The Value of Grid-Scale Variable Renewable Energy Generation in Sub-Saharan Africa

Assessing the Potential Contribution of Variable Renewable Energy to the Reliable Supply of Electricity in Kenya and Ghana

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June 2017

Report for the **Green Growth Diagnostics for Africa** project

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Institute of Development Studies

Contents

Abbreviations and Acronyms

Africa Infrastructure Country Diagnostic	AICD
East Africa Power Pool	EAPP
Electricity Company of Ghana	ECG
Energy Commission of Ghana	EC
Energy Regulatory Commission (of Kenya)	ERC
Expected Energy Not Served	EENS
First Order Reliability	FOR
Generation Adequacy Assessment	GAA
Ghana Grid Company	GRIDCo
Government of Kenya	GoK
Gross Domestic Product	GDP
Independent Power Producers	IPPs
Kenya Electricity Transmission Company	KETRACO
Kenya Power and Lighting Company	Kenya Power
Least Cost Power Development Plan	LCPDP
Liquefied Natural Gas	LNG
Loss of Load Expectation	LOLE
Loss of Load Probability	LOLP
Megawatt	MW
Ministry of Energy (of Kenya)	MoE
U.S. National Renewable Energy Laboratory	NREL
Northern Electricity Distribution Compnay	NEDCO
Nepalese Power System	NPS
Photovoltaic	PV
sequential Monte-Carlo simulation	SMCS
Solar and Wind Resources Assessment	SWERA
sub-Saharan Africa	SSA
Variable Renewable Generation	VG
Volta River Authority	VRA
Wien Automatic Simulation Planning Package	WASP
West Africa Power Pool	WAPP

1. Introduction

Securing a sufficient supply of reliable and affordable electricity is a huge challenge for countries in sub-Saharan Africa (SSA). Many countries in the region are experiencing rapid increases in the size of their populations, and even more rapid growth in their economies (World Bank 2017). As a result, the region experienced a 45 per cent increase in annual energy consumption between the years 2000-2014 (World Energy Outlook 2014), with the growth in some countries much higher.

In 2009, the World Bank stated (Eberhard, Foster, Briceño-Garmendia, Ouedraogo, Camos and Shkaratan 2008) that SSA was amid a power crisis characterised by unreliable supplies, largely due to insufficient generating capacity and high prices. Indeed, in 2008, the World Bank's Africa Infrastructure Country Diagnostic (AICD) project (AICD 2008) calculated that while there was a need for 7,000MW of additional power generation capacity to be installed in SSA countries each year, the total installed in prior years was only 1,000MW per year. This is a costly problem for SSA countries (Deloitte 2015), with the AICD project calculating in 2009 (Econ Poyry 2009) that the region would have to spend roughly four per cent of GDP annually on power sector investments to meet the demands of economic development, keep pace with population growth, and increase energy access. Despite major efforts toward increasing the reach of electricity networks in recent years, the SSA average rate of access in 2014 was only 35 per cent. Access rates are much lower in some countries – for example Chad has only four per cent, while Ethiopia has 73 million people without access.

Thus, building very significant generation capacity is both essential and inevitable in the near future. For many reasons – including location, maturity of technology and speed of building, traditional fossil-fuel power plants are well-suited to fill the gap. However, many stakeholders in the SSA power sector are keen to see these power systems largely avoid such a highly polluting stage. Hydro power is already a major component of SSA's generation fleet, and plentiful resource means that more reservoirs will likely be built. However, in some cases the potential for economically and politically viable development is insufficient to meet the growing demand alone. There is therefore a strong desire to see high penetrations of variable renewable generation (VG) within many systems (Africa Renewable Energy Initiative 2015).

Indeed, the International Energy Agency's 'Energy Outlook' summary for 2016 (World Energy Outlook 2016) states that the deployment of renewable generation already plays an important role in the mitigation of traditional energy security concerns, by moderating oil and gas imports. However, they warn, rising shares of unpredictable and intermittent VG puts electricity security under the spotlight in a different way. Despite the hugely ambitious scale of current and near-future planned VG investments, there has been almost no system-level analysis of the reliability impacts of grid-scale VG in SSA countries. This is true for the academic community as well as governmental and industrial institutions.

The ability of the generators within a power system to consistently meet the demands made of them by customers is known as the system's generation adequacy. Not only is it the case that there has been very little research on the potential contribution of VG to the generation adequacy of SSA power systems: detailed risk-based assessment of generation adequacy in developing countries in general has barely been addressed in the academic and industrial literature. As discussed later in this article, the demand for electricity in some developing countries is fully met only rarely, if ever, which makes the question of defining reliability inherently complicated and ambiguous.

This article will survey the most relevant research, policies and sources of data relevant to generation adequacy assessment in two example SSA countries: Kenya and Ghana. It also includes an exploratory analysis of the temporal relationships between the hydro resource, wind resource and power demand in Kenya, with an emphasis on assessing the impact of limited data availability.

2. Generation Adequacy Assessment

This section presents an overview of what generation adequacy is, as differentiated from other aspects of reliability, along with the information required for its evaluation. After a general introduction to generation adequacy assessment in Section 2.1, Section 2.2 describes the traditional measures of margin and derated margin as measures of adequacy, including their shortcomings. Section 2.3 goes on to describe explicit risk-based measures of generation adequacy, while section 2.4 discusses the modelling requirements for such risk-based assessments.

2.1 Introduction

The reliability of a power system is commonly viewed as consisting of three aspects: adequacy, flexibility and security. Adequacy concerns whether the power system has sufficient resources to keep the risk of capacity shortfalls and consequent failure to meet demand (also known as the system load) at an appropriate level, despite scheduled and unscheduled outages. The flexibility of the system is its ability to deploy its resources to respond to changes in net load, both predicted and unpredicted, and where the net load is defined as the remaining system load not served by VG. The security of a power system is its ability to withstand sudden, unexpected disturbances without any serious consequences for the flow of electricity from generators to customers.

Adequacy assessment of power systems is concerned with obtaining quantitative measures of the extent to which the system can satisfy customer demands at every hour of the year. This may or may not involve consideration of constraints arising from the finite capacities of the transmission and distribution networks. These are the networks that allow bulk transfer of power across a country, followed by local transfer to individual customers, respectively. The extent to which the generation capacity installed in a system can always supply the demand is known as generation adequacy, and we refer to adequacy assessment that does not include network constraints as generation adequacy assessment (GAA). Rigorous GAA is essential to informed energy policy making in any country, but is rarely used to support policy making regarding SSA countries.

Whether GAA provides a complete picture of adequacy varies from system to system. For instance, where there is substantial network capacity to export wind energy from resource rich areas, this tends to imply a relatively low degree to which the network matters for reliability (as opposed to economics) (National Grid 2016). This may not generally be true for SSA countries, since both the transmission and distribution networks are commonly severely insufficient in capacity and unreliable, due to economic and institutional constraints (Econ Poyry 2009). Nevertheless, GAA without consideration of network constraints can still provide a valuable view of wind and solar generation's potential contribution. Thus, particularly given the challenges in obtaining data for rigorous GAA in SSA systems, this article focusses on the GAA aspect only.

2.2 Reserve Margins

The level of redundancy in generation has traditionally been expressed as a reserve margin: the amount by which generation capacity exceeds the projected peak demand, expressed as a percentage of that peak value. For any power system, there are many possible events that would lead to some demand not being met – referred to as generation shortfall events, or simply shortfalls. As the reserve margin increases, so does the number of events involving unavailable generators that do not result in shortfalls. This simple and static approach benefits from being very easy to calculate and communicate – but may also lead to a misplaced sense of deeply understanding risks.

The reserve margin required for a high level of reliability is dependent on the number and nature of generators present in a system. For example, in a small system with 1,000MW peak load (MW = Megawatt, the average demand of about 1000 UK homes) served by 11 generators of 100MW each, the ten per cent reserve margin at 100MW would be sufficient to cover the loss of all single units, and might be deemed adequate. The same cannot be said of a system with two 500MW generators and one 100MW generator. For a much larger system comprising of twenty 500MW generators, the same margin of ten per cent could cover the loss of any two units and thus would be considered adequate. This illustrates that a certain margin in a SSA power system is likely to represent very different risks to the same margin for e.g. the UK system.

The derated margin attempts to provide a more realistic measure by derating units as per their availability properties. The quantities of interest are the probabilities that conventional units will not be available for service when required, due to an unanticipated failure or unavoidable maintenance. These are static values, which may be established from the historical performance of units in the power system in question, or based on international industry experience. The derated capacity of a generation unit is its power capacity multiplied by (1 – probability of being unavailable when needed), and the total derated capacity of conventional units in a power system is the sum of individual values. The derated margin provides a more detailed representation of traditional power systems, but cannot naturally be extended to VG without performing a full risk calculation, due to VG's very different patterns of availability.

2.3 Risk-Based Approaches

A much more rigorous and informative approach to GAA is to explicitly consider the risks of generation capacity being insufficient to fully meet demand, using probabilistic methods to model the balance of supply and demand during each point in time. When significant VG capacity is present, accurate results require that the probabilistic method accurately represents spatial relationships in the resource availabilities across the system's geographical area, to accurately model the aggregated VG generation. Where there is significant presence of energy-constrained generation such as hydropower, it is also vital to capture temporal relationships in the resources, as will be discussed in greater detail later in this article.

Since GAA is usually conducted for the mature power systems of developed countries, studies are concerned with the frequency and severity of those rare events when not all demand can be met, referred to here as generation shortfall events. Although there are many possible metrics to capture a system's capacity adequacy from this perspective, the most popular are:

A) The number of periods during a year – e.g. 30 minute intervals or hours, also referred to as time-steps – for which the generation capacity available is less than the demand. (This is uncertain ahead of time, due for instance to imperfect predictability of weather and plant breakdowns); and

B) The total energy, throughout the year, demanded by customers that cannot be delivered by the system at the time (which again is uncertain ahead of time).

GAA might address the adequacy of some present system during the next peak demand season, or a future system scenario, or both – e.g. calculating metrics for a rolling set of scenarios covering the next 20 years, with projections updated annually. Risk assessment is always based on some statistical model of the possible conditions faced by the system – including weather outcomes and customer behaviour.

Generators in most power systems include thermal generators, such as coal power plants, hydropower reservoirs and VG such as wind farms or large photovoltaic (PV) farms. Large thermal and hydro generators are known as conventional units, and their total power rating is known as the system’s conventional capacity. At a given (modelled) time *t*, the sum of capacity for all conventional generators that are mechanically available, plus the power available from VG due to weather conditions, gives the power demand that the system is capable of satisfying. In GAA, typically a statistical model of available wind or solar capacity for the whole system would be built (taking care to use data coincident in time from different installations within this model).

Under normal operation, the *available* capacity is larger than the power generated. Adequacy is quite separate to operational questions, such as which subset of available generators should be prepared (e.g. sufficiently heated) ready to generate, or the optimal mix of power exports from this subset.

The most commonly used generation adequacy metrics involve expected values (i.e. probability-weighted averages) over the full range of possible out-turns for the balance of supply and demand, given the statistical model constructed to represent this. The most popular probabilistic metrics in GAA are derived from *A* and *B* presented above, and are:

1. The loss of load expectation (LOLE) -- the expected value of (A), i.e. the expected duration of shortfall in the future season under study. This is equivalent to the sum over periods in the future season of the probabilities of shortfall in each period, multiplied by the length of a single period.
2. The expected energy not served (EENS) -- the expected value of (B).

Other metrics relating to extremes may also be of interest, such as the high quantiles of the distributions of shortfall duration or energy not served. In order to go beyond expected value indices and calculate such metrics, a full sequential (or time series) modelling approach is required.

Readers interested in gaining a deeper understanding of probabilistic generation adequacy metrics can find a rigorous exposition of the principles in e.g. (Zachary and Dent 2012), and an example of a GAA study using such metrics – for the Great Britain power system and conducted by the UK's energy regulator – can be found in (National Grid 2016). The authors have not found any complete examples of probabilistic generation adequacy studies for SSA countries, and very few examples for any developing country.

2.4 Modelling Requirements

One of the main modelling challenges in GAA is the construction of statistical models representing the availability of the generators: a model for each conventional generator (whose availabilities are typically assumed statistically independent of each other) and one for the aggregated VG output – or for each cluster of aggregated VG. At any time, the available VG energy resource from a specified fleet of generators is a function of relevant aspects of the weather, such as wind speeds and the total amount of solar radiation incident on the ground (referred to as insolation). Substantial quantities of historical data are generally required in order to derive the necessary statistical models.

For systems with a large capacity of hydro power, there is an economic balance to be struck between using stored water, with zero short run marginal cost energy at a particular time, and keeping that water in store to support future adequacy. The need to balance operational options makes adequacy assessment in hydro dominated systems much more challenging than in systems with just conventional generation, wind and solar. However, if the water resource is sufficient, and the hydropower capacity relatively small, simplifying assumptions may be possible.

Since VG technologies do not consume any fuel, they will always be scheduled in preference to thermal generators when available. However, the ability of the system operator to do this may be constrained by system security and flexibility considerations. It may be the case that the total power generated by VG may not be permitted to exceed some fixed percentage of the load, and if the VG power available exceeds this proportion, then that excess will be curtailed. However this is unlikely to reduce significantly VG's contribution to system adequacy – if VG is curtailed due to high available capacity, then an overall capacity shortfall is unlikely.

As will be discussed in greater detail in later sections, one of the fundamental challenges of GAA for SSA power systems is a lack of data and experience to allow accurate statistical models to be built. It might also be difficult to confirm which commonly made assumptions, such as those listed above, might be reasonable approximations for SSA systems. This is particularly true for systems that are transitioning very rapidly from having essentially no VG to a high proportion of the total capacity.

3. Overview of Case Study Power Systems

This section provides a context-setting overview of the case study countries and their power systems. This includes their historical developments, industry actors and projections of future growth, particularly regarding VG capacity and demand.

3.1 Ghana

Ghana is a West African country of 27.41 million people in 2015 (World Bank 2017), with a GDP in 2015 of US $37.5 billion, having grown rapidly from US $5 billion in 2000 (World Bank 2017), and peaking at US $47.8 billion in 2013. It consists of plains and low hills, and has 560 km of coastline. For decades, Ghana's economy has been fuelled by abundant inexpensive hydro power (Gyamfi, Modjinou and Djordjevic 2015), generated by the Akasombo Dam on the Volta River.

As a developing economy, electricity demand has long been relatively low, with most households relying heavily on traditional biomass for their primary energy supply (Mohammed, Mokhtar, Bashir and Saidur 2013). While hydro power was the dominant source of electricity, in 2008 it accounted for only six per cent of energy consumption. Nonetheless, electrification is extensive compared to many SSA countries, with 72 per cent of the population having access to electricity in 2014, breaking down into 91 per cent for the urban population and 50 per cent for the rural population (World Energy Outlook 2016). However, due to insufficient generation capacity, along with the expense of maintaining the distribution network, the quality of energy access is low for many customers.

Following independence, Ghana's power industry was dominated by the Volta River Authority (VRA) as a monopoly power generation, transmission and distribution utility. Currently it generates most of the nation's power, but Independent Power Producers (IPP's) are an increasing presence. Ghana Grid Company (GRIDCo) owns and operates the transmission system, while two companies own and operate the distribution networks: The Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCO) – a stand-alone subsidiary of the VRA. Two regulatory bodies jointly oversee the electricity sector: the Public Utilities Regulatory Commission, and the Energy Commission (EC), which issues licenses and establishes performance standards. This relatively new structure is intended to enable and encourage the free entry of IPPs into the generation market (Volta River Authority 2015).

At the beginning of 2014 there were three hydropower reservoirs operational in Ghana, with the following capacities: Akasombo – 1020MW, Bui – 400MW, Kpong – 160MW. There were also nine thermal plants, with nameplate capacities totalling 1494MW. With 2.5MW of solar PV and 5MW of embedded generation, the total generation capacity was 3,081MW. However, it is stated by the Ghana Energy Commission (2014) that the 'dependable' capacity was only 2,631MW – the term is not defined precisely, but rather it is simply stated that the figure was obtained from 'many years of operational experience'. The figure therefore seems to represent the EC's point forecast for the capacity available most of the time in the immediate future.

Electricity demand has been rising rapidly in recent years, with a peak value of 1,970MW in 2014 (Ghana Energy Commission 2016). This rise, along with periodic droughts, has left the country increasingly reliant on expensive oil and gas plants, with a resultant drain on the national economy (Gyamfi et al. 2015). From 2000 to 2009 the peak power and annual energy demands grew by 44 per cent and 100 per cent, respectively (Power Systems Energy Consulting 2010), but installed generation capacity grew by only seven per cent. Rolling blackouts (where a limited number of customers are disconnected in a controlled manner in order to balance demand with supply when the latter is insufficient – such disconnections may be rotated over time between different areas) and severe restrictions on energy consumption are often employed by the main utility companies to manage power supply constraints.

The industrial sector in Ghana is one of the major drivers of the nation's economy, particularly aluminium smelting, placing much greater energy demands on the nation's power sector than most other SSA countries (Mohammed *et al.* 2013). The cost to Ghanaian society of insufficient wholesale power supply adequacy and security was estimated in (Power Systems Energy Consulting 2010) to be between US$320 million and $924 million annually, or two per cent to six per cent of GDP, not including several indirect costs.

VG capacity in Ghana is currently very low, but this situation may change within a few years, with a strong ideological commitment to this aim by some actors within the industry and Government, paired with abundant resources. Indeed, the VRA in (Volta River Authority 2014) states that a 'renewable energy development programme is one of the most constructive, cost effective ways to address the challenges of high energy prices, energy security, air pollution, and global climate change'. The Government passed a Renewable Energy Act in 2011 to ensure a target of ten per cent share of renewable energy in the national electricity generation mix by the year 2020. Network security concerns may however act as a barrier to achieving this policy.

A stated aim of the VRA in 2015 was aim to construct 100-150MW of wind power (Volta River Authority 2014) – this programme began in 2012, at locations in the southern part of the country. It was further stated that up to 12MW of solar power generation would also be commissioned in the following years. According to the EC in (Ghana Energy Commission 2016), provisional licences (preliminary and temporary licenses issued to companies that meet the statutory requirements for being licensed to develop a proposed power project) issued by them for VG had risen to 62, with capacity totalling 5,074MW. That figure is much larger than the current total of installed generation of all types. Of these, 44 were for PV generation, with a total capacity of 2,472MW. Licences for other types of VG totalled: wave – 1000MW, biomass – 68MW, waste to energy – 554MW. These are very large numbers given the size of the system, and it seems unlikely that all will actually be developed. According to (Power Systems Energy Consulting 2010), Ghana has an estimated additional hydropower potential of 2000MW, of which 1200MW consists of large schemes (> 100MW), along with many feasible small and medium sites.

3.2 Kenya

Kenya is situated on the eastern coast of Africa, bisected by the equator. It has a coastal length of 470 km (Theuri 2008) varied terrain and rises to 5199 meters above sea level. Kenya's population is rapidly expanding, having increased from 31 million people in 2000 to 46 million in 2015 [(World Bank 2017). The economy has been growing even more rapidly, with GDP growing from US$ 12.7 billion in 2000 to US$ 63.4 billion in 2015 (World Bank 2017).

Most generation in Kenya is operated by KenGen, with a significant minority by IPPs. The power transmission network is operated by the Kenya Electricity Transmission Company (KETRACO), while the Kenya Power and Lighting Company (Kenya Power) is responsible for distribution and retail throughout the country (Kenya Power 2015). Power sector regulation is the responsibility of the Energy Regulatory Commission (ERC), while policy is formed by the Ministry of Energy (MOE). In 2010, only 20 per cent of the total population of Kenya, and only about five per cent of the rural population had access to electricity (Ogola, Davidsdottir and Fridleifsson 2011), although this situation is rapidly improving (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015).

The peak demand on the system rose from 1,107MW in the 2006-07 financial year to 1,512MW in 2014-15 (Kenya Power 2015). The installed generation capacity operated by KenGen on 30/06/2015 (inMW) was: hydro – 820, thermal – 236, geothermal – 488, and wind – 25.5. IPP generation capacity comprised of a mixture of thermal, geothermal and hydro plant, with capacity totalling 654MW, with an additional 30MW of emergency power – giving a total of 2,299MW. This represents a healthy generation margin.

While most of the electricity historically generated in Kenya has been from hydropower, it has not supplied most of the country's *energy* needs – petroleum has, over the years, accounted for about 80 per cent of the country's commercial energy requirements (Oludhe 2008). It is also stated by Oludhe (2008) that the large hydropower potential in Kenya is estimated at about 2263MW while the small, mini and pico hydro capacities are estimated at 3000MW. Further, there is excellent geothermal resource within the Rift Valley, with the generation potential is estimated at over 2000MW.

A major aspect of Kenyan energy policy in recent years is the updated Least Cost Power Development Plan (LCPDP) (Republic of Kenya Energy Regulatory Commission 2011; Republic of Kenya Energy Regulatory Commission 2013). This uses a macro-economic model, aided by resource strength assessments and constraint considerations, to establish generation and transmission capacity expansion plans for each year over a 20-year horizon. The 2013 LCPDP includes the following base-case forecasts for peak demand: 3,207MW by 2020 and 11,318MW by 2033. According to the LCPDP's macroeconomic modelling, the optimal way to meet the projected 2033 demand is with the following generation capacity breakdowns (in MW): hydro – 835, nuclear – 2,600, thermal – 9788, geothermal – 7,264, wind – 2,186, and solar – negligible.

It is stated in (WinDForce for the Ministry of Energy 2013) that in 2013 the Kenyan economy, population and industry were all expanding at such a rate that there is currently a 13.5 per cent annual increase in electricity demand, with demand expected to reach 15,000MW in 2030. To assist the growth of the renewable energy sector, (WinDForce for the Ministry of Energy 2013) states that the Government of Kenya (GoK) plans to invest up to US$ 50bn over the next 20 years. It is stated by the GoK (The Presidency, Republic of Kenya 2013) that they aim to be a middle-income rapidly industrialising country by 2030, achieved through a steady export-led economic growth. The GoK is seeking to reassure international companies that there is an excess of generation capacity in the country (Chair of Lowest Cost Power Development Plan Committee, Energy Regulatory Committee, personal communication, 10th June 2015), and are over-planning their generation capacity accordingly: the capacity was increased by 25 per cent (528MW) within a year in 2014-2015, for example.

4. Energy Resources in the Case-Study Countries

This section reviews the state of knowledge about the relevant energy resources in the case study countries. Understanding patterns of availability for these resources is an essential prerequisite for building statistical models to be used in capacity adequacy assessments.

4.1. VG Resource Assessment

4.1.1. Ghana

A comprehensive review of renewable energy resource assessment activities in relation to Ghana can be found in (Gyamfi *et al.* 2015), a journal paper published in 2015. It reports that a satellite-based, high resolution solar energy resource assessment was carried out in 2002, finding that very strong solar radiation resources are available in many parts of the country, especially the north, with a national average of five kWh/m^2/day.

A comprehensive wind resource assessment of Ghana was carried out by the U.S. National Renewable Energy Laboratory (NREL) in 2002 (Gyamfi *et al.* 2015), forming part of a global project to supply high quality renewable energy resource information – the Solar and Wind Resources Assessment (SWERA). The project developed high resolution (1 km) wind energy resource maps for all of Ghana, and found areas of excellent resource in the south east, a moderate distance inland from the coast. Unfortunately, this area is not very convenient for building large wind projects, so the coast may be favoured, despite the poorer resource. Accordingly, the Ghana EC has undertaken measurements at higher altitudes along the coast, with results presented in (Adaramola, Agelin-Chaab, and Paul 2014). It was found that the resource in this area falls into Category 2 of the commonly used classification scheme developed by the Pacific Northwest Laboratory, and thus is 'marginally suitable for large scale wind energy development or suitable for small scale applications'.

The Ghana EC has granted a provisional licence of up to 1000MW to a wave energy project (developed by Swedish firm Seabased Industry AB, in partnership with Ghanaian company TC's Energy) (SeeNews Renewables 2015). Given the immaturity of this technology it seems unlikely that 1000MW will be installed in the foreseeable future – although some converters are already supplying the grid.

4.1.2. Kenya

It is stated repeatedly in Government publications and the academic literature, e.g. (Saoke 2011) and (Mukulo, Ngaruiya and Kamau 2014), that while Kenya has excellent wind resource, it is currently only beginning to embrace this technology. This slow progress is partly due to the non-availability of site-specific resource data for most parts of the country, since meteorological stations were typically located with agriculture in mind. Further problems, typical of SSA countries, are (Theuri 2008): (i) lack resources to maintain and properly calibrate measuring equipment; (ii) component deterioration in anemometers, so that wind speeds are under-represented; and (iii) the gathered data can be difficult to access and are often not in digitised format.

It is stated (Saoke 2011) that equatorial areas are assumed to have poor to medium wind resource, however Kenya's position means that it might expect westerly winds, and seasonal Monsoon winds caused by large annual temperature differences over land and sea areas (Oludhe 2008). In fact, the Country's topographic features – the Rift Valley and various mountains and plateaus – have endowed the country with excellent wind resource areas. In addition to these features, Oludhe (2008) states that the large inland lakes found in Kenya create meso-scale circulations (land-sea breezes) that modify the horizontal and vertical wind speed profiles, adding to many locations' energy potential. However, such features mean that using wind speed measurements from one location as a proxy for others, and extrapolating between heights using generic formulae for all locations, are unlikely to be accurate.

The first substantial analysis of Kenya's wind energy resource was a Ph.D. thesis completed in 1998 (Oludhe 1998), using meteorological station data. The thesis is insightful insofar as it presents a comprehensive analysis of the spatial and temporal patterns in the wind resource on many scales, however the absolute wind speeds presented are unlikely to be very accurate, as they are extrapolated from meteorological station data. Regarding large-scale temporal patterns, the inter-annual variability of wind speed statistics was discussed, including the impact of El Niño and Southern Oscillation events. A more recent, but less comprehensive analysis using meteorological station data can be found in Kamau, Kinyua and Gathua's work (2010). Several journal papers, e.g. Saoke (2011) and Mukulo *et al.* (2014), report on studies that involve directly measured wind speeds at several heights – with the results being very positive.

A report by the consultancy WinDForce (2013), published in 2013 for the MoE, analysed wind data collected by the latter through a wind-monitoring program funded by the World Bank. The analysis confirmed that the country is bestowed with immense potential, and that certain turbine models would have capacity utilisation factors of 40 per cent or more at sites in Marsabit and Turkana Counties. This could represent a very attractive proposal to investors. An MSc. thesis (Barasa 2013) analysed the wind regime at three sites in Kenya and quantified the power reserve requirements of large-scale wind power production, exceeding 20 per cent of installed capacity, by considering the time varying patterns of wind power production. The data obtained to achieve these objectives included six months of hourly-resolution wind speed data for Ngong obtained directly from the KenGen turbines at a hub height of 50 metres.

The SWERA report (Theuri 2008) also addressed in detail Kenya's solar resource, with atlases derived from satellite data. The report states that while the entire country receives favourable levels of insolation, most of the northern and northeastern areas are excellent. A journal paper (Hammar, Ehnberg, Mavume and Molander 2012) investigated the physical preconditions for many types of renewable ocean energy, in the western Indian Ocean countries. The results show high potential for wave power over vast coastal stretches in southern parts of the region and high potential for ocean thermal energy conversion at specific locations – however the potential for ocean energy seems limited for Kenya.

4.2. The Hydrological Resource

Africa is endowed with enormous hydropower potential that is yet to be harnessed for electricity production (Water for Agriculture and Energy in Africa 2008). The rapid demand growth in both Kenya and Ghana has meant that the required discharges from their hydro reservoirs cannot be consistently delivered, given considerable inter-annual variability in inflows, and levels have repeatedly fallen below the minimum required for operation (Power Systems Energy Consulting 2010). Modelling the associated complex meteorology is extremely challenging, particularly since the effects of climate change are likely to be considerable and hard to predict.

The net inflows for the month of August into lake Volta (powering the Akasombo dam) for the years 2011 – 2014, for example, were approximately 4.7, 4.2, 1.5 and one million acre feet (MAF) – compared to a long term average of 5.5 MA (Volta River Authority 2015). The series of total annual energy generated by the Akasombo dam from 2000 to 2013 has a standard deviation that is 23 per cent of its mean, and a range that is 74 per cent of the mean (Ghana Energy Commission 2014). In Kenya, the annual precipitation in the Masinga dam catchment area from 1981 to 2011 varied considerably, with a factor of two difference between the smallest and largest values. Indeed, it is reported by Oludhe (2008) that a drought in 1999-2000 reduced the hydro-generation capacity to less than 60 per cent of the normal output, resulting in severe energy rationing and devastating effects on the economy. The hydrology of the Masinga dam is explored in considerable detail in section 8.3.

As previously mentioned, there is currently significant interest in developing relatively small hydropower projects (Ghana Energy Commission 2016; Water for Agriculture and Energy in Africa 2008). While many of these might provide energy to communities that are too remote to be connected to the main power grid for the foreseeable future, their presence on the grid would represent a considerable additional modelling challenge.

4.3. Thermal Generation

With a relatively small number of generators, specific events affecting thermal plants in SSA countries will have a much greater impact on generation adequacy than in the large power systems of more developed countries. There are two main challenges regarding the modelling of thermal generation in SSA countries within a generation adequacy context: the mechanical availability of the generators and the reliability of fuel supply. In each case, the defining characteristic for SSA countries is a lack of data, due to rapidly changing circumstances. The mechanical availability of generators itself has two aspects: the frequency with which faults will develop and the time taken to repair various types of faults. There are many uncertainties associated with these – for example there may or may not be supply chain problems in Kenya associated with geothermal generation, which is a much less common type of generation globally than e.g. coal plant.

Fuel supply is particularly uncertain in Ghana, in a large part due to the VRA's participation in the West Africa Gas Pipeline (Volta River Authority 2015) to obtain natural gas from Nigeria to operate its thermal facilities. This scheme promised to significantly reduce the cost of electricity, while increasing reliability and protecting the environment. However, the supply has been highly unreliable – due to economic and political disputes, and accidental damage to the pipeline, with thermal plants operated by a mixture of gas and (expensive) oil. The VRA is considering several alternatives (Volta River Authority 2015), such as re-gasified LNG, with the potential consequences of such decisions for reliability very difficult to predict.

Another factor affecting the reliability of fuel supply in Ghana is the speed at which (fairly modest) domestic gas resources will be developed. For example, it is reported by the Ghana Energy Commission (2016) that 2014 saw the first local associated gas flow from a gas processing plant in the Western Region to nearby thermal plants, and that the development of new fields commenced in 2013. However, the schedule of completion for such projects could be severely delayed for many reasons, including prevailing low oil prices.

5. Demand and Energy Access

5.1. Demand Trends and Forecasts

Demand growth in the Kenya and Ghana power systems has been very rapid during recent years, a trend that is set to continue. For example, Kenya's LCPDP for 2013–2033 (Republic of Kenya Energy Regulatory Commission 2011) has their central forecast for peak demand rising from 1,606MW in 2013 to 11,318MW by 2033. The forecast however has much associated uncertainty, with the feasible 'low growth' forecast being roughly 50 per cent lower than the central forecast by 2033, while the ‘high growth’ forecast is roughly 50 per cent higher.

The forecasts of (Republic of Kenya Energy Regulatory Commission 2011) use macroeconomic analysis to make their predictions, as is typical globally. A classic example of this in the academic literature can be found in Adom and Bekoe (2012), which compares the performance of two advanced econometric models for forecasting demand. However, the limitations of relying solely on such `bottom-up' analysis for rapidly developing systems is highlighted by a research article by the World Bank (Chattopadhyay, Kitchlu and Jordan 2014). The authors point out that accurate demand estimates depend on realistic estimates of disaggregated demand, including suppressed demand – a concept discussed in Section 5.3. Successful forecasts, they state, must account for physical, financial, and institutional constraints and make use of detailed demographic data and distribution network planning.

This has been addressed by several journal papers in recent years, (Kemausuor, Adkins, Adu-Poku, Brew-Hammond and Modi 2014; Parshall 2009; Stevens, Wilcox, Leopold, Taylor and Waters 2016). While incorporating the localised and otherwise disaggregated data into power system planning will generally lead to superior results, the conclusions of such approaches can differ considerably, apparently as a reflection of the world view and academic/ professional background of the researchers. For example, the conclusions of Parshall (2009) are very much in favour of grid expansion – stating that extension of the national grid is less costly than off-grid options under most geographic conditions, while Stevens *et al.* (2016) states that microgrids ‘were found to be cost-competitive or cheaper than grid extension in almost all our case studies’. The core message of Kemausuor *et al.* (2014) is that scenario-based spatial modelling can provide detailed and specific outputs, but that it is essential to complement these outputs with vetting such as expert reviews and field feasibility studies. A factor that should not be neglected is prestige of grid connection (Kemausuor *et al.* 2014), with some communities in Ghana boycotting off-grid systems to pressure the Government into connecting them to the main grid.

5.2. Quantifying Energy Access

This report is concerned with the ability of VG projects in SSA countries to either improve the generation adequacy of power systems given a constant level of demand, or to maintain a constant level of adequacy given a growing demand. It might be reasonable to assume a strong relationship between the ability of VG projects to do this, and their ability to increase the number of poor people with energy access of a reasonable quality. However, the extremely low levels of energy consumption among people who have recently been connected to the grid make this relationship tenuous. Indeed, it was stated during interviews with senior staff at both Kenya Power (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015) and the ERC (Chair of Lowest Cost Power Development Plan Committee, Energy Regulatory Committee, personal communication, 10th June 2015) that the challenge is to encourage and facilitate newly-connected customers to consume more, to increase the economic and political viability of grid extensions. The regulators and policy makers in Kenya and Ghana have created many innovative and successful schemes for increasing access, but most of those benefiting from access for the first time cannot afford appliances that consume electricity. For example, it was estimated in 2015 that 1.5 million customers that would soon be connected to the grid would each consume only 50 kWh per month (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015). It was also estimated that a total of between 3,500 and 5000 domestic customers consume about 60 per cent of the country's power, but that a mere 700-1000MW of additional capacity would be sufficient to supply an additional three million potential domestic customers.

Traditionally, energy access has been measured as the number of people who have a physical connection to a power supply. The energy access of an individual was reported as binary – either there was a physical supply to their village (and the people have access) or there was not. In recent years, international agencies and governments, including SSA countries, have been adopting a more sophisticated approach based on the performance of the energy supply. A commonly adopted approach is that of the United Nations' Sustainable Energy for All programme (Energy Sector Management Assistance Program 2014). In this framework, access to energy is 'the ability to avail energy that is adequate, available when needed, reliable, of good quality, affordable, legal, convenient, healthy & safe, for all required energy services across household, productive and community uses'. The approach to measuring and representing access is multi-tiered, and reflects a continuum of improvement, based on the performance of the energy supply. An alternative framework for Ghana is proposed in Mensah, Kemausuor and Brew-Hammond (2014), involving a multidimensional energy poverty index.

Over the course of a year, a government following the UN framework can report that e.g. 150,000 people went from Tier 0 (no electricity access) to Tier 1 (1 – 50 Watts for four – eight hours/day with regular unscheduled outages). It might also report on the number of people who transitioned from Tier 2 (50 – 500 Watts for four – eight hours/day, with unscheduled outages) to Tier 3 (500 – 2000 Watts for eight – 16 hours/day, with unscheduled outages). The latter is a particularly relevant transition, since Practical Action in Stevens *et al.* (2016) state that Tier 3 was found to be the minimum level at which households should be considered as having electricity 'access' in national plans.

5.3. Suppressed Demand and Alternative Adequacy Metrics

In the mature power systems of developed countries, demand can always be matched by dispatched generation, except for a few rare occasions in exceptional circumstances. Demand side management schemes are seen as a vital component of future power systems – however as they are voluntary they should be seen as part of everyday matching of supply and demand, rather than being an emergency action.

In SSA countries substantial involuntary disconnections might be needed in order to balance supply and demand in the short run. However there is a further phenomenon, known as suppressed demand, where demands which would appear if the supply were reliable do not in fact exist due to the unreliability of supply – for instance this might make commercial investments unviable. It is complex in nature and very difficult to evaluate. On the one hand, a frequent inability to meet demand leads to a reduction in it, with associated missed opportunities for investment in productive activities: from large industrial activities, such as aluminium smelting in Ghana, to micro-businesses in village homes (Power Systems Energy Consulting 2010; Republic of Kenya Energy Regulatory Commission 2011). As the installed generation increases, it is likely (or at least hoped) that the demand will rise as well. However, to fund the construction of additional generation – or attract external investors to do so, it is likely that electricity prices must be raised (Power Systems Energy Consulting 2010), which has the effect of driving down demand among some customers, particularly the poor.

There is clearly considerable potential demand in Ghana curtailed in the short run and suppressed in the long run, and the financial impacts are severe (Power Systems Energy Consulting 2010). In Kenya, as previously discussed, the lack of capacity adequacy in the past means that there is still a widespread belief that the system is highly unreliable, despite the high level of reliability currently experienced in the cities (except during floods) (Chair of Lowest Cost Power Development Plan Committee, Energy Regulatory Committee, personal communication, 10th June 2015). Many areas of Kenya continue to experience an unreliable supply however – to a small extent due to insufficient transmission capacity, but mainly due to problems with insufficient distribution capacity and maintenance challenges (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015).

It could be argued that focussing exclusively on those occasions during which demand is not entirely met is not the most appropriate approach for the capacity adequacy assessment of SSA power systems. In situations where the true demand is highly nebulous, yet almost certainly never entirely met, it may be more appropriate to express (probabilistically) the power that *can* be delivered. Such analysis could report on the deliverable power at different times, e.g. a typical weekday evening, and as a set of quantiles – e.g. the power that can be delivered with a 95 per cent and 99 per cent probability. Such values might be dependent on the operational decisions of hydro resources, which may themselves be a function of a target profile of delivered power.

Such an approach would tie in very well, conceptually, with the approach to electricity access that reflects how often power is scheduled to be delivered, and how well reality matches such schedules. As such, this novel approach to capacity adequacy could predict the number of people that could move up a tier in the UN framework. A caveat here is that other conditions, e.g. relating to safety, may also have to change to make the transition. To the authors' best knowledge, no work has been published that assesses a system's generation adequacy in this way.

5.4 International Power Transfers

It is stated in Eberhard *et al.* (2008) that in 2008, 93 per cent of the continent's economically feasible hydropower potential remained unexploited, due mainly to the resources being concentrated in a handful of countries that are geographically removed from the centres of power demand. The trading of electricity between nations is an excellent way of lowering costs, integrating a higher proportion of VG without curtailment and generally increasing capacity adequacy. Accurate representation of such international flows in probabilistic generation adequacy studies of future SSA power systems could represent a significant additional modelling challenge.

Kenya and Ghana are keen participators in regional programs to facilitate such exchanges (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015; Chair of Lowest Cost Power Development Plan Committee, Energy Regulatory Committee, personal communication, 10th June 2015) – those programs being the East Africa Power Pool (EAPP) (Gebrehiwot 2013) and West African Power Pool (WAPP) (West

Africa Power Pool 2017) respectively. The EAPP in Gebrehiwot (2013) describes its aim as facilitating secure power supply to the countries of the Eastern Africa Region at the lowest possible cost. They plan to achieve this through 'pooling' of resources for better exploitation of the available potential in the region to satisfy the increasing demands based on regional least cost options to benefit all member states. Also, through facilitation & coordination of power exchange among member utilities with the ultimate objective of establishing a regional electricity market.

Kenya is motivated to play an active role by its need in the future to export wind energy during times of high wind speeds and low demand, since there is currently an excess of generation capacity. One obvious choice is its neighbour, Uganda, and through that country to Rwanda (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015). However, demand in both countries is low, which limits the options, and there is generally an excess of generation in the east Africa region (Chair of Lowest Cost Power Development Plan Committee, Energy Regulatory Committee, personal communication, 10th June 2015), despite what the low access rates might suggest.

The VRA reaches its customers both in Ghana and neighbouring countries through GRIDCo's network, which is well connected to neighbouring countries. The international interconnections are governed by WAPP, and seek to provide the region with increased accessibility, availability and affordability (Volta River Authority 2015).

6. Specific Characteristics of the Case Study Systems Relevant to GAA

This section provides a summary of the characteristics of the two SSA power system case studies that are relevant to probabilistic GAA, drawing on the literature reviewed in the previous subsections. In Kenya and Ghana:

- Energy constraints on the power that can be delivered by hydro generation have a strong negative impact on adequacy. This is largely due to a combination of the historical dominance of hydropower and the very significant inter-annual variability of the hydrological resource. This constraint means that governments of both countries are looking to reduce the penetration of large hydropower reservoirs in their generation mix. A modelling consequence is that rigorous capacity adequacy assessment must involve sequential simulation of the system – including the operational decisions of hydro generation, which in turn requires modelling of the actual dispatched power, rather than availabilities alone.

- Energy constraints may also apply, to some extent, to thermal generators in SSA countries. This is certainly the case in Ghana, but there is no evidence that this is currently the case for Kenya – to a large extent due to the large capacity of geothermal generation (that does not require fuel).
- Unplanned load shedding due to equipment failure, particularly in the distribution networks, is common in both countries. Planned load shedding is also common in Ghana, when it is known in advance that the generation capacity will be insufficient. Even without tools for sophisticated GAA available, it is evident that generation capacity is currently adequate in Kenya, but not in Ghana. In Kenya, unplanned load shedding is attributable to the unreliable nature of distribution networks, along with limitations of the system for dynamic planning and management on operational time scales (Chief Engineer for Generation Planning at Kenya Power, personal communication, 9th June 2015). A combination of load shedding and suppressed demand mean that the demand at some specific hour in the recent past cannot be automatically equated with the power dispatched at that time.
- Both Kenya and Ghana have an abundant resource for many types of VG, including but not limited to the mature technologies. Despite this, the VG capacity currently installed in both countries is very small – partially due to a lack of site-specific resource data, and partially due to a lack of expertise about how to manage the systems when VG is present in substantial amounts. However, highly ambitious plans are in place for increasing VG penetration, and in Kenya these plans are soon to become reality.
- For all the reasons mentioned above, the data acquisition and model development work required for a full probabilistic GAA of the Kenya and Ghana systems, even in the near future, would be very challenging. However, given the importance of reliable and affordable electricity supplies to these rapidly developing countries, completing such an exercise is of vital importance.

7. Review of Previous Work Relating to GAA in SSA Power Systems

7.1 Previous Adequacy Assessments in Ghana and Kenya

The previous section identified the characteristics of the power systems of Kenya and Ghana, which define the specific technical challenges that must be overcome to allow rigorous and accurate assessment of generation adequacy. This section moves on to critically review previously published works that have taken steps toward addressing these challenges.

A reliability assessment of the Ghana power system in 2010 was conducted by Power Systems Energy Consulting on behalf of GRIDCo (Power Systems Energy Consulting 2010) – a document that has been referenced several times already in this report. Their assessment of generation adequacy was limited to calculation of the derated capacity margin at the time, and in the coming years, along with an analysis of structural factors limiting the connected capacity. Forced outage rates – i.e. the percentage of time that the plants are required, but are unavailable, are presented for each generator, but without discussion of how they were derived. The report's authors state that it is essential for the system's future reliability that GRIDCo or another institution conduct, on a regular basis, explicit LOLE studies. These would 'establish an official generation reserve margin for the Ghana wholesale power supply system'. Such a statement is rather unfortunate, as it implies that adequacy standards might best be expressed in terms of margin, rather than directly in terms of risk.

Such a probabilistic study for the Ghana power system has not materialised in the years that followed. However, the Energy Outlook for 2015 published by the Ghana EC (Ghana Energy Commission 2014) calculated the generation margin for 2014 – possibly derated, although this is not made clear – and scenario-based forecasts for 2015. The report states that securing the traditional target of a 15 per cent margin could eliminate forced load-shedding, but that there is little chance of acquiring all the additional capacity needed to achieve this margin in the immediate future.

As previously stated, the planning of expansion for Kenya's generation and transmission capacities occurs through their Least Cost Power Development Plans (LCPDP) (Republic of Kenya Energy Regulatory Commission 2011; Republic of Kenya Energy Regulatory Commission 2013). These planning exercises use VALORAGUA – a commercial tool for calculating lowest cost schedules for power systems consisting of hydro and thermal generators. The tool achieves this by evaluating the value of water over a one-year horizon, representing uncertainty in hydro inflows through three sets of hydrological conditions: dry, average, and wet. The load is represented as five steps, ranging from the peak to the base load.

It is stated by Republic of Kenya Energy Regulatory Commission (2011) that in the recent past, stakeholders in the Kenyan power sector have recommended that a LOLE of one day in ten years – a common international standard for a 'reliable' system – should be applied to the LCPDP's, to achieve the country's Vision 2030 goals. This target LOLE is converted to a LOLP value, based on the very strong assumption of equal risk on every day of the year. This is problematic for many reasons, including that demand is higher on weekdays than on weekends, and that the ability of hydro to support demand is typically reduced during the dry seasons. Regardless, ensuring that this daily LOLE value[1] is not exceeded then constitutes one of the constraints of the WASP (Wien Automatic Simulation Planning Package) economic optimisation that is run on outputs from VALORAGUA. The probability model used by WASP to convert a proposed set of generators and demand profile into a set of LOLP values, and from there the daily LOLE, is not clearly stated. However, it may be inferred that generator availabilities are based on first order reliability (FOR) values derived from international experience, and are assumed statistically independent of each other.

7.2 Adequacy Assessments for Other SSA Power Systems

This subsection reports on relevant work in different SSA countries, classified by their fundamental modelling approach. The first category of GAA are those employing essentially the same approach as in the Kenyan assessments described above, except that they use full year-round risk calculations, rather than assuming that a single snapshot day provides sufficient representation.

One example is a series of papers by Pandey et al. on assessing the reliability of the Nepalese power system (NPS), which includes Billinton, Pandey, Aboreshaid and Fotuhi-Firuzabad (2000) and Pandey and Billinton (2000), with Nepal serving as a case study for developing countries. The stated objective of Billinton *et al.* (2000) is to assess an expansion plan proposed by the Nepal Electricity Authority, indicating the reliability implications

[1] Incorrectly stated as an LOLP value in Republic of Kenya Energy Regulatory Commission (2011; 2013)

associated with it, and in so doing, to demonstrate that probabilistic reliability evaluation of power systems in developing countries is both possible and practical.

The second paper on the Nepalese system, Pandey and Billinton (2000), examines the problems associated with using power system reliability cost/worth techniques in a developing country, and presents methods to develop planning criteria incorporating explicit recognition of reliability worth. The authors state that increasing demands for electric power and the resulting large capital investment requirement has created a tremendous economic burden for Nepal. The issue, they state, is not that power development should assume decreased importance, or that this capital-intensive sector will not continue to merit significant resources in the future, but rather that it must be scrutinised carefully, and greater justification is required to implement future power projects. The solution proposed to overcome these difficulties is to explore and implement effective system planning criteria based on fundamental principles of power system reliability and economics. Power system planning criteria used in developing countries, the authors state, are usually extrapolated from similar criteria adopted by more developed countries. This is usually done in the absence of basic system data, and with little recognition of the explicit worth associated with the reliability of electric power supply.

Another highly relevant piece of research that may be classified as GAA of the same type is Ummel and Fant (2014), published by the United Nations University. The authors state that South Africa, along with other countries, face a common challenge: how to turn laudable renewable power aspirations into concrete plans. This, they state, is an exceptionally complex task, and hinges largely on the question of how and where to deploy VG – which for the present study is limited to wind and solar generation. The report is motivated by the fact that well-designed deployment strategies can take advantage of natural variability in VG resources across space and time to minimise costs and maximise benefits, while ensuring reliability. Poor deployment strategies, they state, risk locking countries into multi-decade infrastructure investments that unnecessarily increase the cost of electricity. This is certainly a real danger in the case of Kenya and Ghana.

The next category of GAA in SSA countries also use directly historic data series for the representation of VG output and demand, but calculate the optimal dispatch of thermal generators for each hour. The balance of generation and demand for each hour then has a precise value, and the analysis is deterministic. However, there are some simulated hours where the available generation was insufficient to meet demand, and the frequency and magnitude of these within the (multiple year) hindcast series provide estimates of LOLE and

EENS. This is the approach adopted in Gebretsadik, Fant and Strzepek (2014), another reliability assessment of South Africa's power system by the same main authors. The assessment considers several scenarios for wind generation deployment, and assumes that hydropower generators upstream on the Zambesi River are coordinated with the wind generators to maximise the firm generation available from the latter.

The second work reported in this category is a M.Sc. thesis by Rose, (2013), investigating the ability of grid-scale solar PV generation to displace diesel generation in the Kenyan power system, given that the PV outputs are coordinated with hydropower capacity. The analysis was completed in 2013, and thus refers to a system where a lack of capacity adequacy was much more of a problem than it is now (2017). The basic proposal of the thesis was that grid-connected solar PV offered a fast, flexible and economically viable solution to displace expensive leased diesel generation, capitalising on Kenya's abundant solar resource and avoiding large upfront financing requirements.

For some minority of modelled hours, there is insufficient generation capacity to fully meet the net demand, and the frequency of such events – including the amount of energy not served, was recorded. The results showed that the addition of solar PV reduces the annual unmet load compared with a business as usual scenario, particularly during dry years, but that reliability gains level off after 400MW. The initial adequacy gains derive from reductions in the amount of water required during the day, so that hydropower plants can more frequently operate at full power when demand peaks in the evening. The levelling off at 400MW is attributed to the fact that generation from solar does not coincide with peak demand, so that solar PV cannot directly resolve the capacity shortages that occur during evening peaks. For both examples in this category, it is not clear how the fundamentally random nature of events where generators are mechanically unavailable was translated in a realistic manner into the deterministic methodology.

The final category of relevant GAA found in the literature involves full chronological simulation of the system over time. Since establishing a model that can generate meaningful synthetic demand traces is very difficult, re-scaled historical series are used in conjunction with simulation from the statistical models – a process known as hindcasting.

A journal paper by González-Fernández, Oviedo-Sanabria and Leite da Silva (2014) is concerned with assessing the capacity adequacy contribution of the Itaipu hydropower scheme, the world's largest at the time of writing. The authors emphasise the usefulness of statistical simulation for generating both expectation values and quantiles for several indexes such as the loss of load hours, the energy not served and the frequency and durations of generation shortfall events. Another example of work involving sequential Monte-Carlo simulation (SMCS) is the paper by Karki, Hu and Billinton (2010), which is highly relevant in that the primary objective of the research was to develop a methodology for assessing the capacity adequacy of a power system with significant penetration of wind generation, coordinated with fast-responding conventional generating units.

7.3 Miscellaneous Other Work Relevant to GAA in SSA Countries

This subsection presents other miscellaneous examples from the literature that are relevant to probabilistic GAA in SSA power systems.

An article in the World Bank magazine (Chattopadhyay and Jordan 2015) states that when evaluating long-term investments in power systems, choices about the mix of VG and their geographic distribution must consider seasonal, multi-year, and multi-decade variability – as planners of long-standing hydropower dominated systems are already doing. The authors point out that insight may be gained from data generated by a suite of climate models that are available at almost no cost, but policy makers, planners, and investors in renewable-energy fields have are yet to make extensive use of these. The authors argue that such data are essential in assessing the extent to which VG resources can complement one other or may need to be backed up by further investments in non-renewable sources. This is despite the fact that both spatial and temporal smoothing mean that a considerable amount of the important dynamics are hidden.

A journal paper (Belanger and Gagnon 2002) studied the performance of wind generators within a mainly hydroelectric system. The combined output from wind and hydro generators in Quebec was simulated using historic series at hourly resolution covering the 1990–1996 period. The work found that when hydropower is the option used to compensate for wind fluctuations, a relatively large development of wind power could have significant effects on river flows. Further, it can reduce the minimum flow during dry season and increase the intensity of short-term flow fluctuations.

An M.Sc. Thesis, (Clement 2012) is also concerned with the ability of hydropower capacity to provide the necessary balancing reserves for wind. While hydropower is very well suited for this purpose, this thesis is interested in the extent to which its flexibility and capacity are limited by non-power constraints associated with environmental and water management objectives, claiming that this has not been fully accounted for in previous wind integration studies. The results show that wind at low penetrations adds economic value to the system. However, as the installed capacity increases, additional wind generation has diminishing returns, primarily due to increased reserve requirements. The work demonstrates that complex interactions between policy and the physical system result in a highly non-linear response of the system to changes in wind penetration.

The journal paper by Castronuovo and Peças Lopes (2004) proposes the utilisation of water storage to improve operational economic gains of wind generation, and to attenuate its power output variations, using data for the Portuguese power system as a case study. The journal paper by Jaramillo, Borja and Huacaz (2004) provides a conceptual framework for a hybrid power station that produces constant power output without the fluctuations inherent when using wind power. Two hypothetical facilities are considered as case studies, both in Oaxaca, Mexico. In that country, small-to-medium-scale hydroelectric power plants are typically used to generate electricity during the peak demand, which implies that they operate with a low capacity factor and therefore a high cost. This adds to the desirability of coordinated operation – and is the opposite to the case of the hydropower capacities in Ghana and Kenya. Finally, the journal paper by García-Gonzalez, Ruiz de la Muela, Matres Santos and Mateo Gonzalez (2008) investigated the combined optimisation of a wind farm and a pumped-storage facility from the point of view of a generation company in a market environment.

8. Quantitative Example: The Wind Energy Resource in Kenya

This section explores the potential contribution of large wind energy projects to generation adequacy in the Kenyan power system. It does so by examining temporal relationships between wind resource availability and demand, and also between the wind and hydropower resources, on a coarse resolution.

8.1 The Kenyan Power System Scenario

We consider a scenario for the Kenyan system circa 2020, taken from the 2013-2033 Least Cost Power Development Plan (Republic of Kenya Regulatory Commission 2013), in which the peak power demand is 4GW and there is 925.5MW of installed wind capacity. The wind projects included in this scenario deviate somewhat from Republic of Kenya Regulatory Commission (2013), and are those that seem likely to be built within a few years, based on their legal and financial status as of August 2016. They are: Lake Turkana – 310MW, Meru – 400MW, Kajiado – 100MW, Ngong Hills – 25.5MW, Lamu – 90MW.

The approach adopted involves hindcasting (i.e. using directly historic series directly to represent possible future output), similarly to several examples discussed in the previous section, although the calculation of reliability indices is beyond the scope of this study. With only limited data available, it is necessary to make certain modelling assumptions in order to proceed – as was the case in most of the previous work examples. Therefore, all major aspects of the analysis were completed twice, with contrasting assumptions, to assess the sensitivity of results to those assumptions.

8.2. Temporal Relationships between the Wind Resource and Demand

A 22-year, hourly resolution modelled time series of wind power generation was derived from wind speed series recorded at five meteorological stations in Kenya. The stations were Dagoretti, Lamu, Makindu, Marsabit, and Meru, and the historical wind speeds were from 1980 to 2001. Each series acted as a proxy for the speeds at one of the project locations, with several transformation steps required to obtain the final wind power series.

The first step was to remove the mean pattern across hours of the day. The reason is that the diurnal patterns at hub height are unknown, while it is known that such patterns diminish significantly with height in some climates (Sturt and Strbac 2011). This is a deliberately extreme step, coupled with an equally extreme but contrasting assumption made for a model variant presented below, since the objective is to assess sensitivity to such assumptions. The second step was to apply linear and power transformations to the wind speeds i.e. if the original wind speed at time t is y_t, the new wind speed is $a \cdot (y_t)^b$. The parameter values were specific to each recording station, and were chosen so that the series matched estimated values of both mean wind speed and mean cubed wind speed at the project sites, as given by the SWERA wind resource map of Kenya (Theuri 2008). Next, the adjusted wind speed series were converted to normalised powers, i.e. proportions of the maximum power, using a function known as a power curve. This maps wind speeds to normalised powers – in this case for a wind farm covering a large area, rather than a single turbine. Finally, the normalised power series were scaled by the capacities of the planned projects, and summed. This modelling approach is henceforth referred to as the ‘base model’ for wind.

The resulting estimate of the absolute level of wind resource is gives rather high mean available capacity, as seen in Fig. 8.1 – while Kenya has an excellent wind resource, in general a mean of 50 per cent load factor would be regarded as exceptional at a single location. Due to the limited data available for calibration, the assessment of relative wind resource between different times or different months (for instance the analysis underlying Fig. 8.5) is expected to be much more robust than these absolute levels.

A year-long, hourly resolution time series of generation dispatch was obtained from Kenya Light and Power. The dispatch is taken as a proxy for demand, after being linearly scaled-up to a peak level of 4GW. The validity of such a simple transformation is supported somewhat by the fact that the demand load factor – i.e. the energy consumed in a year, divided by the energy consumed if the demand were constantly at its peak level – remains almost unchanged over the planning horizon in the forecasts of Republic of Kenya Regulatory Commission (2013). There is no discernible annually repeated pattern in the demand trace, and since there is little demand on the system for space heating and cooling, there is no obvious mechanism for demand to vary from year to year given constant underlying patterns.

The modest variability in mean wind power across the months of the year is presented in figure 8.1, which shows average values for the 22-year sample. The figure also demonstrates roughly the season to which each month belongs, and presents average monthly precipitation for a single location, Makuyu, obtained from Climate Data (2017). As is discussed below, the latter is taken in this work as a proxy for the monthly inflow into the Masinga reservoir, the largest hydropower scheme in terms of energy. Figure 8.1 demonstrates that the relative availability of the wind resource during the `hot dry' month is rather disappointing, but it is good during the longer `cool dry' season.

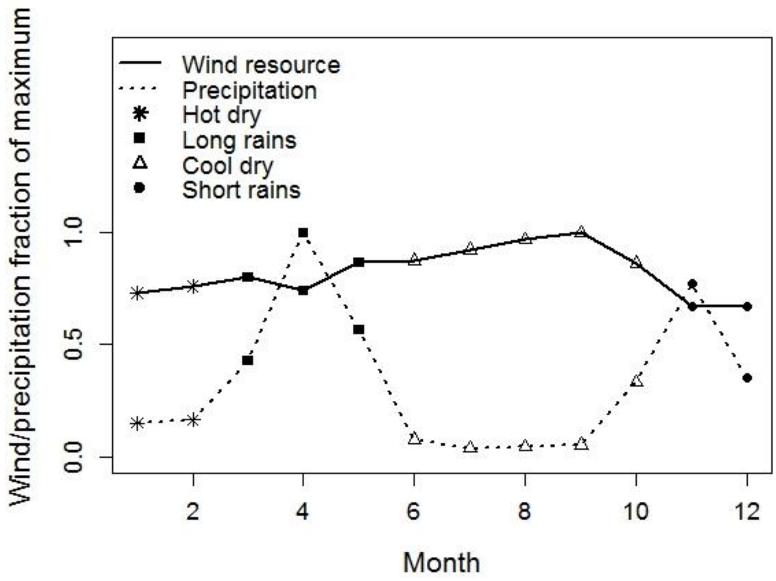

Fig. 8.1. Normalised monthly profiles of modelled wind resource (base model, Kenya 4GW peak scenario) and Masinga reservoir inflow. Four Kenyan seasons indicated.

Figures 8.2-8.4 present duration curves for net demand, i.e. demand with wind generation subtracted, which represent the relative frequency with which each net demand value is exceeded. Several 22-year time series of net demand were obtained, one for each combination of generation model variants. The series were obtained by repeating the scaled-up demand trace 22 times, and subtracting the 22-year-long wind power traces (one for each variant). The plots' horizontal axes represent the net demand value exceeded, with the full range of net demand values observed in the series included. The vertical axes represent the number of hours where each net demand value was exceeded within the 22-year series. Figure 8.2 presents results using a linear scale for the number of hours, while figure 8.3 uses a logarithmic scale for this. The 22-year values were presented in raw form, rather than as average hours per year, to preserve the true discreet nature of the data.

The wind generation model variants in figures 8.2 and 8.3 are: (i) the base model described above; (ii) a `linear scaling' variant, where wind speeds were transformed using linear re-scaling only, but all other aspects are as the base model; (iii) a `single turbine' variant, where the power curve is suitable for representing the output of a single turbine only - but all other aspects are identical to the base model; (iv) there is no installed wind capacity. Results for a 'keep diurnal' variant were also calculated, which involved preserving the diurnal profile in wind speed unchanged. However, results for this variant were omitted from the figures, since they are indistinguishable from the base case. In general, the results are strikingly nonsensitive to the model variants. One partial exception is that results are moderately sensitive to the choice of power curve for peak net demand levels.

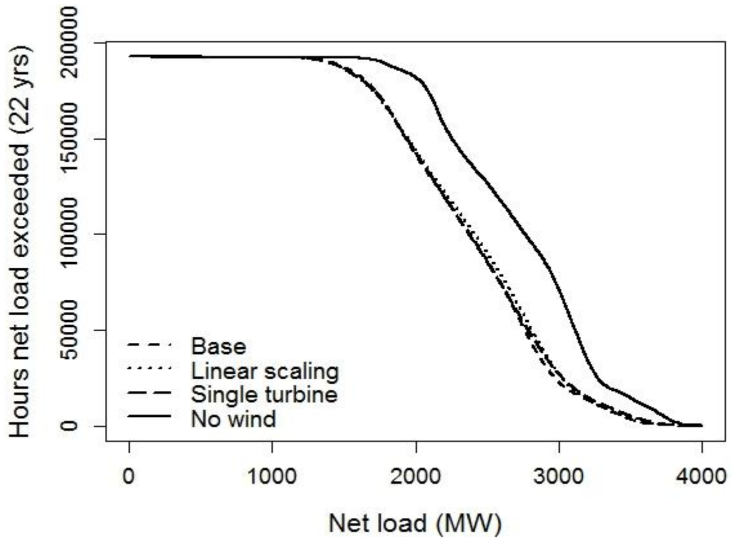

Fig. 8.2. Modelled duration curve for demand net wind generation (base model), 4GW peak Kenya scenario, linear scale.

Load duration curves were also calculated for a 2024 scenario, again based on Republic of Kenya Energy Regulatory Commission (2013) where peak demand has increased to 6GW, and the total wind power capacity has increased by the same proportion. In this case, three scenario variants were considered, exploring the impact of spatial smoothing: (i) the `additional locations' variant, where four additional projects have been built; (ii) only the same five wind projects exist, but the capacity of each has increased by 50 per cent; (iii) there is no wind generation capacity. It was found, rather surprisingly, that there is very little difference in the duration curves for these variants, with a small difference occurring at the high net demand extreme only. There are two implications of this: firstly, we have evidence that any conclusions drawn about the relationships between wind, hydro resource and demand are robust to changes in the location and geographical spread of wind power projects compared to current plans. The other implication is we have some evidence that wind projects should be built where they are most likely to be profitable, and from a generation adequacy perspective there is no need to compromise on this to obtain greater geographical smoothing.

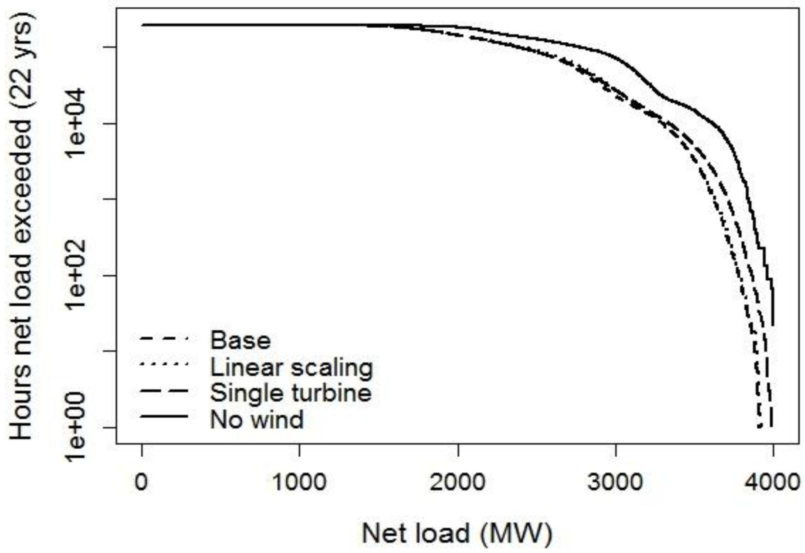

Fig. 8.3. Modelled duration curve for demand net wind generation (base model), 4GW peak Kenya scenario, log scale.

8.3. Temporal Relationships between the Wind and Hydrological Resources

Analysis of relationships between the wind and hydrological resources is limited to monthly resolution data, for two reasons: (i) finer resolution data on the hydropower resource is harder to obtain, and (ii) we do not know what the operating strategy for hydropower might be in the chosen scenario, in particular the extent to which close coordination between wind projects and hydropower reservoirs might be achievable.

Kenya has many hydropower reservoir and run of river schemes, including a cascading scheme of reservoirs. This illustrative analysis requires a single variable that summarises the hydrological resource at a given time, and water inflow to the Masinga reservoir was chosen. As explained by Bunyasi (2012) this variable is suitable since the Masinga dam's essential roles are to regulate water flow into subsequent dams, particularly during the dry seasons, as well as preventing flooding. While downstream reservoirs have much greater power capacities, and have other sources of river inflows apart from Masinga discharge, during the dry season these are insufficient for effective operation. Net inflow here means gross inflow minus evaporation and spillage, and annual values are provided in Bunyasi (2012) for the period 1982– 2011.

To use monthly (rather than annual) resolution data, precipitation must be used as a proxy variable, following calibration. Use was made of two such data sources, each associated with a model variant – again for sensitivity analysis. One of those sources is a monthly-resolution precipitation time series for an unspecified location in Kenya, obtained from a World Bank climate data repository (World Bank Group 2017), spanning the coincident period 1982–2011. The opposing assumptions made are the following: Model (1) – for a given year, the relative contribution from each month to the annual Masinga dam inflow is identical to the relative contribution of each month to the total annual precipitation in the World Bank data. In other words, there is 100 per cent correlation across the county with regard to the division of total precipitation between months of the year; Model (2) – the opposite is true, i.e. there is no correlation across space with regard to the relative contribution from each month. Therefore, for Model 1, the monthly-resolution net inflow series was obtained by re-scaling each year of the precipitation series separately, so that they match the annual net inflows. For Model 2, the monthly-resolution inflow series was obtained by taking a climatological average profile of precipitation for a nearby location, and scaling it so that it matches each year's annual net inflows. The climatological profile was obtained from Climate Data (2017), for Makuyu, located in the hills feeding the Masinga reservoir.

Figure 8.5 presents 20-year series for wind generation and the Model 1 inflow. The plot shows that the size of the wet season `spikes' in the inflow series exhibit distinct but complex clustering behaviour. The wind power series also possesses clear seasonality, but much less pronounced than inflow; also, the wind load factors are consistently high, with the worst month being > 40 per cent of the highest. Rather than clustered spikes, the wind series suggests very low frequency trends, on a time scale of decades, although a longer series would be necessary to establish this more firmly. For Model 2, the inflow series displays the same characteristics, but the exact location and amplitude of spikes within the clusters are occasionally quite different. The resources therefore appear to be somewhat complementary, although the relationship requires further elucidation.

Additional clarity regarding the extent of complementarity between the resources is provided by a scatter plot in figure 8.5. The hydrology data in the figure is not the raw inflow series, rather the accumulation over time of anomalies from the average behaviour. A large positive cumulative anomaly implies that the dams are likely to be full, while a large negative value implies they are likely to be relatively empty. The figure shows that there is not a strong relationship between the two variables. During the most extreme anomaly values, i.e.

roughly in the range −0.44 to −0.36, the wind resource is disappointing. However, most of the strongest months for the wind resource occur when the anomaly is either moderately or strongly negative, i.e. in the range −3.6 to −1, providing evidence that wind can make a useful contribution to adequacy. As discussed above, these results based on relative wind resource between months are expected to be more robust than the assessment of absolute level of wind resource.

The dataset is however too small to draw any firm conclusions. Further, there is considerable disagreement between the two models in the crucial range of about −3.6 to −2.8, despite good agreement broadly. The main improvements to this analysis would be to use longer series, and of course to use direct measurements of the reservoir height. Some of the strongest shortcomings of using inflow anomalies as a proxy for the reservoir level is that there is no information available about how full the reservoir was at the beginning of the period, nor is there any representation of spilling due to the level being too high, or the need to maintain minimum flow for ecological or other reasons. A meteorological analysis, based on the long-term climatology of the region could greatly improve understanding of the relationship.

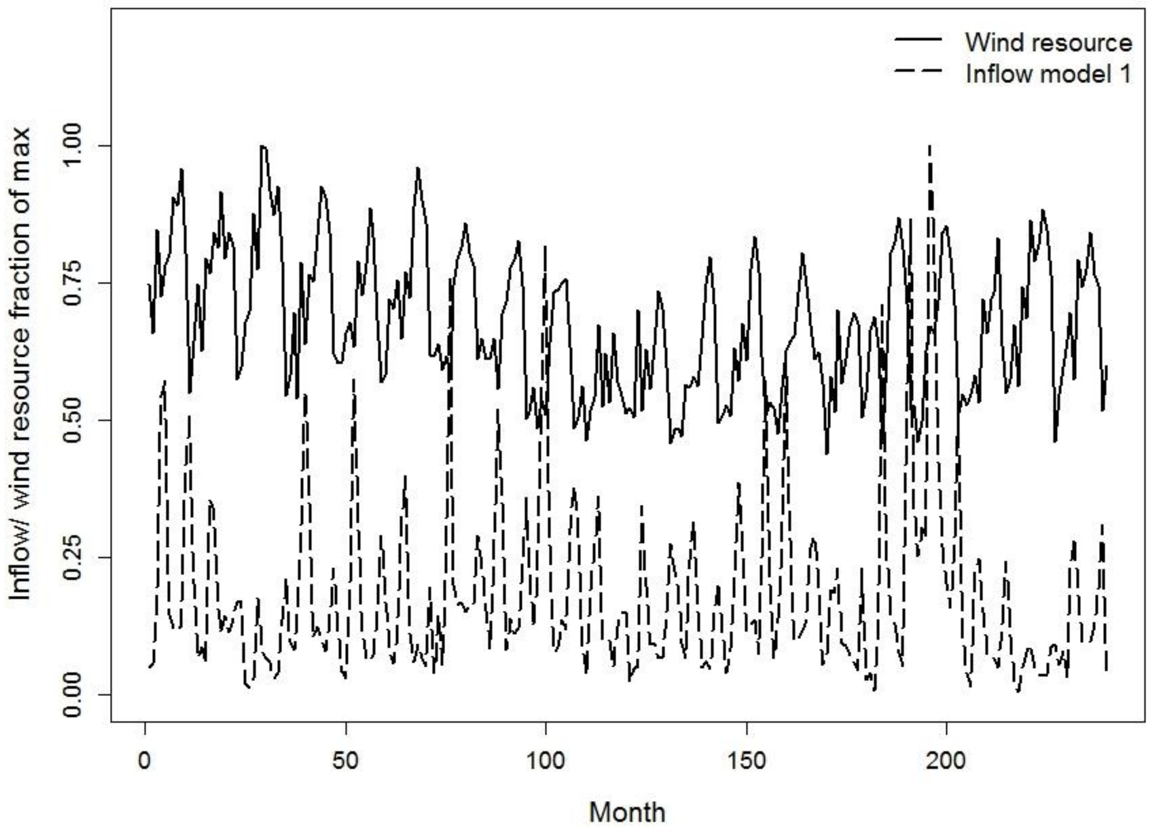

Fig. 8.4. Normalized 20-year series, monthly resolution, for the modelled wind resource (base model), 4GW peak Kenya scenario, and Masinga reservoir inflow (model 1).

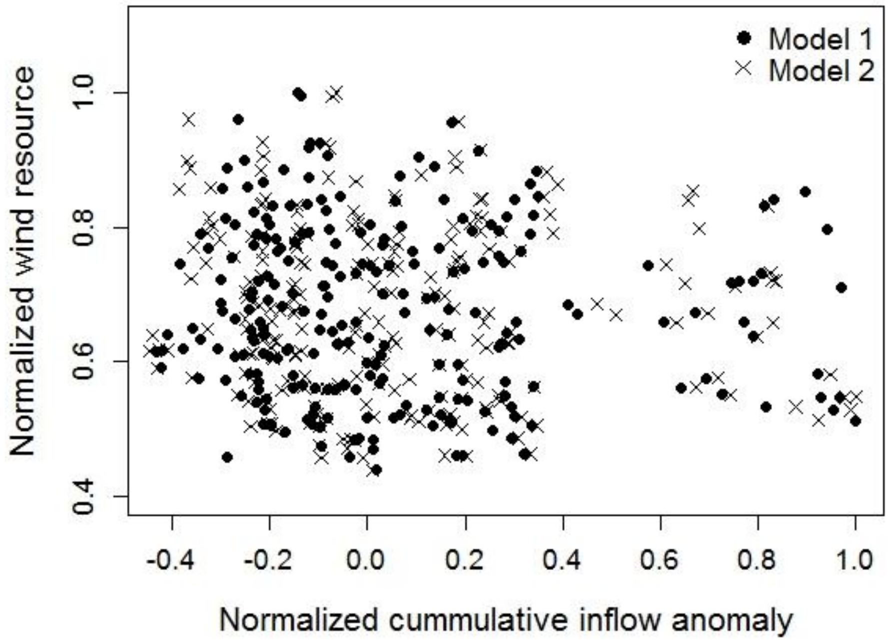

Fig. 8.5. Relationship between wind resource (base model, 4GW peak Kenya scenario) and temporally accumulated Masinga inflow anomalies, both models.

9. Conclusion

This article has demonstrated that there is a strong need to assess the generation adequacy of power systems in sub-Saharan Africa, both in the immediate future and further ahead, as a means of evaluating energy policies and investments. This is particularly true for those countries where demand is growing rapidly, and that are likely to see a large penetration of variable renewable generation. Where this is the case, GAA is of limited value unless it is explicitly risk-based. However, many serious technical challenges must be addressed before such assessments are possible, and SSA countries have limited resources available to do this. Of the two case-study countries, Ghana engages in simple margin-based assessment, while risk-based assessment informs the long-term planning process for Kenya – albeit with deeply flawed methodology. This article has summarised the salient characteristics of the Kenya and Ghana power systems with regard to GAA. – chief among them being severe energy constraints (consistently in Ghana and periodically in Kenya). This necessitates GAA that is sequential and that considers generation dispatch, rather than the availability of generators.

To investigate crucial temporal relationships in greater detail, original data analysis was conducted for the wind and hydro resources in Kenya, as well as demand, for near-future system scenarios. Results indicate that there is a moderately complementary relationship between the wind resource and demand, and between the wind and hydro resources. This provides additional evidence to support the view that the large wind projects soon to be built in Kenya will contribute significantly to generation adequacy of the Kenyan power system.

Acknowledgements

The authors would like to thank our partners in the Green Growth Diagnostics for Africa Project, along with interviewees in Kenya and Ghana who kindly gave their time.

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