Chapter

Balancing Renewable Energy Capacity, Time of Use Tariffs and Energy Storage in Energy Systems

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Abstract

The intermittency of solar energy predicates the simultaneous use of energy storage to maintain secure supplies. However, storage is expensive to instal and maintain, suggesting that there is an optimum design based on the price tolerance of electricity markets. In this chapter, a method for the calculation of the optimal size of a battery energy storage system (BESS), linked to utility-scale photovoltaic (PV) capacity, is presented. The method, which is illustrated by its application to the South African national grid (GridSA), uses historical generation/demand data to construct a spreadsheet model of the energy system. The model assumes that the difference between base load and energy demand, referred to as headroom, will be met using variable energy sources, including wind, solar, diesel/gas and batteries. Optimal sizing of these components to minimize the use of gas in summer, and make maximum use of low-cost solar and wind, leads to a configuration for GridSA consisting of a 22 GW base load (coal and nuclear), a PV installed capacity of 17.8 GW and a BESS capacity of 3.7 GW/10.4 GWh. A peak time of use tariff of ZAR3,500 per MWh (almost double the average tariff) will be optimal to build an economic case for energy storage as a sustainable option for GridSA.

Keywords: renewable energy, battery energy storage, time of use tariff, economic model

1. Introduction

Intermittency is a term used to describe the variability of renewable energy sources such as solar, wind and wave. These sources are not consistently available, as they depend on specific weather conditions. Solar panels, for example, can only generate electricity when there is sufficient illumination and wind turbines need a minimum air velocity to turn. As a result, the output of renewable energy facilities can vary significantly over time. Demand for electricity, on the other hand, is continuous, although also variable in absolute quantities, with higher demand during the 'awake' day (05 h00 to 20 h00) and lower consumption during the 'asleep' night (20 h00 to 05 h00).

Typical profiles for wind and photovoltaic (PV) solar generation, and the demand for electricity by consumers in South Africa's national grid (GridSA) for the first week of December 2022, are shown in **Figure 1**. Solar is highly periodic and, to a large extent, predictable on a 5-day basis, but wind is highly variable and non-periodic, although the summer pattern often reflects strong winds in the late afternoon, which offsets the rapid decline in PV at sunset. Both characteristics of renewable energy generation are clearly visible in **Figure 1** and have also been previously reported [1].

The mismatch between supply and demand creates difficulties for grid management and has driven the development of large-scale energy storage systems, in addition to other approaches such as the increased deployment of gas and hydroelectric turbines. In the longer term, low-carbon storage solutions are essential if all countries are to reach net zero status by 2050. However, these systems are costly, and the cost of energy storage remains a significant barrier to the wider adoption of renewable energy.

In this chapter, the cost of battery-based storage, as revealed through a 2020 tender process in South Africa, is presented and discussed. Using real-time data for GridSA in June and December 2022, it is argued that the deployment of battery-based storage at times of high consumer demand is feasible but will require the wider implementation of time-of-use tariffs (ToUTs) in order to offset the additional cost. Estimates for the scale of the necessary systems, and the necessary ToUTs, are outlined. In all the discussions, GridSA is used as an illustrative example for the main tenets of the chapter. Section 2 presents the background information for the study, including a brief overview of GridSA, the use of renewable energy, the risk mitigation programme, the recent operation of the grid to manage the shortfall between demand and supply, referred to as 'loadshedding' and the practice of ToUTs. Section 3 describes the modelling of electricity supply and demand, and how this can be used to determine a system-level response to ToUTs. The proposed ToUT structure and levels to support greater deployment of battery electric storage systems (BESS) are then discussed in Section 4, followed by the study's conclusions in Section 5.

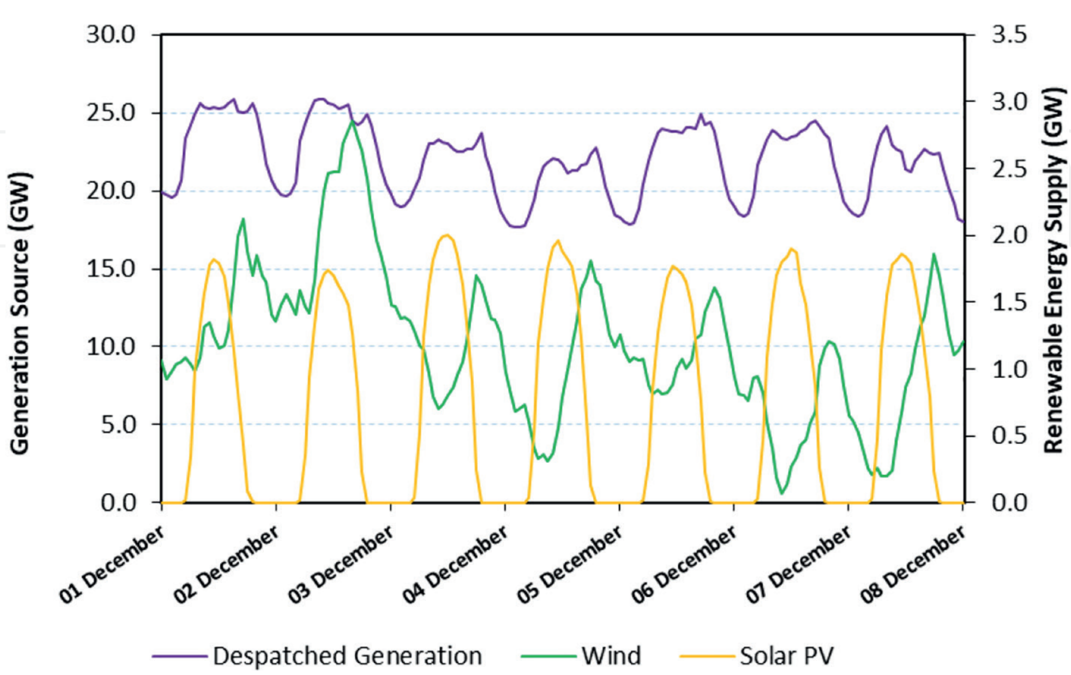

Figure 1.
Typical summer profiles for wind, PV and grid demand in South Africa.

2. Background

2.1 Overview of the South African electricity grid

There are two striking features of GridSA, which shape the structure of the grid itself, its impact on the environment and its relationship with its customers. The first is the dominant role in all three aspects of electricity supply (generation, transmission and distribution) played by a single entity, namely the state-owned energy utility, Eskom, as shown in **Figure 2**. Eskom generates about 180 TWh per annum of electricity, supplying 90% of all electricity used in South Africa [2]. It operates a fleet of 15 coal-fired power stations, one nuclear reactor, 4 gas/diesel turbines and 7 hydroelectric schemes. Its fleet has a total generation capacity of 45 GW, but presently operates at a capacity utilisation factor of less than 50% [3]. The utility's transmission system includes about 28,000 km of high-voltage and 325,000 km of lower-voltage lines, and it supplies directly about 6.7 million direct customers [4].

The second feature is that GridSA is heavily dependent on coal as the main source of energy [5]. For example, as shown in **Figure 3** for the first week of December 2022, coal accounted for 80% of the total energy supplied by the utility. Other sources include diesel, PV, concentrated solar power, wind, hydro and nuclear [6]. Renewables account for 13% of the total supply with the remainder being obtained from nuclear (5%) and diesel (2%).

Demand in the grid follows a conventional square wave pattern, with a small evening peak linked to normal residential activities such as cooking, space cooling and water heating. Higher 'awake' day use is met with the combined use of non-dispatchable generation sources (wind and solar), diesel turbines and pumped storage. Users of electricity are similar to most industrialised countries with the main consumers being industry (51%), residential sector (20%) and the commercial/service sector (15%) [5]. Total demand is about 205,635 GWh, equivalent to an average power need of 23.5 GW.

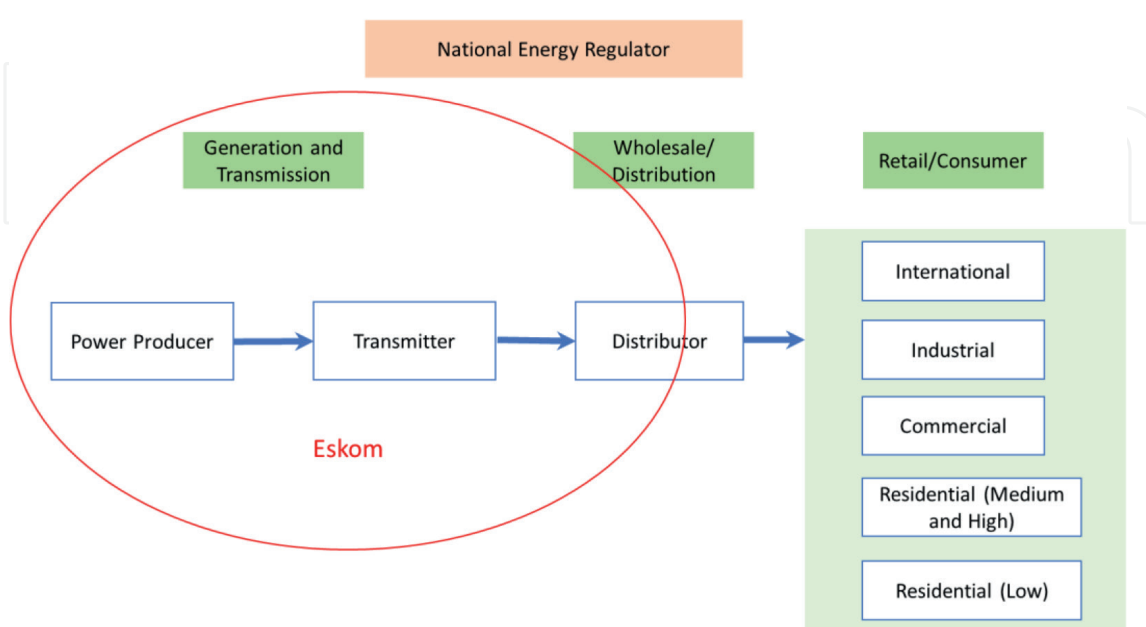

Figure 2.
Components of the electricity value chain.

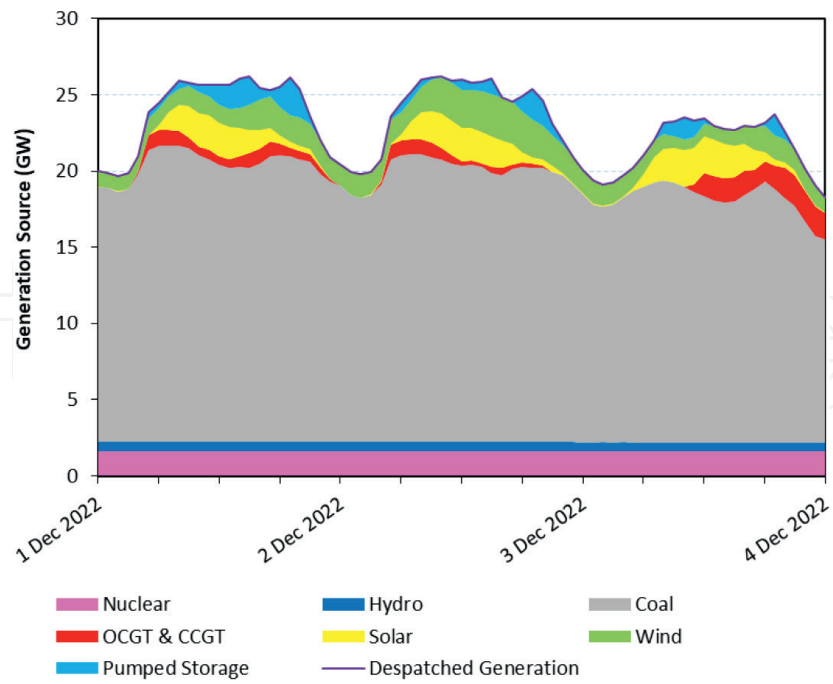

Figure 3.
Profile of GridSA energy supply (December 2022). Source: Own data and the Eskom data portal [3].

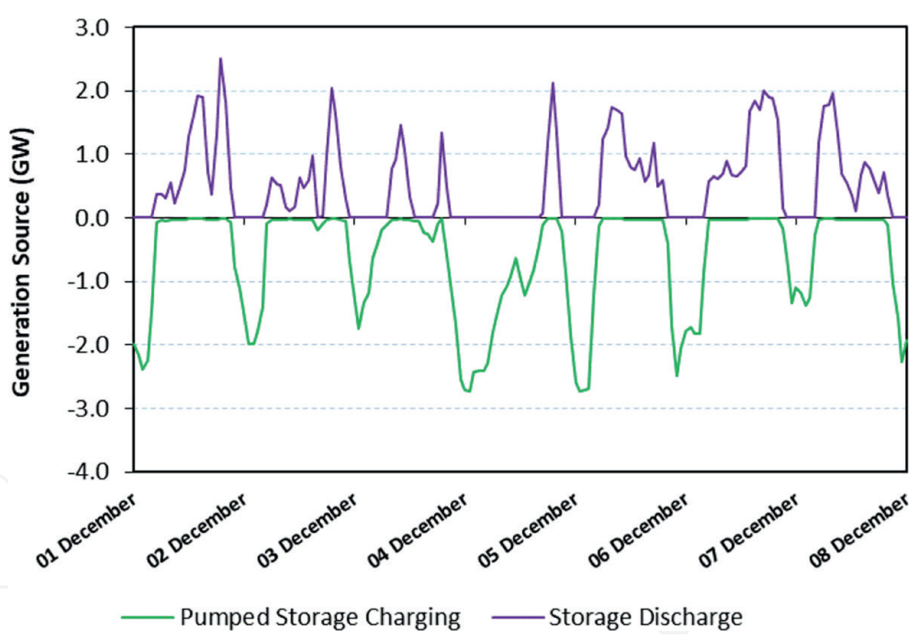

Figure 4.
Load and discharge cycles for GridSA's pumped storage (December 2022). Source: Own data and the Eskom data portal [3].

Pumped hydro is a key feature of GridSA and is a central to the later discussion in this chapter on loadshedding and load-shifting. Eskom operates three pumped storage schemes with a combined capacity of 2.73 GW. Excess energy generated during the night and over weekends by the coal-fired power stations is used to pump water from low to high altitudes; the same water is then returned to low-altitude storage dams during the day, as shown in **Figure 4**. The system has an overall efficiency of only 75% but it allows Eskom to flatten the demand curve and make full use of its available generation capacity during off-peak periods.

The high dependence on coal and pumped storage, which exists due to abundant and cheap coal deposits, and a specific investment programme for new power stations implemented in the 1960s to the 1980s, has become a significant barrier to the decarbonisation of the South African economy [7]. Although South Africa is a signatory of the 2015 Paris Agreement [8], it has made little progress towards the attainment of its nationally determined contributions [9, 10]. The rapid acceleration of its renewable energy programme remains essential if the country is to reach these targets. The programme, referred to as the Independent Power Producers Procurement Programme (REI4P), made some initial gains [11], but these have been largely side-lined and the country is now several years behind its energy transition programme, as outlined by the government's own policy papers [12].

2.2 Energy system reform and transition

Policy proposals to reform the electricity sector in South Africa have been tabled since at least 2008 with the introduction of the Electricity Pricing Policy [13]. The latter set out a number of policy objectives, including the liberalisation of energy markets, the introduction of a renewable energy programme, the establishment of a price control system to ensure that 'an efficient licensee can recover the full cost of its licensed activities' and support for energy access through affordable electricity tariffs [13].

Some of these objectives have since been realised, with the operationalisation of the National Energy Regulator of South Africa (NERSA) and the implementation of the REI4P [11]. However, in most respects, the policy proposals have been largely ignored and the utility has sharply regressed since the 2000s. Electricity prices have risen sharply and are 750% higher than in 2008, increasing at a rate 3 times faster than the rate of inflation. Eskom's debt has ballooned to R400 billion, and its interest expenses exceed operating profits by at least R3 billion, making the utility technically insolvent. Its environmental footprint remains unsustainable, and the utility is now the largest sulphur dioxide emitter in the world, exceeding the total emissions of China and the United States combined. Its carbon emissions are about 200 million tonnes per year, representing 40% of South Africa's total emissions, and all of Eskom's 15 power stations are in breach of the minimum emission standard (MES). The renewable energy programme, which could have partly rescued the country from its energy crisis and environmental non-compliance, was put on ice over the critical period of 2014 to 2021 and is still at least 5 years behind schedule, with a deficit of about 12 GW of renewable energy capacity relative to the initial Integrated Resource Plan 2010 [12]. Finally, the liberalisation of energy markets, including the unbundling of Eskom and the formation of regional electricity distributors, has never materialised.

Other studies have similarly noted a lack of progress towards the policy objectives [14, 15]. One of the more severe consequences of this failure is the growing crisis of supply constraints, the details of which are covered in the following section.

2.3 System constraints and loadshedding

The country has a history of energy shortages, including electricity blackouts in 2007 and 2008, petroleum shortages in 2008 and 2011 and gas shortages in 2011 and 2012 [16]. More recently, Eskom has been unable to meet electricity demand over long periods and has implemented a programme of loadshedding or rolling blackouts, in which power to customers is interrupted on a rotational basis, depending on the level of energy savings to be realised.

The system is more easily understood using the diagram in **Figure 5**. In the first week of December, Grid SA experienced persistent energy shortfalls, leading to progressive stages of loadshedding. For the first 2 days, supply and demand were largely balanced except overnight on the 1st of December, resulting in the use of Stage 1 loadshedding. The notation of 1 vs. 2 vs. 3, etc. refers to the shortfall between anticipated demand and actual supply. Figures for the former are obtained by Eskom from historical data for energy demand, adjusted for both seasonal and daily fluctuations. Stage 1 loadshedding, therefore, refers to a gap of 1 GW between demand and supply, Stage 2 to a gap of 2 GW and so on.

As the supply crisis deepened during the first week of December 2022, the levels of loadshedding increased, as shown in **Figure 5**. By the end of the week, the power shortfall was 4 GW, resulting in Stage 4 loadshedding.

The impact of loadshedding on electricity consumption can also be deduced from **Figure 5**. Although the average demand is 27 GW, there are a group of customers, known as the strategic facilities, where the power is always maintained. Load-shed customers constitute about 18 GW or 67% of the total market. In the event of a supply shortfall of, for example, 2 GW, non-strategic customers lose power for 2.7 (= 2/18*24) hours, making the duration and frequency of loadshedding more severe than might be the case if the blackouts were spread over the whole customer base.

This discussion of system constraints and the practice of loadshedding is germane to the remainder of this chapter, whose focus is whether ToUTs can be used to support the initial introduction of battery energy storage with high levels of renewable energy, particularly PV, within Grid SA. The pattern of loadshedding provides some insight into the question of possible consumer response to ToUTs. This topic is further discussed in Section 4. In the next section, the rationale for a ToUT is explained.

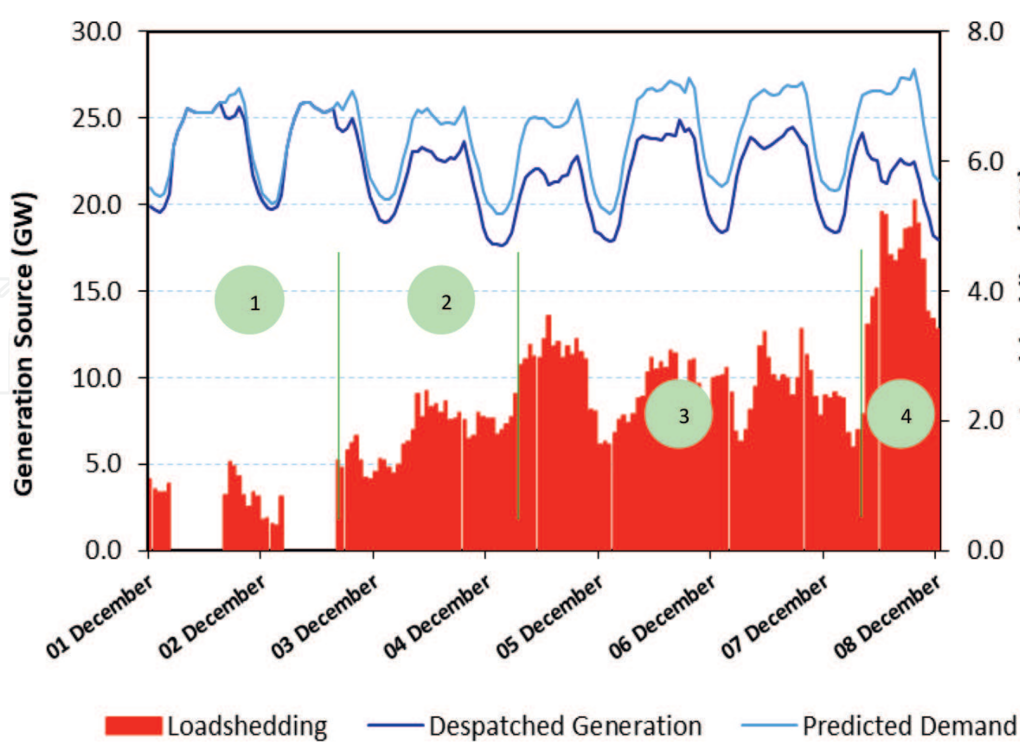

Figure 5.
Loadshedding and energy supply in the GridSA.

2.4 Time of use tariffs

ToUTs are pricing structures for electricity that vary the price depending on the time of day and the season. They are designed to incentivise consumers to use electricity when it is more plentiful or cheaper to produce, thereby reducing their usage during times when the demand or the cost of production is high. ToUTs are one example of several approaches employed by utility companies for demand-side management, with other examples, including the introduction of mechanisms to encourage energy efficiency and loadshedding during periods of high demand.

There are typically three pricing periods for ToUTs: peak, off-peak and shoulder. Peak periods are when demand for electricity is highest, and the price is highest. Off-peak periods occur when demand is lowest, and the price is lowest, mostly during the night. Shoulder periods take place between peak and off-peak, and the price is generally lower than the peak period but higher than the off-peak period.

ToUTs can have positive impacts, for example acting as a tool to manage electricity demand and helping to balance supply/demand in the grid. They can also help to reduce the need for gas- or diesel-based peaking power plants that are only used to meet peak demand and have high environmental impact; they can improve system reliability; they can reduce overall energy costs of consumers and they can lower the investment costs for utility companies.

However, there are some limitations to the use of ToUTs as mechanisms to change consumer behaviour. For instance, in a pilot study of Irish households with smart metering and ToUTs, it was found that instantaneous feedback on energy savings was essential in developing sustained changes to usage, particularly a shift in demand away from peak periods, but a steeper tariff profile (between off-peak and peak rates) had little further impact [17]. Consumers with higher levels of education and income were also more responsive to ToUTs [17].

Notwithstanding the limitations, ToUTs or real-time pricing will be essential to the stable operation of Grid SA, indeed any national grid, with high levels of renewable energy generation, and especially high levels of PV [18]. In the absence of effective demand side management, systems will suffer from the well-known ‘duck curve’ effect, characterised by an oversupply of energy at midday as solar reaches its peak, and a sudden undersupply in the evening as the sun sets and demand accelerates to the evening peak [19, 20].

It is noted that Eskom already applies ToUTs, as listed in the tariff schedule [21]. The off-peak and low-season tariffs are about 50% of the peak values, providing a large incentive for consumers to adjust their energy practices. However, the benefit of lower tariffs can only be realised if consumption is managed through smart metering, connected to an appropriate billing system. Most households and low-energy users do not use such systems, and hence cannot take advantage of the significant discounts presented by the Eskom ToUTs.

In summary, ToUTs, supported by smart metering and changes to consumer behaviour, are critical to higher levels of renewable energy generation in Grid SA. The remaining question for this chapter is the estimated level of the necessary ToUT, which would drive behavioural change and provide a reasonable return on investment to the utility company. This question is now covered.

3. Modelling the energy system

Modelling of GridSA was undertaken with spreadsheet models using real-time data downloaded from the Eskom Data Portal [3]. The raw data were first processed to generate profiles for total demand, and energy production per source of supply. Simulations of the required energy storage, and hence the necessary tariff, were then developed for a winter month (June) and a summer month (December).

The accuracy of the modelling depends, inevitably, on the quality of the data from the portal. Assessments of the extent of power generation outside GridSA, unrecorded on the data portal, are that this is limited to about 5% of the total energy. In other words, 95% of electricity supply is covered by the data portal.

In order to model the required tariff, data from the Risk Mitigation Independent Power Producers Procurement Programme (RMI4P) were used as the benchmark for the cost of providing energy in the PV shoulder periods (early morning and late evening). The supply crisis, as outlined in Section 2.3, precipitated the initial conceptualisation of this programme by the South African government in 2020 [1]. The main objectives of the programme were to establish independent power producers able to provide 2 GW of emergency power on a flexible basis between the hours of 05 h00 and 21 h30, and to be able to respond to needs of the electricity system operator based on an automatic generation control load-following ability [22].

Following the call for proposals issued in August 2020, 28 bids were received by the South African government, of which 7 were announced as preferred bidders in mid-2021. The weighted average feed-in tariff for the winning bids was ZAR1.61/kWh[1], with the sum of the bid capacity being 2 GW. A summary of the preferred renewable energy-based bids is given in **Table 1** (one bid based on natural gas has been excluded).

The bids provide a clear indication of the cost of electricity over the peak period, relative to the Eskom standard tariff and the present price of solar. Benchmarks for the former values can be obtained from the Eskom booklet on tariffs and schedules [21], and for the latter from the Bid Window 6 contracts, recently awarded to

Bidder	Size (MW)	Energy Cost (ZAR/kWh)	Gas/Diesel (MW)	PV (MW)	Wind (MW)	BESS	
						MW	MWh
ACWA	150	1.46	15	422	0	150	900
Mulilo/Total Coega	198	1.89	198	216	0	0	0
Mulilo/Total Hydra	75	1.52	20	216	0	150	600
Omoyilanga	75	1.72	12	138	77	75	450
Oya	128	1.55	106	155	83	40	400
Scatec	150	1.88	0	150	0	540	2250

Table 1.
Summary of preferred RMI4P bids.

[1] The exchange rate (March 2023) is ZAR18.4/USD

independent power producers [23]. The values are ZAR1,250 per MWh and ZAR490 per MWh, respectively.

The real-time data and the values from the RMI4P provided the basis for the calculation of energy tariffs, the results of which follow in the next section.

4. Proposed tariff structure to support battery storage

The central question of this chapter is whether ToUTs can be used to allow greater penetration of PV within GridSA. There are two reasons for this proposition, the first being that ToUTs could prevent the occurrence of the notorious duck curve, and the second being that the additional revenue from a peak tariff and/or shoulder tariffs could be used to justify the use of BESS.

As indicated earlier, the loadshedding data presented in Section 2.3 and **Figure 5** provide some insight into possible consumer responses to ToUTs. Interestingly both the total predicted, and the actual curtailed, demand have similar profiles, indicating little change to hourly consumption. Electricity consumption appears to be mostly instantaneous or inflexible; when supply is curtailed, consumers cannot power their homes, devices or activities from the grid, and either do not use energy or find alternative means of supply, such as local diesel-based generators or PV. The similar pattern of the two curves in **Figure 5** suggests that there is limited load-shifting in response to loadshedding, or use of BESS. In other words, further load shifting, other than that already introduced by the Eskom ToUTs, may not be realised with ToUTs; instead, customers will use the available electricity, despite its higher cost. This behaviour reflects supply, and not demand, elasticity.

This anticipated response provides a strong basis for the implementation of BESS, despite its additional cost to Grid SA, as long as this cost remains competitive to independent power generation already being accessed by customers on the grid, such as PV and diesel. Indicative values obtained from the RMI4P tender prices suggest that this requirement will indeed be possible. For instance, the price from Mulilo/Total Hydra proposal of **Table 1** for emergency power in the shoulder and peak periods is ZAR1,520 per MWh (vs. a diesel-based tariff of ZAR6,000 per MWh).

Mulilo/Total Hydra is a particularly relevant model for the issue being explored in this chapter. The proposal consists of three generation technologies, namely PV (216 MW), BESS and a small quantity of diesel (20 MW). The project was designed to supply 70 MW of power to the grid, as shown in **Figure 6**. The profiles indicate that solar component was overdesigned to ensure sufficient power for recharging the BESS under both winter and summer conditions. During the latter, there is no need for gas-based generation, but in winter, the lower peak of solar-based generation and the increased likelihood of cloudy skies requires use of gas/diesel on certain days (see 9th June in **Figure 6**).

The data from Mulilo/Hydra can now be extended to the broader question of whether a PV/BESS configuration could meet the electricity demand of Grid SA, and, if so, at what additional cost. The first assumption in this analysis is to extend the concept of headroom, as previously developed for the national grid in the United Kingdom [24], to GridSA. The concept considers that supply can be separated into two components, namely the base load and the headroom, where the latter is the difference at any one moment in time between total demand and base load, as given in Eq. 1.

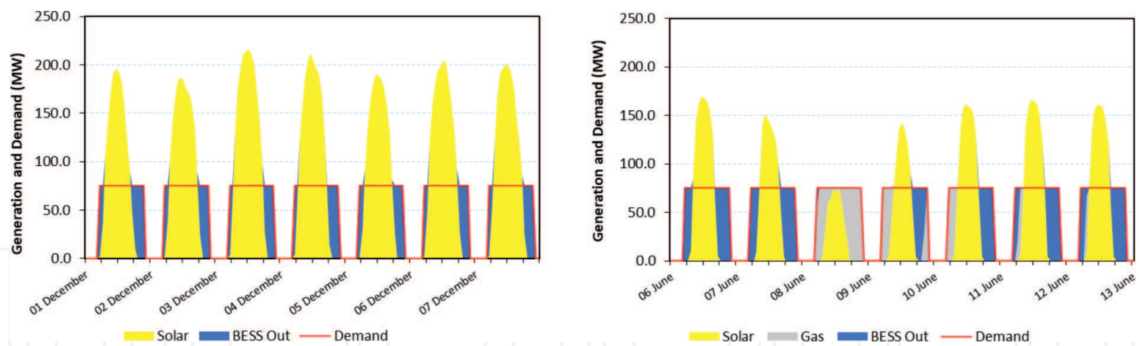

Figure 6.
Energy generation (by source) and supply for Mulilo/Total hydra (summer and winter).

$$\text{Total Energy Supplied} = \text{Base Load} + \text{Headrooom} \tag{1}$$

Base load on GridSA is typically about 22 GW, with remainder being supplied by wind, pumped storage, solar and diesel/gas turbines, all of which are variable or intermittent inputs. Adopting the value of 22 GW in the model, and assuming a wind energy input of 5 GW, which is 175% of the present capacity on GridSA, it is now possible to calculate the required PV capacity from Eq. 2, the historical data for the summer and winter months and a summer PV efficiency in South Africa of 37%.

$$\text{Required } PV = \frac{\max\left(\text{Headroom} - \text{Wind}\right)}{\text{PVEfficiency}} \tag{2}$$

For the 2022 data set, which was used as the basis of this study, the summer and winter values for the largest difference between the headroom and the energy derived from wind are calculated to be 4.4 and 8.3 GW, respectively, giving a required PV capacity of 17.8 GW (summer conditions and a 50% overdesign factor). On the basis that the summer demand should be met by wind and solar only, without the use of gas turbines, the BESS power rating and the total energy storage can now be calculated using the following algorithm:

1. Input the PV capacity and calculate the maximum BESS output for the summer conditions.

2. Enter this value in the spreadsheet as the design power capacity for the BESS facility.

3. Calculate the necessary BESS energy rating such that in summer conditions, the gas turbines are not required.

This approach leads to the result that the optimal BESS specification is 3.7 GW/10.4 GWh. The output of this proposed system is shown in **Figure 7**. It is noted that 10.4 GWh is significantly larger than the present BESS facilities; the largest existing BESS is the Moss Landing Energy Storage Facility in California with a capacity of 1.6 GWh. Multiple facilities giving a total storage capacity of 10.4 GWh over several sites are, therefore, recommended.

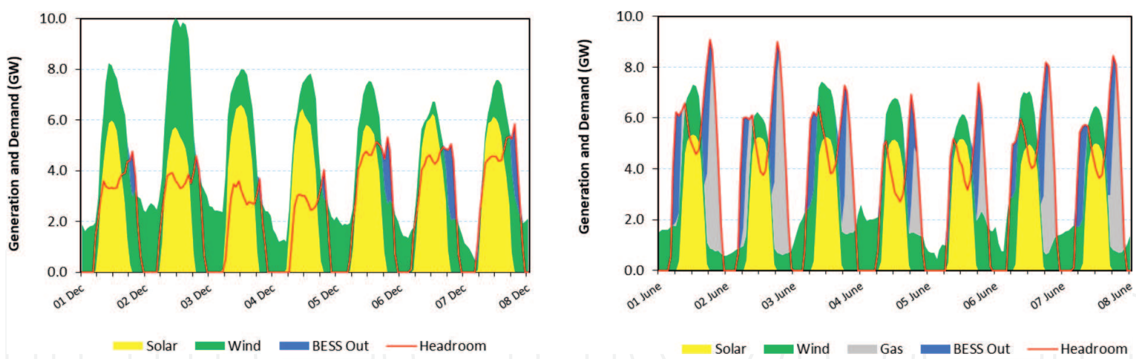

Figure 7.
Proposed solar/BESS energy generation for grid SA (winter and summer).

The cost of such an arrangement, and the level of ToUTs to support the investment, must now be considered. The bid price for the Mulilo/Total Hydra proposal of the RMI4P was ZAR1,520 per MWh. Using the spreadsheet model of Mulilo/Total Hydra, it is calculated that BESS will contribute an average of 23% to the total energy output. Moreover, it has already been mentioned that the current cost of PV is ZAR490 per MWh, leading to the result that the BESS contribution to the total cost is ZAR4,970 per MWh. It is noted that this estimate is similar to other values reported in the literature of ZAR4,000 to 5000 per MWh [25–27].

The same calculation can be repeated for the GridSA model. Given that wind and solar capacity are overdesigned and, as shown in **Figure 7**, this approach leads to significant excess generation, it is also assumed that the additional energy can be absorbed by GridSA's pumped storage capacity, hence maintaining a low unit energy cost. In the extreme case, such as may occur in winter, the evening peak period would be supplied by wind, diesel and batteries in the proportions of 30, 40, and 30%, respectively, from which the required evening tariff can be calculated at ZAR3,500 per MWh.

It is also evident from **Figure 7** that PV/BESS combination introduces another factor to the discussion on ToUTs. Peak power during daylight hours can be met reliably with solar PV, but shoulder energy demand, which lies typically between 06 h00 and 09 h00 in the mornings and 16 h00 to 19 h00 in the evenings, must be supplied by either BESS or diesel. The latter is a more expensive option and should, therefore, be allocated a higher tariff. The earlier discussion on cost suggests that this tariff could be set at nearly double the peak tariff, the latter being presently about ZAR2,000 per MWh in South Africa.

Patterns of consumption during periods of loadshedding indicated that consumers adopt a behaviour of supply elasticity, preferring to find alternative sources of energy during loadshedding rather than to shift consumption to other times of the day. This response, as already noted, is not surprising. Most entities, including schools, commercial businesses, hotels, restaurants and retail outlets, have fixed hours of work with little flexibility in terms of their operations. Finding alternative sources of electricity is then not a matter of choice, it is a necessity.

At present, much of the independent power production relies on small-scale diesel, although PV is growing throughout the commercial and residential sectors. The cost of these alternatives is close to ZAR6,000 per MWh, suggesting that a Grid SA shoulder tariff of ZAR3,500 per MWh may be 'accepted' by the market, particularly if the cost of peak power (used over the period 09 h00 to 16 h00) could be reduced through an increase use of PV. The latter has a levelised cost of energy, which is nearly one-quarter of the present retail price for electricity in South Africa, as already noted in the earlier discussion.

5. Conclusion

The advent of renewable energy, particularly PV, heralds the possibility of widespread low-cost energy with a vastly reduced environmental footprint [11]. Solar conditions in South Africa are excellent for energy generation, and when combined with energy storage systems such as pumped storage or BESS, could lead to the necessary reform of Grid SA.

However, BESS is costly to instal and presently not feasible at the scale, which would be required to support energy demand within South Africa. In this chapter, the use of ToUTs has been explored as a means of providing an economic incentive for private investors, or the state, to build large-scale BESS, coupled with PV. Using a time series model based on real-time data, and information collected from the RMI4P, it is calculated that 6.3 GW of effective capacity would be optimal for a PV/BESS facility, which could be met under summer conditions with a PV installed capacity of 17.8 GW and a BESS capacity of 3.7 GW/10.4 GWh.

The facility would require a ToUT during the shoulder periods of ZAR3,500 per MWh, which is nearly double the present Eskom tariff and will lead, at least initially, to consumer resistance. However, data from the periods of loadshedding in South Africa reflect supply elasticity in the behaviour of South African consumers. When supply is curtailed, consumers either survive without power, or they access other sources of electricity, even if the latter is more costly, such as diesel and rooftop solar. Furthermore, the shoulder ToUT could be offset by a lower peak tariff, made possible through the widespread use of PV with a levelised cost of energy of about one-third of the Eskom tariff.

This pattern of behaviour suggests that the introduction of ToUTs with smart metering will enable energy companies and Eskom to recover the additional cost of BESS, which will be necessary to support the use of higher levels of PV within Grid SA.

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References

[1] Walwyn DR. Providing emergency power in national energy systems: South Africa's Risk Mitigation Programme is costly and environmentally disastrous. In: 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET). Cape Town: IEEE; 2021. pp. 1-5

[2] Eskom. Integrated Annual Report 2021/22. Johannesburg: Eskom; 2022

[3] Eskom. Eskom Data Portal. Johannesburg: Eskom; 2021

[4] Eskom. Company Information Overview: Eskom. 2021. Available from: https://www.eskom.co.za/about-eskom/company-information/

[5] International Energy Agency. Electricity generation by source. 2021. Available from: https://www.iea.org/regions/

[6] Pierce W, Ferreira B. Statistics of Utility-Scale Power Generation in South Africa in 2021. Pretoria: CSIR; 2022

[7] Parr B, Swilling M, Henry D. The Paris Agreement and South Africa's Just Transition. Melbourne: Melbourne Sustainable Society Institute; 2018

[8] UNFCCC. FCCC/CP/2015/L.9/rev.1: Adoption of the Paris Agreement. Paris, France: UNFCC; 2015

[9] Walwyn DR. Turning points for sustainability transitions: Institutional destabilization, public finance and the techno-economic dynamics of decarbonization in South Africa. Energy Research & Social Science. 2020;**70**:101784

[10] Tyler E, Hochstetler K. Institutionalising decarbonisation in South Africa: Navigating climate mitigation and socio-economic transformation. Environmental Politics. 2021;**30**(suppl. 1):184-205

[11] Walwyn DR, Brent AC. Renewable energy gathers steam in South Africa. Renewable and Sustainable Energy Reviews. 2015;**41**(1):390-401

[12] Department of Energy. Integrated resource plan 2019. In: Energy Do. Pretoria: Department of Energy; 2019

[13] Department of Minerals and Energy, editor. Electricity Pricing Policy of the South African Electricity Supply Industry. In: Department of Minerals and Energy. Pretoria: South African Government; 2008

[14] Todd I, McCauley D. Assessing policy barriers to the energy transition in South Africa. Energy Policy. 2021;**158**:112529.

[15] Presidential Climate Commission. Laying the Foundation for a Just Transition Framework for South Africa. Pretoria: Presidential Climate Commission; 2021

[16] Sparks D, Madhlopa A, Keen S, Moorlach M, Dane A, Krog P, et al. Renewable energy choices and their water requirements in South Africa. Journal of Energy in Southern Africa. 2014;**25**(4):80-92

[17] Di Cosmo V, Lyons S, Nolan A. Estimating the impact of time-of-use pricing on Irish electricity demand. The Energy Journal. 2014;**35**(2):119-138

[18] Sarfarazi S, Mohammadi S, Khastieva D, Hesamzadeh MR, Bertsch V, Bunn D. An optimal real-time pricing strategy for aggregating distributed

generation and battery storage systems in energy communities: A stochastic bilevel optimization approach. International Journal of Electrical Power & Energy Systems. 2023;**147**:108770

[19] Krietemeyer B, Dedrick J, Sabaghian E, Rakha T. Managing the duck curve: Energy culture and participation in local energy management programs in the United States. Energy Research & Social Science. 2021;**79**:102055

[20] California Independent System Operator. Fast Facts: What the Duck Curve Tells Us About Managing a Green Grid California 2013. Available from: http://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf

[21] Eskom. Tariffs & Charges Booklet 2022/2023. Johannesburg: Eskom; 2022

[22] IPP Office. IPP Risk Mitigation. Pretoria: IPP Office; 2021

[23] IPP Office. List of Preferred Bidders for Bid Window 6 as Announced on 8 December 2022. Pretoria: IPP Office; 2022

[24] Stephens A, Walwyn DR. Wind energy in the United Kingdom: Modelling the effect of increases in installed capacity on generation efficiencies. Renewable Energy Focus. 2018;**2018**(27):44-58

[25] Mayyas A, Chadly AA, Khaleel I, Maalouf M. Techno-economic analysis of the Li-ion batteries and reversible fuel cells as energy-storage systems used in green and energy-efficient buildings. Clean Energy. 2021;**5**(2):273-287

[26] Lazard. Levelized Cost of Storage. New York: Lazard; 2020

[27] Roy S, Sinha P, Ismat SS. Assessing the techno-economics and environmental attributes of utility-scale PV with battery energy storage systems (PVS) compared to conventional gas peakers for providing firm capacity in California. Energies. 2020;**13**(2):488