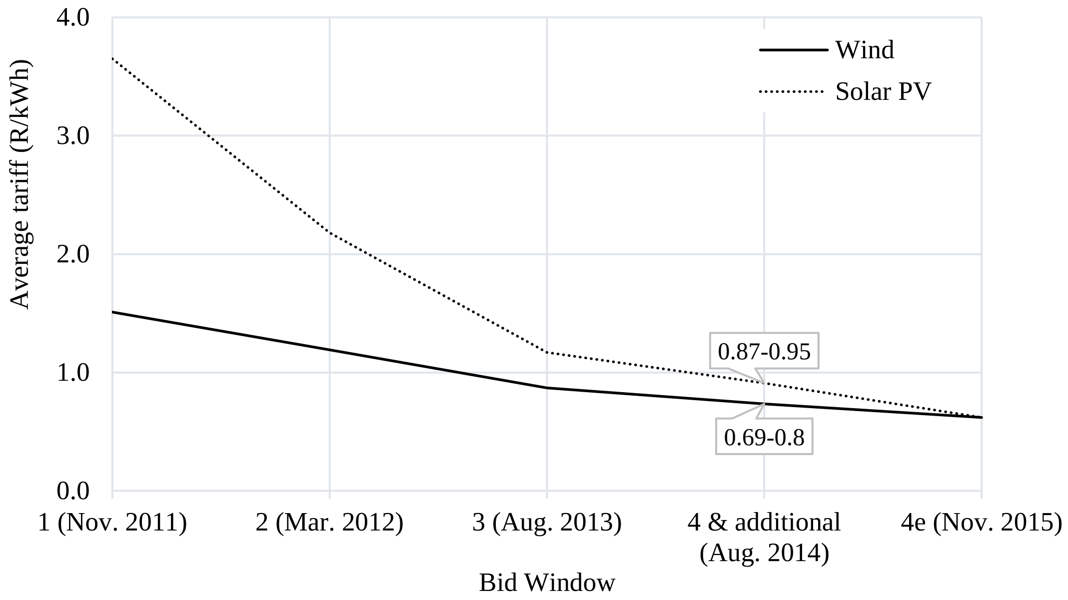

Figure 7 Actual average tariffs, R/kWh (April, 2016)
Source: Adapted from Wright et al. 2017

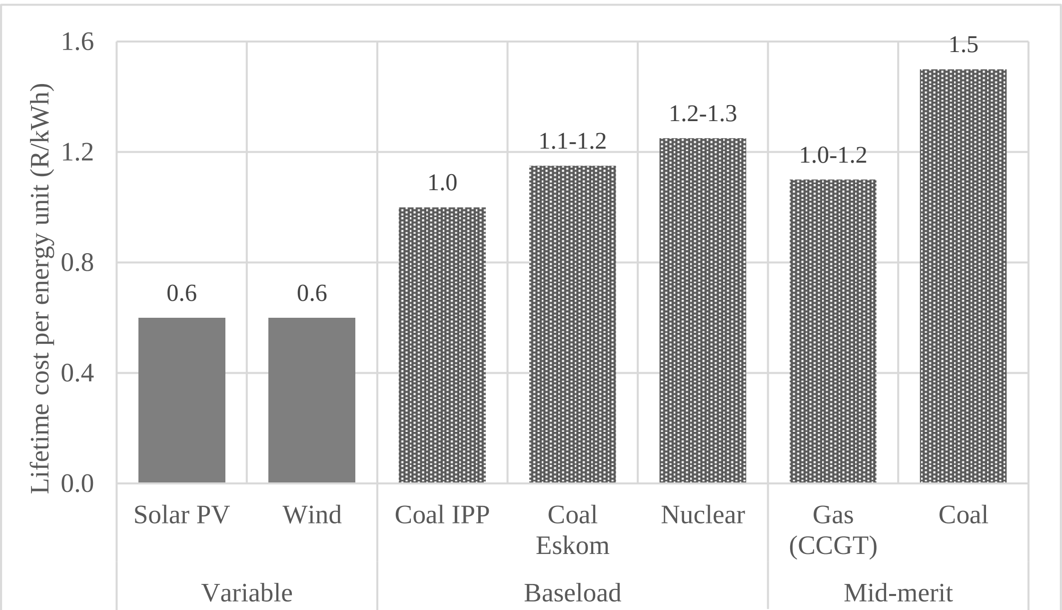

Figure 8 Comparison of lifetime energy costs per technology (R/kWh)
Source: Adapted from Wright et al. 2017

In 2016, Eskom announced that it would not sign several power purchasing agreements (PPAs) citing costs and electricity overcapacity in the country as reasons for its decision (Business Day, 5 June 2017). This has effectively halted the REIPPPP and South Africa has since been overtaken by many countries where auctions have continued to deliver substantial cost related benefits for both wind and solar PV (IRENA 2017b). Eskom's refusal to sign further agreements stops expected capacity from bid windows 4 and onwards, with an investment value of R58 billion (Business Day, 5 June 2017), from coming online and places uncertainty on the future of the REIPPPP and increasing investor risk.

Since recent developments in renewable energy in South Africa, Wright et al. (2017) conservatively estimates renewable energy technology cost assumptions presented in Figure 9. The overnight costs included are based on the most recent renewable energy prices in South Africa, i.e. REIPPPP Bid Window 4 (i.e. Bid Window 4e). A discount rate of 8.2% with a load factor of 20% for solar PV, 60% for CSP and 36% for wind is assumed. Moderate learning is assumed for solar PV while no further learning is assumed on wind.

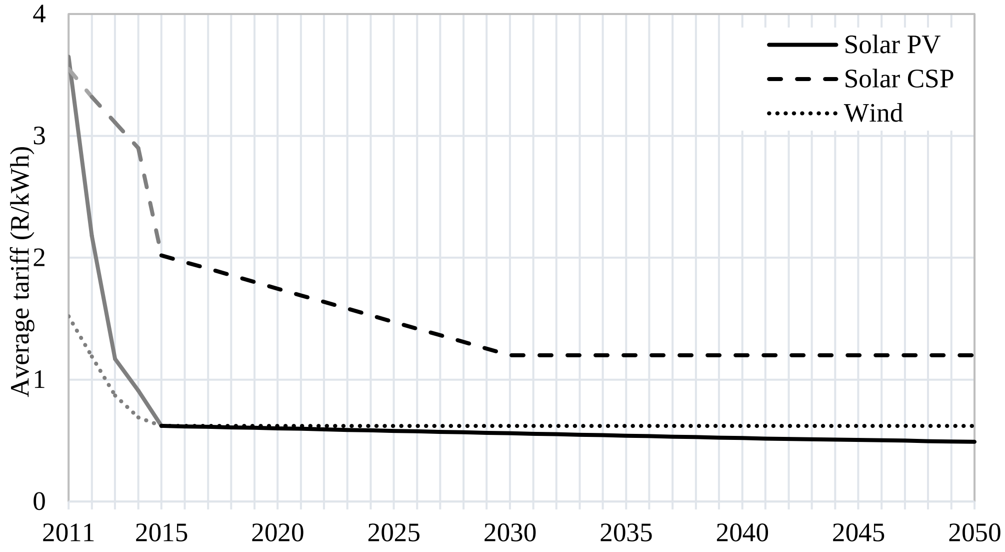

Figure 9 Observed and future projections for VRE tariffs in South Africa (conservative learning)
Source: Adapted from Wright et al. 2017

Wright et al. (2017) indicates that further learning is likely and will further reduce these costs. In this alternative and more likely scenario, further levels of learning are assumed for solar PV, wind and CSP.

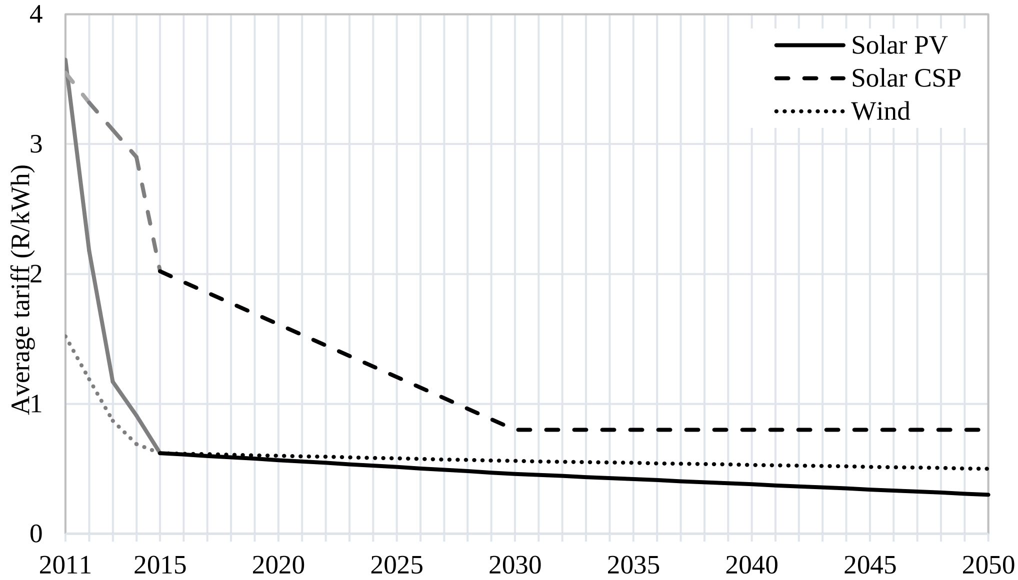

Figure 10 Observed and future projections for VRE tariffs in South Africa (less conservative learning)
Source: Adapted from Wright et al. 2017

4. Barriers to adopting renewable energy

As technology matures and costs fall, wind and solar power are becoming increasingly viable options in utility-scale power systems. The greatest barriers to adopting VRE are no longer modular costs but the technical, institutional, policy, and market adjustments required to incorporate renewable energy, and particularly VRE, cost-effectively into an electric system. These challenges are collectively referred to as system integration. Among the most prominent of these challenges is the variable and not fully predictable nature of VRE coupled with the need to balance electricity supply and consumption at all times. However, system integration and its associated costs are increasingly well understood as countries like Denmark approach 50% of total generating capacity derived from VRE (IEA 2017a). A considerable reserve of both technical and policy best practices is emerging. For instance, IRENA identifies key planning stages and provides guidelines for short- and long-term planning targets for systems aiming to scale up to high shares of VRE (IRENA 2017a). Capitalizing on this knowledge is essential to reduce integration costs and fully capture the advantages of wind and solar. (IRENA 2017a, 2017c, 2016c, 2015a 2015b; IEA 2017a, 2016b). Scaling up VRE is likely less challenging when demand is growing or a significant share of generation is retiring and being replaced (IEA 2016a). Thus, developing markets, where demand for electricity is increasing, are particularly well poised to develop policy, institutions, and systems to efficiently and effectively incorporate solar and wind resources in large shares into electric systems.

The process of integrating VRE into the electricity generation mix depends on several factors specific to each generation system including geography, existing units, and the institutional and regulatory climate. Challenges to integration generally mount as the share of electricity generated from VRE grows beyond a few percentage points. Initially, planning and power system operation upgrades and adaptions are all that are needed to accommodate VRE. In the next phase, energy policies pertaining to system and market integration of renewables become critical (IEA 2016a). Ultimately, as VRE becomes a primary generation source, integration requires a comprehensive and systematic approach that involves an overall transformation of the power system (IEA 2016a).

Integration is easiest when the availability of VRE corresponds to demand both diurnally and seasonally. However, a poor correlation is not insurmountable as evidenced by Denmark's high VRE share. Geographical considerations also impact the ease of integration. Resources situated far from demand centres require greater transmission costs. Systems spread over large geographical areas help mitigate issues with, for example, cloud cover by reducing the probability that all systems are impacted by cloud cover simultaneously. Larger systems - achievable through intersystem and interregional cooperation - can achieve a portfolio effect of more stable generation via greater geographical diversity.

Flexibility of conventional fuel technology in terms of start-up times, minimum load, and ramping speed facilitates greater VRE adoption. Costs to plants of cycling in and out of production and running at minimum loads vary by type of plant and with the extent of VRE penetration. Generation flexibility can be achieved both through modifications to existing units or additions of more flexible capacity. As technology progresses, particularly for newer natural gas plants, older plants impose relatively greater costs to integration. Natural gas combustion turbines, hydropower plants, and internal combustion engines provide the most flexibility while coal and nuclear units are among the least flexible. Generally, greater diversity in the mix of generation technology results in greater flexibility. In addition to flexible generation, system flexibility can also be achieved via storage, demand-side flexibility, interregional coordination; and well-coordinated institutional arrangements, operational practice, and technology (Luckow et al. 2015; IEA 2016a, 2017a).

As noted developing electricity markets are in a relatively favourable position to plan toward integrating high shares of VRE. For example, demand in Africa is expected to triple by 2040 reaching 1300 terawatt-hours (TWh), which includes a fivefold increase in residential demand to a level of 520 TWh (IEA 2014). This rapid increase excludes latent electricity demand. Between 2014 and 2040 electricity capacity is expected to triple from 185 to 563 GW in 2040. (IEA 2017b). With such a large share of capacity growth, African countries can plan now for a coordinated transformation of the system which harnesses the potential of VRE while increasing supply flexibility. Such planning will reduce integration costs while ultimately creating more cost-effective resilient systems. However, numerous obstacles remain including limited data, and shortages of expertise, tools and methodologies (IRENA 2015b). International partnerships will be instrumental in filling these gaps.

5. Potential for system integration in South Africa

a. Renewable energy resources

Africa has some of the best solar resources in the world, resulting in high solar PV energy yields. However, this resource has yet to be adequately exploited. A PV project at a typical location in Africa generates almost twice as much energy as the same project in Germany. An illustration of significant underutilization of solar power in Africa as a continent as compared to Germany as a single country can be noted in the fact that Germany currently has around 45GW of installed solar PV, nearly equivalent in capacity to the total power system capacity of South Africa (see Figure 11). South Africa possesses some of the best solar and wind resources in the world, with vast areas of the country suitable for generating electricity at low cost from renewable energy using solar PV, CSP, and wind technologies (Hagemann 2008; Fluri 2009; WASA 2015; CSIR & Fraunhofer 2016). Potential for solar

PV in South Africa is extensive with over 220 GW of potential identified in Renewable Energy Development Zones alone (CSIR & Fraunhofer 2016). An additional 72GW of solar PV has also been identified as installable on rooftops in South Africa (CSIR & Fraunhofer 2016).

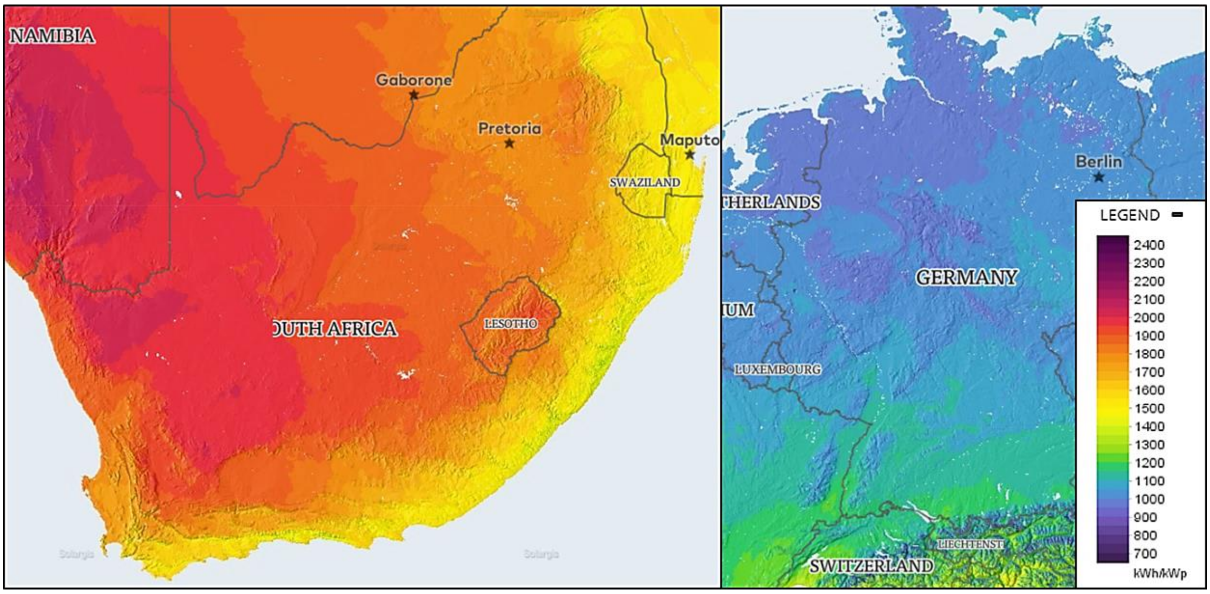

Figure 11 Comparison of the long-term solar PV production potential from a typical solar PV project in South Africa (left) compared to the same project in Germany (right)
Source: SolarGIS 2017

Recent studies have also shown that South African wind resources are significantly greater than previously estimated with vast inland resources beyond the previously assumed high resource sites along the coast. The CSIR and Fraunhofer (2016) extended the existing work done by the Wind Atlas of South Africa project (WASA 2015) and showed that between 55% and 65% of South Africa's land area has technically recoverable wind capacity exceeding a 35% load factor (totalling ~3500-4500GW and ~11500-14500 TWh/a).

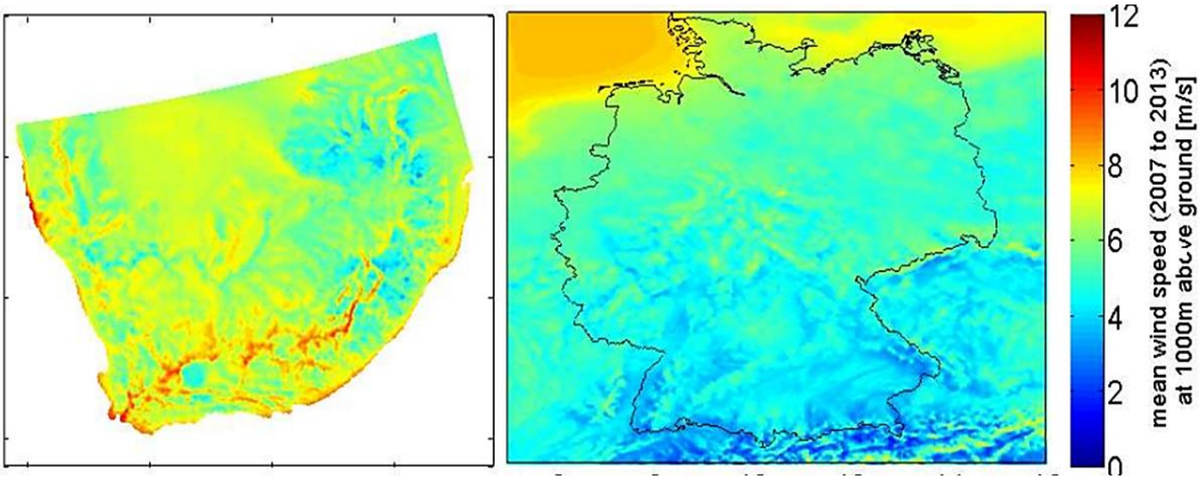

Figure 12 Comparison of wind speed averages across South Africa (left) compared to Germany (right)
Source: WASA 2015; CSIR & Fraunhofer 2016

b. Renewable production performance in South Africa

The variability of non-dispatchable energy is a challenge for using renewable energy, especially for a large share of energy production. Wind and solar PV aggregation research undertaken in CSIR and Fraunhofer (2016) characterises wind and solar PV power profiles for South Africa. Their findings for the grid-focussed scenario in this research showed that wind and solar PV profiles had annual capacity factors of 36% and 20.4%, respectively. Figure 13 and Figure 14 show sample time series of the aggregate wind and solar profiles for both summer and winter days in South Africa. Sites chosen in the REIPPPP would have higher capacity factors than presented here.

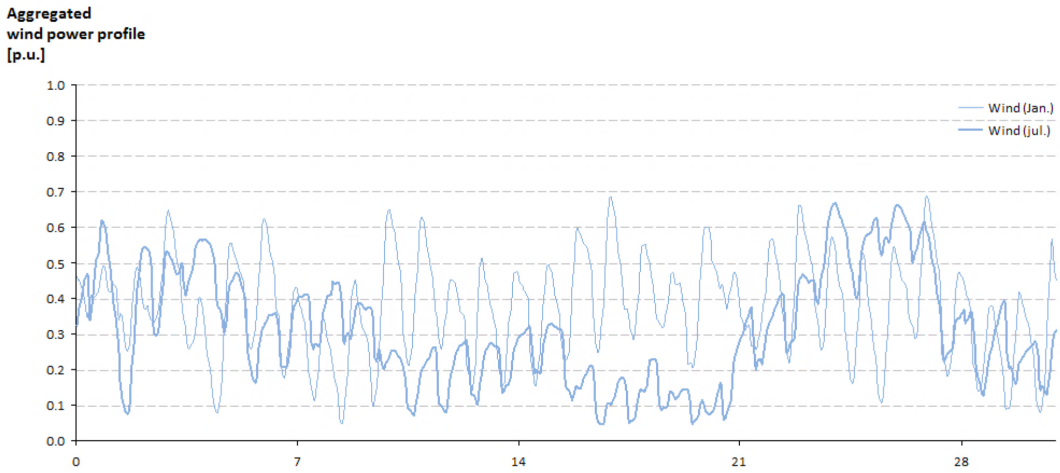

Figure 13 Aggregated winter/summer wind power profiles for South Africa
Source: Wright et al. 2017

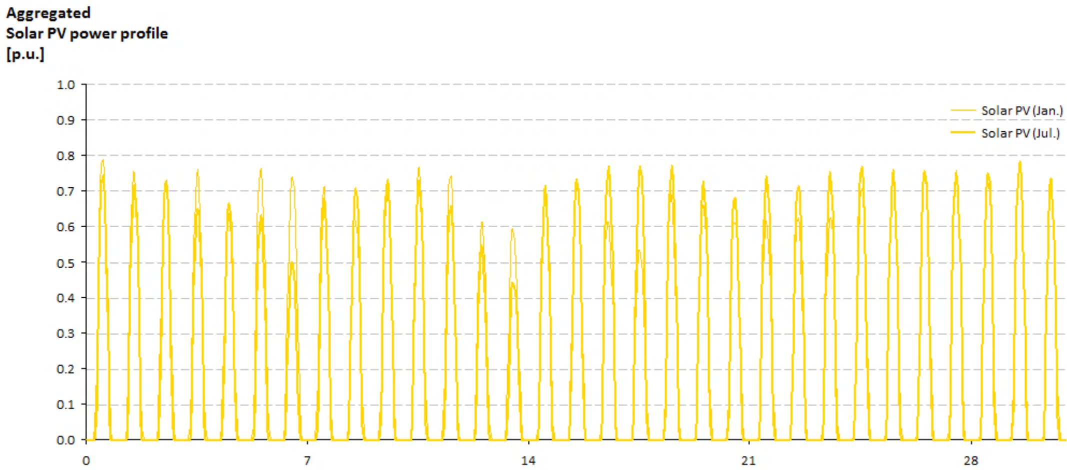

Figure 14 Aggregated winter/summer solar PV power profiles for South Africa
Source: Wright et al. 2017

Usefully for South Africa, the combined solar and wind resources are highly complementary, with the combination of their typical daily outputs matching the country's electrical demand surprisingly well. The demand coverage factor typically matches ideally for 50% of weeks in the year (see Figure 15 where a relative comparison to Denmark is made). This implies that including a balanced combination of variable wind and solar PV will therefore not contribute significantly to rapid fluctuations in the power system due to their aggregating effect if they are distributed across the country (Mushwana et al. 2015; CSIR & Fraunhofer 2016). Very high peak penetrations of variable renewables have already been achieved in Denmark and Germany (140% wind on 9 July in Denmark in 2015 and 67% wind and solar in May 2016 in Germany). Improved matching of the demand profile with wind and solar PV profiles in SA combined with relatively low seasonality makes system integration easier as a lower level of flexible complementary resources are required.

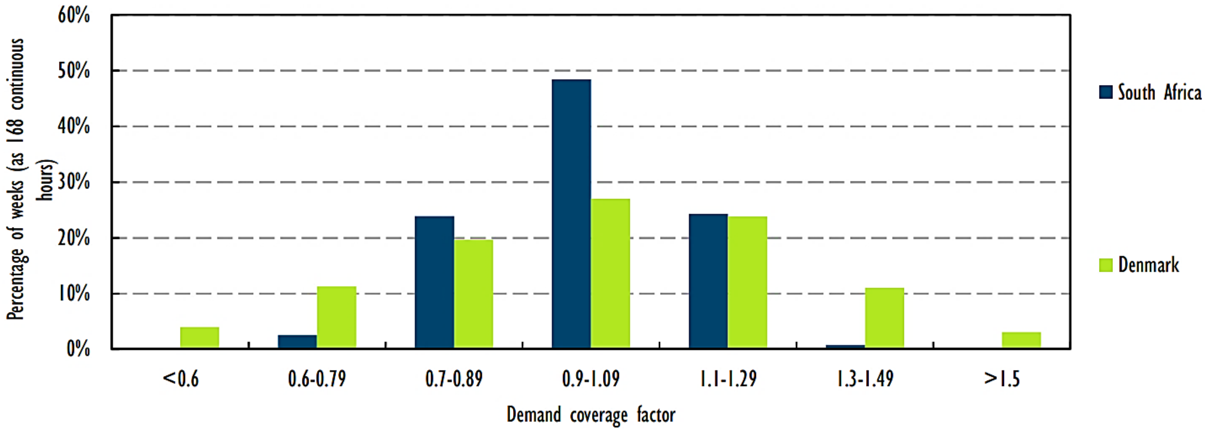

Figure 15 Demand coverage factors for South Africa and Denmark: wind and solar
Source: IEA 2016c

6. The role of mini-grids

VRE can also be harnessed in smaller off-grid systems. Mini-grids are interconnected generation systems of less than 10 MW that are capable of meeting commercial, industrial, institutional, or community electricity needs through local distribution networks. Mini-grids may be self-contained or connected to a main grid, often where grids are unreliable. It is possible to operate mini-grids entirely using VRE and storage solutions. However, systems powered by diesel, hydropower or biofuel, or hybrid systems which combine these resources with VRE and possibly storage are currently the most reliable and cost-effective. As PV prices fall, solar is displacing diesel in existing mini-grids. Solar only mini-grid are likely to become increasingly economically viable as the cost of storage continues to decline.

Solar home systems have become economically feasible solutions for individual consumers in recent years. Pay as you go SHSs offer small amounts of electricity - commonly enough to power a few lights and charge a mobile phone. Small productive stand-alone systems ensure constant electricity where grids are unreliable and allow business hours to extend into the evening hours. Analysis by Bloomberg suggests that in India solar irrigation pumps are a cost-effective alternative to diesel pumps (BNEF 2017b). The mini-grid often proves to be a more flexible and cost-effective alternative to these stand-alone systems. Mini-grids can provide greater loads to consumers while reducing costs through economies of scale. Combining residential and commercial uses balances day and night-time loads further improving asset use and economies of scale. Agenbroad et al. (2017) quantifies the trade-off between grid-extension, mini-grids, and SHSs in terms of distance and load size and finds that mini-grids are most appropriate as both loads and distance from the grid increase.

Mini-grids offer great promise for bring electricity to remote areas. Globally an estimated 1.06 billion people live without access to electricity, which translates to an overall electrification rate of 85.3% and 73% in rural areas (IEA/World Bank 2017). The majority of those without electricity live in rural Africa and Asia. In rural sub-Saharan Africa, the electrification rate is only 27%; it is also the only region where population growth outstripped electrification between 2012 and 2014 (IEA and World Bank 2017).

Off-grid solutions, particularly those powered by renewables, will be pivotal in bringing electricity to remote areas. Current projections suggest that a considerable share of unmet need can be satisfied through renewable mini-grids. Renewable off-grid capacity increased ten-fold in Africa since 2005 with a 65% increase in 2015 alone (IRENA 2016a). IRENA further estimates that 10 million Africans are currently served by renewable mini-grids or stand-alone systems with higher power rating than SHSs. The IEA expects off-grid capacity will almost triple by 2022 (includes industrial, SHSs, and mini-grids) (IEA 2017b). The World Resource Institute notes that with targeted-action it is possible to bring electricity to 140 million rural Africans by 2040 through the construction of mini-grids (Odarno et al. 2017, IEA 2014, UN 2015). IRENA (2017c) notes the potential for off-grid systems to provide 60% of the new electricity needed globally to achieve universal electrification, with the potential for renewables to supply most of this. In Africa, this new electricity would be supply 40, 17, and 42% through mini-grids, stand-alone systems, and grids, respectively (IEA, UNDP and UNIDO 2010). In many rural areas, renewables are now the most cost-effect option and often significantly cheaper than diesel fired generators and kerosene lighting (IRENA 2017c).

To meet such ambitious goals, key players must act now to foster adoption. The limited economic viability and scalability of current mini-grid business models along with poor information, perceived risk, financing constraints, and policy and regulatory shortfalls are significant barriers to expansion (Agenbroad et al. 2017, IRENA 2017c). With the expansion of off-grid solutions in areas such as Tanzania and Uttar Pradesh in India comes the opportunity to develop a knowledge base. Recent reports by the World Energy Institute (Odarno 2017), the World Bank (2017), and SEforAll (2017) as well as partnerships such as the World Bank's Global Facility on Mini-Grids specifically seek to make information regarding best practices accessible. These and other reports (e.g. Agenbroad et al. 2017, IRENA 2017c) provide common suggestions for essential steps in moving forward, which include proving the business model; reducing barriers to financing; capacity building; and ensuring an optimal environment through streamlined policy and regulation. In this early stage, development partners, NGOs, and governments are crucial players. Ultimately greater private sector participation, particularly in financing, is essential (IRENA 2017c). Sustainable Energy for All, a UN/World Bank partnership, warns that current finance flows fall short to achieve the seventh UN SDG, but provides guidelines to accelerate progress (SEforAll 2017).

There is reason for optimism as international agencies, the private sector, and donors, as well as African governments demonstrate a commitment to promoting renewable mini-grids. For example, Nigeria, identified by the IEA and World Bank (2017) as a high impact country for electrification, has taken several steps in the last year to foster mini-grid expansion. First, the national assembly moved to reduce regulatory barriers in adopting the Nigerian Electricity Regulatory Commission Mini-Grid Regulation in early 2017. This regulation is designed to encourage decentralized generation and to facilitate electrification of areas outside grids. Second, the critical need for financing was addressed in the announcement of the N1billion ($3 million) Solar Energy Fund for Micro, Small and Medium Enterprises (MSMEs) by the Bank of Industry. This public-private partnership targets the negative impact of unreliable electricity on economic development. Furthermore, continued support for Economic Community of West African States' (ECOWAS) Renewable Energy Policy (EREP) fosters cooperation in a region with one-third of sub-Saharan Africa's population and one of the lowest electricity access rates in the world. EREP seeks to establish an environment that encourages renewable energy investments and markets with the goal of meeting the electricity needs of 71.4 million people by 2020 through the creation of nearly 60,000 renewable and hybrid mini-grids (ECOWAS 2012).

7. Discussion

This technical report provides an overview of the developments in VRE technologies globally and in South Africa. It highlights the significant advances made in these technologies, which are already resulting in structural shifts in energy systems globally. This is seen by the increased share of electricity being produced by VRE, which in some countries exceeds 100% at times. The cost of renewable energy, globally and in developing countries such as South Africa, is currently competitive with that of new fossil-fuel power plants (coal in particular) and is expected to become comparable to existing coal power plants in the near future.

With the costs of wind and solar beginning to dip below that of their non-renewable competitors, system integration, policy, and institutional arrangements become increasingly important in removing barriers to VRE adoption. Promotion of VRE electricity generation in both power systems and mini-grids requires advanced planning now for maximum impact. Developing country markets, where electricity demand is growing, are well poised to develop policy, institutions, and systems to efficiently and effectively incorporate solar and wind resources in large shares. For utilities, this entails a coordinated transformation of the electric system to harnesses the potential of VRE while increasing supply flexibility. Such planning will reduce integration costs while ultimately creating more cost-effective resilient systems. International partnerships will be instrumental in overcoming obstacles including shortages in data, expertise, tools, and methodologies.

International partnerships will also be crucial in bridging current barriers hindering growth of renewable mini-grids. Essential steps in moving forward include proving the business model, reducing barriers to financing. capacity building and ensuring an optimal environment through streamlined policy and regulation. VRE technology and markets are already falling into place. If such coordinated efforts are achieved, there will be plenty of reason for optimism. International goals to limit global temperature rise to below two degrees Celsius (Paris Agreement) and to attain universal electrification while shifting toward clean and sustainable energy (UN SDG7) appear to be increasingly plausible.

Understanding the complex interactions of the numerous interconnected factors involved, and the implications of various planning choices for the environment and national objectives are essential to prepare adequate national transition plans, roadmaps and policies. Transparent, flexible and integrated energy systems models are therefore essential tools for providing credible evidence-based knowledge for future energy infrastructure planning. These tools also allow for a full analysis of the implications of VRE cost declines. While the measure of LCOE can be useful for comparing the overall observed and expected energy cost from different technologies it can be misleading when comparing technologies with very different characteristics e.g. non-dispatchable solar PV and wind do not provide the same value to the system as dispatchable generators. The actual value (and costs) to the energy system of any technology is a complex and dynamic combination of all prospective new and existing capacity and their overall ability to meet demand. Both demand and supply options change over time (over a day, week, month, year) as the structure of the overall power system evolves. Future research should therefore focus on assessing the impact of changes in renewable and storage technologies on potential electricity and energy pathways as well as the economic implications of these pathways.

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