Determining and Unlocking Untapped Demand-Side Management Potential in South Africa: Demand Response at the Grid Edge

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List of Acronyms

AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
CAIDI	Customer Average Interruption Index
CAISO	California Independent System Operator
CFL	Compact-Fluorescent Lamps
CSIR	Council for Scientific and Industrial Research
CTCN	Climate Technology Center and Network
CVR	Conservation Voltage Reduction
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DMRE	Department of Mineral and Energy Resources
DMS	Distribution Management System
DOE	Department of Energy
DR	Demand Response
DSI	Department of Science and Innovation
DSM	Demand-Side Management
DSO	Distribution System Operator
EAF	Energy Availability Factor
EE	Energy Efficiency
EE/DSM	Energy Efficiency/Demand-Side Management
EMS	Energy Management System
EPC	Energy Performance Certificates
EV	Electric Vehicle
FAN	Field-Area Network
FERC	Federal Energy Regulatory Commission
FGT	Foster-Greer-Thorbecke
GW	Giga-Watt
HAN	Home-Area Network
HPS	High-Pressure Sodium
HVAC	Heating, Ventilation, and Air Conditioning
IBT	Inclining Block Tariffs
IDM	Integrated Demand Management
IEEE	Institute of Electrical and Electronic Engineers
IIP	Independent Power Producers
kbps	Kilobytes per second
kHz	Kilohertz
km	Kilometer
LCOE	Levelized-Cost of Energy
LED	Light-Emitting Diode
LSM	Living Standards Measure
LVCT	Line-Voltage Communicating Thermostat
Mbps	Mega-bytes per second
MDMS	Meter Data Management System
MEPS	Minimum Energy and Performance Standards
MHz	Mega-Hertz

MLR	Manual Load Reduction
MW	Megawatt
MWh	Megawatt Hour
M&V	Measurement and Verification
NAN	Neighborhood-Area Network
NCPC-SA	National Cleaner Production Centre of South Africa
NDE	National Designated Entity
NEES	National Energy Efficiency Strategy
NEM	Net Energy Metering
NERSA	National Energy Regulator of South Africa
NREL	National Renewable Energy Laboratory
NSP	Network Service Provider
PLC	Power Line communication
PV	Photovoltaic
TOU	Time-of-Use
TSO	Transmission System Operator
TWh	Tera watt-Hour
UNEP	United Nations Environmental Programme
VAR	Volt-Amp Reactive
RE	Renewable Energy
REIPPPP	Renewable Energy Independent Power Producers Procurement Programme
REIPPP	Renewable Energy Independent Power Producers Program
RF	Radio Frequency
R&D	Research and Development
SANEDI	South African National Energy Development Institute
SCADA	Supervisory Control and Data Acquisition
SSEG	Small-Scale Embedded Generation
SWH	Solar Water Heating
WAN	Wide-Area Network
WiFi	Wireless Fidelity
WiMAX	Worldwide Inter-operability for Microwave Access

Executive Summary

The National Renewable Energy Laboratory (NREL), funded through the Climate Technology Center and Network (CTCN), has provided technical assistance to the Council of Scientific and Industrial Research (CSIR) and key energy sector entities in South Africa to examine untapped demand-side management (DSM) potential. This technical assistance was facilitated by the CTCN National Designated Entity (NDE) in South Africa, the Department of Science and Innovation (DSI) at the request of CSIR who submitted the proposal to the CTCN to build its research capabilities in DSM. The project included key South Africa stakeholders: Eskom, the South African National Energy Development Institute (SANEDI), and the Department of Mineral and Resources and Energy (DMRE).

South Africa is currently experiencing an energy crisis with extensive load shedding being implemented to address the supply-demand imbalance. The principal challenge is the low energy availability factor (EAF) of the coal-fired component of the existing generation capacity (for 2022, the weekly EAF average was approximately 62%). These shortages have been because of a combination of unplanned breakdowns and maintenance and units being out of service for planned maintenance. The energy crisis in South Africa is a supply side problem, as the country does have excess installed dispatchable generation capacity of 48.3 GW compared to a peak demand of 34.4 GW in 2022.

Demand-side management provides opportunities to achieve energy efficiency and to reduce peak demand, which can lower system costs. DSM also has the potential to help alleviate load shedding, which is a last-resort DSM mechanism. There is clearly potential for alternative DSM measures to help mitigate periods of over 6 GW of loading shedding and 8 TWh of energy shed in 2022. A comprehensive examination of possibilities for DSM programs for South Africa is presented in this report. Many are already well-understood, and this report highlights those that warrant further examination. The later sections of this report are focused on the potential for a less well-studied DSM measure in South Africa, targeted demand response from smart loads. Advanced Metering Infrastructure (AMI)—also referred to as smart metering—is a key enabler of targeted demand response, as well as a technology that enables multiple DSM opportunities.

DSM covers a broad range of programs including demand response, energy efficiency, and distributed generation. Demand response can be dispatchable and non-dispatchable, with options to implement programs in the retail or wholesale market. DSM can provide many benefits, including peak demand reduction, enhanced reliability, market participating reserves, and flexibility to support renewable generation integration. A broad taxonomy of DSM is presented in Figure 9. We examine the applicability of each of these measures in South Africa.

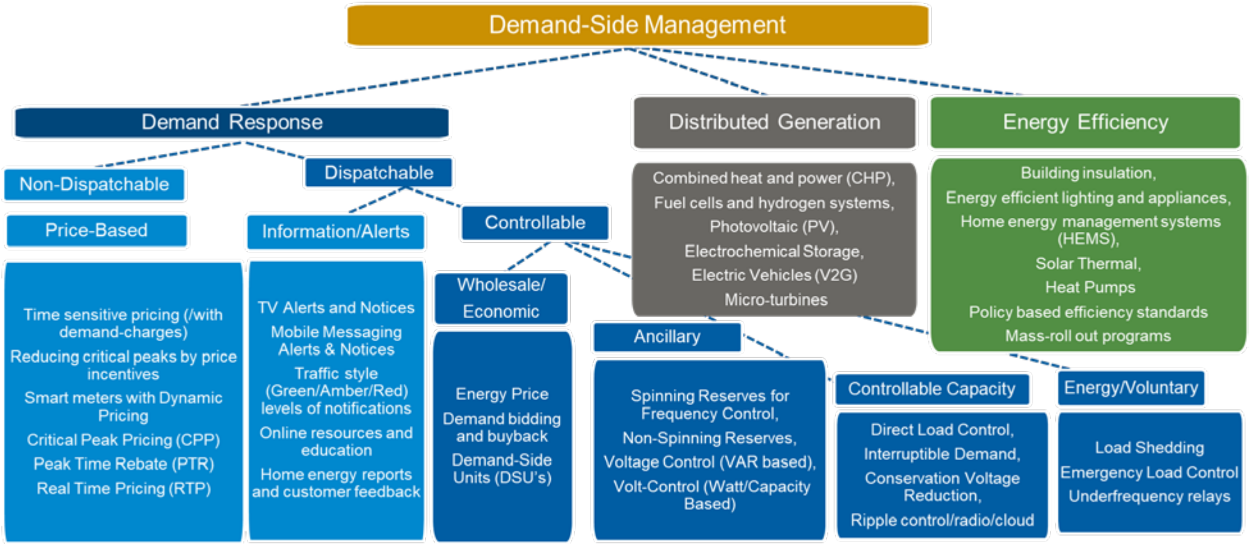

Figure 1. Taxonomy of Demand-Side Management Schemes.

We identified several well-studied demand-side initiatives in South Africa that could provide major benefits, including solar hot water heating, water heater ripple control, distributed solar and battery systems, heat pump water heaters, and further roll-out of efficient lighting. South Africa could consider continuing to pursue these programs.

There are further opportunities that have not been well-studied in the South Africa context, including the following:

- **Electric storage heaters:** Many residential and small commercial customers rely on portable small plug-in electric space heaters in the winter season. Electric heating is estimated to account for 1,346 MW and 808 MW[1] of peak demand for the commercial and residential sector respectively. Electric storage heaters—wall-mounted in-room units that heat thermal bricks using resistive heating during off-peak hours (i.e., nighttime periods) to slowly release heat when needed, are a potential technology that could alleviate peak demand. Although not energy efficient, storage heaters have low upfront capital costs and can provide peak load reduction. Although heat pumps are another alternative for providing more efficient heating, the high capital cost of heat pumps for space heating, particularly given the short heating season, remains a barrier. Potential for bi-directional heat pumps is low due to low cooling demand.
- **Advanced metering infrastructure (AMI)/smart meters and smart tariffs:** Advanced metering infrastructure provides benefits in terms of improving meter reading efficiencies, data for asset planning, operations for outage detection, ability to assess power quality, characterizing and identifying losses, and enabling demand and energy efficiency smart tariffs. Smart meters are a multi-DSM enabling technology, providing a pathway for smart-tariffs (e.g., time-of-use), remuneration for distributed generation export to the grid (i.e., bidirectional billing), customer feedback, and customer measurement and verification for other demand response and aggregator programs.

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[1] This is derived from end-use data provided by Eskom and scaled to meet 2021 demand.

Efforts are ongoing in South Africa to rollout AMI, and the overall rollout must be coupled with detailed and stacked (i.e., AMI is most cost-effective when use-cases are maximized) cost-benefit analysis.

- **Information via mobile emergency alert programs:** Wireless emergency alerts have been used extensively in the United States that allow federal agencies and local government to provide targeted mobile alerts to all mobile devices within specific geographic bounds (via proximity to cellular towers). Although this program was principally developed for emergency alerts (e.g., natural disasters, public safety, missing persons, etc.) more recently it has been used in emergency grid scenarios to achieve demand reductions. Both California and New York have used the program to successfully reduce peak demand, with the Californian Independent System Operator recently using the scheme to avoid load shedding and achieving a reduction of 2.1 GW (on a peak demand of 51.4 GW).

A potential challenge for DSM schemes and demand response (DR) is that load shedding presents a challenge to obtaining greater levels of load reduction from other traditional DSM programs. DSM and DR programs must reach massive levels of enrollment and capacity to be able to provide an alternative to load shedding. Load shedding far exceeds any capacity that these other traditional DSM programs could provide and presents a challenge in program implementation because much of this load has already been shed—and critical mass of enrollment must be reached for DSM programs to be a viable alternative to load shedding. There were nearly 3,800 hours of load shedding in 2022, i.e., for more than 40% of the year. At its height, over 20% of peak load was shed. A major challenge in the implementation of load shedding thus far is that most of the capacity on any given distribution feeder would need to participate in a DR program to be load shed exempt under current regulations [1].

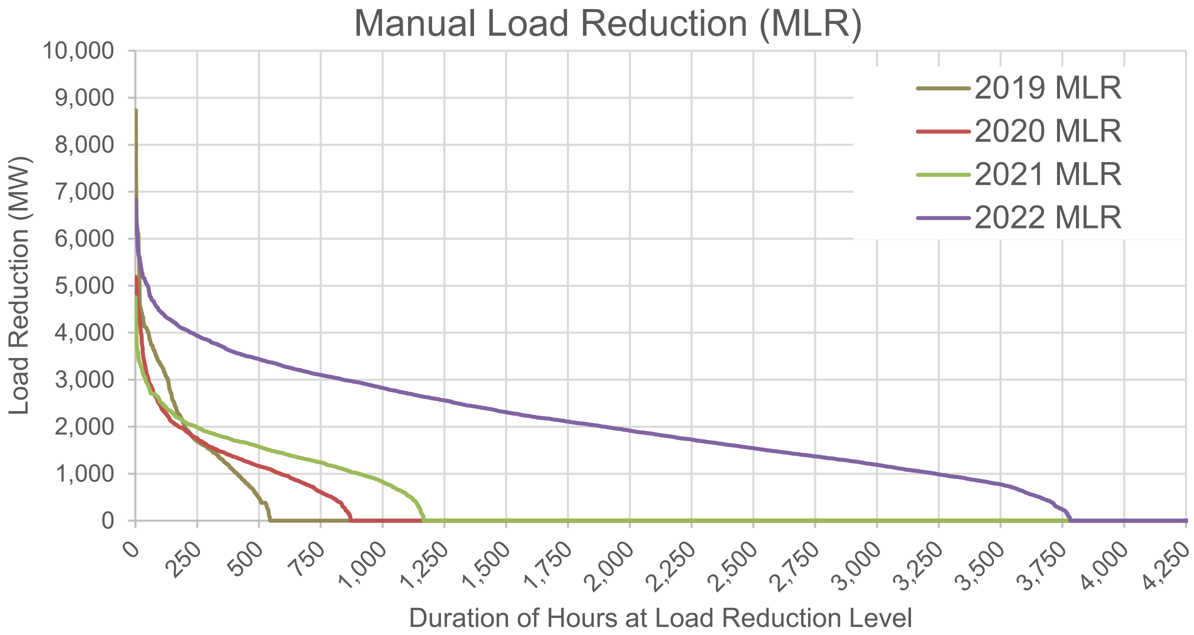

Figure 2. Manual load reduction (MLR) load reduction duration curve using data from April 2018 to August 2022.

Current load-shedding programs de-energize entire communities for up to four hours and have no means of isolating critical infrastructure on feeders targeted for load shedding, de-energized equipment is at risk of theft, load shed events cause electrical equipment wear and tear (i.e., circuit breakers), comeback load is challenging to manage, and overall load shedding creates large economic impacts (directly and indirectly). One potential solution is to use targeted demand control as an alternative to load shedding. Targeted demand control (targeted load reduction, targeted load shedding, or large aggregator programs) could help isolate critical infrastructure, provide more equal outcomes in terms of duration of load reductions, keep electrical equipment energized, help manage comeback load, and enable more control in terms of shorter load reductions. Two-way communication and leveraging targeted demand control using smart metering could provide multiple stacked benefits in terms of enabling net metering for solar, time-of-use for energy efficiency and peak load reduction and flexible loads. We identify AMI as a key enabling technology for targeted load shedding, targeted demand response, and aggregator programs.

Targeted demand response can leverage AMI or another suitable two-way communication infrastructure to provide several benefits:

- Targeted demand response can support faster rotation of service interruption. This can minimize the impact on individual customers directly (by reducing outage durations) and can create opportunities to distribute service interruptions equally over more customers.

- Targeted demand response provides flexibility in the implementation of when and where load is dispatched. Schedules for demand response can be customized to reduce social burden and cater to heterogeneous customer preferences.

- Flexibility in location of demand response dispatch reduces cold load pickup/comeback load on distribution circuits, improving efficiency of reenergization and reducing wear and tear of electrical equipment.

- Because of the ability to de-energize at the grid-edge (downstream of the distribution feeder, at the customer point of connection) distribution equipment will remain energized, reducing opportunity for theft.

- Load limiting or reducing the amperage that can be used at a customer premise with a smart meter, can be an effective method for peak load reduction that is an alternative to load shedding. This has recently been successfully trialed by Eskom.

- Aggregators can work with the transmission system operator (TSO) and distribution system operator (DSO) to coordinate targeted demand response or possible load limiting. The aggregator can then remunerate the participating customers and schedule demand response dispatches to suit customer preferences.

- If implemented with AMI or smart meter infrastructure, time-of-use or time-varying tariffs can be expanded, resulting in a reduction in operation costs and additional demand response mechanisms.

Although supply-side solutions are key to addressing the current energy crisis, DSM can play a major role in providing energy efficiency, reducing demand, and alleviating the impacts of the energy crisis. DSM energy efficiency programs can continue to help customers reduce their consumption and bills, and the flexibility resulting from DR can support the further integration of clean energy technologies. DSM peak load reduction programs will provide the greatest benefit if they are being designed as an alternative to load shedding, for which targeted demand control could provide significant benefits.

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1 Introduction: Characterization of Load Sectors and End-Use in South Africa and Current Demand-Side Management Programs

South Africa is facing major challenges because of shortages in electricity supply. In the face of shortages of generation capacity, the country has implemented active load shedding programs. These shortages have been because of a combination of unplanned breakdowns and maintenance and units being out of service for planned maintenance. In 2022, South Africa's Council for Scientific and Industrial Research (CSIR) reported 3,773 hours of load shedding, and the forecast for South Africa is for continued widespread load shedding. Demand-side management (DSM) is one of the tools to help achieve energy reductions through energy efficiency and load shifting. Eskom, South Africa's major public electric utility, has already implemented significant DSM measures that have helped reduce energy consumption and provide demand flexibility. This project investigates additional DSM measures that can provide South Africa's power system with further demand reduction and flexibility.

This study is led by the National Renewable Energy Laboratory (NREL), a national laboratory of the U.S. Department of Energy (DOE), and includes the CSIR, the Department of Mineral Resources and Energy (DMRE) of South Africa, Eskom, and the South Africa National Energy Development Institute (SANEDI). The research is funded by the Climate Technology Centre and Network (CTCN), an implementation arm of the Technology Mechanism of the United Nations Environment Program (UNEP). CSIR initiated the proposal for this work through the National Designated Entity of South Africa (NDE-RSA), the Department of Science and Innovation (DSI), as a country request to CTCN. This multi-partner collaboration aims to both bring about analysis on unlocking untapped DSM potential in South Africa, and provide training on DSM to power system researchers and technical analysts in South Africa.

Overall, the remainder of this report is broken down into four sequential areas of focus:

1. Characterization of Load Sectors and End-Use in South Africa and Current DSM Programs

2. Identifying Untapped Potential and Applicable DSM Schemes for Under-Utilized Load Sectors

3. Dispatchable Smart Loads & Targeted DR/Load Shedding

4. Targeted DR Implementation Plan Considerations

1.1 Overview of South Africa's Electricity System and Demand Characteristics

Electricity consumption in South Africa grew rapidly from the late 1980's to the mid-to-late 2000's from a combination of broad-based improvement in living standards from redressing inequity after the end of apartheid in the 1990's, electrification and providing broader electricity access, and overall economic growth. From the late 2000's economic growth has stagnated and from 2007 South Africa started experiencing challenges because of a shortage of operating generation capacity. As of the end of 2021, South Africa has an installed generation capacity of 57.9 GW (of which approximately 48.3 GW is dispatchable thermal generation capacity), compared to a peak demand in the same year of 31.5 GW, see Figure 3.

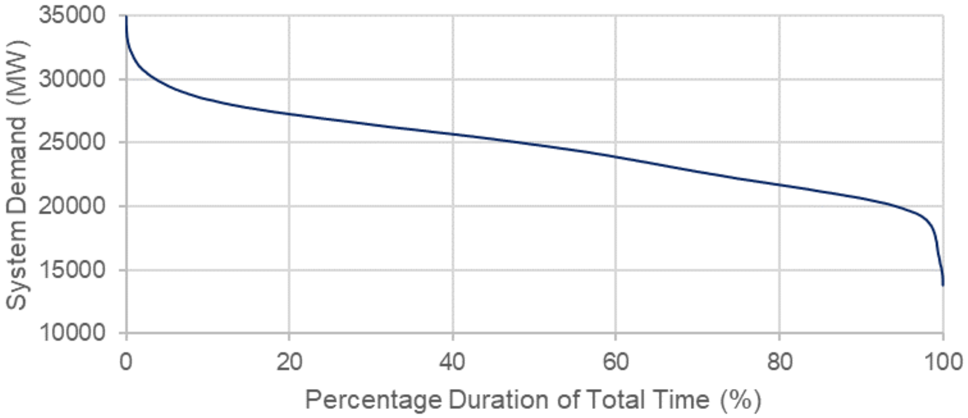

Figure 3. System load duration curve over a four-year period from August 2018 through August 2022. [Data Source: Eskom Data Portal]

The system load duration curve is presented in Figure 3 for the four years through August 2022. Although South Africa has sufficient installed generation to meet peak demand, the energy availability of that capacity—particularly of coal-fired generation, which makes up most of the dispatchable supply—has been low because of unplanned generation outages. South Africa's generation mix is dominated by coal, with coal extraction and processing being a large domestic industry. The low availability of installed generation has led to supply shortages and major challenges for the power system. The installed generation capacity mix is given in Figure 4, with coal representing over 75% of installed capacity. In 2021 coal contributed to 81.4% of energy generation, with 5.4% being from nuclear and 6.7% being renewable energy, including hydro generation. Eskom has open-cycle gas turbine peaking generation that runs on kerosene and diesel that contribute toward high peak load electricity prices.

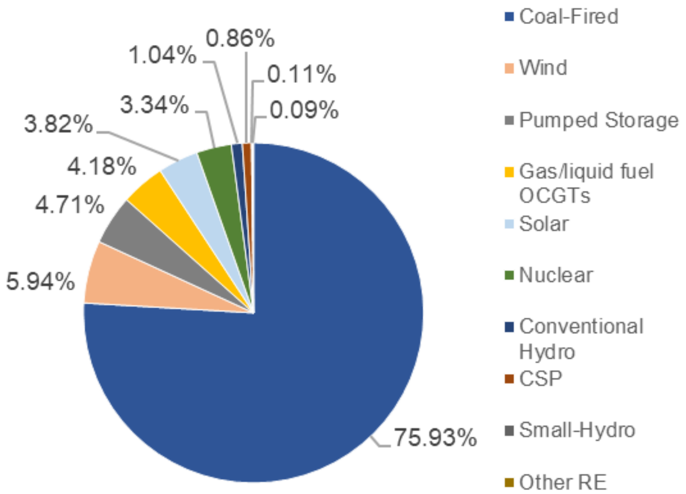

Figure 4. Breakdown of South Africa system installed capacity as of December 2021

The major utility in South Africa is Eskom, a vertically integrated power utility (i.e., responsible for generation, transmission, operation, and part of distribution). Eskom is planning to restructure the company into distinct divisions (e.g., transmission, generation, market operation, and distribution) and is tackling multiple challenges in terms of revenue losses, maintaining the generation fleet, and achieving increased transparency and good governance. Eskom owns the most generation, including almost all of the country's coal-fired capacity, operates the market and the transmission system, and is responsible for some distribution. Eskom own approximately 51,860 MW of generation capacity as of December 2021. South Africa's renewable energy independent power producer program (REIPP) has been responsible for most of the renewable energy (RE) installed capacity, with over 6,000 MW of installed RE capacity by December 2021. Eskom sells its electrical energy to municipalities, which make up most of its sales. For customers not served by municipals, Eskom services those directly, including industry, mining, and some residential areas. Most distribution is managed by eight large metropolitan municipalities (i.e., Johannesburg, Cape Town, eThekwini, Ekurhuleni, Tshwane, Nelson Mandela, Buffalo City, and Mangaung), with the rest being served by district municipalities and Eskom [1]. The six largest metropolitan municipalities purchased 64% of Eskom's total sales in 2016 [2]. The National Energy Regulator of South Africa (NERSA) has oversight to regulate electricity, including licensing and compliance, infrastructure planning, regulatory reform, and pricing and tariffs.

Shortages in generation supply have been due to maintenance backlogs, unplanned outages, and repurposing power plants that are due for retirement. The annual average energy availability factor (EAF), or the amount of energy available versus installed capacity, was 62% for 2022. A key element of the low EAF was high levels of planned maintenance during the summer months and high levels of unplanned outages [4]. Load shedding occurred for 3,773 hours (8,301 GWh) in 2022, which has led to increased costs to, and lost revenue for, both Eskom and the South African economy. The annual electricity generated, duration of outages, and volume of estimated energy shed, as estimated by CSIR, is shown in Table 1. From 2018 to 2021 the volume of energy lost to load shedding has continued to increase, with 2022 showing a further increase, more than tripling the energy shed in 2021. Load shedding is achieved by Eskom's different load shedding schedules, which currently run from Stage 1 through Stage 8, with an additional 1,000 MW of load shedding at each stage. Schedules are provided to municipalities, who are given predetermined times (based on time of day and day of month), and volume of load to be shed corresponding to each stage. This has been rolled out to try balance the impact of forced outages among customers.

Table 1: Total Electricity Generation and Impact of Load Shedding from 2018 through 2021 [3]

Year	Annual Electricity Production (TWh)	Duration of Outages (Hours)	Energy Shed (GWh)	Energy Shed % of Total Generation
2018	241	127	192	0.08
2019	239	530	1,352	0.56
2020	227	859	1,798	0.79
2021	234	1169	2,521	1.07
2022	233	3,773	8,301	3.56

South Africa's electricity system is winter peaking, with demand during colder winter months being higher due to electric space heating and water heating. Summer demand has historically been lower as there is not a lot of electric cooling load from HVAC equipment. Bulk generation planned maintenance is scheduled for summer months due to the lower demand. The highest and lowest total energy consumption days and their corresponding system demand profiles are given in Figure 5, in addition to average summer and winter load profiles. Peak demand occurs in the evening, due to a coincidence of peaking residential demand and residual commercial and industrial demand which starts to decrease in these hours. Load shedding can occur year-round, but tends to occur most frequently and severely (i.e., periods with the highest levels of load shed capacity) during these peak periods in the winter and during the evening peak. In 2022, load shedding occurred for 18 consecutive days in the early weeks of July (winter) while no load shedding occurred in February (summer). The highest capacity of load shed (up till 2022) was 6.85 GW at 6 PM on July 4, 2022.

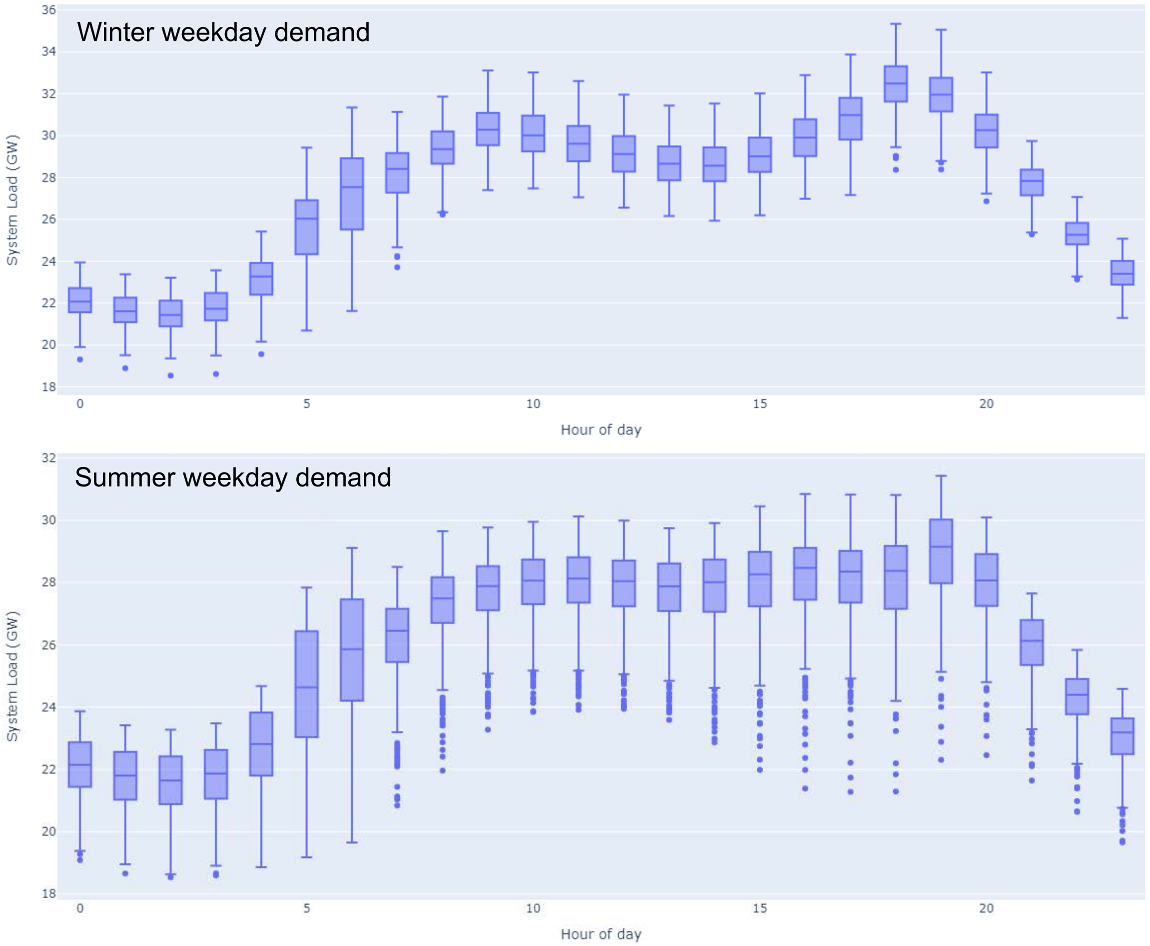

Figure 5. System summer (December, January, and February) and winter (June, July, and August) weekday demand showing hourly interquartile ranges, median, and outliers using Eskom system load over the past four years from August 2018 through August 2022. [Data Source: Eskom Data Portal]

1.2 Drivers of Demand, Load Sectors, and End-Use Breakdown

Quantification of the end-uses that contribute to system demand is the first step to understanding potential for DSM solutions. Furthermore, the drivers of demand and social context of demand change in each sector and end uses are important to consider in developing sustainable and equitable DSM programs. The primary causes for increases in load and constraints that suppress demand in recent years are explored in Section 1.2.1. Energy and a peak demand by sector (residential, commercial, and industrial) are described in Section 1.2.2. Section 1.2.4 describes the impacts and considerations for energy equity on each of these sectors, and finally work to determine consumption disaggregated by end-use is presented in Section 1.2.3.

1.2.1 Demand Drivers

South Africa system peak demand reached its historical high of 37.16 GW in 2008 (with 36.51 GW supplied by Eskom) with subsequent demand falling, decreasing to 34.16 GW in 2021 with 31.47 GW supplied by Eskom[5]. Demand has been suppressed due to constraints on the supply side that have resulted in high prices, extensive load shedding, and other demand-side measures, making it challenging to accurately quantify demand characteristics and anticipated growth. The low EAF has been a major issue, due to unplanned maintenance and generation outages, which have constrained supply, with an average EAF of 62% for 2022. Consumption in the industrial sector has decreased due to successful energy efficiency efforts (between 2000 and 2012, overall energy intensity decreased from 0.533 kilowatt-hours per rand (kWh/R) to 0.350 kWh/R), installation of onsite generation, and the decline of some industry activity, particularly in mining and minerals [6]. Concurrently to this, consumption in the residential sector has increased. The residential sector is forecasted to increase its electrical consumption from 45.95 TWh (2015) to 66.22 TWh (2040) due to increases in electrification, increased ownership of electrical appliances, growth in the number of households, and improvement in standard of living [2]. The number of households has increased by 42% from 2000 to 2012 and, and as households with upward economic mobility acquire more amenities and appliances, consumption has increased [3] (details in section 1.2.3). Finally, access to electricity has improved from less than 33% in 1990 to 95% in 2023 [7], [8].

South Africa is a winter peaking system with an evening peak driven by the residential demand. The industrial sector, while responsible for the majority of consumption, maintains a relatively flat level of demand throughout the day [9]. Colder temperatures drive peak demand in the winter, due to electric space and water heating, with an estimated one degree Celsius decrease in temperature resulting in a 600-700 MW increase in peak demand [10]. Reduced daylight hours also impacts load (in particular lighting load), with decreased winter daylight hours increasing the load. Summer demand is lower due to the absence of space heating in the residential and commercial sectors, as well as a decrease in electric water heater, lighting, and miscellaneous plug load consumption.

Future load growth is expected to primarily come from growth in the residential sector, with industry expected to level-off and only modest short-term growth expected for electric vehicles (EV). Although EV growth must be supported by the network to enable EV charging, the current market share of EVs is marginal in South Africa. To date, regulations for EVs are still in their infancy and there has not been a roll out of government incentives. Investments in charging infrastructure have been slow to gain momentum and there is overall low level public awareness of EVs[11] [12]. The South African government has drafted a long-term automotive industry transformation plan on low-carbon vehicles strategy and has published an “Auto Green Paper”. This policy reform has not been finalized by the cabinet at the time of writing. EV targets have not been set or announced to date. The South African automotive industry, which is one of the leading manufacturing industries in the country, will need to accelerate EV development to keep up with global transitions, particularly as most of the vehicle exports are to countries with targets for new vehicle sales to be zero emission by 2040 and 2035[13].

1.2.2 Load Sectors

Load in the residential sector has continued to grow, with residential electricity consumption at 37.8 TWh in 2021 [10], up from 32.4 TWh in 2003 [14] (see Table 2). The share of system consumption from the residential sector has steadily increased, from 17% in 2003 to 19 % in 2021. This has been because of an increase in the number of households, expanded electricity access, and a decrease in the electricity consumed by the industrial sector. In 2003, industry accounted for 49% of total electricity consumption or 93.3 TWh [14], while by 2021 consumption decreased to 40.05% of total electricity consumption, or 79.6 TWh [10]. This is partially because of energy efficiency efforts as well as a decline in industry economic activity. The commercial sector, although a much smaller portion of overall consumption than either the residential or industrial sectors, has grown the most from 19 TWh in 2003 to 30.6 TWh in 2021.

The residential sector is now the greatest contributor to the peak demand, at 27.4%. The industrial sector (with mining and agricultural sectors considered separately) follows residential at 27.0%. The commercial sector is the third largest contributor at 12.7%.

Table 2. Consumption and Demand in 2003 and 2021 by Sector.

	Energy Consumption			Peak Demand		
Sector	**2003**	**2008**	**2021**	**2003**	**2008**	**2021**
Residential	17%	17.7%	19%	35%	34.7%	27%
Commercial	10%	13.9%	15%	10%	10.8%	13%
Industrial	49%	36.3%	40%	52%	27.4%	27%
Mining	18%	14.8%	14%		10.5%	11%
Agricultural	4%	2.5%	3%		1.8%	3%
Other	2%	14.8%	9%	3%	14.8%	19%
System Total	190.4 TWh	226.4 TWh	198.9 TWh	31.9 GW	36.5 GW	31.5 GW

For 2003, demand is provided for the industrial, agricultural, and mining sectors together. System peak demand increased after 2003, peaking at 37 GW in 2008, after which point it steadily decreased. The 'Other' category includes exports, losses, and traction.

1.2.3 Residential End-Use

End-use describes the activities that make up overall electricity consumption, for example, electric space and water heating, lighting, refrigeration loads, and cooking. Studies by Hughes and Larmour [7], [19], [20] examined residential appliance use via survey data from July to September 2020 and calibrated their results with top-down national estimates, we present end-use breakdown in Figure 6. Their findings were broken down into three income groups as end-use varies with the diversity of households. Appliance ownership and aggregate energy consumption findings are presented in detail in Hughes and Larmour's "Review of Residential Energy Efficiency Targets in South Africa" [19]. The highest income level uses five to six times as much electricity as low-income households. As Ye and Koch note, lower-income households tend to rely more on other forms of energy—primarily wood and paraffin for heating and cooking [15]. This trend also appears in 2013–2015 survey data presented in Reference [21], with wood and paraffin each accounting for more energy use than electricity for the lowest two bands of the Living Standards Measure (of a total of 10bands).

End-uses that are common across all income levels include lighting, cooking appliances, and space heating. Electricity consumption for these end-uses varies across income groups, with the highest income groups using nearly twice as much electricity for lighting per household as the lowest income group. Notably hot water heaters exceed all other appliances in electricity consumption in both middle- and high-income households (noting that there were not enough households in the lower-income group[2] with hot water heaters to be included in the analysis).

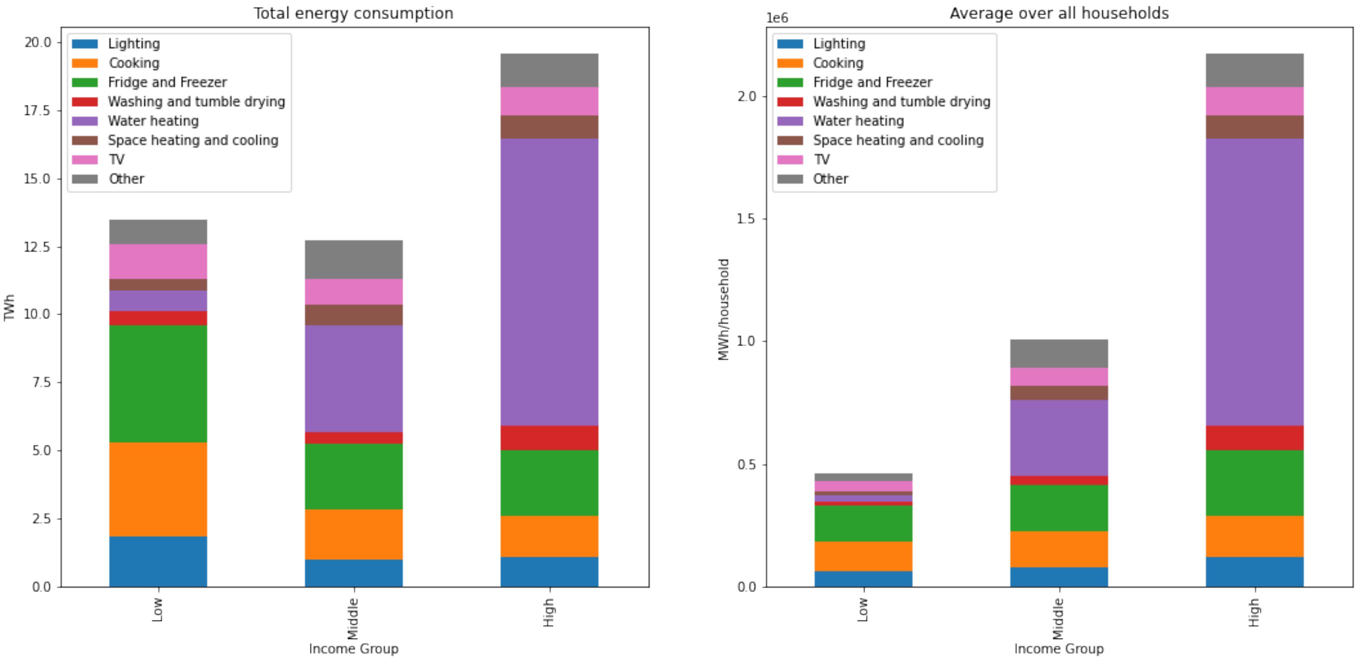

Figure 6. National estimated total residential energy consumption (TWh) and average energy consumption per household for 2020 [20].

Disaggregated data of the end-use of the commercial sector are limited and not widely available at fidelity [21]. However, research presented in South Africa's Department of Energy's Second Annual Monitoring Report suggests that energy efficiency in the commercial sector may have improved while an increase in office equipment resulted in overall growth in electricity consumption. Data from 2007 [9] indicate an average winter peak demand of 5,500 MW, with major end-uses of consumption including HVAC, lighting, and other sources.

Disaggregated data of energy consumption in the industrial and mining sectors are similarly limited. An example of industrial and mining sector data from 2007 data for an average winter day [9] shows that (excluding mining) most industrial process electricity is consumed by motors, with an approximate aggregate demand of 5,000 MW during the demand peak. Fans, pumps, compressors, and HVAC account for up to 4,000 MW of average weekly winter peak demand. Total peak demand in the industrial sector was approximately 12,000 MW, with little variation between seasons. The mining sector shows a similar distribution of end-use, with motors resulting in 1,700 MW of peak demand and fans, pumps, compressors, and HVAC accounting for 1,300 MW. Electricity demand in mining amounts to 4,200 MW of peak demand.

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[2] The report defines income groups; low-income groups (monthly income <R5,000), middle income groups (monthly income >R5,001 and <R20,000), high income groups (monthly income >R20,001).

1.2.4 Energy Equity in South Africa

Energy equity is becoming increasingly important in South Africa, particularly because there is a large gap between affluent communities with primarily electric end-use and those with little to no electricity access. It should be emphasized that while 95% of households are connected to the grid, many connected households curb electricity use and rely on alternative energy sources due to issues of affordability (see section 1.2.3). Solutions in South Africa must consider a diverse landscape of district-municipal and metropolitan-municipal-run distribution utilities and customers to avoid solutions that only increase inequality. There is a large potential to achieve increased electrification and sustainable electricity growth in South Africa, but challenges on the supply side may hamper that growth.

Determining energy poverty levels in South Africa is challenging because of a lack of data and diverse communities, but several methodologies have been developed. A study by Ye and Koch applied Foster-Greer-Thorbecke (FGT) indices—generalized poverty measures—to find the number of households below the energy poverty line. Using the standard FGT formula, a household is considered to be below the energy poverty line if that household's actual energy consumption is less than the household-specific poverty line, which is defined as the energy required to meet basic needs. [15]. These results indicated that 58% of households were energy poor, while 18% of households spent over 10% [3]of their household budget on energy. Other literature finds national energy poverty levels ranging from 13% in 2014 to 69% in 2008.

Eskom's electricity prices have steadily increased from 2008 to 2018, because of a combination of increased primary energy costs, revenue recovery, increased emergency procurement from independent power producers, and increased costs associated with maintenance [6]. From 2007 to 2022, annual Eskom tariff increases have frequently outpaced inflation by a factor of 2–6. Electricity distribution is operated by both district municipalities and large metropolitan municipalities, with the remainder being served by Eskom. Load serving distribution entities in South Africa face diverse challenges, which has had impacts on Eskom's business model as well as challenges in equity of electricity access and revenue recovery. The Deputy President of South Africa reported to the National Assembly that municipals owe Eskom a debt of 56.3 billion Rands. Regional challenges include preexisting socioeconomic and racial inequalities, as explored by Baker and Phillips, who argue that as more affluent customers and communities integrate distributed energy resources, reduction in revenue will negatively impact electricity services of poorer municipalities [6]. Inclining block tariffs (IBTs) have increased costs for higher-income, high-energy consumers, motivating this group to seek alternatives such as solar photovoltaics (PV). Affluent communities with high load consumption are seeking alternatives to achieve energy independence, while municipalities that are losing revenue may require intervention. For example, Cape Town is planning to generate a portion of its own power in the future, which will help improve customer reliability of supply, but will also reduce Eskom revenues—potentially increasing the challenge of achieving reliability for all [16]. Motivated by

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[3] The "10% affordability indicator" has been used to define energy poverty and indicates whether a household must spend more than 10% of its income on energy consumption. DOE examines energy poverty using this indicator in their 2012 and 2013 studies. Ye and Koch highlight that many households spending 10% or more of their budget on energy may be curbing their energy use; if these households were to freely consume energy to meet their daily needs without effectively restricting energy use, this income percentage would be higher.

increased resilience, reliability, and carbon neutrality, the city of Cape Town has outlined plans to install up to 200 MW of generation including PV and battery systems beginning in 2025, and has issued an RFP for demand response aggregators [17]. Other municipalities have repeatedly faced challenges in being able to pay for their electricity consumption, resulting in a pilot program of "active partnering" with Eskom [18]. Eskom has taken over revenue collection for the Maluti-a-Phofung Local Municipality and stepped in to maintain local infrastructure. This landscape may present added challenges for Eskom, as sources of revenue such as Cape Town are reduced, and other municipals face increasing energy prices and challenges in revenue collection. This presents a major equity challenge because affluent municipals, which have likely been subsidizing transmission and generation infrastructure for municipals with low-income communities, are exploring means of becoming independent of Eskom. This can exacerbate the financial challenges for financially struggling municipalities if more affluent municipalities find means to become independent.

1.3 Demand-Side Management Programs in South Africa

South Africa has been proactive in creating holistic DSM programs to help alleviate supply side constraints that have led to widespread load shedding. The National Energy Efficiency Strategy (NEES) is an effort to improve overall energy efficiency, originating from a 2005 mandate from DMRE [21]. It includes specific targets for percent improvements in energy efficiency by sector and is not restricted to electricity consumption. Although outcomes of NEES include measurements of improved energy efficiency and expanded standards for energy efficiency (more detail is presented next) no mandatory targets for load sectors or customers or enforcement of energy efficiency measures exist. The Energy Efficiency and Demand-Side Management (EEDSM) Programme, which evolved into the Integrated Demand Management (IDM) Programme, was initiated by Eskom in 2004, and eventually became IDM under the National Energy Regulator of South Africa [22]. The EDSM/IDM efforts include energy efficiency (these efforts have contributed to meeting the NEES targets), load shifting, and peak shaving. More recently, Energy Performance Certificates (EPC) for buildings have been introduced by SANEDI to evaluate building performance. The National Cleaner Production Centre (NCPC) at CSIR has partnered with Eskom to provide support for businesses to improve energy efficiency [23]. This is an ongoing effort.

1.3.1 National Energy Efficiency Strategy

The energy efficiency impacts outlined in the DMRE reports, "Post-2015 National Energy Efficiency Strategy" [12] and "South Africa's Energy Efficiency Targets: Second Annual Monitoring Report" for 2015 [2], show that efficiency has improved since the implementation of NEES, with almost every sector[4] meeting or exceeding its respective targets. Energy efficiency is measured as the percent reduction in energy consumption relative to the baseline consumption projected from the year 2000.

The industrial sector improved energy efficiency by 28.6% between 2000 and 2015, while overall electricity consumption increased from 2000 to 2012. During the same period the share of industrial energy use from coal dropped from 57% to 34%. Of the four sectors examined, the

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[4] The Second Annual Monitoring report lacked data on transportation, which is primarily not electrified.

commercial and public sectors have exhibited the lowest improvements in energy efficiency metrics with 2003–2013 data indicating efficiency improvements of only 0.47% per year [21]. Energy efficiency in this sector may, however, be masked by growth in office computers and peripheral plug-loads. The report emphasizes that, because of a lack of reliable data, energy efficiency in the commercial sector may be higher than the reported 0.47% improvements per year.

The residential sector has exceeded energy efficiency goals. This is attributed to both technological improvements and behavioral changes, motivated by both increased education and energy efficiency awareness and financial incentives to save money [21]. The 2013–2015 survey found that energy efficient technologies such as efficient lighting (e.g., compact fluorescent lamps [CFLs] and light-emitting diodes [LEDs]), roof and wall insulation, hot water heater blankets, ripple control for water heating, and low-flow shower heads had greater adoption at higher Living Standards Measure (LSM) levels, as defined by the South African Audience Research Foundation and used by DOE in the Second Annual Monitoring Report. It should be noted that at lower LSM levels, electrical appliances are not used as often, because of a lack of grid connection, electricity access, and appliance costs—e.g., candles are used for lighting and wood is used for water heating.

The Second Annual Monitoring report identifies opportunities for improvement in promoting awareness of energy efficiency in new appliance purchases. Based on survey data, relatively few respondents considered energy efficiency when making first-time purchases. The post-2015 National Energy Efficiency Report highlights the continuation of solar water heating (SWH) and future mass roll out programs as opportunities for continued energy efficiency improvement. The SWH program saved 600 GWh from 2010 to 2014, as estimated in a study by Hughes and Lamour’s work, [7], [19], [20], notable as electric water heating accounts for the largest portion of electricity use in the residential sector. Increased adoption of SWH and hot water heat pumps as an alternative to traditional hot water heaters is modeled, resulting in 2.97 TWh of energy savings in the residential sector alone.

As part of the NEES effort, the Minimum Energy and Performance Standards (MEPS) were expanded. MEPS are compulsory legal requirements for commercial use of appliances in South Africa and are intended to improve energy efficiency in the residential, commercial, and industrial sectors. In a study by Hughes and Lamour, it was demonstrated that tightening MEPS will continue to improve residential sector energy efficiency, with the most extensive implementation scenario of MEPS estimated to have a potential energy savings of 6.66 TWh from 2025 to 2040. Standards and Labeling policies were introduced and eventually made compulsory for ten types of appliances: electric water heaters, electric ovens, refrigerators, freezers, dishwashers, tumble dryers, washer-dryer combinations, washing machines, air conditioners, heat pumps, and audio and video equipment [25].

1.3.2 Energy Efficiency and Demand-Side Management/Integrated Demand Management Program

The EEDSM/IDM is an extensive program that includes energy efficiency efforts and extends to load shifting and peak shaving objectives. This program has achieved a reduction in demand of 4,500 MW and a reduction in energy of 47,600 TWh from 2004 to 2018 [22] [26]. Demand management initiatives span industrial, commercial (including agricultural), and residential sectors. Crosscutting efforts including a CFL rollout that achieved at least a 1,950 MW reduction in demand [22], see Table 3.

Table 3. Demand Reductions Achieved by EEDSM/IDM Projects

EEDSM/IDM Program Effort	Demand Reduction (MW)
CFL rollout	1,950
Industrial and mining sectors (process optimization, fans, pumps, refrigeration, conveyor systems, waste heat recovery)	1,000
Agricultural sector (pumping loads)	100
Commercial sector (lighting, HVAC)	200
Mass roll outs (excluding CFL)	170
Geyser ripple control	120
Total	4,500

The demand reduction in the residential sector benefitted from the EEDSM program. A mass rollout program of a collection of technologies included LED lamps, pool pump and hot water heater timers, energy efficient shower heads, and ripple control of hot water heater loads. DSM programs in the commercial sector focused on lighting, shower heads, heat pumps, SWH, and process optimization. Energy use in the industrial sector benefitted from process optimization, lighting, heat pumps, HVAC, compressed air, and improved ventilation.

Eskom has the capability to dispatch DSM and can deploy these sources to meet system needs. Up to 1,014 MW of instantaneous demand response can provide Eskom's DR fast frequency response service (respond within 6 seconds) as a form of operating reserve. This instantaneous DR is planned with day ahead scheduling and can be dispatched within six seconds of reaching a predetermined network frequency. Up to 364 MW of supplemental demand response can be called upon with a 30-minute notification to reduce load during peak hours via instruction from the system operator. Up to 62 MW of critical peak day reserves has been provisioned from critical peak pricing (international tariff). Finally, approximately 300 MW of demand response has been achieved from Power Alert updates, historically TV and radio announcements during peak hours (between 5 pm and 9 pm). Currently, Power Alert has been reintroduced to communicate the power system status to the public via certain TV channels [27].

1.3.3 Current Efforts in Commercial & Industrial: Energy Performance Certificates for Buildings and National Cleaner Production Centre Business Support

In 2020, DMRE introduced regulation to make EPC displays compulsory in an effort to reduce demand in the commercial sector and reduce greenhouse gas emissions from buildings [28], [29]. The EPC Guideline dictates data requirements that must be submitted to SANEDI, which will baseline the energy performance of buildings and result in a performance rating (A through G, with A being the lowest tier of energy consumption). Building owners should target at least a D rating, which is benchmarked as the midpoint of average for South African buildings [30]. EPCs must be displayed at the building entrance.

NCPC-SA has partnered with Eskom to support businesses in energy management efforts[23]. This service includes technical assistance from Eskom and the NCPC-SA to reduce energy and water consumption. Free tools and videos have been made available; this effort also provides energy assessments, training, guidance for obtaining financing and tax incentives for energy efficiency measures, and support in pursuing advanced certifications.

1.3.4 Active Use of Demand Response Programs and Load Shedding

Eskom actively uses several DR programs on an ongoing basis to deal with supply-side challenges. Eskom has faced major challenges in the energy availability of its fleet, with an annual average EAF of 58.1% for 2022 (i.e., on average, 41.9% of the generation fleet was unavailable). A key factor of the low EAF has been the high levels of planned maintenance during the summer months and high levels of unplanned generation outages [4]. Given the low EAF, DR schemes have been used extensively by Eskom to avoid a nationwide blackout. Eskom characterizes the different DR programs as follows:

- Manual load reduction (MLR): Demand that has been reduced because of load shedding and/or curtailment. In general, this is the largest source of DR with 6,993 GWh of load MLR used from April 2018 to August 2022. Figure 7 shows the duration curve of the use of MLR for 2022, and Figure 8 shows the peak usage on July 4 for the same year.

- Interruptible load shed (ILS): This is consumer load that can be contractually interrupted without notice and is reduced by remote control and/or instruction from Eskom National Control. There are individual contracts in place that can limit the use of ILS. This has been the second largest source of DR with 617 GWh of load ILS utilized from April 2018 to August 2022.

- Interruption of supply (IOS): This is contracted and mandatory demand reduction utilized by Eskom National Control. It also includes interruption of supply due to transmission system faults. It was the lowest source of DR, with 221 GWh of load IOS used from April 2018 to August 2022.

DSM has huge potential to help alleviate load shedding, which is a last resort form of DSM. There is clearly potential for alternative DSM measures to help mitigate the more than 6 GW and 5.7 TWh (January to September 2022) of load shedding. However, the situation in South Africa is a supply side—specifically availability of existing supply capacity, rather than a demand-side problem.

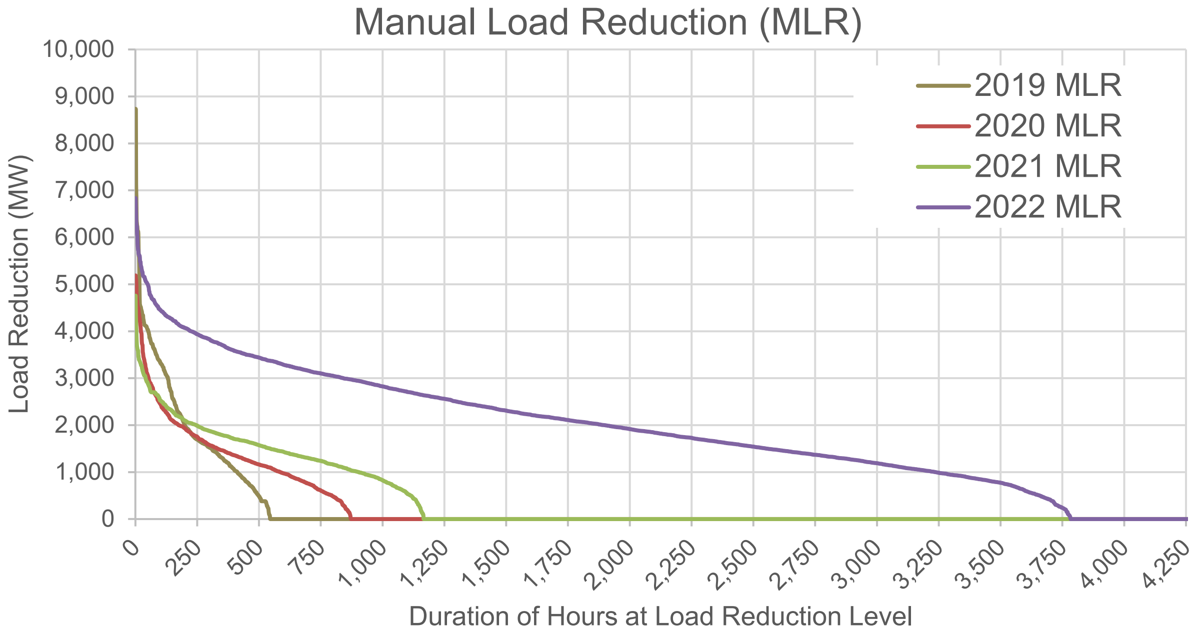

Figure 7. Manual load reduction duration curve using data from 2019 to 2022 [Source: Eskom Data Portal].

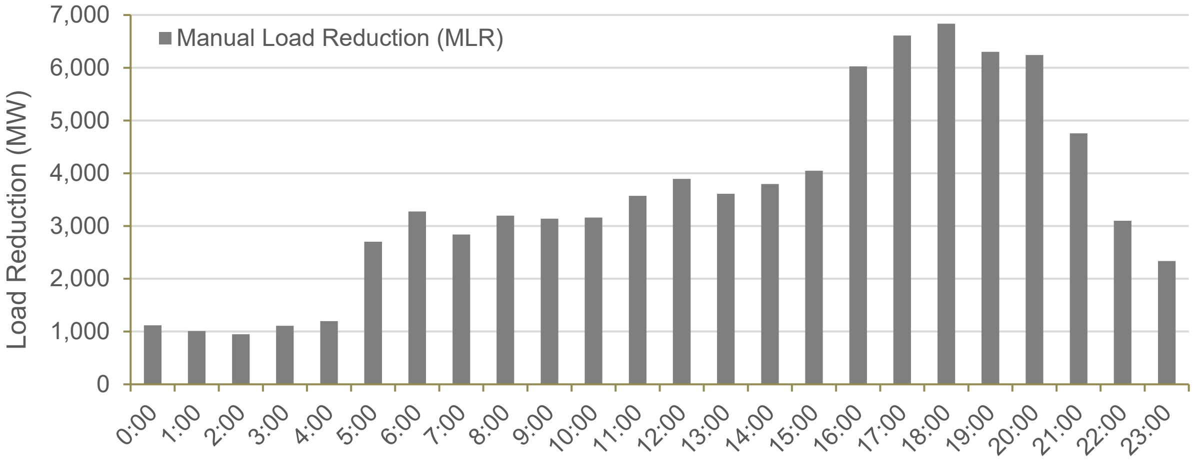

Figure 8. Manual load reduction daily usage for July 4 2022 (the highest use of MLR in 2022) [Source: Eskom Data Portal].

1.4 Taxonomy of Demand-Side Management Programs: World Examples, Use, and Applicability in South Africa

DSM covers a broad range of programs including demand response, energy efficiency, and distributed generation. Demand response can be dispatchable and non-dispatchable, with options to implement programs in the retail or wholesale market. DSM can help achieve peak demand reductions to achieve generation and network capacity investment deferrals. Using DSM to shave peak load can also reduce reliance on expensive peaking generation which can overall lower the levelized cost of electricity.

Demand response can also be used to offer enhanced reliability, providing the following:

- A range of services from non-dispatchable peak load alleviation through peak price signals and information alerts
- Market participating reserves and reductions
- Emergency load reductions through participating customers, underfrequency relays, and direct load-shedding programs.

Flexibility on the demand side can also be used to integrate renewable generation, providing a source to use excess renewable energy generation and shift load from hours with low renewable energy availability. A broad taxonomy of DSM is presented in Figure 9. In Table 4, we break down the broad categories and sub-programs, give an overview of their use and world examples, and their applicability in South Africa

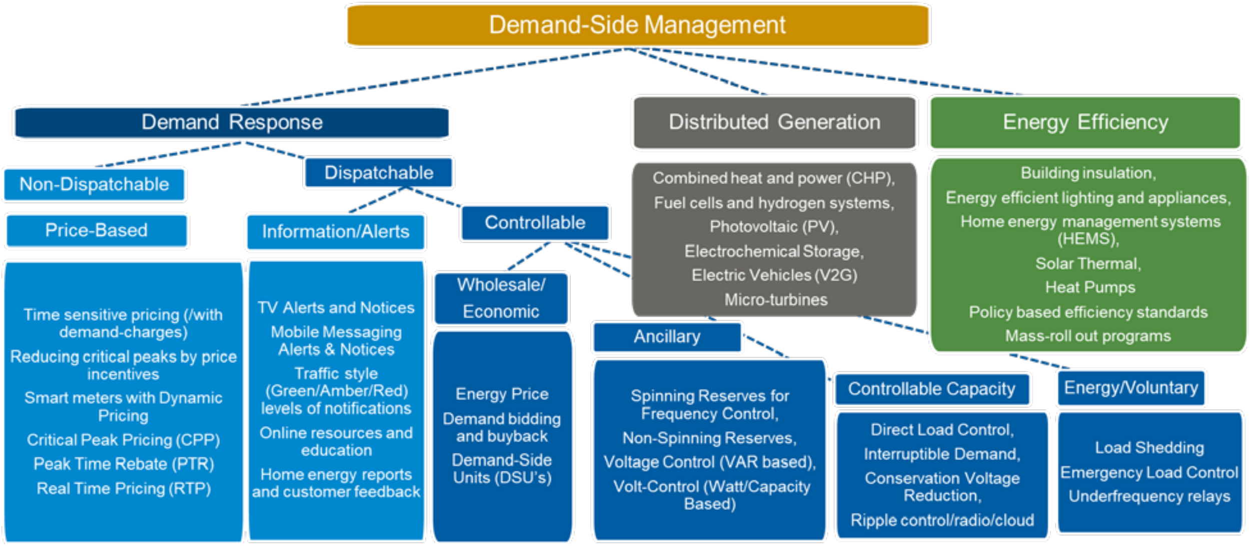

Figure 9. Taxonomy of demand-side management schemes.

Table 4. A Breakdown and Overview of Demand-Side Management Programs, World Examples, and Their Applicability and Use in South Africa.

DSM Schemes and Use/Potential in South Africa			
Demand Response	**Dispatchable**	**Wholesale/ Economic**	**Demand biding and buyback programs:** DR customers bid load curtailment/reductions into the day-ahead or real-time markets which are in direct competition with supply side bids. These demand-side units usually are expensive and require high levels of dependability to compete with the reliability of supply-side dispatch [31]. This demand can also be called upon to provide reserve capacity, because it is typically more expensive than peaking generation. The California Independent System Operator (CAISO) offers market products for DR to offer energy, spinning, non-spinning, and demand-side unit commitment services to operate in the day-ahead and real-time wholesale markets [32]. CAISO's extensive DSM program has been relying on the demand-side for capacity relief during summer months and during load shedding events. EirGrid, which operates the market and national control center in Ireland, offers a demand-side unit (DSU) program, allowing demand-side resources to bid demand reductions into the wholesale market [33]. ➢ **Use in South Africa:** Eskom is not using any demand bidding or buyback programs where DR is participating in the wholesale market. **Energy Price:** Subjecting the demand-side to the wholesale market price encourages customers to shift demand from peak-price hours to off-peak periods (typically peak-prices occur during peak demand hours, but renewable generation is moving the system *net* load peak). Subjecting customers to the real-time price also subjects customers to large price fluctuations and volatility in the wholesale market. A good example of this is Griddy Energy, a company that operated in Texas and subjected their customers to the wholesale price. During the week of the Texas winter storm and blackouts in 2021 a surge in wholesale prices resulted in residential customers with bills that exceeded $1,200 for a single week [34]. ➢ **Use in South Africa:** Eskom and the municipalities do not offer their customers the wholesale electricity price.

		Controllable	Ancillary	**Frequency services:** Frequency regulation services help keep supply and demand balanced at times and is the principal means of maintaining system frequency and stability (50 Hz in South Africa). Frequency regulation can range from instantaneous (i.e., inertia services that resist initial rate-of-change-of-frequency in a contingency event), primary response (response time of seconds, i.e., droop control from generator governor response), secondary response (i.e., minutes—typically from online reserve generation with automatic generator control), and tertiary response (tens of minutes—typically from bringing online additional generation from dispatch). DSM can provide each of these regulation services, with online motors providing inertial response (the demand-side has inertia that is intrinsic and not remunerated), and primary and secondary response provision enabled by advanced fast-acting and automatic demand response and energy storage [35]. The Electric Reliability Council of Texas uses demand response to provide frequency services; in particular, it uses under-frequency relays for load shedding as a mechanism for DR participation in the ancillary service market [36]. ➢ **Use in South Africa:** Eskom's Instantaneous DR program had certified 1,014 MW of demand that can be called upon to provide DR fast frequency response, a minimum of 10 MW of load reduction capability is required to participate and must be able to be called upon within 6-seconds of notification. This demand response results from large industrial customers, who are scheduled a day ahead and receive payment for the capacity on standby. These loads respond within six seconds of network frequency exceeding a predetermined threshold. **Voltage control (demand-side watt and VAR control):** Demand-side resources—in particular those that are inverter-based resources—can provide voltage control through either active (watt) or reactive power (VAR) control. These functions have been specified in standards (e.g., IEEE 1547-2018) and can be adopted in utility interconnection standards. Using demand-side resources to provide watt and VAR control to regulate voltage provides grid-edge support which can help alleviate power quality challenges related to distributed energy resource (DER) grid integration and can increase DER hosting capacity. Both Rule 21 in California and Rule 14H in Hawaii, by respective state public utility commissions, have mandated the use of volt-VAR and volt-watt functions for behind-the-meter solar photovoltaic inverters [31], [38]. ➢ **Use in South Africa:** Unknown whether any municipalities in South Africa are using these functions yet. **Voltage control (conservation voltage reduction):** Conservation voltage reduction (CVR) and volt-VAR optimization is a voltage strategy to both flatten and lower the voltage profile on the distribution network, while keeping voltages within defined character of service bounds (i.e., in South Africa, service voltage is to be kept within ±10%) [39]. This strategy helps lower energy consumption because of the voltage responsiveness of the load. Traditionally, the majority of CVR gains were from incandescent and halogen lighting (resistive lighting exhibits a relationship closer to V^2/R, where power is proportional to the square of voltage). As more loads have power electronic interfaces (i.e., either inverters or switch-mode power-supplies), the benefits of CVR have decreased but overall energy reductions can still be achieved. CVR has been shown to deliver energy savings on the order of 0.3–3%, but are dependent on the load characteristics (resistive loads offer

DSM Schemes and Use/Potential in South Africa				
				better savings) ; existing voltages are already operated on the high side of the character of service bounds [40]. ➢ **Use in South Africa:** Unknown whether municipalities in South Africa are using CVR.
			Capacity Energy/ Voluntary	**Direct load control and interruptible demand:** This form of DSM is directly controllable by the system operator/control center. This will interrupt demand to end-users and control is enabled by communications. The control can be coupled with visibility of response, i.e., some form of metering. Historically, this type of control has been enabled by ripple control schemes, but more recently includes more advanced communication systems and aggregators. Interruptible demand can be arranged by agreed-on customer energy curtailment levels (or duration and number of interruptions) incorporated into rate discount, bill credits, or other agreements to reduce demand during system contingencies. Depending on the agreement the customer can be interrupted unannounced or may require advanced notice. The agreements can include an agreed season, number, hours, and duration of interruptions. There are many variations on direct load control and interruptible demand. One example is Hydro-Quebec's Line-Voltage Communicating Thermostat (LVCT) pilot for baseboard heaters, where LVCTs communicated through customers home Wi-Fi to a central Cloud platform where a trial ran set-point modulations to pre-heat homes before peak periods. Another example is Vector Energy, based in Auckland, New Zealand, who ran a hot water load management trial for the residential and commercial sector (frequently the largest source of building load). This program revamped a ripple control system to use a radio device commonly used for street lighting applications. This node was connected to the participant's smart meter and then connected to the relay that used to receive the ripple signal, providing more flexibility and control [41]. ➢ **Use in South Africa:** In South Africa 400,000 homes are enrolled in hot water heater ripple control (approximately 200 MW). While each hot water heater can contribute 3 kW of demand, not all hot water heaters are on when the signal is received. Ripple control therefore results in 0.5-0.6 kW of reduction in demand per hot water heater. **Load shedding:** Load shedding is a last resort for system operators and can take multiple forms. Load shedding can be scheduled in advance in the case of known shortages of capacity, it can be triggered by under-frequency load shedding relays typically placed at key load serving infrastructure (e.g., distribution substations). Under-frequency load shedding programs must coordinate the amount and location of load to be shed and activate frequency thresholds to avoid exacerbating contingency events. ➢ **Use in South Africa:** Eskom has developed an efficient and highly impactful load shedding program, with eight stages of load shedding, each of 1,000 MW of demand. As discussed in section 1.1, load shedding is regularly used to reduce demand when supply is challenged to meet it.

DSM Schemes and Use/Potential in South Africa			
	Non-Dispatchable	Time-sensitive pricing & Information/Alert Based Programs &	**Time-sensitive and Smart Pricing:** Time-sensitive pricing can take many forms, from traditional time-of use, critical peak pricing, demand-charges, peak time rebates, and other multi-tiered tariff structures (e.g., electric vehicle tariffs with an additional night-time off-peak period). These can also be more dynamic to include day-ahead and real time pricing, although these structures subject customers to more volatility and risk associated with the wholesale market. These pricing structures do require interval billing capable meters (i.e., advanced metering infrastructure and some automatic meter reading devices). Advanced tariff structures have included demand-charges, which charge customer for peak demand events, that are currently used by Arizona Public Service, a utility based in Phoenix [33]. Other advances in tariff structures have included those in Hawaii, where very high levels of rooftop solar exports have results in smart export programs to try motivate increased customer self-consumption of solar [43]. ➢ **Use in South Africa:** Eskom distribution purchases from its single-buyer power market and sells on to customers, including all transmission network and ancillary service charges. For municipals, Eskom charges time-of-use pricing schemes through its Municflex and Municrate tariff schemes. Time-sensitive pricing is in its infancy in terms of the roll-out to residential and commercial customers as the AMR/AMI roll-out is still ongoing. Eskom offers multiple time-sensitive pricing tariff structures, including critical peak pricing to non-municipal customers (e.g., large industrial and agricultural customers) on their Megaflex, Megaflex Gen, Miniflex, Ruraflex and Ruraflex Gen tariffs who have half-hourly interval metering enabled [44]. Eskom is working towards tariff restructuring to modernize the system to reflect a changing supply and demand environment and help prepare for future unbundling of the utility's business entities. **Information/Alert Based Programs:** Customer education is key to obtaining any form of non-dispatchable demand response. Time-sensitive and smart pricing often needs to be coupled with extensive customer education programs, and pilot programs have shown that information media enhanced response to smart pricing schemes [45]. Information based programs include online education, mobile applications, emails, information flyers, and mobile alerts. Home energy reports with customers' bills have become a frequently used feature for utilities after an AMR/AMI roll-out. These programs are common for utilities with AMI, a more recent example of a home energy report pilot was implemented in Delhi by BSES Rajdhani Power Limited (BRPL) with a control group (i.e., that do not receive the update, with both online and mobile-based analytics) and those that do. Other information-based systems include the California Independent System Operator (CAISO) Flex Alert program to notify customers to voluntarily conserve electricity during periods of system stress. The Flex Alert program comes with recommendations to raise thermostats (used for cooling), avoid using major appliances, and turn off unnecessary lights. In an emergency scenario in September 2022, California recently used the state Governor's Office of Emergency Services (Cal OES) to issue a cell phone alert during an extreme load event immediately before having to resort to load shedding, a subsequent 2,100 MW reduction was observed (approximately 4% of that day's peak demand) [46]. ➢ **Use in South Africa:** Eskom's Power Alert system asks for voluntary requests for residents to reduce energy use and is broadcasted daily over four different television stations. These broadcasts include system information via a color status that indicates the power system condition, i.e., stable, strained, severe, or critical.

Distributed Generation/DER	**Solar Photovoltaic (Rooftop):** Rooftop solar has multiple benefits for utilities; decreasing grid imports, reduced CO_2 emissions, and potential peak demand reductions. Adoption of rooftop solar has been driven by a combination of falling solar prices evolving tariff and rate structures offering customer remuneration for grid exports (e.g., net-energy metering, feed-in tariffs), and a desire for renewable self-generation for energy independence and sustainability. Net energy metering (NEM) has been adopted and mandated by many utilities and public utility commissions in the U.S., and now, with solar targets having been met or exceeded by NEM programs, 'NEM 2.0' is being explored with feed-in-tariffs, demand-charges, and other tariff structures [47]. ➢ **Use in South Africa:** Currently, the majority of customer meters in South Africa are not enabled for solar exports and the country does not have a large net-energy-metering program, either at the federal, state, or municipal/metropolitan level. There are programs for DER generation at municipalities and metropolitans. The city of Cape Town has a Small-Scale Embedded Generation (SSEG) program for customers to install rooftop solar [48]. If a customer wishes to also export solar the municipality will install a bi-directional meter for applying feed-in-tariffs, but customer will pay for the meter [49]. Other municipalities are incorporating SSEG into their network. The number of municipalities participating on SSEG has increased from 10 in 2016 to 56 in 2020 [50]. Eskom has a both a Wheeling program (i.e., remote generation can be used to offset local consumption), and a net billing program for its customers [51]. **Solar Photovoltaic (Community & Solar Farms):** Larger-scale solar photovoltaic that is more distribution centric can take the form of independent power producers developing solar farms and having power purchase agreements with the utilities to which they connect, or in the form of community solar. Community solar programs allow customers to lease or buy part of an offsite shared solar farm and receive benefits from their participation. Both of these forms of solar have the same impact with reducing the power generation needed from the bulk system during production hours. ➢ **Use in South Africa:** Community organizations can work with developers to build community owned solar as part of the REIPPPP (Renewable Energy Independent Power Producers Procurement Programme), e.g., ownership through community trusts [52]. A challenge of community solar in the REIPPPP is developing community engagement, education, and achieving equity in the ownership model, either through working with non-profit or for-profit developers. Community solar is being viewed as a means of reducing reliance on expensive electricity from the bulk system, and increasing grid-edge resilience from communities, with programs by larger metros such as Cape Town to smaller community projects (e.g., Matsila Community Development Farm) [17], [53]. REIPPP developments are tasked to contribute towards local community development, enterprise and socioeconomic development, local ownership, and job creation, although local engagement can be unequal and challenging. **Electrochemical Storage:** Energy storage can provide system services of energy arbitrage, energy shifting, peak shaving, solar self-consumption, and backup power if enabled to form a microgrid. Lithium-ion has been the forerunner for electrochemical stationary energy storage as lithium-ion energy storage prices have decreased 73% from 2010 to 2016 [54]. Similar to solar, energy storage can be sited behind-the-meter or can be used in front-of-meter applications. Battery storage has been adopted for behind-the-meter applications for customers on price-plans that motivate solar self-consumption, energy shifting, and for demand-charge reduction. Customers are also adopting energy storage for backup power applications. Xcel Energy, with service territories across the U.S., is an example of a utility offering customers an incentive program to install storage for utility use to study their impacts for reducing peak load. Utility tariff structures (e.g., demand charges and zero export tariffs) are motivating customers to purchase energy storage for rate-based use-cases for peak shaving and solar self-consumption. ➢ **Use in South Africa:** DMRE is required to procure 513 MW of energy storage, with a minimum of 4 hours of storage and a minimum size of 77 MW, which would exclude most smaller community and customer applications. The South Africa Local Government Association is assisting municipals with understanding energy storage and its use-cases.

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Municipals, such as Capetown, are planning to invest in utility scale battery storage systems as a form of grid-edge resiliency and capacity. Municipals could use energy storage as a means of arbitrage, peak shaving, network capacity deferrals, or as reserve capacity in constrained load shedding events.

Other DERs and Distributed Generation: Other forms of distributed energy resources (DERs) include electric vehicles, fuel cells and electrolyzers, combined heat and power, micro-wind, diesel generators, and Stirling engines. These other DERs have opportunities to be used in demand-side management programs (e.g., EV's and smart charging, fuel cells and electrolyzers for hydrogen-to-grid applications, combined heat and power efficiency gains, etc.).

- **Use in South Africa:** South Africa has limited adoption of EV's or hydrogen systems. There are some commercial and industrial applications using combined heat and power.

Energy Efficiency

Energy Efficient Lighting: Energy efficient lighting has come from major advances in compact fluorescent lamps (CFL's) and semiconductors with light-emitting diodes (LED's). These have significantly reduced lighting consumption from traditional incandescent and halogen lighting that have low lumens per watt efficiency. CFLs and LEDs can reduce power ratings by up to a factor of four for the same lighting output. Energy efficient lighting has been adopted due to enthusiasm from customers for their lower running costs and longer bulb operational lifetimes. Additionally, countries have motivated efficient lighting adoption through a combination of directives banning the sale of traditional incandescent and halogen lighting, incentives for customers, and roll-out programs. Street lighting provides a major opportunity to achieve efficient lighting. An example is ACTO Energy, based in Alberta Canada, who replaced their high-pressure sodium (HPS) street lighting with LED bulbs and installed an intelligent street lighting system that provided lighting on demand (i.e., dimming lights when the presence of vehicles, cyclists and pedestrians are not detected). LED street lighting over HPS provide benefits in terms of; reduced energy consumption, higher lighting quality, longevity and reduced maintenance, less light pollution, and faster transition to full light output [41].

- **Use in South Africa:** For South Africa the CFL rollouts of the national energy efficiency programs were impactful, resulting in a demand reduction of 1,950 MW. Studies indicate that there is still substantial use of halogen bulbs and CFLs, but few LEDs [7].

Solar Thermal: Behind-the-meter solar thermal can be used for multiple end-use applications to reduce electricity consumption. Solar thermal can be used for space heating, but more traditionally, for hot water. Solar thermal can displace electricity demand and has the same grid impact as other energy efficiency measures. There are many forms of solar thermal for space and water heating, these include; unglazed, solar pool, transpired, flat-plate, evacuated tube, and concentrating solar collectors [55]. In cold weather environments an active closed-loop system with antifreeze, passive or active drainback systems can be used to prevent freezing conditions damaging the system.

- **Use in South Africa:** A solar water heater (SWH) rebate program in South Africa resulted in over 400,000 SWH installed between 2008 and 2018 [56]. The program initially had a target of 1.75 million installations, and so far, installations have been prioritized in areas of low electricity consumption [57].

Energy Management Systems: Energy management systems (EMS) provide enhanced control to provide energy efficiency (e.g., more closely meeting occupancy schedules, more closely matching thermostat set points with user needs, etc.), and moving load from on to off-peak hours to help reduce peak demand costs (e.g., schedulable loads and timers). EMS can provide customers with energy reductions but can also help shift loads under time-sensitive pricing tariffs. An EMS can also enhance occupant comfort by providing enhanced control, more closely matching the operation of heating and cooling systems with occupant needs [58] .

- **Use in South Africa:** Energy management systems for consumer load shifting and peak shaving do not have a customer motivation due to a lack of AMR/AMI interval billing and customer time-of-use tariffs. EMS could be rolled out by providing incentives for their installation, but customers could not be directly rewarded for energy shifting. EMS can also provide efficiency by providing control over time-of-use of heating and cooling systems, and more closely matching energy use with occupancy.

Heat Pumps: Heat pumps represent a major opportunity to electrify fossil-fuel fired heating systems (e.g., gas, oil, or diesel space and water heating), and to improve overall energy efficiency. When transitioning from a non-electric heating solution, heat pumps do result in a major new electrical load on the system. Reversible heat pumps can be used for heating and cooling purposes, and in a climate where heat pumps are primarily introduced for heating, cooling load may be introduced where formerly there was no load. Heat pumps can be used in both space and water heating applications.

- **Use in South Africa:** South Africa has had roll-out programs of heat pump water heaters to replace traditional electric hot water heater. Hot water heaters typically have a load of around 3 kW while heat pumps, at full load, are typically only 1 kW. Heat pump water

DSM Schemes and Use/Potential in South Africa	
	heaters could help reduce the water heater load while also providing customer energy efficiency. **Building Retrofits and Efficiency:** Achieving energy efficiency through building improvements can both improve occupant standard of living and reduce energy consumption. Measures include increased insulation in walls and roofs, reducing infiltration and air tightness, and double and triple-glazed windows [59]. These can be achieved by building codes and standards for new builds, motivating improvements in efficiency by building efficiency ratings, and programs and incentives for retrofits. Building retrofits are a vital part of achieving energy reductions, as many estimates have shown that the majority of today's building stock (approximately 80% for estimates for the UK [60]) will still be in existence in 2050. ➢ **Use in South Africa:** Municipals and metros have developed retrofitting schemes; Cape Town has programs that focused on retrofitting low-income communities susceptible to health impacts from moisture levels and cold temperatures. These saw benefits, both in reducing energy costs, and improving health impacts such as lowering the incidence of tuberculosis. Barriers to building retrofits and built environment energy efficiency have been identified as households with low income, high upfront investment costs, occupant resistance to retrofits, and low consumer enthusiasm [61],[62].

2 Identifying Untapped Potential and Applicable Demand-Side Management Schemes for Under-utilized Load Sectors

South Africa has myriad of different DSM schemes that have been implemented, including the NEES and EEDSM/ IDM programs discussed in section 1.2.4. This next analysis seeks to understand the different end-uses (e.g., motors, HVAC, and water heating, etc.) in each load sector (i.e., industrial, residential, commercial, mining.) in terms of their potential for flexibility and contribution to peak demand. The potential of untapped dispatchable and non-dispatchable DSM programs is then discussed with respect to their peak load reduction potential and readiness level.

2.1 Sector End-Uses, Peak Demand, and Current Demand-Side Management Schemes

In 2021, the industrial sector accounted for the largest volume of total electrical energy sales, followed by the residential sector. However, it was estimated that the residential sector accounted for at least the same portion of peak demand consumption (17%); see Figure 10. The industrial sector had a peak-to-average ratio of 0.93 (i.e., industrial demand stays relatively flat during the day) as opposed to the residential sector with a peak-to-average ratio of 2.0 (i.e., residential peak load is double its average consumption levels). From estimated data from Eskom, most load sectors have a relatively flat demand profile, see Table 5.

The industrial load sector is responsible for the majority of dispatchable DR program capacity; see Table 6. Eskom has 346 MW of supplemental DR, 1,014 MW of instantaneous DR and 62 MW of critical peak day DR—with the majority of each of these programs coming from the industrial load sector. The residential sector participates in a limited set of voluntary DSM programs. Non-dispatchable demand response from the residential sector is achieved through Eskom Power Alert programs, which are alerted through TV and mobile applications. All load sectors involuntarily participate in load shedding programs. Ripple control programs for water heaters have approximately 400,000 customers enrolled from the residential sector, with dispatching resulting in approximately 200 MW of reductions.

To understand the potential flexibility and opportunity for DSM schemes, the end-use for each load sector must be clearly understood. The time-series end-use for each load sector, based on estimated Eskom data and scaled for 2021 demand, is provided in Figure 11. This provides insight into which end-uses increase their demand during peak hours, which have high peak-to-average ratios (which can suggest opportunities for load shifting), and the overall contribution of each load sector and end-use.

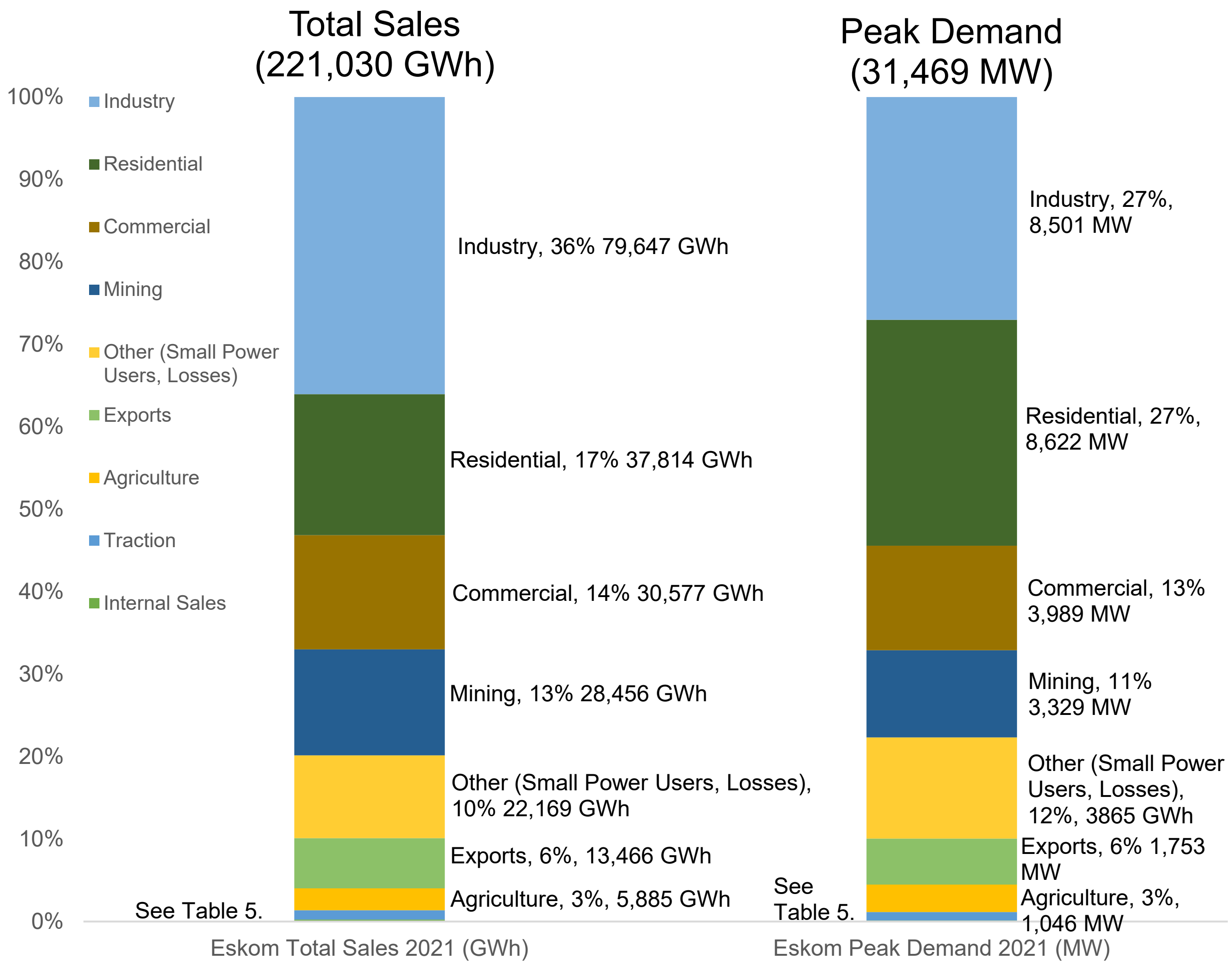

Figure 10. Eskom total electricity sales and peak demand by load sector for 2021. Internal sales and traction account for less than 1.3% of sales and peak demand, further details are provided in Table 5.

Table 5. Eskom total electricity sales and peak demand by load sector for 2021. Additional load metrics are provided. The highest sector for each metric is highlighted in green. Note that the category "Other (Small Power Users, Losses)" are not sales, and the majority of this category are likely system losses.

Sector:	Eskom Total Sales 2021 (GWh)	Percent of Total Sales 2021 (%)	Eskom Peak Demand 2021 (MW)	Percentage of Peak Demand (%)	Average Demand (MW)	Peak to Average Ratio
Internal Sales	521	0.2	38	0.1	59	0.64
Traction	2,495	1.1	326	1.0	285	1.14
Agriculture	5,885	2.7	1,046	3.3	672	1.56
Exports	13,466	6.1	1,753	5.6	1,537	1.14
Other (Small Power Users, Losses)	22,169	10.0	3,865	12.3	2,531	1.53
Mining	28,456	12.9	3,329	10.6	3,248	1.02
Commercial	30,577	13.8	3,989	12.7	3,491	1.14
Residential	37,814	17.1	8,622	27.4	4,317	2.00
Industry	79,647	36.0	8,501	27.0	9,092	0.93

Table 6. Eskom certified capacity in different DSM programs and load sectors that support each program.

Program	MW Certified (Eskom)	Sectors
Supplemental DR	364	Industrial
Instantaneous DR	1,014	Industrial
Critical Peak Day	62	Industrial
Water Heater Ripple Control	200 MW	Residential
Power Alert	Approx. 300	All sectors but aimed at residential
Load Shedding	1,000 MW increments for each stage from Stage 1to Stage 8	All sectors

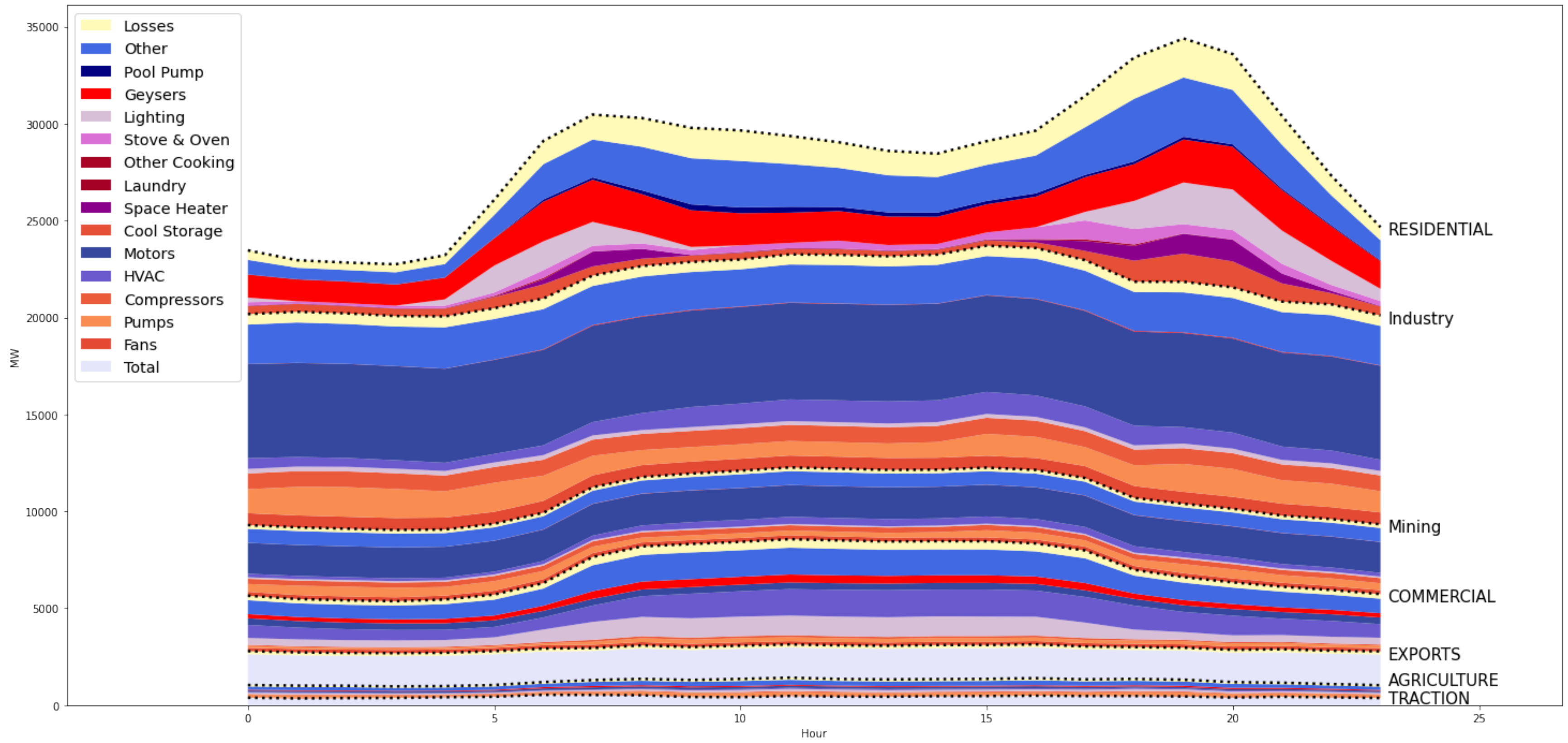

Figure 11. Load profile of the Eskom system during the peak demand day, separated by sector and end-use. End-use data are from 2007 and scaled to the 2021 peak demand (note that 'Geysers' are electric water heaters).

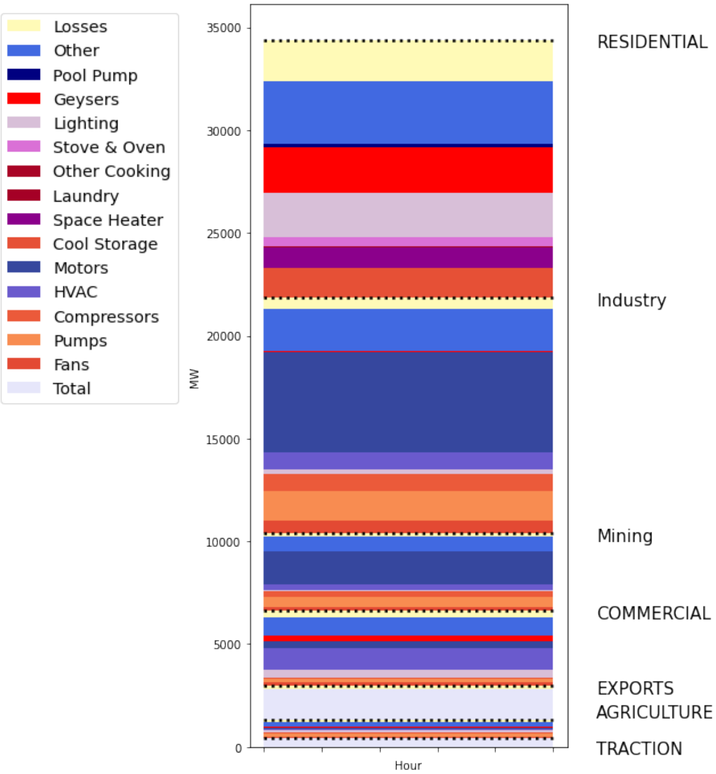

Figure 12. Eskom system peak demand, separated by sector and end-use. End-use data is from 2007 and scaled to the 2021 peak demand.

2.2 Demand-Side Management Technologies and Load Impact

Specific, untapped end-use technologies are discussed in Section 2.2.1, dispatchable DSM schemes are discussed in 2.2.2, and non-dispatchable DSM schemes are discussed in 2.2.3. In characterizing end-use technologies and DSM programs that would most benefit the South Africa power system, assumptions regarding the impact on the system peak demand were made based on 2007 M&V data scaled to the 2021 peak load, provided by Eskom [9]. New disaggregation studies could be conducted to obtain more accurate load profiles to refine this analysis. Categories for technology maturity were identified for each opportunity using the five stages of the technology adoption cycle described in the *DSPx Grid Modernization Vol. II* [63]. These are described briefly in Table 7.

Table 7. DSPx grid modernization technology adoption stages.

Pre-operational Under test/evaluation	R&D (includes pilots)
	Operational demonstrations
Operational Proven and in production use: • Greater than three operational production implementations • Market choice (two or more vendors)	Early commercial deployment
	Mature deployment
	Obsolete & replace

2.2.1 End-Use Opportunities

Opportunities for peak demand reduction were identified in end-uses in the residential and commercial sectors that make larger contributions to the peak demand. These sectors are examined because there is already a large volume of industrial load participating in Eskom DSM schemes and industrial load consumption has been declining. Furthermore, the residential and commercial sectors do not have large-scale participation in DSM programs and have a high peak coincidence. Potential end-uses for these sectors include lighting (2,070 MW), water heating (2,300 MW), and space heating (2,150 MW) are presented in Table 8. Consumption because of space heating and water heating can be reduced with the introduction of more energy-efficient technologies including alternatives to electric space heaters (portable electric plug-in space heaters are predominately used) and hot water heaters or improved building airtightness and insulation. Electric water heater load can be reduced with the deployment of solar water heaters. SWH typically needs to be supplemented with auxiliary heating elements, which would reduce this impact on the load reduction. The use of auxiliary heating during cold Winter days may be a concern for seasonal peak load alleviation. Heat pump water heaters could provide load reductions by up to a third of the load consumed by traditional hot water heaters, because of increased efficiencies. Similarly, heat pumps for space heating could reduce the load consumed by electric space heaters—although by how much would depend on local environmental factors. Heat pumps can use as little as 35% of the energy required by electric space heaters in temperate climates but this can increase to 50% in colder climates. Finally, replacing CFLs with LEDs represents the smallest maximum potential peak demand reduction (just under 1,000 MW) but may have the lowest barrier to implementation and provide lasting reductions in energy consumption.

2.2.2 Dispatchable Demand-Side Management Opportunities

Utility controllable or dispatchable DSM can be implemented through technologies described in Table 9, which rely on autonomous or centralized communications for control. These technologies fall into two categories: demand response and distributed energy storage. It is feasible to implement the former through several methods. An expansion of the ripple control program to shut off commercial and residential hot water heaters could reduce the peak demand by up to the entire hot water heater peak load, or 2,300 MW. Other technologies, of varying maturation stages, can target multiple end-uses such as hot water heaters, pool pumps, or refrigeration, resulting in a greater peak demand reduction than ripple control for hot water heater loads alone at approximately 3,600 MW. Manipulating the demand for refrigerators requires active temperature monitoring and has been historically been better suited to large commercial and industrial refrigeration given their larger thermal mass. These facilities can remain cool for long periods without compressors running. Residential has lower cost potential because of the volume of communications and control infrastructure needed to obtain the same level of reduction from larger commercial and industrial refrigeration. Dispatchable DSM can be achieved via smart circuit breakers, control center communication with customer home energy management systems connected to smart loads, or control center communication with AMI and flexible loads. Common challenges of these technologies include lower maturity stages (relative to ripple control) and a substantial need for new infrastructure and operations.

The potential impact of distributed energy storage on peak demand is difficult to quantify without understanding the potential capacity that could be leveraged. Solutions that avoid modulating or reducing end-use consumption include energy storage. Energy storage can be used to reduce grid imports without affecting customer comfort, and this reduction will be additive to any concurrent DSM investment made—e.g., ripple control plus energy storge do not leverage the same resources, whereas ripple control plus SWH target the same end-use. Energy storage is being deployed through South Africa's REIPPPP, introduced in 2011 enabling capacity procurements from independent power producers. Because of the energy crisis declared in Spring 2023, the previous licensing threshold for distributed energy generation of 1 MW was increased to 100 MW. This has allowed municipals to procure increased DER capacity independently.

2.2.3 Non-dispatchable Demand-Side Management Opportunities

Non-dispatchable technologies cannot be directly controlled to meet immediate system needs, but many of the non-dispatchable technologies listed in Table 9 have the advantage of low barriers to implementation, i.e., mature technologies with little additional infrastructure required. These include efforts to replace appliances for more energy efficient models, or load-shifting alternatives such as those listed in Table 9. Mass rollouts of such appliances can have an immediate impact, while subsidies, incentive-based programs, and the dissemination of information via product labeling will require consumer engagement and may be adopted more slowly as new purchases gradually replace existing appliance stocks.

Unlike efforts to introduce more energy-efficient or load-shifting appliances, AMI requires a significant investment in new assets but has the potential advantage of enabling many of the dispatchable technologies described previously. For instance, AMI can enable the interval pricing required to motivate charging storage heaters at night after peak hours, and AMI is prerequisite to smart-meter-based dispatch signals from centralized control. Historically, AMI and time-of-use (TOU) pricing reduces peak load by 0.5–2%, which would equate to 60–250 MW from the commercial and residential sectors of South Africa. AMI, however, has additional benefits of improving insight into situational awareness of the distribution system, such as being able to evaluate losses. Losses in the residential and commercial sectors account for 2,200 MW of the peak demand; AMI rollout could provide an opportunity to reduce this loss or characterize root causes. The main benefits of AMI typically come from reducing labor costs for manual meter reading and general efficiencies related to billing.

Non-dispatchable DSM through communication programs is also examined. Wireless emergency alerts pushed to mobile phones can be used to issue voluntary requests for customers to decrease energy use when the system is under stress. The United States has implemented a nationwide program for emergency alerts [64], [65] that is used to issue warnings to mobile phones for emergencies including natural disasters, missing persons, and shelter-in-place alerts. More recently, in California and New York, the system has been used to issue power system alerts calling for a reduction in electricity consumption. This emergency alert program is led by the U.S. Department of Homeland Security and represents a multi-agency effort that has matured since its inception in 2012. For its use in California and New York [66] for the power system, the system achieved peak demand reductions of 1.5–4%. Such a system has many benefits that extend beyond reliable electricity service, but it requires leveraging services from wireless providers, a secure gateway to handle and push alerts, and new operations including regular testing. Customers will need to have purchased mobile devices that are programmed to receive emergency alerts. The impact of such alerts may depend on the frequency of use because of customer habituation; it is suggested that the alerts be used rarely and may not be suitable for frequent alerting and or requests for customer response.

Table 8. Non-dispatchable End-use and Energy Efficiency Technologies to Reduce or Shift Load.

Technology	Maximum Peak Aggregate Potential Reduction (MW)	Estimated Readiness Level
Heat Pump (HP) for Space Heating	**Residential** 400-525 MW **Commercial** 673-875 MW **Assumption:** It is estimated that heat pumps can result in a load reduction of 50–65% compared to electric space heaters [67]. Assuming a maximum potential of replacing the entire space heating stock with heat pumps (808 MW for residential, 1,346 MW for commercial), the maximum peak aggregate reduction would be 400-525 MW for residential and 673-875 MW for commercial. Changes in usage of heat are not considered in this estimation, but such changes could be attributed to the rebound effect in deploying more efficient technologies. Heat pumps may be used more frequently because of their lower cost of operation once deployed, which may increase the total energy consumption–reducing the potential reduction estimation here. Barriers to heat pump deployment include the large upfront capital costs for customers. Most houses in South Africa would need to install a heat distribution system, e.g., ducted air, underfloor radiating, or water/oil-filled radiators. Heat pumps are a mature technology with commercial systems available in the marketplace. The high upfront capital costs, and relatively short heating season duration in South Africa, are barriers for their uptake.	Mature Deployment Timeframe for rollout: 1–5 years
Heat Pump Water Heater (HPWH)	**Residential** 1,343 MW **Commercial** 200 MW **Assumption:** Total existing hot water heater load for the residential and commercial sector during peak hours are 2,005 MW and 299 MW, respectively. Electric water heater load represents the largest peak load of the residential sector and has a high peak-to-average ratio. Replacing electric water heaters with heat pump water heaters would represent significant savings for residential customers in terms of electricity consumption. We assume that a heat pump would consume roughly one third of the electricity consumption that an all-electric water heater would. Replacing the entire population of electric water heaters with heat pump water heaters would give a maximum peak load reduction of two-thirds of the current hot water heater load for the residential and commercial sector. Barriers to deployment include the large upfront capital cost of installing a heat pump water heater; however, these are much more likely to break even given year-round hot water use, compared to the short heating season for heat pumps for space heating.	Mature Deployment Timeframe for rollout: 1–5 years
Solar Water Heater	**Residential** 2,005 MW	Mature Deployment

Technology	Maximum Peak Aggregate Potential Reduction (MW)	Estimated Readiness Level
	Commercial 299 MW **Assumption:** SWH have already been deployed in South Africa as an alternative to traditional electric resistive hot water heaters [68]. SWHs can significantly reduce electricity consumption, and for seasons/times-of-day with sufficient solar resource can be the sole source of hot water. However, SWHs have an auxiliary electric heater to supplement solar thermal gains during cold weather days. Estimates have shown that solar water heaters reduce household electricity consumption from between 40 and 60%. The challenge of using solar water heaters are the high upfront capital costs of installing the system. However, once installed they will reduce customer electricity consumption and provide a resilient form of heating in the event of load shedding. The peak reduction of solar water heaters is challenging to quantify, particularly because on cold days that drive the system peak it is more likely to use the auxiliary heating element.	Timeframe for rollout: 1–5 years
Energy Efficient Lighting (LEDs)	**Residential** 996 MW **Assumption:** LEDs can reduce electricity consumption to 35% of that of CFLs, and end-use reports for household surveys indicate that most households are using CFLs [69]. Although more households may have incorporated CFLs since the 2020 survey conducted in Reference [69], a rollout of LED bulbs could mirror the 2004 rollout of CFLs, which had a potential reduction of 1,950 MW [22].	Mature Deployment Timeframe for rollout: 1–5 years
Storage heaters	**Residential** 808 MW **Commercial** 1,346 MW **Assumption:** Storage heaters use electric resistive heating to store thermal energy in ceramic bricks, allowing daytime thermal energy to be stored during the nighttime, shifting the daytime electric heating load. Storage heaters have been deployed in Europe since the 1970's to reduce peak electric heating load and reduce reliance on fossil-fuel-fired heating. They require a financial incentive to motivate charging these units during nighttime. This has typically been achieved with a two-tariff meter–a meter capable of interval billing–enabling two-tariff billing (peak and off-peak). For the entire residential sector and commercial sector to switch to storage heaters represents a maximum peak load reduction of 808 MW and 1,346 MW respectively. Barriers to deployment include upfront capital cost (although these may be lower than those for heat pumps) and the requirement for a two-tariff or interval billing capable meter. Storage heaters are an inefficient heating solution, and will increase the overall electric heating consumption, but can entirely shift heating demand away from peak hours. Heat pumps far outperform storage heaters in terms of efficiency; however, given the short heating season, the need to move consumption away from	Mature Deployment Timeframe for rollout: 1–5 years

Technology	Maximum Peak Aggregate Potential Reduction (MW)	Estimated Readiness Level
	peak hours, and the lower upfront capital costs, storage heaters are a solution that may offer advantages.	
Energy efficient air tightness/ insulation	The peak reduction for energy efficiency measures is difficult to quantify given the large range of measures it can entail. Overall, it will equate to some percentage reduction of space heating load. Air-sealing measures to reduce air changes from leaks is a cost-effective way to cut heating and cooling costs, improve durability, increase comfort, and create a healthier indoor environment. Properly insulated and designed homes would have benefits of providing warmth in the winter and cooling in the summer (e.g., using awnings). Air sealing and insulation are mature technologies that can provide energy and corresponding bill savings. The barriers to deployment are the high upfront costs, which could be tackled through subsidized home-improvement and incentivize programs. Low-income households are those that can least afford energy efficiency retrofits and typically have the highest energy costs per square foot. Inefficient buildings typical of low-income households lead to energy poverty because these customers pay greater percentages of their disposable income on heating. Creating incentive schemes that allow low-income households to overcome high upfront capital costs of energy efficiency programs (e.g., through energy-as-a-service or pay-as-you-save models) can help incentive programs to reach those who need assistance most, rather than providing financial assistance to affluent customers who may not need it.	Mature Deployment Timeframe for rollout: 1–5 years

Table 9. Dispatchable Demand Response Technologies and Corresponding Challenges and Opportunities.

Technology	Maximum Peak Aggregate Potential Reduction (MW)	Readiness Level	Communications Required	Equity Impact	New Assets and Infrastructure Required	New Operations Required
AMI Smart Meter Communication to Flexible Loads	**Commercial and Residential hot water heaters:** 2,304 MW **Residential Pool Pumps:** 146 MW **Refrigeration:** 1,145 MW **Assumption:** There are multiple end-uses that have	R&D Timeframe for rollout: > 5 years	Ethernet/Wi-Fi/RF/Cell HAN, LAN, NAN/FAN	If customers must purchase and install participating devices such as smart thermostats that can communicate with a utility operation center, benefits may be limited to customers who can afford such smart loads. Dispatches could be issued with both system performance and	Smart meters, compatible smart devices, communications, and control system (e.g., cloud-based).	Meter Data Management System control center communication to dispatch load response
Smart Circuit Breakers on Household Circuits		Operational demonstrations Timeframe for rollout: 1–5 years	Wi-Fi HAN, LAN, NAN/FAN		Smart circuit breakers (some are equipped with metering), communications, and control systems (e.g., cloud-based)	Centralized dispatch center with communications to remote smart circuit breakers.

Technology	Maximum Peak Aggregate Potential Reduction (MW)	Readiness Level	Communications Required	Equity Impact	New Assets and Infrastructure Required	New Operations Required
Wi-Fi or Zigbee Communications with Smart Loads (Home Energy Management with Utility Communications)	varying degrees of flexibility (hot water heater, refrigeration, laundry, pool pumps). Enabling communications with these devices allows for potential interruption of consumption during peak hours. This could be achieved through smart meter home area networks (HANs) with flexible loads, smart circuit breakers on household circuits on the main load panel, or home energy management controllers with communications.	Operational demonstrations Timeframe for rollout: > 5 years	Wi-Fi HAN, LAN, NAN/FAN	customer equity considerations. Pay-as-you-save and energy-as-a-service models could help provide a more equitable rollout for these solutions.	In-home smart loads, communications	Meter Data Management System control center communication to dispatch load response or communications with customer home energy management systems.
Next-Generation Ripple Control	**Commercial and Residential Hot Water Heaters:** 2,304 MW **Assumption:** Eskom currently has an ongoing ripple control scheme with approximately 400,000 homes enrolled that achieves reductions of up to 200 MW. Expanding this to the full population could capture up to 2,304 MW of potential peak load reduction. Currently technology could be used or modernized to use radio signals to a smart meter and connected to a relay. More advanced line voltage communications, utilizing customer Wi-Fi, or other HAN set-ups could also be used.	Mature deployment Timeframe for rollout: 1–5 years	Expanding current program: power-line communication Modernizing the program: smart meters with Wi-Fi, HAN, radio communications, or combining with power-line communication	None identified.	Expansion of previous ripple control implementation	Expansion of current Eskom program or addition of new communications infrastructure. Comeback load will need to be considered and managed as before.

Technology	Maximum Peak Aggregate Potential Reduction (MW)	Readiness Level	Communications Required	Equity Impact	New Assets and Infrastructure Required	New Operations Required
Distributed Energy Storage	Residential and Commercial Ownership and/or Municipal Ownership Dependent **Assumption:** Distributed energy storage can be customer owned or could be owned and operated by the municipal or independent owner/operator. Currently, there is little financial motivation for customers to own behind-the-meter energy storage. Municipalities, such as Cape Town, are starting to invest in energy storage. South Africa's REIPPP has enabled municipals to procure DER capacity up to 100 MW independently because of changes in licensing procurement thresholds.	Mature deployment Timeframe for rollout: 1–5 years	None	The high capital cost for storage is a barrier for customer adoption. High-income customers who can afford storage can receive the financial benefit of potentially lowering levelized cost of energy (LCOE) while fixed charges are leveraged on fewer customers. Municipality owned storage can pass financial benefits down to all customers.	To motivate energy arbitrage, self-consumption, and energy shifting, residential and commercial customers will require storage tariffs and interval bidirectional metering.	Distributed storage requires new metering and tariff structures and/or DER storage programs with measurement and verification in addition to new interconnection standards.

Table 10. Non-dispatchable Demand Response Technologies, Customer Demand-Side Management and Energy Efficiency Programs, and Corresponding Challenges and Opportunities.

Technology/ Program	Maximum Peak Aggregate Potential Reduction (MW)	Readiness Level	Communications Required	Equity Impact	New Assets and Infrastructure Required	New Operations Required
AMI + Smart Tariffs Time-of-Use Peak Period Reduction	**Residential** 43-172 MW **Commercial** 20-80 MW	Mature deployment Timeframe for rollout: 1 - 5 years	Metering communication infrastructure	Potential higher levelized cost of electricity for consumers who cannot afford to respond/shift demand from peak hours. Tariffs could be designed considering potential equity impact and low-income	Advanced metering infrastructure	Meter data management system

Technology/ Program	Maximum Peak Aggregate Potential Reduction (MW)	Readiness Level	Communications Required	Equity Impact	New Assets and Infrastructure Required	New Operations Required
	Assumption: AMI can bring multiple benefits, including more efficient billing, energy efficiency through feedback reports, reduced meter-reading costs, data for load growth and forecasting, and use in outage management systems. AMI can enable time-of-use pricing, for which peak period pricing can result in a 0.5–2% reduction in peak demand for the population of participating customers.			customers with high peak-to-average ratio consumption. Providing customers with information and means on how they can reduce peak demand can raise the level of peak reduction achieved.		
Mass Rollout	Varies with technologies included, see Table 8. **Example:** SWH, LEDs, and storage heaters are incorporated into the program: **Residential** 3,810 MW **Commercial** 1,645 MW Although adoption rate may be gradual, impacts will be long lasting.	Mature deployment Timeframe for rollout: 1–5 years	None	Rolling out new energy-saving appliance subsidies to high-income groups may provide the largest load reductions. However, this can come at the disadvantage of investing in electrification and appliance adoption for low-income communities. Rollout programs can focus on both reducing existing load (likely high-income groups) and ensuring that low-income groups adopt efficient appliances.	None	None
Subsidies/ Incentive Programs		Mature deployment Timeframe for rollout: 1–5 years	None	Subsidy and incentive programs can suffer from providing financial rewards to high income groups who can afford to purchase new appliances. Although these tools accelerate adoption, they suffer from not equally dispersing benefits across diverse income brackets. Pay-as-you-save and energy-as-a-service programs can provide more equitable distribution of	None	None

Technology/ Program	Maximum Peak Aggregate Potential Reduction (MW)	Readiness Level	Communications Required	Equity Impact	New Assets and Infrastructure Required	New Operations Required
				subsidy and incentive programs.		
Distributed PV Net-Energy Metering Programs and/or Feed-in Tariffs	No Winter Peak Contribution Low Summer Peak Contribution **Assumption:** PV generation will not be coincident with the system winter peak contribution. Although PV integration may alleviate energy consumption and thus supply constraints, it will not directly reduce the peak aggregate load.	Mature deployment Timeframe for rollout: 1–5 years	None	Barriers for low-income groups may include high upfront capital cost of PV systems. In cases of large PV installations driven by municipalities, considerations must be made regarding funding and the distribution of benefits in the community. Community solar programs can provide an equitable path for solar deployment.	Metering	Forecasting
Information: Mobile Alerts / Emergency Alert Programs	**System-wide reduction** 315–1,260 MW **Assumption:** Wireless emergency alerts calling for customer energy conservation have resulted in a 1%–4% reduction of the peak load in California and New York. Frequency of use may be a concern in South Africa as it benefits may be reduced by customer fatigue.	Operational Timeframe for rollout: > 5 years	Cellular communications	These will be voluntary requests. These alerts can be targeted to polygons areas determined by cell towers in the alert vicinity. If there are communities with limited cellular network infrastructure, this could limit participation and/or the ability to target specific localities.	Gateway from alerting authority to broadcast, message router, enablement on customer devices.	Roles and responsibilities regarding who can issue alerts will need to be determined. Wireless service providers will need to be enlisted and meet technical and operational requirements for reliable program participation. Regular testing can be performed.
Information: Energy Efficiency Appliance Ratings + Energy Use	Consumer choice will impact adoption rate, and the savings impact will be partially determined by MEPS. Savings are estimated to be 1.3% of consumption over five years for a moderate MEPS scenario [70]. Although the adoption rate may be gradual, impacts will be long lasting.	Operational Timeframe for rollout: 1–5 years	None	This will benefit households purchasing new appliances.	None	Incentives or enforcement for supplying information.

3 Dispatchable Smart Loads and Targeted Demand Response/Load Shedding

In identifying the untapped potential of DSM in South Africa, the project team and stakeholders (CSIR, Eskom, and SANEDI) chose to focus on the potential of dispatchable smart loads. This section provides details on the potential communication network architecture, load-level applications, a framework for selection of the protocol stack, and a targeted dispatchable smart load application in load application in targeted load shedding.

In examining dispatchable smart load programs, the project team identified load shedding as a key barrier for procuring additional demand response load reductions (because of customer fatigue, double-counting of capacity, and so on). However, a broad rollout of dispatchable DR has the opportunity to provide an alternative to the current load-shedding regimen. Creating a DR program that enables customers to be load-shed-exempt is a key criterion because customers cannot simultaneously participate in load shedding and DR programs[5]. Additionally, load shedding has reached up to Stage 6 (6-GW load reduction); this level of capacity provision is extremely challenging to achieve for most other traditional DR programs that may be based on one end use and/or voluntary load reduction. Although DR programs can reduce the hours of load shedding required by supplying a portion of that capacity, they will not eliminate the need for load shedding.

Load shedding has had a massive detrimental societal and economic impact in South Africa. Using dispatchable loads to alleviate the impact of current load shedding practices is explored in this section. Targeted load shedding (also referred to as “surgical load shedding” in the literature [71]) was identified as a DR program that could reduce the societal and economic impacts of load shedding by providing a more equitable outcome, faster rotations of forced outages, and the ability to isolate and keep critical infrastructure energized. This technology is described in more depth in Section 3.5.

3.1 Network Architecture

This section details the network architecture options and technologies to enable dispatchable loads. The architecture can cover communication from a centralized control center down to the grid-edge appliance or customer-level dispatchable loads. Communication architecture and the physical and network layers are presented in Figure 13.

Field area networks (FANs)/neighborhood area networks (NANs) can serve communication needs from the distribution substation (and possibly control center) to the utility endpoints, i.e., customers. FAN traffic can then be aggregated at cluster routers and sent to wide area network (WAN) routers. Ultimately, WANs support the core of smart grid communications, and WAN technology will need to support the transmission of aggregated data from FANs/NANs over long distances. This requirement dictates WAN architecture. FANs, which might include NANs, have shorter communication paths, and less data on each path, creating other options for physical layer selection. Each FAN or NAN might use two different technologies, which are described in more detail in Section 3.4. Finally, home area networks (HANs) or building area networks (BANs) can

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[5] Current regulations require that 80% of demand on a feeder participate in a DR program to be exempt from load shedding [1].

manage devices at the customer premise. Alternatively, a specific device can receive signals directly from the FAN/NAN, bypassing the need for a HAN. A HAN may provide improved customer comfort but is an additional investment. The overall network can comprise multiple physical communication layers.

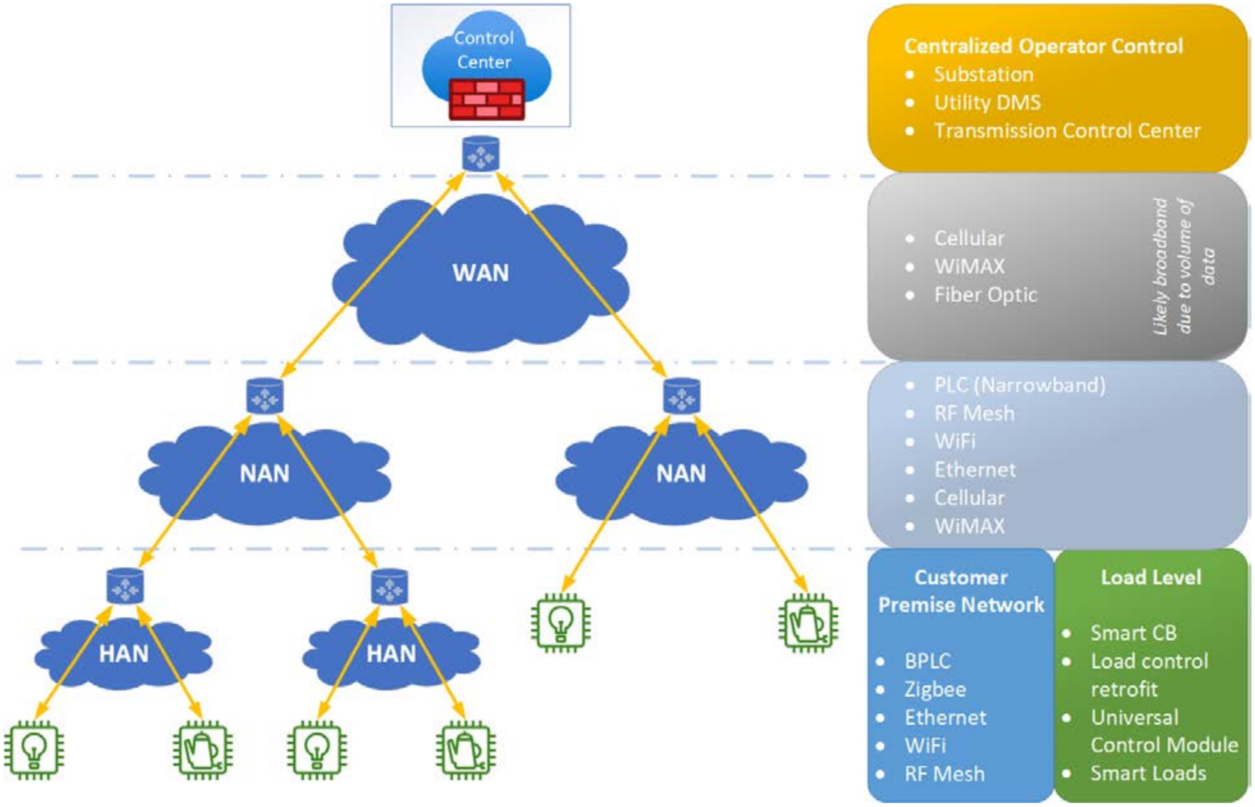

Figure 13. Communication architecture from control center to dispatchable load, detailing WAN, NAN, HAN, and technology options

In the case of AMI, meters communicate with a meter data concentrator (or collector) from the customer premises through the NAN or possibly FAN (a neighborhood might have its own area network because of its size or terrain, or a customer meter might connect directly to a FAN). Meter data concentrators might reside at the substation or, in the case of power line communication (PLC) as a physical layer of a FAN/NAN, at the secondary side of the distribution transformer. The concentrators communicate with the head end at the control center via the WAN.

3.2 Centralized Control

Many distribution-utility enterprise systems, such as meter data management systems and distribution supervisory control and data acquisition (SCADA), are centralized at the distribution center. Traditional load shedding, for balancing purposes, will begin with a dispatch from the TSO to the DSO. The distribution control center then commands remote circuit breakers at the feeder mainline. For targeted load shedding, the control center could dispatch customer premise relays, smart circuit breakers, or AMI/smart meters. Customer selection for targeted load shedding will occur at the distribution control center. Centralized control will allow for algorithms prioritizing critical facilities, equity-aware algorithms that consider customer impact, and coordinated reenergization and dispatch. Individual customers will then be sent a signal over the utility FAN. Depending on the size and topology of the distribution communication system, these signals might be delivered directly to the customer premises or routed to a NAN that is then connected to the customers.

3.3 Load-Level Applications

Dispatchable loads comprise both an end use to be controlled (e.g., water heating, washing loads, and so on) and a means by which they are controlled (e.g., timers, remote turnoff, and so on). The control can either be remote (e.g., controlling the energization of the device) or embedded (e.g., smart thermostats/timers). Remote control can include relays, circuit breakers, and plug timers; embedded control can include timers and other smart-enabled loads (see Table 11).

Table 11. Device-Level Controllers: Remote and Embedded Controls for Dispatching Loads

Device	Description
Relay (remote)	Electromechanical relays use a mechanism to move a lever to change (open/close to deenergize/energize the relay) the position of electrical contacts, which is actuated using an electromagnet. These relays have been used in PLC ripple control, which adds audio frequency (100- to 2.4-kHz) signals that are picked up to energize or deenergize relays. In South Africa, ripple control and relays have been used to dispatch electric water heaters using PLC ripple control and electromechanical meters. Smart relays can use other forms of communication (e.g., RF, PLC, cellular, and so on) to open or close relays and can include additional ICT for programmable logic, measurement, logging, and data export (real-time, interval transfer, and so on).
Smart circuit breaker (remote)	Customer-sited circuit breakers reside in the service entrance section to the whole home and in the customer breaker panel/load panel, with individual breakers on each household circuit (e.g., lighting, cooking, plug-loads, hard-wired appliances, and so on). The principal purpose of circuit breakers is to trip/deenergize the circuit for overcurrent protection. Smart circuit breakers have communication and programmable logic to receive a dispatch command to trip/deenergize the circuit. These could be used either for the main circuit breaker for the entire customer premise or for individual circuits.
Schedulable load/remote timer (remote/ embedded)	Schedulable loads typically have a programmable logic controller and user interface to either schedule the start time of an appliance (e.g., for a delayed start for washing machines/dishwashers/dryers) or for cyclical operating times (e.g., for a water heater or space heating and cooling). This control is usually embedded in the device, although it can also be an external smart plug that controls (e.g., remote timer) when devices are energized—either by an electromechanical timer (rotating gears, electronic, or semiconductor timers).
Smart loads (embedded)	Embedded smart controls include smart thermostats for space heating and cooling systems, which can control operation based on occupancy,

Device	Description
	preheat or precool buildings in advance of peak periods, or have energy-efficient modes and dynamic schedules.
Home energy management system (embedded and remote)	Home energy management systems (HEMS) and building energy management systems (EMS) can be used to control a suite of end uses, including space heating and cooling, hot water, and ventilation. These systems can communicate with sensors through a LAN or Zigbee protocols and with the premise electrical smart meter to monitor consumption.

Some devices are more suited to different forms of remote and embedded control as outlined in Table 12. A major factor for the use of relays and smart circuit breakers is whether the end-use is a plug-load or is hard wired. Water heaters, for example, are ideally suited for relays and smart circuit breakers because they are hard-wired appliances. Space heating, although it accounts for a major portion of residential energy demand and drives winter peak events, is poorly suited because South Africa residential customers typically use portable plug-load space heaters—meaning that customers can change the circuit to which these are connected. Pool pumps, however, are typically hard-wired and so might also be suitable for use with relays and smart circuit breakers.

Of the end-use technologies, water heaters stand out, both for the volume of energy consumption they are responsible for and for their controllability given that they are hard-wired. Stove and oven device control will heavily impact consumer comfort; lighting is highly distributed (providing low device/kW response); similarly, cold storage and laundry use relatively low amounts of energy. Outside the residential sector, commercial water heating and space heating may be good candidates in terms of impact of the device per energy availability, and commercial customers with large-scale refrigeration—unlike the residential customer—may be able to provide a high device/kW response.

Table 12. End Use, Energy, and Potential Load-Level Controller for the Residential Sector

Load	Energy	Relay	Smart Circuit Breaker	Schedulable Load	Remote Timer
Water heaters	39%	x	x	x	x
Space heating	16%	[Plug-load, multiple circuits]	[Plug-load, multiple circuits]	[Plug-load, multiple circuits]	
Pool pumps	11%	x	x	x	x
Stove and oven	7%	x	x	N/A	N/A
Lighting	6%	[Plug-load, multiple circuits]	[Plug-load, multiple circuits]	N/A	N/A
Cold storage	5%	x	x	x*	x*
Laundry	3%	x	x	x	x

The ability of end-use control devices (e.g., relays, circuit breakers, and smart thermostats) to provide different communication capabilities—including measurement, verification, and end-use control—is presented in Table 13.

Table 13. Communication Requirements, Measurement and Verification, and Multiple End-Use Controllers

End Controller	One-Way Communications	Two-Way Communications	Measurement and Verification	Multiple End-Use Control
Electromechanical relays	x	-	-	-
Smart relays	-	x	(x)	(x)
Smart circuit breaker	-	x	x	(x)
Smart thermostat (device add-on)*	-	x	x	-
Smart schedulable load (device embedded)	x	x	x	-
Smart EV charger (device embedded)*	x	x	x	-
Frequency-based end controller (resistor divider and Schmitt trigger)	-	-	-	(x)

3.3.1 Stacking Applications

When selecting a communication solution, it can be important to examine application stacking (i.e., examining a communication network that could support multiple applications). When designing for a single application, the required data rate, speed of response, and reliability may motivate one outcome. However, it can ultimately be more efficient to develop a communication architecture that can support future applications. Additionally, examining the capacity of existing communication infrastructure to host new applications can be considered to avoid building redundant networks. For example, if communications exist that enable distribution automation, this network might also fulfill the requirements to support AMI.

3.4 Selecting Protocol Stacks: Physical and Network Layers by Application and Power System Constraints

The process for designing a communication network for power system operations varies greatly depending on the application, network size (number of endpoints), and network topology. Physical constraints, such as the distances between nodes and surrounding terrain, can dictate the physical layer of the communication system. Additionally, the required speed of response and volume of anticipated data transfer will also drive design choices. A decision-making framework is presented in Figure 14, including detailed descriptions of each major physical layer technology Table 14 summarizes common physical layers, their primary features, and uses for consideration in communication network design.

Figure 14. Design methodology for the selection of common physical layers. Cost constraints and benefits will vary by location. High data rate requirements may add constraints.

Galli et al. define high data rate as tens of kbps and greater [72]. Most sources consider AMI, AMR, and some distribution automation to be low-data-rate applications.

Table 14. Common Physical Layers in Smart Grid Communication: Defining Features and Considerations in Selection for Network Design. Information Assembled from References [74]–[78].

Physical Layer	Wireless	Cost	Protocol Options*	Distance Limitations	WAN/ NAN/ HAN	Additional Notes (features, latency)
PLC (broadband)	No	Varies	IEEE Std 1901, HomePlug, ITU-T G.hn 9960/61, ITU-T G.hn 9960/61 LCP	Tens of meters (this is rapidly evolving)	HAN/NAN	In recent years, broadband PLC has progressed from a technology suited only to the building level to an emerging option for MV networks.
Zigbee (802.15.4)	Yes	Low	SEP 1.0, SEP 2.0	<100 m	HAN/NAN	Designed for HANs.
Ethernet (twisted-pair) (802.3)	No	Medium	OpenADR, DNP3, Modbus, SEP 2.0	<100 m	HAN/NAN	
Wi-Fi (802.11)	Yes	Medium	OpenADR, DNP3, Modbus, SEP 2.0	≤100 m	HAN/NAN	Suffers from a lack of reliability.
RF Mesh (802.15.4)	Yes	Low/medium	802.15.4	300 m–1 km (node to node)	HAN/NAN	Operating costs may be low, but there must be a workforce to plan, maintain, and repair.
PLC (OFDM/ narrowband)	No	Medium (<WiMAX)	IEEE Std 1901.2-2013, PRIME, G3-PLC, ITU-T G.hn 9955/56	<1 km	NAN	Low speed, high latency (tens of ms); repeaters required.
Ripple control	No	Low			NAN/WAN	
Cell (LTE, 5G)	Yes	Medium		> 100 km	NAN/WAN	Cell coverage is typically provided by a third party: network is subject to

Physical Layer	Wireless	Cost	Protocol Options*	Distance Limitations	WAN/ NAN/ HAN	Additional Notes (features, latency)
						provider infrastructure, upgrades, and maintenance.
WiMAX	Yes	Medium	802.16	≤50 km	NAN/WAN	
Fiber optic	No	High	Ethernet (OpenADR, DNP3, Modbus, SEP 2.0)	100 km	NAN/WAN	

*Many protocol options that can run on top of the physical layers listed exist. Protocols listed here are some of the most frequently used or recommended in the literature.

High data rate is typically considered to be greater than tens of kbps. AMR and AMI applications typically fall in the category of low data rate requirements, but data rates depend on the number of meters and the number of meter reads in a given period of time (see Table 15). In general, application data rates depend on the number of devices and frequency of data transmission, though reasonable assumptions can be made for these metrics.

Table 15. Communication system applications and data requirements

Application/Network	Data Size or Data Rate
AMR	100–200 bytes per meter read [73]
AMI: On-demand (one meter)	100 bytes, <15 s [74]
AMI: interval read	1600–2400 bytes per meter read; varies with readings per transmission [74]
AMI: Pricing applications (e.g., broadcast price for RTP or CPP)	100 bytes, <1 min [74]
DLC (from utility to customer device)	100 bytes [74]
Service switch	25 bytes [74]
Distribution automation (volt/VAR, VR, switching, fault detection, protection)	25–1000 bytes [74]
Substation automation	~12.75 Mbps (varies) [73]
PMU	6–24 kbps (varies with reporting frequency) [73]
HAN	1–100 kbps [74]
NAN/FAN	100 kbps–10 Mbps [74]
WAN	10 Mbps–1 Gbps [74]

3.4.1 Power Line Communication

PLC technology has evolved considerably since its original, high-voltage, low-data rate inception as a voice-carrier for internal utility use [79]. Current versions of PLC range from narrowband to broadband; it can be used in low-voltage or medium-voltage systems and bypass distribution transformers or pass through them with amplification [80]. Thus, PLC as a class of technology can support many grid modernization applications at all areas of the network. The appropriate type of PLC must still be selected for the application. Narrowband PLC can support AMI billing use cases at a low data rate, but higher data rates might be needed for certain applications of distribution automation [77]. Higher data rates for narrowband technologies and broadband have been made possible with Orthogonal Frequency Division Multiplexing (OFMD). Open standards for high-data-rate, narrowband PLC include Power Line Intelligent Metering Evolution (PRIME), G3-PLC, and IEEE 1901.2 [81]. The latter includes LV and MV and communication that passes through distribution transformers. In the case of targeted load shedding, considerations can be made for the data rate that will be required to transmit a signal to the maximum number of customers that would be dispatched at a given time.

Hardware considerations can be made to inform the system cost. PLC collectors must be installed at every distribution transformer [77]. These collectors relay the AMI data from each customer served by their respective secondary to the FAN, which may be PLC-based but can use any of the physical layer options appropriate for FANs. Cost efficiency may then be determined by the number of customers at each secondary. Although RF mesh requires a certain density of nodes, PLC may require an even greater density of customers to become more cost-effective than RF mesh.

3.4.2 Radio Frequency Mesh

RF mesh networks require a minimum density of nodes to maintain connectivity. They are best suited to sufficiently dense areas but have been used in locations that are described as rural. These networks can include data forwarding nodes that are installed to relay data between meter and/or collector nodes. Nodes require a clear line of sight to the next hop for reliable transmission, but the network can be considered “self-healing” because of its dynamic, redundant (mesh) configuration. Effective data rates are reduced with an increasing number of hops in a mesh network, so network size should be considered when determining whether RF mesh technology can support the targeted application(s). Data rates can be increased with frequency hopping. RF mesh is frequently used for AMI NANs [77] and has been used to implement targeted load shedding [71].

3.4.3 Ethernet (Twisted Pair)

Ethernet typically refers to a twisted-pair wired connection but is technically a data link layer protocol that can operate over many types of wired layers and even microwave. Here, we discuss the relatively affordable twisted-pair technology. Ethernet benefits from ease of implementation, being relatively simple to administer and maintain [82]. Ethernet is suitable for FANs and NANs [74]. It can generally support the data rates required for frequent (sub hourly) AMI meter reading, distribution automation, and customer internet access.

3.4.4 Wi-Fi

Wi-Fi benefits from the flexibility and minimal material investment of wireless technologies. It can be used at the FAN/NAN level and has been used in demand response programs. Wi-Fi is considered one of the least reliable options because it is subject to interference [82]. Unlike RF, which typically uses a dedicated band of spectrum in the 900-MHz range, Wi-Fi channels at the 2.4- and 5-GHz bands are open to public use—increasing the possibility of interference. Wi-Fi communication can also result in higher power consumption and may not be ideal for many embedded devices. Wi-Fi can be deployed in a mesh network like RF, but mesh Wi-Fi is a relatively new technology that is not yet common. Wi-Fi can support similar applications to Ethernet but cannot always meet the same reliability requirements.

3.4.5 Cellular

Cellular may be best provided through a network service provider (NSP). Private cellular options vary by country, but, if available, costs can be shared with other agencies with similar mission-critical communication needs. Cellular can be used for WAN or FAN/NAN applications and can often reach remote customers or other endpoints when fiber optics or other wireless WAN technologies cannot.

3.4.6 Fiber Optics

Fiber optics are widely regarded as state-of-the-art physical layer technology. Fiber offers the greatest reliability and performance, given its high data rates of tens of Gbps, fast transmission speed, and long-distance capabilities. Fiber-optic utility networks are often private, adding a layer of security and predictable network traffic (avoiding congestion). It is also one of the most expensive communication solutions. Therefore, fiber may be used in combination with other technologies. It is often used for a utility's WAN, where it can support the increased data rate because packets are collected from many utility endpoints and gathered at data collectors in the FAN/NAN before being transmitted over the WAN.

3.4.7 WiMAX

With a range of up to 50 km, WiMAX can be used for WANs and NANs/FANs. WiMAX is more affordable than fiber optics, the other common WAN option. It is more limited in range and has a substantially lower data rate of 75 Mbps but is sufficient to support a wide range of applications. Utilities may already have licensed portions of the microwave spectrum. In this case, WiMAX may be preferred because it can be used at no additional cost. In selecting any WAN technology, a utility must assess the full range of applications a network needs to support to determine data rate, reliability, and latency requirements.

3.4.8 Network Service Providers

Network service providers (NSPs) can be a cost-effective alternative to utility-owned communication infrastructure. Different arrangements with an NSP can be available to support the required communication reliability, speed, and security. The utility will benefit from identifying these requirements for its targeted applications prior to engaging NSP services. DSL is a prevalent but older technology that must be subscribed to through an NSP. It is suitable for FAN-/NAN-level networks, but because of distance limitations of less than 7 km is not suitable for WANs. Utility-owned communication infrastructure can also be combined with NSP services to extend their communication network.

3.5 Dispatchable Smart Loads Application: Targeted Load Shedding

In examining dispatchable load applications, a major barrier to their success in providing load reductions is the ongoing energy crisis and the degree to which load shedding in South Africa has already been implemented. The key problem is that enrolling a customer in a DR program cannot exempt them from load shedding, given that load shedding is happening at the feeder circuit breaker—providing no means to electrically isolate DR participating customers. This makes it challenging to offer DR participation as an alternative to load shedding (for some large industrial customers with dedicated circuits, this is possible). If customers participating in DR programs are not exempt from load shedding, then some additional incentive would have to be provided to encourage load reductions beyond those already experienced through load shedding.

Given that challenge, the project team decided to examine the potential of targeted load shedding that could be part of an enhanced dispatchable load framework. Targeted load shedding refers to implementing service interruption at a more granular level than at the feeder. Current load shedding strategies in South Africa take place on the distribution system at breakers at the substation. Most load shedding in South Africa is rolling blackouts, which are planned load-shedding events because of a lack of available generation to meet demand.[6] This load shedding is performed using remote circuit breakers at the feeder mains on distribution circuits; see Figure 15.

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[6] Underfrequency load shedding in the event of system contingencies use underfrequency relays (load shedding increases system frequency, so it is used only in contingencies in the event of an underfrequency event). Underfrequency load-shedding relays are typically configured to shed an increasing percentage of system load the lower system frequency nadir reaches in the event of a contingency. These devices are installed in distribution substations. Because most load shedding that occurs in South Africa is scheduled load shedding or rolling blackouts, we focus on targeted load shedding as an alternative to scheduled load shedding.

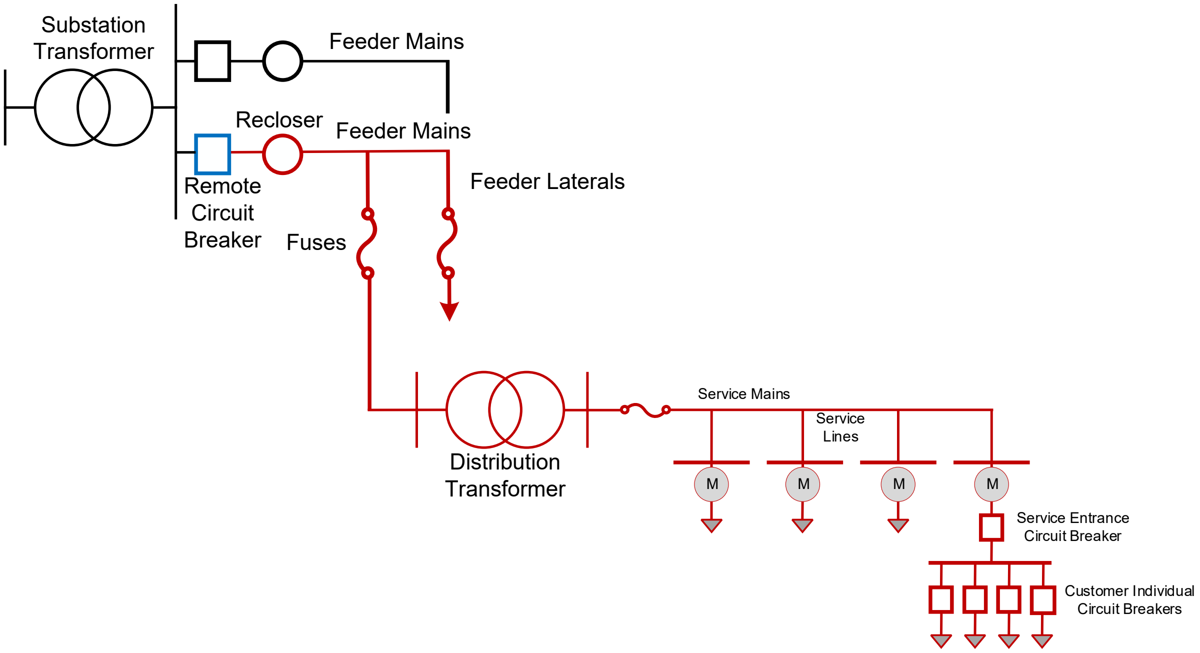

Figure 15. Electrical single-line diagram of a substation, distribution feeders, service, and customer meters. Load shedding is typically performed at the remote circuit breaker on the feeder mainline, leaving the entire circuit deenergized.

Targeted load shedding can also be implemented downstream of the feeder circuit breaker, which represents an opportunity to improve the situation in South Africa. Targeted load shedding can be implemented on individual low-voltage networks (service remote circuit breakers), entire customer premises (meter with remote turn-off or service entrance section breaker), or customer individual circuits (smart circuit breakers) or at the appliance level (relays), as illustrated in Figure 16.

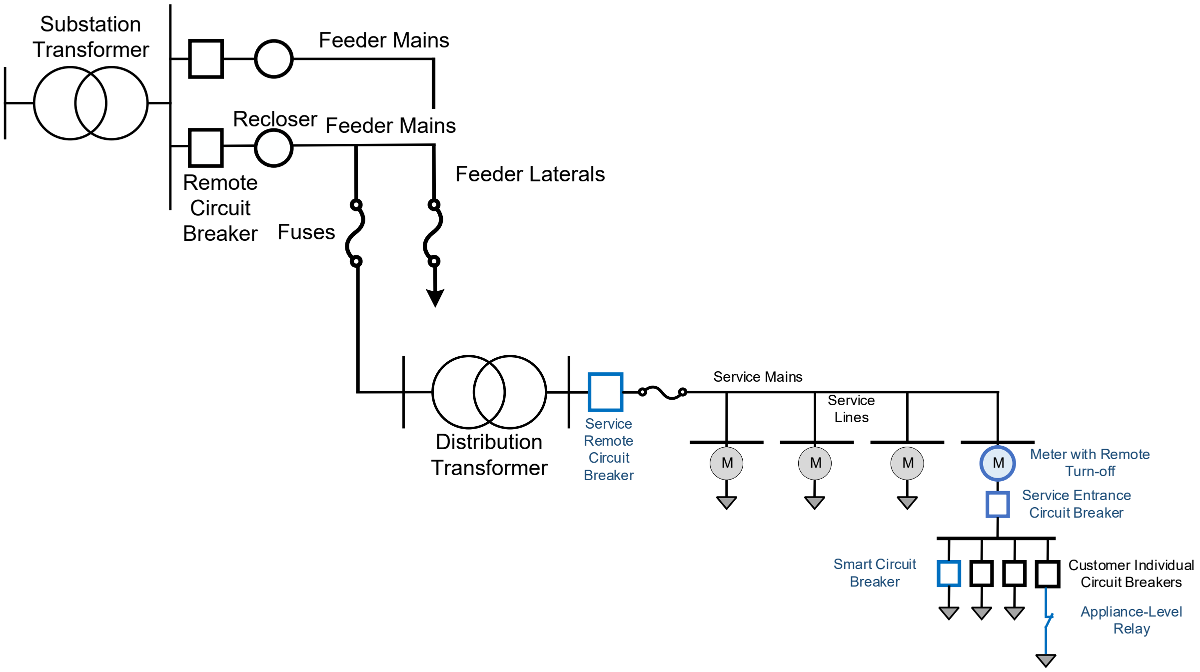

Figure 16. Electrical single-line diagram of a substation, distribution feeders, service, and customer meters. Alternative options for devices that can provide targeted load shedding are highlighted in blue.

Targeted load shedding at the customer premise can enable a scenario in which some customers on a shared feeder or secondary are load shed while others on the same feeder contribute to DR programs, enabling the system to benefit from DSM solutions while load shedding. This reduces the capacity required from load shedding. When implemented at the customer premise, targeted load shedding can use AMI meters equipped with remote turn-off and turn-on functions. Other devices can be used, but AMI may already exist, or targeted load shedding may be a use case that increases the motivation for an AMI rollout. For these reasons, targeted load shedding using AMI can be cost-effective, particularly in South Africa where an AMI rollout is in its early stages. There are further social benefits to targeted load shedding, including reduced outage durations; faster, more reliable reenergization; and increased access to essential services during outages.

The key goals of designing/identifying such a program were to examine the following:

- Potential large-scale capacity usage of targeted load-shedding schemes.
- Ability to isolate customers downstream of a feeder mainline breaker. This would enable:
    (1) **Spatial control in energization:** Targeted load shedding could keep parts of a distribution circuit/feeders energized, keeping critical loads online (e.g., medical facilities, water treatment facilities and pumping, street lighting, and so on). Keeping circuits energized also prevents the risk of theft of deenergized distribution assets (e.g., conductors, transformers).

(2) **Rotational load shedding:** Faster rotation of customer load shedding could be enabled by targeted load shedding, ensuring that customers have shorter durations where they are deenergized. This benefit, combined with Benefit (1), can reduce the impact of load shedding on customers.

(3) **Managing comeback load:** Management of the comeback load (also known as cold-load pickup) can be challenging. Currently, many South Africa municipal circuits are old and cannot handle the volume of load that comes online after an outage. This can trip overcurrent protection devices, challenging the ability of a utility to restore service. Targeted load-shed schemes could avoid shedding entire feeders and could stagger customer reenergization on the same circuit. NREL aimed to answer the following questions to understand the potential benefits and limitations of targeted load shedding:

- How can faster rotation of customers impact the individual customer experience in terms of outage duration and total daily outage duration?
- Are there times during which customers must be load shed for longer durations to meet system requirements?
- Can faster rotations result in decreased total outage time for each customer by allowing for a more even distribution of load shedding across a population?
- How many customers enrolled would be necessary to have sufficient capacity in a rotational targeted load-shed program?
- How do different outage durations impact cold-load pickup upon reenergization?

3.5.1 Analysis of the potential of targeted load shedding

To examine the potential of targeted load shedding and answer key questions about some of the benefits to customers of shortening the duration of load shedding and increasing the rate of rotation, we perform an analysis of different load-shedding strategies. Eskom Manual Load Reduction (MLR) dispatch signals for 2022 and both total system load (contracted demand) and system net load (residual demand) are used in the analysis.

3.5.1.1 Methodology

We disaggregate the 2022 Eskom system load into the key different load sectors (e.g., residential, commercial, industrial, agricultural, and so on). We also take the Eskom MLR signal for 2022, which is used as the dispatched load-shedding profile. From the disaggregated system load, approximations are made to establish customer-level profiles, so that customers can be tracked for the duration that any individual customer experiences load shedding.

Load shedding is currently performed at the circuit breaker level, shedding entire feeders. We approximate blocks of load to represent feeders in South Africa and notionally assign customers to these blocks of load.[7] This allows comparison of the ability to shed individual customers vs. shedding feeders.

Cold-load pickup is the phenomenon of customer load increasing after the duration of an outage event. This is the result of load forgone (e.g., customers having to delay activities with electrical consumption—e.g., cooking); thermostatically controlled loads that stray outside of their temperature deadband have coincident starts once load is reenergized (e.g., 20% of loads online pre-outage, goes to 100% after) [83]. Cold-load pickup can be approximated by a function that closely resembles a decaying sinusoid, with a rebound peak magnitude, and decaying load as loads gradually desynchronize consumption patterns (e.g., thermostatically controlled loads can be approximated by duty cycles that gradually desynchronize). Cold load pickup is modeled with the following equation:

$$P(t) = P_0\left(1 + A_0 \times e^{\Delta t/\tau} \times \cos(\omega t)\right) \qquad \text{[Equation 1]}$$

Where *P(t)* is the load after the start of a load-shedding event, P_0 is the initial load, A_0 is the magnitude of the pickup load, *t* is the time-step, τ is the time constant of the pickup decay, *t* is the time postoutage, and ω is the periodicity of the comeback load decay. The magnitude of the initial rebound pickup load can be described by:

$$A_0 = A_{rebound} \times (1 - e^{-\left(\frac{t_{outage}}{t_{saturation}}\right)}) \qquad \text{[Equation 2]}$$

Where A_0 is the percentage value of the increase in load because of the load-shed event. $A_{rebound}$ is the saturated rebound; i.e., this is as high as rebound can get because load rebound eventually saturates with time. The saturated rebound is reached after $t_{saturation}$, where t_{outage} is the duration of the outage/load-shed event. The values selected for each constant along with the justification are presented in Table 16.

Table 16. Constants Selected for Cold Load Pickup Model and Sources

Constant	Value	Notes
$A_{rebound}$	0.8 (i.e., pickup load is 180% of pre-load-shed event)	From National Energy Regulator of South Africa (NERSA) National Rationalized Specification (NRS) 048-9 [1].
$t_{saturation}$	180 minutes*20%	This is the time to saturate to 20% of the diversified preload value.
τ	64 minutes	This is the time constant for load decay, taken from Ihara and Schweppe [84].
$\omega = {}^{2\pi}/_{\tau}$	π/32 rad/s	This is angular frequency, which is the periodicity of the load decay.

Figure 17 shows the results of the cold-load pickup model, examining the response level of the pickup/comeback load as a function of the duration of the outage. As outages increase, the initial

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[7] One block is approximately 1,045 residential customers and 7 commercial customers, or 6.8 industrial customers.

magnitude of the comeback load increases, saturating to a maximum comeback load after approximately 180 minutes.

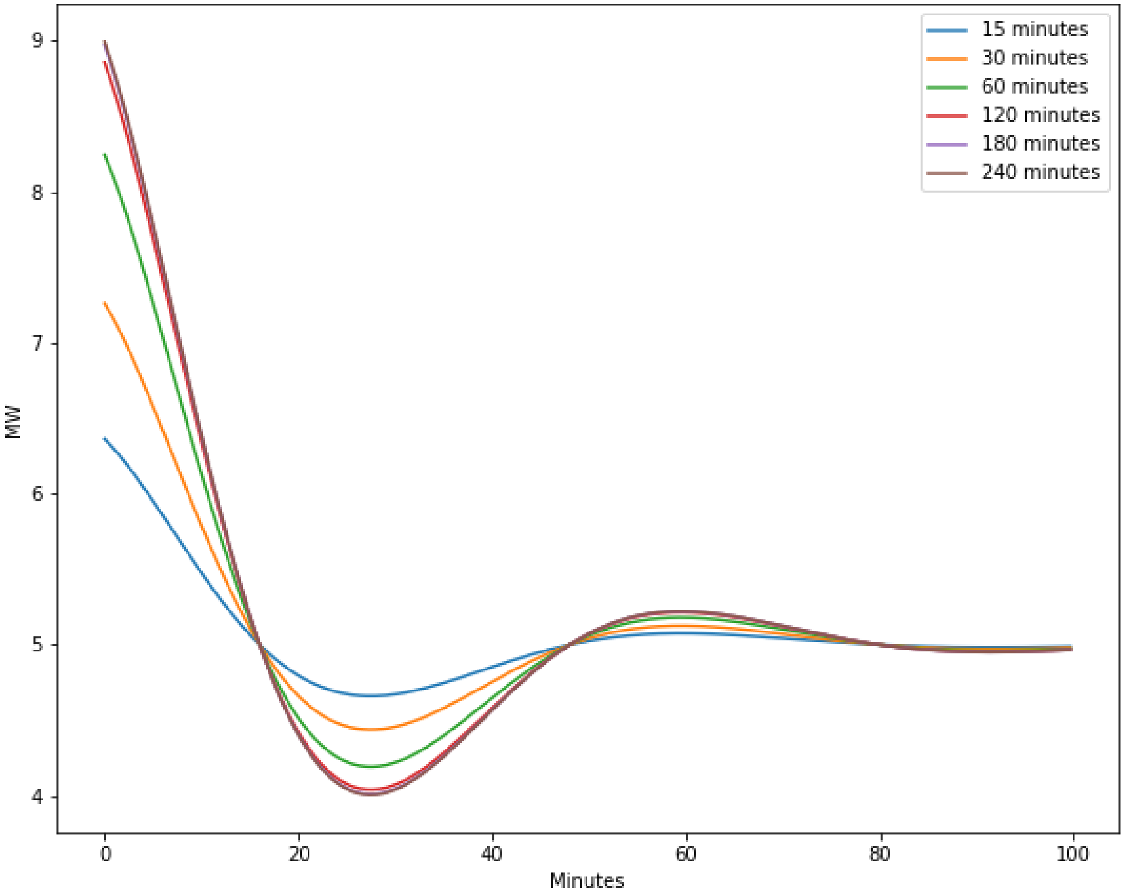

Figure 17. Load after reenergization following outages of different durations. In this example, the original load P_0, is 5 MW.

In modeling cold-load pickup for many blocks of customers at a time, P_0 of Equation 1 was equal to the load of the dispatched blocks. The added load of reenergization, is the difference between $P(t)$ and the original load data P_0. In practice, reenergization of feeders or load blocks could be staggered in time, reducing the magnitude of cold-load pickup. These results therefore demonstrate a worst-case scenario of simultaneous reenergization for all scenarios.

3.5.1.2 Results

Modeling results are organized by the research questions they address, which are introduced in Section 3.5. Analyses that do not explicitly address the effects of cold-load pickup do not include modeling of cold-load pickup and demonstrate only the effects of reduced outage durations and scheduling. Cold-load pickup is examined in isolation to understand along with implications of increased frequency of deenergization and reenergization.

How can faster rotation of customers impact the individual customer experience in terms of outage duration and total daily outage duration? Are there times in which customers must be load shed for longer durations to meet system requirements?

This research question is addressed by identifying metrics that describe the impact of load shedding to the customer in terms of the continuous length of time that they are without power. Targeted load shedding can benefit customers by reducing this burden. Here we quantify that impact with the Customer Average Interruption Duration Index (CAIDI). CAIDI is calculated with the following equation from IEEE Standard 1366-2022 [85]:

$$\mathrm{CAIDI} = \frac{\sum \text{Customer Minutes of Interruption}}{\text{Total Number of Customers Interrupted}}$$

CAIDI can be thought of as the average outage duration a customer experiences and the average service restoration time.

As rotation durations are specified in the load-shedding model, CAIDI is expected to reflect this and roughly equal the rotation duration. Deviations may occur if blocks of customers are scheduled for back-to-back slots of load shedding or if the MLR signal decreases and few blocks need to be dispatched to meet the load-shedding requirements. The impact of specifying different rotation durations on CAIDI can be seen in Table 17.

Table 17. CAIDI for Different Rotation Durations During July 2022

Rotation Duration (minutes)	15	30	60	120	180	240
CAIDI (minutes)	15	30	70	99	116	126

Although CAIDI represents the average outage duration, Figure 18 shows the distribution of outage durations experienced by customers for each specified rotation duration. In all cases, there is a possibility of a block being scheduled for two consecutive slots of load shedding, as is the case in the current load-shed schedules. The model was designed this way to provide a closer comparison to current load-shedding practices. As the rotation duration decreases, back-to-back scheduling decreases. Assumptions were made about the reenergization of blocks when the MLR signal changes within a scheduled time block: The MLR signal can change hourly, so the dispatched load can be changed hourly; i.e., if a block is shed and is scheduled for a 2-hour slot, but MLR decreases in the next hour, that block can be reenergized. An alternative approach is that if a block must be shed at any time in a 2-hour slot, it is shed for the entire 2 hours. This would increase CAIDI and total daily outage durations for all scenarios. In reality, this will depend on scheduling and how the distribution control center chooses to manage load-shedding dispatch.

Because the 15- and 30-minute rotation duration cases assume that the MLR can decrease within an hour—and that blocks can be dispatched or reenergized on a more frequent basis to meet that load-shedding requirement—these scenarios result in reducing the total number of customers that must be shed at a time to meet the MLR signal. This contributes to fewer instances of customers being shed multiple times in a row. See Figure 16.

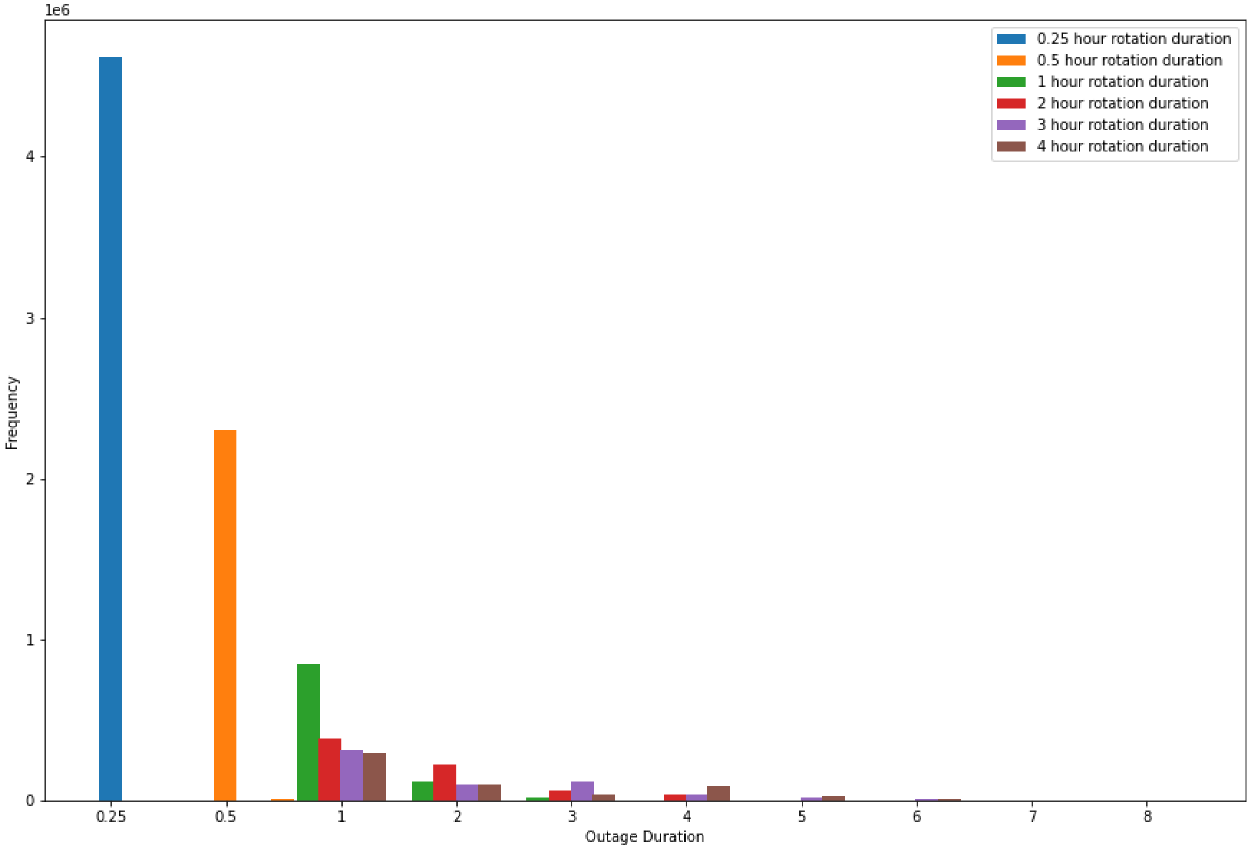

Figure 18. For different rotation durations, customers experience different outage durations. The length of outage durations experienced is shown for each rotation duration modeled.

Can faster rotations result in decreased total outage time for each customer by allowing for a more even distribution of load shedding across a population?

More frequent rotations can more evenly distribute the outages across a population. Intuitively, if rotation durations are shorter, they are shared between more customers. This can be seen in Figure 19: 4-hour rotations result in many customers who are shed for hours a day and many who experience less than half an hour on average. As the outage durations decrease, the distribution of typical daily outage time becomes narrower: Service interruption can be more evenly distributed throughout the population.

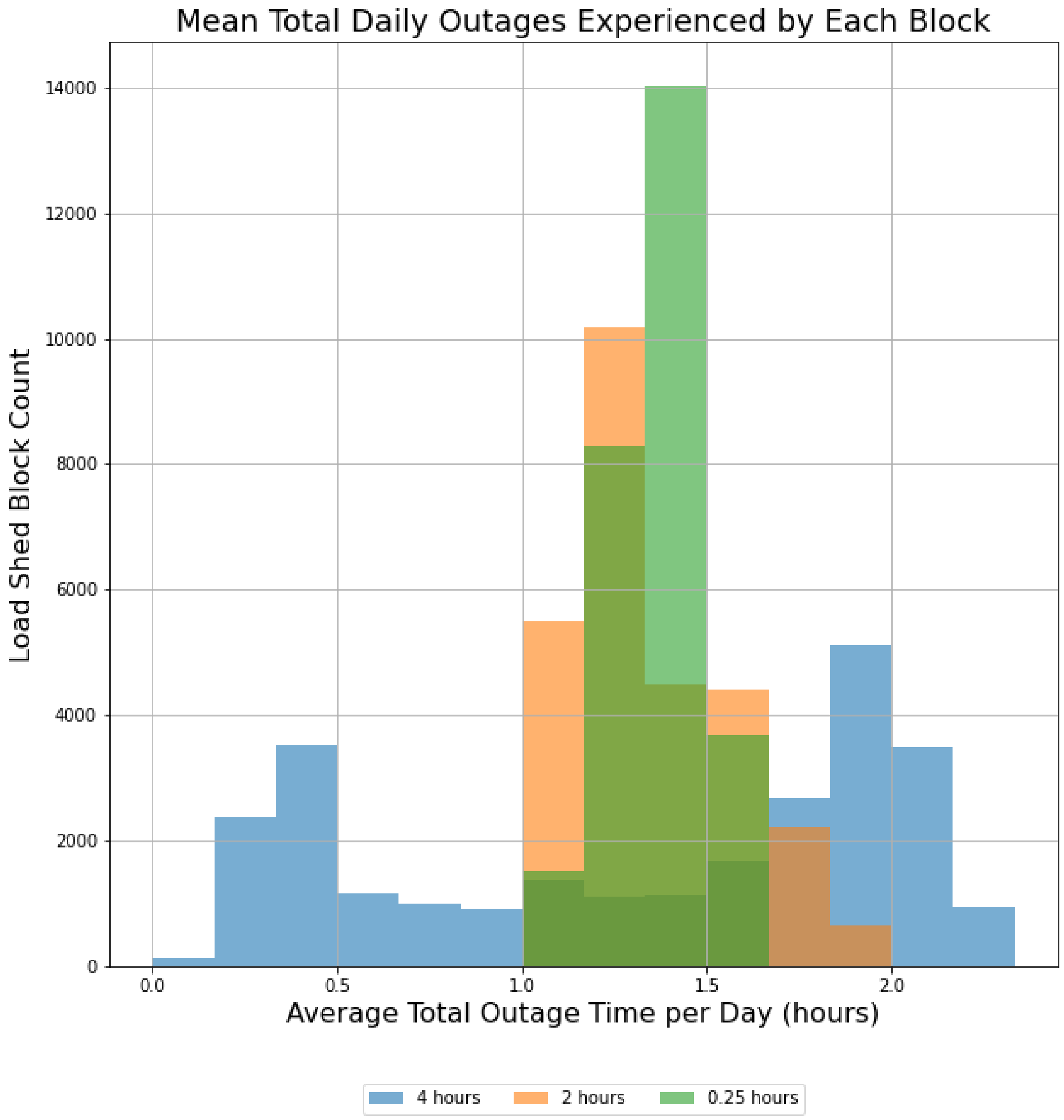

Figure 19. Histogram of the mean total nonconsecutive hours of outages experienced by each load-shed block in July 2022. As the duration of load-shedding rotation decreases, the disparity in the average total outage time experienced by customers per day decreases.

Maximum daily outage information for each rotation duration modeled is presented in Table 18. With more frequent rotations, the most cumulative (nonconsecutive) service interruption that customers experience in a day decreases. Customers are less likely to experience upwards of 6 hours of outages in a single day.

Table 18. Averages of the Maximum Cumulative (i.e., Nonconsecutive) Hours of Service Interruption in a Day Experienced by Each Block of Customers for Different Rotation Durations

Rotation Duration (hours)	0.25	0.5	1	2	3	4
Average Maximum Daily Outage (hours)	4.09	4.40	6.15	6.44	6.23	6.38

It should be noted that distribution of outages can be influenced by scheduling independent of rotation durations. A dynamic queueing algorithm—in which, if a block is shed, it is then moved to the end of a queue so that it is not shed again until every other block has had its service interruption—can ensure a more equal distribution. However, such dynamic scheduling requires centralized control that retains memory of which blocks were shed when. It also results in less predictability for customers, who may prefer to know when service interruption will occur and schedule their own livelihood and businesses accordingly. Lowering the risk of any individual customer experiencing more frequent, longer outage duration may be preferential for some load sectors (e.g., residential), whereas other load sectors (e.g., commercial and industrial) may prefer advanced predictable scheduling—even at the risk of an inequitable outcome.

How many customers enrolled would you need to have sufficient capacity in a rotational targeted load-shed program?

As mentioned previously, if rotation durations are shorter, outages must be shared by more customers. To meet the MLR signal in 2022, the load allocated (275,000 blocks of customers, ranging from 0.47 MW to 1.15 MW each) is sufficient in all scenarios modeled. If rotations are more frequent and more distributed across a population, it is possible that more customers could be impacted during a given load-shed event. It is challenging to describe the change in the number of customers impacted by each load-shedding event: There are many times during which load shedding continues for days or even weeks (e.g., MLR is in constant use from June 28, 2022 from 5:00 a.m. to midnight on July 15, 2022), so it can be misleading to describe load shedding as a discrete event at these times. Instead, statistics can be provided on the number of customers impacted during a particular window of time when load shedding occurs. Table 19 shows the increase in customers or blocks impacted within a 4-hour period for rotation durations less than 4 hours. For example, in the case of 15-minute rotations, 1.8 to 9.9 times the number of feeder blocks will be dispatched to meet the same demand as a single feeder block that is dispatched for 4 hours.

Table 19. Ratios of the Amount of Demand Dispatched in a 4-Hour Period for Each Rotation Duration vs. the Amount of Demand Dispatched for 4-Hour Rotation Durations

Rotation Duration (hours)	Maximum Increase in Load (ratio)	Minimum Increase in Load (ratio)	Mean Increase in Load (ratio)	Median Increase in Load (ratio)
0.25	9.9	1.8	5.3	4.8
0.5	7.9	1.5	4.0	3.6
1	3.9	0.7	2.2	2.2
2	2.6	0.6	1.6	1.5
3	2.6	0.6	1.5	1.4

For outage durations less than an hour, fewer customers may experience outages during a 15-minute window of time. Table 20 shows that as few as 30% of the same number of feeder blocks can be dispatched with 15-minute rotations compared to 4-hour rotations. This is because the model interpolates the hourly MLR signal at a 15-minute resolution. In the 15-minute outage duration scenario, there are times at which the MLR signal is less than the hourly signal. This has implications for real-world implementation: If load shedding could be dispatched to meet the system needs on a more granular basis (i.e., reflect the 15-minute demand rather than the hourly demand), the amount of load shedding dispatched could more accurately reflect the demand that must be dispatched. Fewer customers would need to be load shed to meet system needs.

Table 20. Ratios of the Amount of Demand Dispatched in a 15-Minute Period for 15-Minute and 30-Minute Rotation Durations vs. the Amount of Demand Dispatched for 4-Hour Rotation Durations. For Durations of an Hour or Greater, There Is No Change Because the Dispatch Can Change on an Hourly Basis for 4-Hour Rotation Durations.

Rotation Duration (hours)	Maximum Increase in Load (ratio)	Minimum Increase in Load (ratio)	Mean Increase in Load (ratio)	Median Increase in Load (ratio)
0.25	2.4	0.3	1.0	1
0.5	1.9	0.5	1.0	1

The ratios in Table 20 can change with different scheduling strategies. A scheduling algorithm designed to distribute the load shedding as much as possible would result in a larger ratio, while a schedule that targeted the same portion of the population in a particular window of time (perhaps because of customer preference, due to incentives or desire for predictability) would result in a lower ratio.

How do different outage durations impact cold-load pickup upon reenergization?

Cold-load pickup from the synchronized reenergization of customer premises results in load changes shown in Table 21. The maximum amplitude of the comeback load increases with the rotation duration (or duration of service interruption) until the rotation duration exceeds 3 hours. This is because of the 3-hour saturation time selected in the model (see Section 3.5.1.1). More devices become synchronized as the duration of service interruption increases until this saturation point. Because these devices are now synchronized, they can also be expected to turn off more in-phase after the pickup event, resulting in the temporary decrease in load shown in the minimums in Table 21 (see Figure 17 for context).

Table 21. Descriptive Statistics of the Change in Load Because of Cold-Load Pickup During July 2022 for Different Rotation Durations

Rotation Duration (hours)	Maximum (MW)	Minimum (MW)	Median (MW)	Mean (MW)
0.25	1862	-123	133	247
0.5	3073	-736	0	170
1	4451	-1069	0	88
2	5047	-1213	0	58
3	5374	-1292	0	42
4	4642	-1115	0	32

Average increase in load because of cold-load pickup is greater for shorter rotation durations. Plots of the load with and without cold-load pickup show that for the shorter rotation durations (Figure 20 through Figure 23), the next instance of reenergized load occurs before the cold-load pickup impacts have settled. Figure 17 shows that the settling time is typically greater than 60 minutes in all cases.

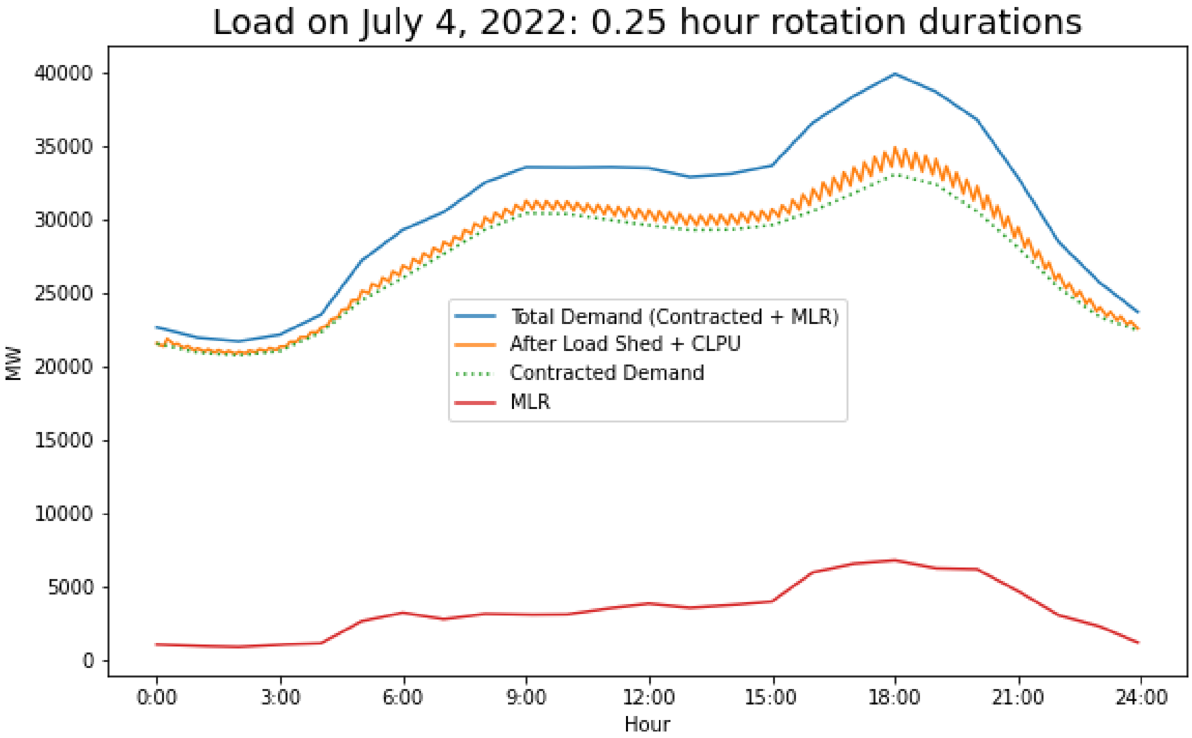

Figure 20. Load on the day of maximum load shedding—July 4, 2022—with different load-shedding blocks dispatched and reenergized every 15 minutes. This frequency results in continuous impacts of cold-load pickup as new blocks of demand are reenergized before the cold-load pickup from the previous block has settled.

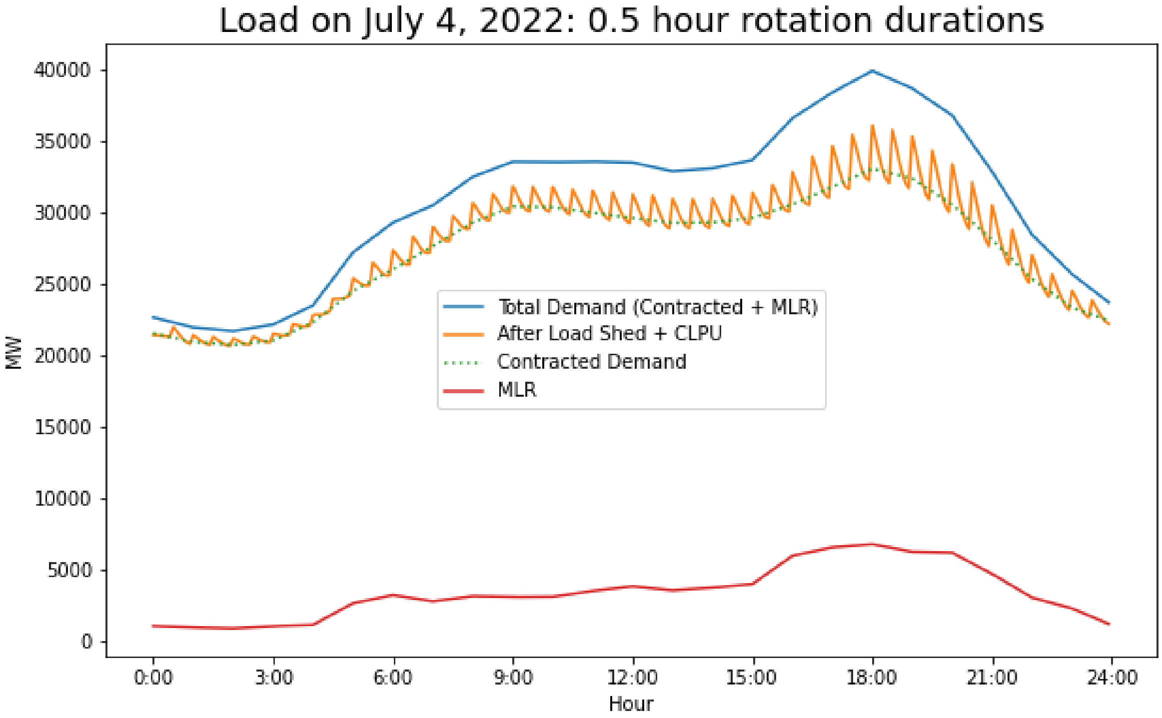

Figure 21. Load on the day of maximum load shedding—July 4, 2022—with different load-shedding blocks dispatched and reenergized every 30 minutes.

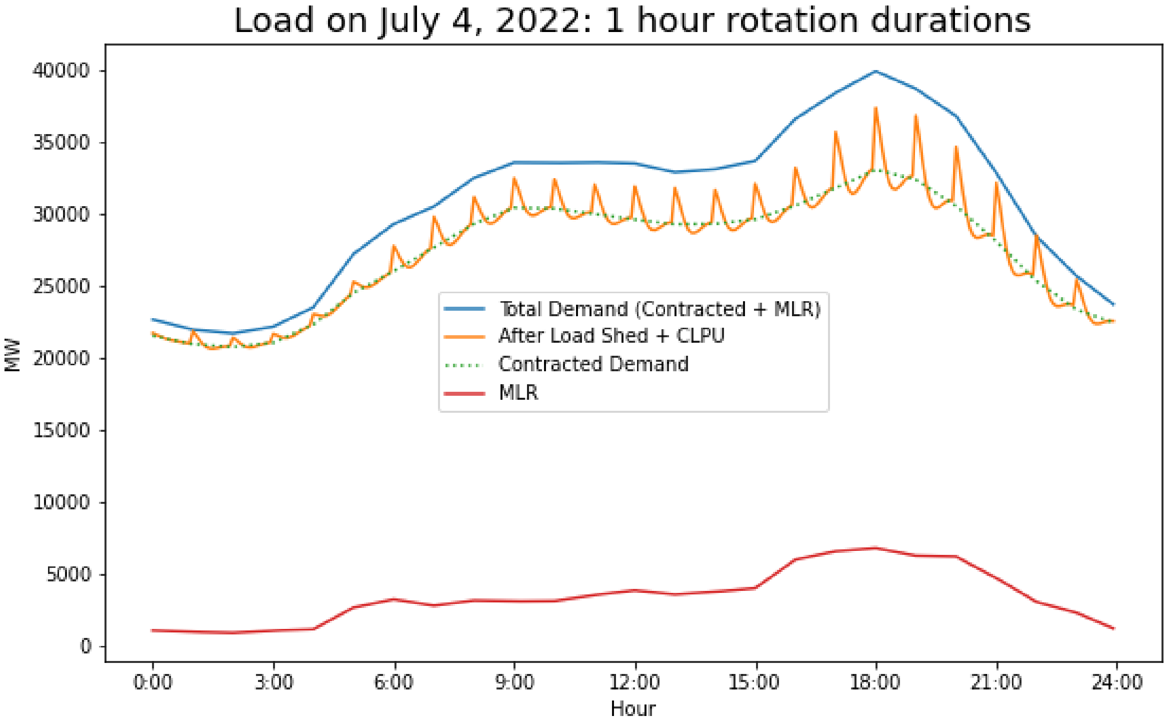

Figure 22. Load on the day of maximum load shedding—July 4, 2022—with different load-shedding blocks dispatched and reenergized every hour.

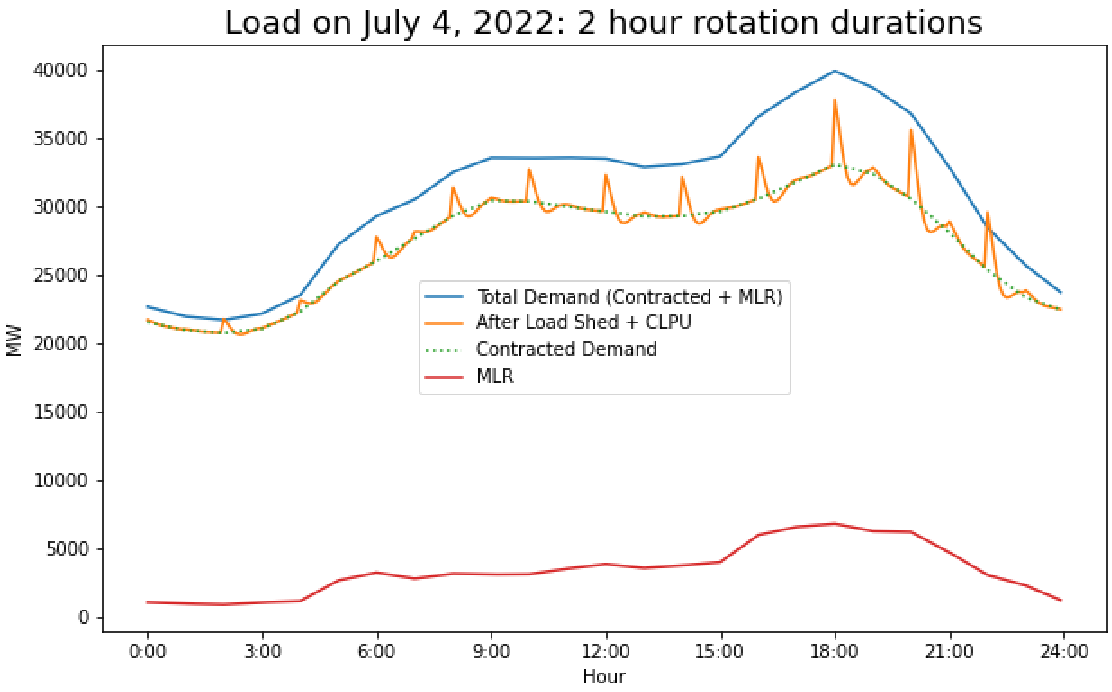

Figure 23. Load on the day of maximum load shedding—July 4, 2022—with different load-shedding blocks dispatched and reenergized every 2 hours.

In comparing the 3-hour and 4-hour rotations, it is observed that both the minimum and maximum change in load because of cold-load pickup is greater in magnitude in the case of 3-hour rotations. This is explained by comparing Figure 24 and Figure 25. In the 3-hour case (Figure 24), service is interrupted at the peak demand at 6:00 p.m. This results in a large comeback load, the magnitude of which is a function of the demand at the time the load was dispatched (see Equation 1). In the 4-hour case (Figure 25), dispatch signals occur on either side of the peak load, avoiding a maximized comeback load.

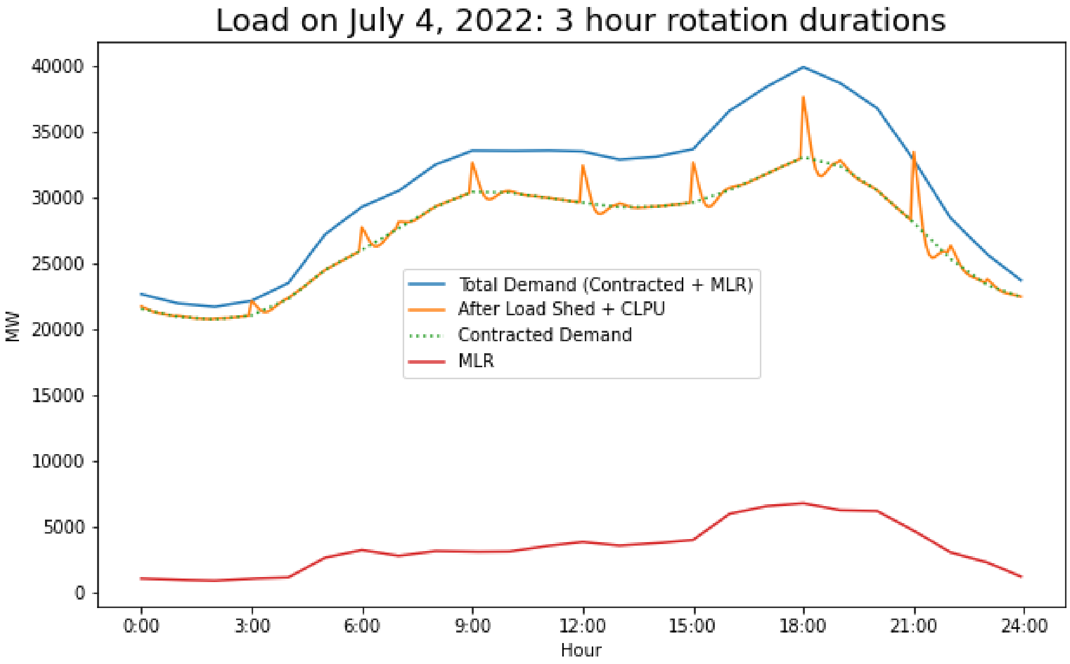

Figure 24. Load on the day of maximum load shedding—July 4, 2022—with different load-shedding blocks dispatched and reenergized every 3 hours. At 6:00 p.m.—the peak demand interval—a new cohort of demand is dispatched. This results in a large amount of comeback load when the cohort is reenergized at 9:00 p.m.

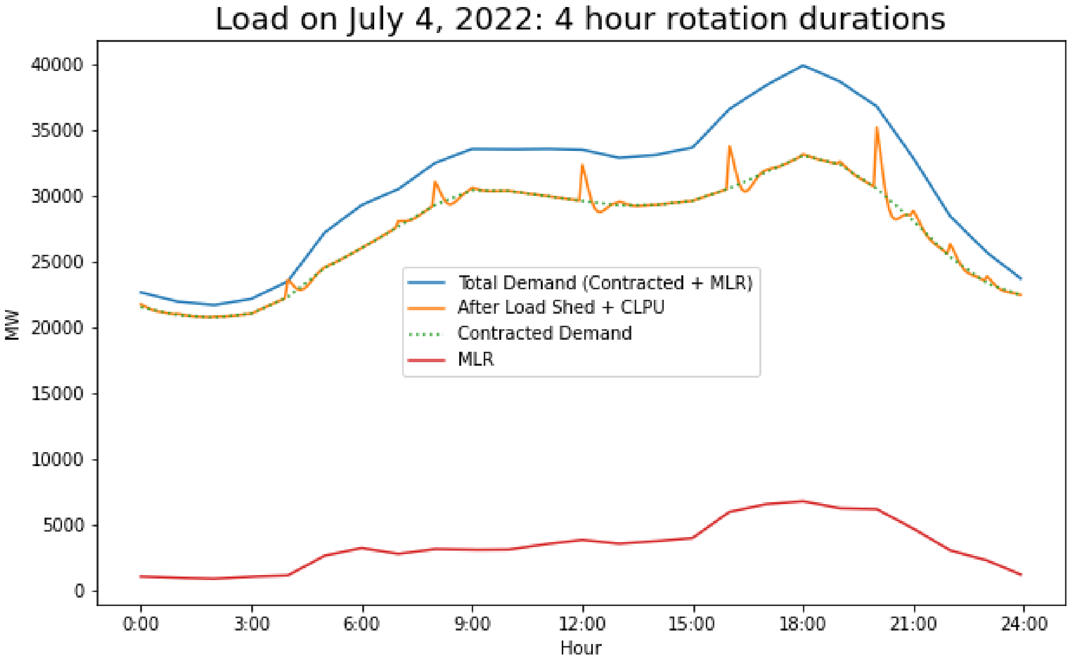

Figure 25. Load on the day of maximum load shedding—July 4, 2022—with different load-shedding blocks dispatched and reenergized every 4 hours.

3.5.2 Aggregators

Many of the communication architectures and much of the dispatch and control outlined in this section may also enable aggregator capabilities. Initiatives to increase aggregator participation in the South Africa power system can benefit from considerations of infrastructure required for dispatchable DR (e.g., smart metering can enable measurement and verification of response from aggregator dispatch). Although a third-party aggregator may not have the situational awareness required for implementation of load shedding of entire customer premises, direct load control of specific devices can leverage the same or similar technologies. Aggregators that use direct load control to operate demand response assets will require many of the communication network components described previously in this section.

In addition to the infrastructure already outlined, a central management system to coordinate load dispatch and reenergization and manage measurement and verification is required for aggregator provision of targeted load shedding. Requirements for aggregator DR services will vary with the specifics of implementation and type of demand-side and distributed generation being dispatched (e.g., distributed energy resource management system [DERMS] is required for distributed generation). DERMS specifications will vary with the type of aggregator (sole-source, third-party, or utility) and the makeup of the participating DER fleet, which are described next:

- **Sole-source vendor:** Sole-source vendor (e.g., inverter manufacturer) provides vendor-developed cloud solutions that typically rely on customer Wi-Fi for communication and local inverter metering for measurement and verification.

- **Aggregators and DER gateways:** Aggregators are responsible for communications with many diverse vendor technologies, with communication established locally through a hub/DER gateway. The aggregator will work with DER vendors to establish communications and can be a third party or the distribution utility.

Establishing interconnection standards/common communication protocols is critical to enabling the aggregation of DERs and customer resources. In the utility connection process, it is critical to ensure that DERs are compliant with future standards to enable DERMS (e.g., IEEE 2030.11), secure communication protocols (e.g., those specified by IEEE 1547-2018, which uses SEP 2.0, DNP3), and DR communication protocols (e.g., OpenADR).

3.5.3 Future Considerations

Different scheduling algorithms can impact nearly all the results presented in Section 3.5.1.2. Scheduling can impact the distribution of service interruption across a population as well as change the amount of load (number of people) dispatched to meet the MLR signal. Dynamic scheduling algorithms can be the fairest (distributing outages equally) but require a centralized system to execute. Other drawbacks include a lack of predictability, which may be counter to customer preferences. Furthermore, “fairness” defined simply as “equal distribution” does not account for a heterogeneous customer base. Different customers will have different preferences (such as predictability); some may be impacted more severely impacted (such as those depending on life-sustaining electrical equipment), and others may benefit the community if they are able to maintain power (such as hospitals, community centers, or even grocery stores). Advanced scheduling algorithms will need to be investigated to better understand the potential for targeted load shedding to improve customer wellbeing.

The results presented in this section do not capture the geospatial benefits that targeted load shedding introduces. By introducing geospatial diversity in power outages, there is potential to reduce the social burden on those impacted by load shedding. As mentioned previously, if outages are reduced for customers providing essential services to the community, everyone benefits. Customer benefits of more granular outage control can be measured with metrics such as social burden, i.e., access to services. Energy justice can be evaluated by examining relationships between community characteristics (e.g., census data) and outage data associated with location. Such analyses can inform equitable considerations by identifying disproportionate impacts on women or customers of other historically marginalized groups. This requires data that are sufficiently granular to capture community diversity and outages for particular communities. Power system models that include asset locations or connectivity can also provide information about system wear and tear, which could be reduced if load shedding is distributed across many feeders.

4 Targeted Demand Response Implementation Plan Considerations

This section outlines high-level requirements and considerations to implement a smart dispatchable load pilot program, a summary of which is provided in Table 22. Considerations focus on implementing a targeted DR or load-shedding program at the customer premise level as described in Section 3.5. Many of the considerations made in this section could also be applied to any direct load control application. The basic architecture outlined for direct load control and two-way communications could be extended to support additional use cases (e.g., aggregators, virtual power plants, flexible interconnection, and so on).

4.1 Location Requirements

Targeted DR or load-shedding programs are best piloted on a single distribution feeder. Multiple—i.e., two to three—feeders could be targeted to provide greater diversity of customer classes (e.g., residential, commercial, industrial). The targeted DR can be used as an alternative to load shedding for the study duration. It is assumed that the area selected serves a load level so that a failure to adhere to timely dispatch of targeted load shedding will not have detrimental system impacts. Feeders can be selected that serve critical infrastructure that would benefit from exclusion during load-shedding events (e.g., medical facilities, water pumping, and other critical infrastructure). Meshed networks may add a layer of complexity that can be addressed after a pilot demonstration, therefore radial feeders should be considered for the initial pilot. Feeders should be part of an AMI rollout. Targeted AMI load shedding can be considered a stacked benefit of AMI and can be planned for as AMI is rolled out in South Africa. The use of AMI for traditional billing purposes and targeted load dispatch can be cost-effective if they are combined. Feeders can be operated by Eskom distribution or a municipal distribution operator.

4.2 Customer Selection

Mixed customer types, reflecting residential, commercial, and industrial sectors, will be advantageous. Customers can be surveyed to identify preferences for scheduling and outage duration. Residential, commercial, or industrial customers may have different preferences for targeted load-shedding schedules; e.g., an industrial customer might prefer an advanced-notified 8-hour window of shedding to isolate impacts to a single shift. Residential customers may not place the same value on the ability to anticipate an outage and prefer shorter but less predictable outages. This will allow for deeper investigation into more advanced scheduling options that improve customer satisfaction and wellbeing. Possibilities for introducing incentives or remuneration for volunteered load reduction (i.e., increased frequency and magnitude) could be explored. Considerations for equity impacts are critical in this work because equitable opportunities for program enrollment can be balanced with the possibility that financial incentives can trigger the most vulnerable customers to shoulder a disproportionate amount of outage burden. Targeted load shedding could enable isolation and exemption of critical infrastructure (e.g., medical facilities, infrastructure needed for power system restoration, water treatment plants, and emergency responders).

4.3 Partner Selection

This pilot requires the cooperation of multiple partners. Because this work involves planning and hardware installations at a distribution feeder and coordination of load-shedding demand reductions, both Eskom and a municipality/metropolitan distribution operator (including potentially Eskom distribution) must be involved. Eskom distribution has recently run a pilot program for smart meter load limiting that has many similar features to targeted load shedding, including their lessons learned; potential scaling of that program would be beneficial.

Although many different devices can be used to provide targeted DR/load shedding (e.g., smart relays, circuit breakers, etc.), AMI meters have the greatest potential in terms of providing stacked benefits. AMI rollout is already underway in South Africa, and targeted load shedding through AMI can be an additional benefit of this technology. An AMI vendor to support AMI remote energization, particularly with respect to head-end software and ensuring sufficient communication bandwidth, is a key requirement (additional details provided in Section 4.4). Certified electrical contractors and installers and a communication network provider are also required. The communication network architecture has the option to be dedicated utility bandwidth and be used for additional utility communications and control (e.g., SCADA, DMS, DERMS).

4.4 Technology Requirements

The partners mentioned previously must support communication architecture and hardware integration. The communication architecture, latency, and bandwidth design will need to be designed to meet the minimum network traffic requirements (i.e., maximum volume of meters to be simultaneously dispatched, required response time, data transfer, etc.) for this application. If a communication network already exists, it will need to be assessed to ensure that it can support all required applications sharing the network. Of critical importance is the head-end meter data management system (MDMS) that will be used to dispatch the meters. Although remote turn-off of smart meters is a well-established technology, the software to remotely dispatch meters is nascent. Sections 3.1–3.4 describe the communication infrastructure selection in depth and can be used to guide preliminary identification of appropriate network technologies given targeted applications.

The AMI technology selected will need to have remote service turn-off and turn-on capabilities (i.e., the service disconnect switch), which is standard in most systems for billing noncompliance. Load-limiting meters, as recently implemented by Eskom, could be an alternative to full meter disconnect. Individual meters will need to be sufficiently responsive that the service disconnect can be remotely dispatched; ideally, meters will respond within seconds of receiving a dispatch signal. The actual meter itself would remain energized while the customer premise has been disconnected and deenergized.

4.5 Data Requirements

Measurement and verification of load reduction from targeted load-shed dispatch will quantify overall success, and minimum data resolution and fidelity will need to be established. Principal means of quantifying the response would be through time-series AMI measurements and validated at the feeder head through distribution SCADA measurements at the substation. These data can verify response to load-shed dispatch and reenergization signals and verify adherence to disparate customer preferences. For this pilot, customer load data will need to be measured at least twice the frequency of the minimum outage duration; e.g., if 30-minute rotations are being implemented, 15-minute data measurement intervals are required. Feeders that already have SCADA implemented may be ideal for pilot validation.

Survey data can also be collected before and after the pilot to understand customer preferences and experiences as part of the program. If the pilot is sufficiently long, surveys can be conducted midtrial, and feedback can be incorporated during the pilot. Having a pretrial survey would be valuable to baseline customer experiences under the existing load-shed regimen.

4.6 Duration and Season

This pilot could cover a period of operation that lasts 3 months at a minimum, with 1 year being ideal. This period can include the winter season when the most load shedding occurs. This will ensure testing of the pilot system at a time when its capabilities will be enlisted with greatest frequency. This will expose the novel technology implementation to a reasonable amount of stress in the form of frequent and realistic dispatches.

4.7 Regulatory Frameworks and Policy Considerations

Any implementation of load shedding will need to be consistent with NERSA’s NRS 048-9 [1]. Critical considerations include verification that load is dispatched and reenergized rapidly enough to comply with NRS 048-9. Timely notification to customers of load-shed events will still be required, even with targeted load-shedding schedules that are potentially more variable and dynamic. Any implementation of load shedding shall still adhere to real-time operational reporting requirements to the Eskom control room.

4.8 Equity and Gender Considerations

Energy equity objectives can be clearly defined in advance of the pilot implementation. In Section 3.5.1, metrics and expected outcomes for customer impacts are introduced. These include average daily cumulative outage durations, CAIDI, and distributions of outages over a population. Increased frequency of outage rotations can result in decreased daily service interruption time, decreased CAIDI, and more equal outage distributions. These metrics can be tracked during the pilot, and analyses that determine disproportionate variations in these metrics by customer demographics can be performed to address equity concerns. Examples of metrics that can be measured and studied to ensure that disproportionate impacts are avoided include the following:

- Access to essential services during outages (i.e., social burden [86], [87])
- Outages experienced by different customer classes (e.g., residential, commercial, industrial)
- Outages experienced by different socioeconomic groups (e.g., living standard measures, income brackets)
- Number of people experiencing outages (as opposed to households)
- Number of customers with disabilities or life-sustaining medical equipment experiencing outages
- Outage numbers and durations parsed by gender (e.g., by women-owned businesses)

- Reliability of the electricity during the evening peak in the residential sector and its impacts on household cooking

Research shows that electrification can improve gender equity by increasing women's employment opportunities [80], education, quality of life, and safety [89]. Although little work has been done to investigate gender disparity in the impacts of load shedding in South Africa, data in the pilot studies could be collected to understand the impact of decreased outage durations and social burden on customers of different demographics. Targeted demand response can be scheduled to consider reduced impact across different demographic groups.

Customer preferences for scheduling, as described in Section 4.2, can be accounted for in this pilot, although it should be noted that these preferences may be shaped by preexisting inequities. For example, cheaper electricity or compensation to be load shed first can result in a tendency of lower-income customers to enroll in these programs. The result is that the most vulnerable population may incur more service interruption that could exacerbate already existing levels of inequity. Any load-shedding implementation will need to carefully account for this possibility to avoid the exacerbation of such inequities. In selection areas for the targeted load control pilot, a baseline for the area(s) will need to be established. To measure socioeconomic benefits for historically disadvantaged communities, an area in which current load-shedding practices impact the community via economic hardship or burden in the form of access to technologies or services could be selected. Appropriate data collection, in the form of socioeconomic survey data, census data, and geospatial data for residences and essential services will need to be established.

Table 22. Summary of Implementation Plan Requirements and considerations

	Implementation Considerations
Where	• One entire feeder is the minimum requirement • Must be excluded from traditional load shedding during program • Serves critical infrastructure • Suburban, radial feeders
Who: Customers	• Customers from residential, industrial, and commercial sectors ○ Customer preferences for scheduling surveyed • Critical customers that benefit from being isolated
Who: Partners	• Implementation partner (municipality/metropolitan distribution utility or Eskom distribution) • AMI vendor • Installers ○ Certified electrical contractors ○ Communications vendor

	Implementation Considerations
When	• Implementation for a full year will provide an opportunity to examine customer impacts through all seasons and load-shed stages • Implementation for 3–6 months during times of greatest load-shedding dispatch will provide data to assess system implementation at the highest volume of network traffic and greatest customer impacts
What: Technology	• Communications ○ Communication network architecture that supports targeted AMI load-shed dispatch and reenergization • Customer premise hardware: ○ AMI with responsive remote turn-off and turn-on • Head-end AMI MDMS capable of orchestrating remote dispatch of meters
How: Data Requirements	• Per-customer data (from AMI) must be available at a frequency of twice that of the minimum outage duration (Nyquist frequency) for measurement and verification • Distribution SCADA data on a feeder to validate response
How: Policy and Regulation	• Implementations must adhere to NRS 048-9
How: Energy Equity	• A priori considerations for disproportionate customers impacts: ○ The data to measure these impacts must be collected, including demographic data, customer type data, and outage data that can be tied to customers ○ Metrics include CAIDI, maximum outage duration per customer, and daily cumulative outage duration

4.9 Laying the Foundation for Aggregators

Many of the baseline technologies (e.g., AMI, communication networks) provide key enabling functions that are required to unlock aggregator participation in the market. Customer incentives to participate in demand response can either be through dedicated utility incentive programs or provided by opportunities to participate in the wholesale market through demand-side aggregators. Liberalized energy markets are a key enabler for the participation of third-party aggregators in wholesale markets; however, utility aggregators can still be introduced to regulated markets. The UK's Demand Flexibility Service has implemented a program in which a third party has provided the market interface (i.e., bidding, dispatch, measurement and verification, and settling) for aggregators to participate in the wholesale market. The Federal Energy Regulatory Commission (FERC) recently issued an order (FERC Order 2222) that describes the requirements for utilities to meet that will enable DERs to participate in the wholesale market [90].

This pilot can be an opportunity to identify roles and responsibilities for the distribution system operator (DSO) in coordinating aggregated demand response with the transmission system operator (TSO). Full aggregator market participation have many technical and regulatory requirements and will require the participation of multiple stakeholders, including demand-side entities, DER developers, owners, and operators, DSOs, market operators, and TSOs [91], [92]. TSO and market operators will need to both create a market and operational framework for aggregator and DSO participation to enable receiving bids, issuing dispatch, and receiving M&V data from aggregators. The DSO will ultimately need to have some form of visibility of, or issuing of constraints to, aggregators for dispatch and operations to ensure that distribution network constraints are not violated in service of transmission system objectives (e.g., dispatch that could erode load diversity, which is fundamental to distribution system design). The DSO must have the visibility necessary to determine safe operating conditions and be given the ability to override any aggregation dispatch if these conditions cannot be satisfied. The TSO must be able to depend on aggregations that bid into any market. Roles and responsibilities of the aggregator, TSO, and DSO must be defined to ensure safe and reliable DER aggregation operation.

Looking ahead to future applications of targeted load control and the communication architecture supporting it, consideration can be made for the emergence of aggregators. Successful operation of an aggregation of distributed energy resources including demand response via direct load control will require two-way communications to devices that make up the aggregator fleet. These communications may be similar or the same (shared communications) as those installed for this pilot. Also critical is the interconnection standards that utilities use in connection agreements for DERs; recent key standards include IEEE 1547-2018 [93] and IEEE 2030.11 [94] that lay the foundation for grid support functions and communication requirements for DERs. Setting clear expectations and requirements for services offered by aggregators—such as energy, capacity, or ancillary services—is critical to establishing communication architectures that will provision these system services. These requirements will inform technical specifications such as data rate and communication latency and coordination with transmission and distribution system operators to ensure safe and reliable operation and adherence to grid constraints.

5 Conclusions

This report has explored how demand-side management (DSM) can provide benefits in terms of alleviating the impacts of the current electricity crisis, achieving energy efficiency gains, and providing enhanced demand-side flexibility and control. Enhanced demand-side flexibility also aids the integration of variable renewable energy resources. DSM programs provide customers with benefits through energy efficiency and corresponding bill savings. This report has explored a multitude of DSM programs and identified multiple untapped opportunities in South Africa.

Load shedding remains a major challenge for South Africa, and although critical measures such as load shedding are needed to maintain power system supply and demand, current load shedding programs have numerous downsides beyond customer service interruption. Current drawbacks include large economic impacts, the deenergization of entire communities for up to 4 hours, limited means of isolating critical infrastructure, the risk of theft of deenergized equipment, additional wear and tear to electrical equipment from frequent switching, and challenges of managing comeback load. Targeted demand control (either targeted load reduction or targeted load shedding) presents a major opportunity as an alternative to load shedding. Properly implemented, targeted load control can keep critical infrastructure energized, reduce theft by deenergizing customer premises only (not the network itself), reduce outage durations and more equally distribute outage durations, and help manage the comeback load. The potential use of smart meters to provide grid-edge control for targeted load control was explored and has also recently been piloted by Eskom in a smart load limiting control scheme. Two-way communication and leveraging targeted demand control through smart metering could provide multiple stacked benefits in terms of enabling net metering for solar, flexible loads, and time-of-use tariffs for energy efficiency and peak load reduction.

Future work for the implementation of targeted demand control can include a pilot to examine the real-world considerations for the requirements described in this report. Diversity in distribution systems can lead to diverse solutions for preferred communication network technologies. Additional modeling can provide deeper understanding of geospatial effects and advanced scheduling considerations. This can inform expected customer impacts when customer heterogeneity or preference is considered, including providing lessons for equitable implementation, improving social burden via access to essential and community resources, and providing more precise results for physical benefits such as reducing cold-load pickup and electrical asset wear and tear.

References

[1] "NRS048-9: ELECTRICITY SUPPLY — QUALITY OF SUPPLY PART 9: CODE OF PRACTICE – LOAD REDUCTION PRACTICES, SYSTEM RESTORATION PRACTICES AND CRITICAL LOAD AND ESSENTIAL LOAD REQUIREMENTS UNDER POWER SYSTEM EMERGENCIES." National Energy Regulator of South Africa (NERSA), 2019. [Online]. Available: https://buffalocity.gov.za/CM/uploads/documents/20201001011578662897NRS048-9-LoadReductionfinalwebsiteversion.pdf

[2] "Electricity: big business for municipalities | Statistics South Africa," Stats SA. Accessed: Nov. 29, 2022. [Online]. Available: https://www.statssa.gov.za/?p=10186

[3] T. Creamer, "CSIR statistics underline how significantly loadshedding has intensified during 2022." Accessed: Nov. 29, 2022. [Online]. Available: https://www.engineeringnews.co.za/article/csir-statistics-underline-how-significantly-loadshedding-has-intensified-during-2022-2022-11-14

[4] Warrick Pierce and Bianca Ferreira, "Statistics of utility-scale power generation in South Africa in 2021," CSIR Energy Centre, Apr. 2022.

[5] A. Gildenhuys, "Electricity Cons Prov.xlsx." provided by Eskom in correspondence with NREL, Sep. 22, 2022.

[6] L. Baker and J. Phillips, "Tensions in the transition: The politics of electricity distribution in South Africa," *Environ. Plan. C Polit. Space*, vol. 37, no. 1, pp. 177–196, 2019, doi: 10.1177/2399654418778590.

[7] A. Hughes and R. Larmour, "Residential Appliance Electricity Use in South Africa".

[8] "Power Africa in South Africa | Power Africa," U.S. Agency for International Development. Accessed: Nov. 20, 2023. [Online]. Available: https://www.usaid.gov/powerafrica/south-africa

[9] A. Gildenhuys, "2019 Base Year Annual End-use Forecast ver8.xlsb." provided by Eskom in correspondence with NREL, Oct. 2022.

[10] Eskom, "Energy Contribution 2020,"

[11] Tanzila Khan, Sumati Kohli, Zifei Yang, and Josh Miller, "Zero-emission vehicle deployment: Africa," INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION, Apr. 2022.

[12] "Green Transport Strategy for South Africa: (2018-2050)," Department of Transport: REPUBLIC OF SOUTH AFRICA.

[13] "Auto Green Paper on the Advancement of New Energy Vehicles in South Africa; The South African Road to Production Of Electric Vehicles (The Roadmap)." GOVERNMENT GAZETTE, May 21, 2021.

[14] T. Nortje and Eskom DSM, "South Africa's demand side management programme," *Install. Contract.*, no. 011, pp. 1–7, 2006.

[15] Y. Ye and S. F. Koch, "Measuring energy poverty in South Africa based on household required energy consumption," *Energy Econ.*, vol. 103, p. 105553, Nov. 2021, doi: 10.1016/j.eneco.2021.105553.

[16] A. Sguazzin, "South Africa to Allow Municipalities to Source Their Own Power," *Bloom. News*, Oct. 2020, [Online]. Available:

https://www.bloomberg.com/news/articles/2020-10-16/south-africa-to-allow-municipalities-to-source-their-own-power{\#}xj4y7vzkg

[17] City of Cape Town, “Loadshedding Mitigation Program,” Aug. 2022.

[18] Siphelele Dludla, “Eskom is getting ready to take over defaulting municipalities,” *Independent Online SA*, Feb. 15, 2021. [Online]. Available: https://www.iol.co.za/business-report/companies/eskom-is-getting-ready-to-take-over-defaulting-municipalities-d640674c-e14d-411e-b579-1762eb55585a

[19] A. Hughes and R. Larmour, “Review of Residential Energy Efficiency targets in South Africa,” 2021.

[20] A. Hughes and R. Larmour, “Residential Appliance Electricity Use in South Africa,” no. i, 2020.

[21] Department of Energy South Africa, “South Africa’s Energy Efficiency Targets Second Annual Monitoring Report,” no. September, 2015.

[22] L. Padachi, “Demand Management Initiative,” Oct. 10, 2022.

[23] “CSIR - NCPC partnership - Energy Advisory Services.” Accessed: Nov. 04, 2023. [Online]. Available: https://www.eskom.co.za/eas/csir-ncpc-partnership/

[24] Department of Energy South Africa, “Post-2015 National Energy Efficiency Strategy: Comments invited,” 2018.

[25] “South Africa’s Appliance Energy Efficiency Standards and Labeling Program Impact Assessment,” Department of Energy, Feb. 2020.

[26] T. Skinner and A. Gildenhuys, “Integrated Demand Management (IDM) Market End Use Knowledgebase.” Apr. 2013.

[27] “Power alert - Energy Advisory Services.” Accessed: Nov. 03, 2023. [Online]. Available: https://www.eskom.co.za/eas/power-alert/

[28] “GUIDELINE FOR ENERGY PERFORMANCE CERTIFICATES FOR BUILDINGS RELEASED BY SANEDI | ECASA.” Accessed: Nov. 04, 2023. [Online]. Available: https://ecasa.co.za/publications/guideline-for-energy-performance-certificates-for-buildings-released-by-sanedi/

[29] “Energy Performance Certificates – SANEDI.” Accessed: Nov. 04, 2023. [Online]. Available: https://sanedi.org.za/energy-performance-certificates/index.htm

[30] “SA’s First Energy Performance Certificate,” Business Media MAGS. Accessed: Nov. 04, 2023. [Online]. Available: https://businessmediamags.co.za/built-environment/infrastructure-pr/sas-first-energy-performance-certificate/

[31] J. Saebi, H. Taheri, J. Mohammadi, and S. S. Nayer, “Demand bidding/buyback modeling and its impact on market clearing price,” in *2010 IEEE International Energy Conference*, Manama, Bahrain: IEEE, Dec. 2010, pp. 791–796. doi: 10.1109/ENERGYCON.2010.5771788.

[32] California ISO, “Proxy Demand Resource (PDR) & Reliability Demand Response Resource (RDRR) Participation Overview,”

[33] EirGrid, “DSU Interview.”

[34] T. S. Popik and R. H. Humphreys, “The 2021 Texas Electric Grid Failure: Causes, Consequences, and Cures,” *J. Crit. Infrastruct. Policy*, vol. 2, no. 1, Jul. 2021, doi: 10.18278/jcip.2.1.6.

[35] B. Anderson, J. Reilly, and V. Krishnan, “Load Control for Frequency Response - A Literature Review,” NREL/TP-5000-77780, 1846936, MainId:30695, Feb. 2022. doi: 10.2172/1846936.

[36] K. Ögelman, “Overview of Demand Response in ERCOT,” Sep. 16, 2021.

[37] *Electric Rule No. 21: Generating Facility Interconnections*, vol. 42298-E. 2018.

[38] Hawaiian Electric, *Rule no. 14, Service Connections and Facilities on Customer’s Premises*.

[39] South Africa Department of Mineral and Energy Affairs, *Electricity Act 1987, regulation 2665*. 1990.

[40] Z. Wang and J. Wang, “Review on Implementation and Assessment of Conservation Voltage Reduction,” *IEEE Trans. Power Syst.*, vol. 29, no. 3, pp. 1306–1315, May 2014, doi: 10.1109/TPWRS.2013.2288518.

[41] T. R. Lowder, J. S. Logan, E. I. Chen, and 21st Century Power Partnership (21CPP), “Innovative Utility Offerings at the Distribution Edge: Case Studies from Around the Globe,” NREL/TP--7A40-73800, 1523611, May 2019. doi: 10.2172/1523611.

[42] A. Chitkara, D. Cross-Call, B. Li, and J. Sherwood, “A Review Of Alternative Rate Designs: Industry Experience with Time-Based and Demand Charge Rates for Mass-Market Customers,” Rocky Mountain Institute, Boulder, CO, May 2016.

[43] “Hawaii PUC Smart-Export CGS Fact Sheets.”

[44] Electricity Pricing, Eskom, Distribution, “Proposed new Critical Peak Pricing tariff, called ‘Critical Peak Pricing’(CPP) for the purpose of phase 2 pilot testing,” Oct. 2020.

[45] “Electricity Smart Metering Customer Behaviour Trials (CBT) Findings Report,” The Commission for Energy Regulation, Dublin, Ireland, May 2011.

[46] “California consumers respond to appeals for electricity conservation during heat wave.” Accessed: Nov. 03, 2023. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=54039

[47] T. Stanton, “Review of State Net Energy Metering and Successor Rate Designs”.

[48] City of Cape Town, “Requirements for Small-Scale Embedded Generation: Application and approval process for small-scale embedded generation in the City of Cape Town.” Sep. 2021.

[49] Luke Daniel, “You can sell excess solar power back to govt – but it may take around 7 years to break even,” *Business Insider SA*, Jan. 23, 2021. Accessed: Nov. 29, 2022. [Online]. Available: https://www.businessinsider.co.za/you-can-sell-excess-solar-power-back-to-govt-but-it-can-take-around-7-years-to-break-even-2021-1

[50] “Status of Small Scall Embedded Generation (SSEG) in South African Municipalities.” South African Local Government Association (SALGA), Nov. 2020. [Online]. Available: https://www.sagen.org.za/publications/all-publications/112-status-of-small-scale-embedded-generation-in-south-african-municipalities/file

[51] “Wheeling Concept Introduction.” Eskom, 2022.

[52] E. M. Nkoana, “Community acceptance challenges of renewable energy transition: A tale of two solar parks in Limpopo, South Africa,” *J. Energy South. Afr.*, vol. 29, no. 1, pp. 34–40, Feb. 2018, doi: 10.17159/2413-3051/2018/v29i1a2540.

[53] Lucas Ledwaba, “Solar energy is the way and the light for this Limpopo village,” *Daily Maverick*, Apr. 20, 2022. Accessed: Nov. 29, 2022. [Online]. Available: https://www.dailymaverick.co.za/article/2022-04-20-solar-energy-is-the-way-and-the-light-for-this-limpopo-village/

[54] C. Curry, “Lithium-ion Battery Costs and Market,” Jul. 05, 2017.

[55] H. Kayali and Asst. P. Dr. Halil Alibaba, “Comparison of Different Solar Thermal Energy Collectors and Their Integration Possibilities in Architecture,” *Sustain. Environ.*, vol. 2, no. 1, p. 36, Feb. 2017, doi: 10.22158/se.v2n1p36.

[56] Nomawethu Qase, “Feedback on Progress Regarding the Appointment of Technical Feasibility Assessment and Social Facilitation Consultants,” Aug. 28, 2018.

[57] Mokgadi Modise, “Overview Presentation on the Implementation of Solar Water Heater (SWH) Programme,” presented at the Inception Workshop, May 31, 2018.

[58] J. Dean and J. Dice, “Energy Management Information Systems Technical Resources Report,” U.S. Department of Energy, Energy Efficiency Renewable Energy Office, Jul. 2021.

[59] “Chapter 5: Increasing Efficiency of Building Systems and Technologies,” U.S. Department of Energy, Sep. 2015.

[60] T. Putnam and D. Brown, “Grassroots retrofit: Community governance and residential energy transitions in the United Kingdom,” *Energy Res. Soc. Sci.*, vol. 78, p. 102102, Aug. 2021, doi: 10.1016/j.erss.2021.102102.

[61] O. A. Oguntona, B. M. Maseko, C. O. Aigbavboa, and W. D. Thwala, “Barriers to retrofitting buildings for energy efficiency in South Africa,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 640, no. 1, p. 012015, Nov. 2019, doi: 10.1088/1757-899X/640/1/012015.

[62] “Cape Town renovates for energy efficient homes and healthy residents.”

[63] P. De Martini *et al.*, “Modern Distribution Grid (DSPx) Volume II: Advanced Technology Maturity Assessment,” US Department of Energy: Office of Electricity, Version 2.0, Nov. 2019. [Online]. Available: https://gridarchitecture.pnnl.gov/media/Modern-Distribution-Grid_Volume_II_v2_0.pdf

[64] “Wireless Emergency Alerts Mobile Penetration Strategy”.

[65] *Wireless Emergency Alerts Second Report and Order and Second Order on Reconsideration PS Docket No. 15-91*.

[66] “‘Conserve Energy’: New York City Begs Residents to Help Avoid Outages - The New York Times.” Accessed: Mar. 06, 2023. [Online]. Available: https://www.nytimes.com/2021/06/30/nyregion/nyc-energy-alert-heatwave.html

[67] “Is a Heat Pump the Best Heating System for Your Florida Home?,” Kobie Complete Heating & Cooling Inc. Accessed: Feb. 22, 2023. [Online]. Available: https://kobiecomplete.com/blog/is-a-heat-pump-the-best-heating-system-for-your-florida-home/

[68] S. Peter, N. Kambule, S. Tangwe, and K. Yessoufou, “Assessing the Feasibility and the Potential of Implementing Solar Water Heaters in Dimbaza, a Township in Eastern Cape, South Africa,” *Sustainability*, vol. 14, no. 19, p. 12502, Sep. 2022, doi: 10.3390/su141912502.

[69] A. Hughes and R. Larmour, “Residential Energy Efficiency Report,” University of Capetown, Apr. 2021.

[70] A. Hughes and R. Larmour, “Review of Residential Energy Efficiency targets in South Africa”.

[71] M. Panwar, R. Hovsapian, F. Eldali, T. Thomas, and C. Koplin, “Design of Resilient Electric Distribution Systems for Remote Communities: Surgical Load Management using Smart Meters,” in *2021 Resilience Week (RWS)*, Salt Lake City, UT, USA: IEEE, Oct. 2021, pp. 1–4. doi: 10.1109/RWS52686.2021.9611791.

[72] S. Galli, A. Scaglione, and Z. Wang, “Power Line Communications and the Smart Grid,” in *2010 First IEEE International Conference on Smart Grid Communications*, Gaithersburg, MD, USA: IEEE, Oct. 2010, pp. 303–308. doi: 10.1109/SMARTGRID.2010.5622060.

[73] R. H. Khan and J. Y. Khan, “A comprehensive review of the application characteristics and traffic requirements of a smart grid communications network,” *Comput. Netw.*, vol. 57, no. 3, pp. 825–845, Feb. 2013, doi: 10.1016/j.comnet.2012.11.002.

[74] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, “Communication network requirements for major smart grid applications in HAN, NAN and WAN,” *Comput. Netw.*, vol. 67, pp. 74–88, Jul. 2014, doi: 10.1016/j.comnet.2014.03.029.

[75] Y. Kabalci, “A survey on smart metering and smart grid communication,” *Renew. Sustain. Energy Rev.*, vol. 57, pp. 302–318, May 2016, doi: 10.1016/j.rser.2015.12.114.

[76] M. Emmanuel and R. Rayudu, “Communication technologies for smart grid applications: A survey,” *J. Netw. Comput. Appl.*, vol. 74, pp. 133–148, Oct. 2016, doi: 10.1016/j.jnca.2016.08.012.

[77] K. C. Budka, J. G. Deshpande, and M. Thottan, *Communication networks for smart grids*. Springer, 2016.

[78] D. V. Oksman, “New ITU-T Recommendations for Smart Grid in-home and access communications,” presented at the ETSI Smart Grid Workshops, Sophia Antipolis, France, Apr. 2011.

[79] D. Dzung, I. Berganza, and A. Sendin, “Evolution of powerline communications for smart distribution: From ripple control to OFDM,” in *2011 IEEE International Symposium on Power Line Communications and Its Applications*, Udine, Italy: IEEE, Apr. 2011, pp. 474–478. doi: 10.1109/ISPLC.2011.5764444.

[80] S. H. Mahmood, A. M. Salih, and M. I. Khalil, “Broadband Services on Power Line Communication Systems: A Review,” in *2019 22nd International Conference on Control Systems and Computer Science (CSCS)*, Bucharest, Romania: IEEE, May 2019, pp. 465–470. doi: 10.1109/CSCS.2019.00085.

[81] “IEEE Standard for Low-Frequency (less than 500 kHz) Narrowband Power Line Communications for Smart Grid Applications,” IEEE. doi: 10.1109/IEEESTD.2013.6679210.

[82] L. L. Peterson and B. S. Davie, *Computer Networks: A Systems Approach*. Elsevier, 2007.

[83] G. Strbac, “Demand side management: Benefits and challenges,” *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, Dec. 2008, doi: 10.1016/j.enpol.2008.09.030.

[84] S. Ihara and F. Schweppe, “Physically Based Modeling of Cold Load Pickup,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-100, no. 9, pp. 4142–4150, Sep. 1981, doi: 10.1109/TPAS.1981.316965.

[85] “IEEE Std 1366$^{\text{TM}}$-2022, IEEE Guide for Electric Power Distribution Reliability Indices,” 2022.

[86] A. Wachtel, D. Melander, and R. Jeffers, “Measuring Social Infrastructure Service Burden”.

[87] S. S. Clark, S. K. E. Peterson, M. A. Shelly, and R. F. Jeffers, “Developing an equity-focused metric for quantifying the social burden of infrastructure disruptions,” *Sustain. Resilient Infrastruct.*, vol. 8, no. sup1, pp. 356–369, Jan. 2023, doi: 10.1080/23789689.2022.2157116.

[88] T. Dinkelman, “The Effects of Rural Electrification on Employment: New Evidence from South Africa,” *Am. Econ. Rev.*, vol. 101, no. 7, pp. 3078–3108, Dec. 2011, doi: 10.1257/aer.101.7.3078.
[89] S. Kannan and D. L. Bessette, “Time-use among men and women in Zambia: A comparison of grid, off-grid, and unconnected households,” *Energy Sustain. Dev.*, vol. 76, p. 101276, Oct. 2023, doi: 10.1016/j.esd.2023.101276.
[90] US Federal Energy Regulatory Commission, “FERC Order 2222 - Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators.” Sep. 17, 2020. Accessed: Mar. 14, 2021. [Online]. Available: https://www.ferc.gov/sites/default/files/2020-09/E-1_0.pdf
[91] “Aggregators – Innovation Landscape Brief”.
[92] “Pathways to Commercial Liftoff: Virtual Power Plants”.
[93] “IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces,” *IEEE Std 1547-2018 Revis. IEEE Std 1547-2003*, pp. 1–138, Apr. 2018, doi: 10.1109/IEEESTD.2018.8332112.
[94] “IEEE Guide for Distributed Energy Resources Management Systems (DERMS) Functional Specification,” IEEE. doi: 10.1109/IEEESTD.2021.9447316.

Bibliography

"A Paradigm Shift for Utility Load Management?" 2020. Energy Central. September 30, 2020. https://energycentral.com/o/EPRI/paradigm-shift-utility-load-management.

Abdullah, Muhammad Mehroze, and Barry Dwolatzky. n.d. "Demand-Side Energy Management Performed Using Direct Feedback via Mobile Systems: Enables Utilities to Deploy Consumer Based Demand Response Programs." In *2010 IEEE International Energy Conference*, 172–77. IEEE. https://doi.org/10.1109/ENERGYCON.2010.5771670.

"Aggregators – Innovation Landscape Brief." n.d.

Anderson, Benjamin, Jim Reilly, and Venkat Krishnan. 2022. "Load Control for Frequency Response - A Literature Review." NREL/TP-5000-77780, 1846936, MainId:30695. https://doi.org/10.2172/1846936.

"APS Cool Rewards FAQ · EnergyHub BYOT." n.d. Accessed January 31, 2023. https://www.apscoolrewards.com/faqs/apscoolrewards-faq/.

Asbery, Christopher W., Xiangqing Jiao, and Yuan Liao. 2016. "Implementation Guidance of Smart Grid Communication." In *2016 North American Power Symposium (NAPS)*, 1–6. Denver, CO, USA: IEEE. https://doi.org/10.1109/NAPS.2016.7747879.

"Auto Green Paper on the Advancement of New Energy Vehicles in South Africa; The South African Road to Production Of Electric Vehicles (The Roadmap)." 2021. GOVERNMENT GAZETTE.

Baker, Lucy, and Jon Phillips. 2019. "Tensions in the Transition: The Politics of Electricity Distribution in South Africa." *Environment and Planning C: Politics and Space* 37 (1): 177–96. https://doi.org/10.1177/2399654418778590.

Bashir, Noman, Zohaib Sharani, Khushboo Qayyum, and Affan A. Syed. 2015. "Delivering Smart Load-Shedding for Highly-Stressed Grids." In *2015 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 852–58. Miami, FL, USA: IEEE. https://doi.org/10.1109/SmartGridComm.2015.7436408.

Budka, Kenneth C., Jayant G. Deshpande, and Marina Thottan. 2016. *Communication Networks for Smart Grids*. Springer.

"California Consumers Respond to Appeals for Electricity Conservation during Heat Wave." n.d. Accessed November 3, 2023. https://www.eia.gov/todayinenergy/detail.php?id=54039.

California ISO. n.d. "Proxy Demand Resource (PDR) & Reliability Demand Response Resource (RDRR) Participation Overview."

"Cape Town Renovates for Energy Efficient Homes and Healthy Residents." n.d.

"Chapter 5: Increasing Efficiency of Building Systems and Technologies." 2015. U.S. Department of Energy.

Chitkara, Aman, Dan Cross-Call, Becky Li, and James Sherwood. 2016. "A Review Of Alternative Rate Designs: Industry Experience with Time-Based and Demand Charge Rates for Mass-Market Customers." Boulder, CO: Rocky Mountain Institute.

City of Cape Town. 2021. "Requirements for Small-Scale Embedded Generation: Application and Approval Process for Small-Scale Embedded Generation in the City of Cape Town."

———. 2022. "Loadshedding Mitigation Program." August.

Cloete, Andrew Hector. 2017. "A Domestic Electric Water Heater Application for Smart Grid." PhD Thesis, Stellenbosch University.

Communication Networks for Smart Grids. n.d.

"'Conserve Energy': New York City Begs Residents to Help Avoid Outages - The New York Times." n.d. Accessed March 6, 2023. https://www.nytimes.com/2021/06/30/nyregion/nyc-energy-alert-heatwave.html.

Creamer, Terence. n.d. "CSIR Statistics Underline How Significantly Loadshedding Has Intensified during 2022." Accessed November 29, 2022. https://www.engineeringnews.co.za/article/csir-statistics-underline-how-significantly-loadshedding-has-intensified-during-2022-2022-11-14.

"CSIR - NCPC Partnership - Energy Advisory Services." 2021. April 21, 2021. https://www.eskom.co.za/eas/csir-ncpc-partnership/.

Curry, Claire. 2017. "Lithium-Ion Battery Costs and Market." July 5.

Dean, Jesse, and James Dice. 2021. "Energy Management Information Systems Technical Resources Report." U.S. Department of Energy, Energy Efficiency Renewable Energy Office.

Department of Energy South Africa. 2010a. "Demand Side Management - IRP 2010 Input Parameter Information Sheet." http://www.doe-irp.co.za/factsheets/D6{_}Demand{_}Side{_}Management.pdf.

———. 2010b. "Policy to Support the Energy Efficiency and Demand Side Management Program for the Electricity Sector through the Standard Offer Incentive Scheme," no. May: 13.

———. 2010c. "Policy to Support the Energy Efficiency and Demand Side Management Program for the Electricity Sector through the Standard Offer Incentive Scheme," no. May: 13.

———. 2015. "South Africa's Energy Efficiency Targets Second Annual Monitoring Report," no. September.

———. 2018. "Post-2015 National Energy Efficiency Strategy: Comments Invited."

Department of Energy South Africa and South African National Energy Development Institute. 2021a. "Energy Footprint Analysis - The South Africa Automotive Sector," 1–7.

———. 2021b. "Energy Footprint Analysis - The South African Pulp and Paper Subsector," 1–7.

Dinkelman, Taryn. 2011. "The Effects of Rural Electrification on Employment: New Evidence from South Africa." *American Economic Review* 101 (7): 3078–3108. https://doi.org/10.1257/aer.101.7.3078.

Dzung, Dacfey, Inigo Berganza, and Alberto Sendin. 2011. "Evolution of Powerline Communications for Smart Distribution: From Ripple Control to OFDM." In *2011 IEEE International Symposium on Power Line Communications and Its Applications*, 474–78. Udine, Italy: IEEE. https://doi.org/10.1109/ISPLC.2011.5764444.

Ebeid, Emad, Sergi Rotger-Griful, Soren Aagaard Mikkelsen, and Rune Hylsberg Jacobsen. 2015. "A Methodology to Evaluate Demand Response Communication Protocols for the Smart Grid." In *2015 IEEE International Conference on Communication Workshop (ICCW)*, 2012–17. London, United Kingdom: IEEE. https://doi.org/10.1109/ICCW.2015.7247476.

Eberhard, Rolfe. n.d. "The Municipal Electricity Industry – Key Dynamics with a Focus on the Metros," 27.

EirGrid. n.d. DSU Interview.

Electric Rule No. 21: Generating Facility Interconnections. 2018. Vol. 42298-E.

"Electricity: Big Business for Municipalities | Statistics South Africa." n.d. Stats SA. Accessed November 29, 2022. https://www.statssa.gov.za/?p=10186.

Electricity Pricing, Eskom, Distribution. 2020. "Proposed New Critical Peak Pricing Tariff, Called 'Critical Peak Pricing'(CPP) for the Purpose of Phase 2 Pilot Testing." October.

"Electricity Smart Metering Customer Behaviour Trials (CBT) Findings Report." 2011. Dublin, Ireland: The Commission for Energy Regulation.

Emmanuel, Michael, and Ramesh Rayudu. 2016. "Communication Technologies for Smart Grid Applications: A Survey." *Journal of Network and Computer Applications* 74 (October): 133–48. https://doi.org/10.1016/j.jnca.2016.08.012.

"Energy Management Circuit Breaker." n.d. Eaton. Accessed January 17, 2023. https://www.eaton.com/us/en-us/markets/innovation-stories/energy-management-circuit-breaker.html.

"Energy Performance Certificates – SANEDI." n.d. Accessed November 4, 2023. https://sanedi.org.za/energy-performance-certificates/index.htm.

Energy Sector Management Assistance Program. 2011. "Implementing Energy Efficiency and Demand Side Management - South Africa's Standard Offer Model." *Briefing Note 007/11*.

Eskom. 2012. "Eskom's Approach to Energy Efficiency and Demand Side Management." https://www.google.com/url?sa=t{\&}rct=j{\&}q={\&}esrc=s{\&}source=web{\&}cd={\&}ved=2ahUKEwjdrbTGwY75AhXiQUEAHSXTD6kQFnoECAYQAQ{\&}url=https{\%}3A{\%}2F{\%}2Fpmg.org.za{\%}2Ffiles{\%}2Fdocs{\%}2F120906eskom{_}0.pdf{\&}usg=AOvVaw04nalRKP5PeudyG3D0F1FE.

———. n.d. "Energy Contribution 2020."

Fan, Zhong, Parag Kulkarni, Sedat Gormus, Costas Efthymiou, Georgios Kalogridis, Mahesh Sooriyabandara, Ziming Zhu, Sangarapillai Lambotharan, and Woon Hau Chin. 2013. "Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities." *IEEE Communications Surveys & Tutorials* 15 (1): 21–38. https://doi.org/10.1109/SURV.2011.122211.00021.

Fortuin, Wayne. n.d. "Eskom Integrated Demand Management Update," 27.

Fréchet, Jacques. 2000. "Demand-Side Management: The E7 Experience, An Electric Utility Overview of Policies and Practices in Demand-Side Management." The E7 Network of Expertise For The Global Environment.

Galli, Stefano, Anna Scaglione, and Zhifang Wang. 2010. "Power Line Communications and the Smart Grid." In *2010 First IEEE International Conference on Smart Grid Communications*, 303–8. Gaithersburg, MD, USA: IEEE. https://doi.org/10.1109/SMARTGRID.2010.5622060.

Gildenhuys, Andries. 2022a. "Electricity Cons Prov.Xlsx." provided by Eskom in correspondence with NREL.

———. 2022b. "2019 Base Year Annual End-Use Forecast Ver8.Xlsb." provided by Eskom in correspondence with NREL.

"Green Transport Strategy for South Africa: (2018-2050)." n.d. Department of Transport: REPUBLIC OF SOUTH AFRICA.

"GUIDELINE FOR ENERGY PERFORMANCE CERTIFICATES FOR BUILDINGS RELEASED BY SANEDI | ECASA." 2022. June 20, 2022. https://ecasa.co.za/publications/guideline-for-energy-performance-certificates-for-buildings-released-by-sanedi/.

Gull, Muhammad S., Nasir Mehmood, Huzaifa Rauf, Muhammad Khalid, and Naveed Arshad. 2022. "Soft Load Shedding Based Demand Control of Residential Consumers." *Electronics* 11 (4): 615. https://doi.org/10.3390/electronics11040615.

Gungor, V. Cagri, Dilan Sahin, Taskin Kocak, Salih Ergut, Concettina Buccella, Carlo Cecati, and Gerhard P. Hancke. 2013. "A Survey on Smart Grid Potential Applications and Communication Requirements." *IEEE Transactions on Industrial Informatics* 9 (1): 28–42. https://doi.org/10.1109/TII.2012.2218253.

Gungor, V.C., and F.C. Lambert. 2006. "A Survey on Communication Networks for Electric System Automation." *Computer Networks* 50 (7): 877–97. https://doi.org/10.1016/j.comnet.2006.01.005.

"Hawaii PUC Smart-Export CGS Fact Sheets." n.d.

Hawaiian Electric. n.d. *Rule No. 14, Service Connections and Facilities on Customer's Premises*.

Hebert, Aurelie. n.d. "Communication Protocols and Standards for Residential Demand Response."

Hlalele, Thabo G, Jiangfeng Zhang, Raj M Naidoo, and Ramesh C Bansal. n.d. “Multi-Objective Economic Dispatch with Residential Demand Response Programme under Renewable Obligation” 218: 119473. https://doi.org/10.1016/j.energy.2020.119473.

Hughes, Alison, and Richard Larmour. 2021. “Residential Energy Efficiency Report.” University of Capetown.

———. n.d. “Residential Appliance Electricity Use in South Africa.”

———. n.d. “Review of Residential Energy Efficiency Targets in South Africa.”

“IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads.” n.d. IEEE. Accessed May 17, 2023. https://doi.org/10.1109/IEEESTD.2011.6018239.

“IEEE Standard for Low-Frequency (Less than 500 KHz) Narrowband Power Line Communications for Smart Grid Applications.” n.d. IEEE. Accessed May 16, 2023. https://doi.org/10.1109/IEEESTD.2013.6679210.

“IEEE Std 1366^{TM}-2022, IEEE Guide for Electric Power Distribution Reliability Indices.” 2022.

Ihara, Satoru, and Fred Schweppe. 1981. “Physically Based Modeling of Cold Load Pickup.” *IEEE Transactions on Power Apparatus and Systems* PAS-100 (9): 4142–50. https://doi.org/10.1109/TPAS.1981.316965.

Integrated Demand Management. 2018. “Eskom Integrated Demand Management: The Way Forward,” no. November.

International Energy Agency. 2019. “Energy Efficiency and Demand Side Management Programme Overview.”

“Is a Heat Pump the Best Heating System for Your Florida Home?” 2017. Kobie Complete Heating & Cooling Inc. November 17, 2017. https://kobiecomplete.com/blog/is-a-heat-pump-the-best-heating-system-for-your-florida-home/.

Jain, Shilpi, and P K Jain. 2017. “The Rise of Renewable Energy Implementation in South Africa.” *Energy Procedia* 143: 721–26. https://doi.org/10.1016/j.egypro.2017.12.752.

Kabalci, Yasin. 2016. “A Survey on Smart Metering and Smart Grid Communication.” *Renewable and Sustainable Energy Reviews* 57 (May): 302–18. https://doi.org/10.1016/j.rser.2015.12.114.

Kannan, Sudha, and Douglas L. Bessette. 2023. “Time-Use among Men and Women in Zambia: A Comparison of Grid, off-Grid, and Unconnected Households.” *Energy for Sustainable Development* 76 (October): 101276. https://doi.org/10.1016/j.esd.2023.101276.

Kayali, Humam, and Asst. Professor Dr. Halil Alibaba. 2017. “Comparison of Different Solar Thermal Energy Collectors and Their Integration Possibilities in Architecture.” *Sustainability in Environment* 2 (1): 36. https://doi.org/10.22158/se.v2n1p36.

Kazmi, Hussain, Fahad Mehmood, Zhenmin Tao, Zainab Riaz, and Johan Driesen. 2019. “Electricity Load-Shedding in Pakistan: Unintended Consequences, Opportunities and Policy Recommendations.” *Energy Policy* 128 (May): 411–17. https://doi.org/10.1016/j.enpol.2019.01.017.

Khan, Reduan H., and Jamil Y. Khan. 2013. “A Comprehensive Review of the Application Characteristics and Traffic Requirements of a Smart Grid Communications Network.” *Computer Networks* 57 (3): 825–45. https://doi.org/10.1016/j.comnet.2012.11.002.

Kuzlu, Murat, Manisa Pipattanasomporn, and Saifur Rahman. 2014. “Communication Network Requirements for Major Smart Grid Applications in HAN, NAN and WAN.” *Computer Networks* 67 (July): 74–88. https://doi.org/10.1016/j.comnet.2014.03.029.

Liu, Xin, Bo Chen, Chen Chen, and Dong Jin. 2020. “Electric Power Grid Resilience with Interdependencies between Power and Communication Networks – a Review.” *IET Smart Grid* 3 (2): 182–93. https://doi.org/10.1049/iet-stg.2019.0202.

Lowder, Travis R., Jeffrey S. Logan, Emily I. Chen, and 21st Century Power Partnership (21CPP). 2019. “Innovative Utility Offerings at the Distribution Edge: Case Studies from Around the Globe.” NREL/TP--7A40-73800, 1523611. https://doi.org/10.2172/1523611.

Lucas Ledwaba. 2022. “Solar Energy Is the Way and the Light for This Limpopo Village.” *Daily Maverick*, April 20, 2022. https://www.dailymaverick.co.za/article/2022-04-20-solar-energy-is-the-way-and-the-light-for-this-limpopo-village/.

Luke Daniel. 2021. “You Can Sell Excess Solar Power Back to Govt – but It May Take around 7 Years to Break Even.” *Business Insider SA*, January 23, 2021. https://www.businessinsider.co.za/you-can-sell-excess-solar-power-back-to-govt-but-it-can-take-around-7-years-to-break-even-2021-1.

Mahmood, Salih Hassan, Abdulkreem Mohammed Salih, and Muhammed Ismail Khalil. 2019. “Broadband Services on Power Line Communication Systems: A Review.” In *2019 22nd International Conference on Control Systems and Computer Science (CSCS)*, 465–70. Bucharest, Romania: IEEE. https://doi.org/10.1109/CSCS.2019.00085.

Mohagheghi, Salman, James Stoupis, Zhenyuan Wang, Zhao Li, and Hormoz Kazemzadeh. 2010. “Demand Response Architecture: Integration into the Distribution Management System.” In *2010 First IEEE International Conference on Smart Grid Communications*, 501–6. Gaithersburg, MD, USA: IEEE. https://doi.org/10.1109/SMARTGRID.2010.5622094.

Mokgadi Modise. 2018. “Overview Presentation on the Implementation of Solar Water Heater (SWH) Programme.” Presented at the Inception Workshop, May 31.

Molteno, Christopher. 2018a. “Evaluating Demand Side Management in South Africa,” 1–5.

———. 2018b. “Evaluating Electricity Demand Side Management Opportunities in South Africa,” 1–5.

Monyei, C G, and A O Adewumi. 2017. “Demand Side Management Potentials for Mitigating Energy Poverty in South Africa.” *Energy Policy* 111: 298–311. https://doi.org/10.1016/j.enpol.2017.09.039.

Monyei, C.G., and A.O. Adewumi. 2018. “Integration of Demand Side and Supply Side Energy Management Resources for Optimal Scheduling of Demand Response Loads – South Africa in Focus.” *Electric Power Systems Research* 158 (May): 92–104. https://doi.org/10.1016/j.epsr.2017.12.033.

Morovati, Samaneh, Seddik M. Djouadi, Mohammed Olama, Jin Dong, Kevin Tomsovic, Aly Fathy, and Teja Kuruganti. 2021. “Inertia Emulation Control Using Demand Response via 5G Communications.” In *2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 1–5. Chicago, IL, USA: IEEE. https://doi.org/10.1109/PEDG51384.2021.9494275.

Ngarava, Saul, Leocadia Zhou, Thulani Ningi, Martin M. Chari, and Lwandiso Mdiya. 2022. “Gender and Ethnic Disparities in Energy Poverty: The Case of South Africa.” *Energy Policy* 161 (February): 112755. https://doi.org/10.1016/j.enpol.2021.112755.

Nkoana, Elvis Modikela. 2018. “Community Acceptance Challenges of Renewable Energy Transition: A Tale of Two Solar Parks in Limpopo, South Africa.” *Journal of Energy in Southern Africa* 29 (1): 34–40. https://doi.org/10.17159/2413-3051/2018/v29i1a2540.

Nomawethu Qase. 2018. “Feedback on Progress Regarding the Appointment of Technical Feasibility Assessment and Social Facilitation Consultants.” August 28.

Nortje, Tobias and Eskom DSM. 2006. “South Africa’s Demand Side Management Programme.” *Installations & Contracting*, no. 011: 1–7.

“NRS048-9: ELECTRICITY SUPPLY — QUALITY OF SUPPLY PART 9: CODE OF PRACTICE – LOAD REDUCTION PRACTICES, SYSTEM RESTORATION PRACTICES AND CRITICAL LOAD AND ESSENTIAL LOAD REQUIREMENTS UNDER POWER SYSTEM EMERGENCIES.” 2019. National Energy Regulator of South Africa (NERSA). https://buffalocity.gov.za/CM/uploads/documents/20201001011578662897NRS048-9-LoadReductionfinalwebsiteversion.pdf.

Nwulu, Nnamdi. 2017. “A Mathematical Modelling Framework for Optimal Demand Response Incentives and Retrofit.” In *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, 3821–26. Chennai: IEEE. https://doi.org/10.1109/ICECDS.2017.8390179.

Nwulu, Nnamdi, and Yanxia Sun. 2016. “Optimal Incentivized Demand Response and Building Retrofits.” In *2016 International Conference on Advances in Computing and Communication Engineering (ICACCE)*, 418–22. Durban, South Africa: IEEE. https://doi.org/10.1109/ICACCE.2016.8073785.

Ögelman, Kenan. 2021. “Overview of Demand Response in ERCOT.” September 16.

Oguntona, O A, B M Maseko, C O Aigbavboa, and W D Thwala. 2019. “Barriers to Retrofitting Buildings for Energy Efficiency in South Africa.” *IOP Conference Series: Materials Science and Engineering* 640 (1): 012015. https://doi.org/10.1088/1757-899X/640/1/012015.

Oksman, Dr Vladimir. 2011. “New ITU-T Recommendations for Smart Grid in-Home and Access Communications.” Presented at the ETSI Smart Grid Workshops, Sophia Antipolis, France, April.

Özdemir, Enver Doruk, Sheetal Dattatraya Marathe, Jan Tomaschek, Audrey Dobbins, and Ludger Eltrop. 2012. “Economic and Environmental Analysis of Solar Water Heater Utilisation in Gauteng Province, South Africa.” *Journal of Energy in Southern Africa* 23 (2): 2–19. https://doi.org/10.17159/2413-3051/2012/v23i2a3157.

Padachi, Lawrence. 2022. “Demand Management Initiative.” October 10.

Panwar, Mayank, Rob Hovsapian, Fathalla Eldali, Tony Thomas, and Clay Koplin. 2021. “Design of Resilient Electric Distribution Systems for Remote Communities: Surgical Load Management Using Smart Meters.” In *2021 Resilience Week (RWS)*, 1–4. Salt Lake City, UT, USA: IEEE. https://doi.org/10.1109/RWS52686.2021.9611791.

Parizy, Ehsan Saeidpour, Hamid Reza Bahrami, and Seungdeog Choi. 2019. “A Low Complexity and Secure Demand Response Technique for Peak Load Reduction.” *IEEE Transactions on Smart Grid* 10 (3): 3259–68. https://doi.org/10.1109/TSG.2018.2822729.

“Pathways to Commercial Liftoff: Virtual Power Plants.” n.d.

Perera, B. S.P., K. Nguyen, V. J. Gosbell, N. Browne, S. Elphick, and J. Stones. 2002. “Ripple Signal Amplification in Distribution Systems: A Case Study.” *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP* 1 (January): 93–98. https://doi.org/10.1109/ICHQP.2002.1221414.

Peter, Sinethemba, Njabulo Kambule, Stephen Tangwe, and Kowiyou Yessoufou. 2022. “Assessing the Feasibility and the Potential of Implementing Solar Water Heaters in Dimbaza, a Township in Eastern Cape, South Africa.” *Sustainability* 14 (19): 12502. https://doi.org/10.3390/su141912502.

Peterson, Larry L., and Bruce S. Davie. 2007. *Computer Networks: A Systems Approach*. Elsevier.

Popik, Thomas S., and Richard H. Humphreys. 2021. “The 2021 Texas Electric Grid Failure: Causes, Consequences, and Cures.” *Journal of Critical Infrastructure Policy* 2 (1). https://doi.org/10.18278/jcip.2.1.6.

“Power Alert - Energy Advisory Services.” 2021. April 21, 2021. https://www.eskom.co.za/eas/power-alert/.

Putnam, Tobias, and Donal Brown. 2021. “Grassroots Retrofit: Community Governance and Residential Energy Transitions in the United Kingdom.” *Energy Research & Social Science* 78 (August): 102102. https://doi.org/10.1016/j.erss.2021.102102.

Rabaza L. Busisiwe, Sumbwanyambe Mbuyu, and Netshikweta N. Reginald. 2021. “A Fuzzy Logic Based Residential Electrical Energy.” *International Energy Journal* 21 (September): 415–26.

Rankin, R, and P G Rousseau. 2008. “Demand Side Management in South Africa at Industrial Residence Water Heating Systems Using in Line Water Heating Methodology.” *Energy Conversion and Management* 49 (1): 62–74. https://doi.org/10.1016/j.enconman.2007.05.022.

Repo, Sirpa, Jouni Pylvanainen, Markku Kauppinen, Sami Repo, and Pertti Jarventausta. 2018. “Automatic Meter Infrastructure (AMI) as a Part of Flexibility Market.” In *2018 15th International Conference on the European Energy Market (EEM)*, 1–5. Lodz: IEEE. https://doi.org/10.1109/EEM.2018.8469765.

Saebi, Javad, Hamid Taheri, Javad Mohammadi, and Seyedeh Sara Nayer. 2010. “Demand Bidding/Buyback Modeling and Its Impact on Market Clearing Price.” In *2010 IEEE International Energy Conference*, 791–96. Manama, Bahrain: IEEE. https://doi.org/10.1109/ENERGYCON.2010.5771788.

Sarkodie, Samuel Asumadu, and Samuel Adams. 2018. “Renewable Energy, Nuclear Energy, and Environmental Pollution: Accounting for Political Institutional Quality in South Africa.” *Science of The Total Environment* 643 (December): 1590–1601. https://doi.org/10.1016/j.scitotenv.2018.06.320.

“SA’s First Energy Performance Certificate.” n.d. Business Media MAGS. Accessed November 4, 2023. https://businessmediamags.co.za/built-environment/infrastructure-pr/sas-first-energy-performance-certificate/.

Setlhaolo, Ditiro, and Xiaohua Xia. 2016. “Combined Residential Demand Side Management Strategies with Coordination and Economic Analysis.” *International Journal of Electrical Power & Energy Systems* 79 (July): 150–60. https://doi.org/10.1016/j.ijepes.2016.01.016.

Sguazzin, Antony. 2020. “South Africa to Allow Municipalities to Source Their Own Power.” *Bloomberg News*, October. https://www.bloomberg.com/news/articles/2020-10-16/south-africa-to-allow-municipalities-to-source-their-own-power{\#}xj4y7vzkg.

Siano, Pierluigi. 2014. “Demand Response and Smart Grids—A Survey.” *Renewable and Sustainable Energy Reviews* 30 (February): 461–78. https://doi.org/10.1016/j.rser.2013.10.022.

Simmins, John, Andrew Hudgins, Ismael Mendoza, and Xin Jin. n.d. “National Renewable Energy Laboratory (NREL) Topic 2 Final Report: End-to-End Communication and Control System to Support Clean Energy Technologies.”

Siphelele Dludla. 2021. “Eskom Is Getting Ready to Take over Defaulting Municipalities.” *Independent Online SA*, February 15, 2021. https://www.iol.co.za/business-report/companies/eskom-is-getting-ready-to-take-over-defaulting-municipalities-d640674c-e14d-411e-b579-1762eb55585a.

Siqueira de Carvalho, Ricardo, Pankaj Kumar Sen, Yaswanth Nag Velaga, Lucas Feksa Ramos, and Luciane Neves Canha. 2018. “Communication System Design for an Advanced Metering Infrastructure.” *Sensors* 18 (11): 3734. https://doi.org/10.3390/s18113734.

Skinner, Tom, and Andries Gildenhuys. 2013. “Integrated Demand Management (IDM) Market End Use Knowledgebase.”

“Smart Circuit Breakers: The Next Frontier of the Grid Edge?” n.d. Accessed January 17, 2023. https://www.greentechmedia.com/articles/read/smart-circuit-breakers-the-next-frontier-of-the-grid-edge.

South Africa Department of Mineral and Energy Affairs. 1990. *Electricity Act 1987, Regulation 2665*.

“South Africa’s Appliance Energy Efficiency Standards and Labeling Program Impact Assessment.” 2020. Department of Energy.

Stanton, Tom. n.d. “Review of State Net Energy Metering and Successor Rate Designs.”

“Status of Small Scall Embedded Generation (SSEG) in South African Municipalities.” 2020. South African Local Government Association (SALGA). https://www.sagen.org.za/publications/all-publications/112-status-of-small-scale-embedded-generation-in-south-african-municipalities/file.

Steyn, S. J. M., and R. Chetty. 2013. “Development of a Residential Appliance Control Interface (ACI) Module Using Smart Systems.” In *2013 IEEE International Conference on Industrial Technology (ICIT)*, 820–25. Cape Town: IEEE. https://doi.org/10.1109/ICIT.2013.6505778.

Strbac, Goran. 2008. “Demand Side Management: Benefits and Challenges.” *Energy Policy* 36 (12): 4419–26. https://doi.org/10.1016/j.enpol.2008.09.030.

Supporting Sub-Saharan African Municipalities with Sustainable Energy Transitions (SAMSET). 2015. “Smart Metering : Overview and Considerations for South African Municipalities,” no. July: 27.

Tanzila Khan, Sumati Kohli, Zifei Yang, and Josh Miller. 2022. “Zero-Emission Vehicle Deployment: Africa.” INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION.

Tonder, Mr AJM van, M Kleingeld, and Dr JH Marais. n.d. “Investigating Demand Response Potential in a Mining Group,” 5.

Tyagi, Rajesh, and Jason W. Black. 2010. “Emergency Demand Response for Distribution System Contingencies.” In *IEEE PES T&D 2010*, 1–4. New Orleans, LA, USA: IEEE. https://doi.org/10.1109/TDC.2010.5484598.

Unhauzer, Attila. 2012. “The Future of Centralized Ripple Control System in Hungary-State-of-the-Art Trends.” *20th IMEKO World Congress 2012* 2: 1115–20.

Wang, Wenye, Yi Xu, and Mohit Khanna. 2011. “A Survey on the Communication Architectures in Smart Grid.” *Computer Networks* 55 (15): 3604–29. https://doi.org/10.1016/j.comnet.2011.07.010.

Wang, Zhaoyu, and Jianhui Wang. 2014. “Review on Implementation and Assessment of Conservation Voltage Reduction.” *IEEE Transactions on Power Systems* 29 (3): 1306–15. https://doi.org/10.1109/TPWRS.2013.2288518.

Warrick Pierce and Bianca Ferreira. 2022. “Statistics of Utility-Scale Power Generation in South Africa in 2021.” CSIR Energy Centre, April.

“Wheeling Concept Introduction.” 2022. Eskom.

“Wireless Emergency Alerts Mobile Penetration Strategy.” n.d.

Wireless Emergency Alerts Second Report and Order and Second Order on Reconsideration PS Docket No. 15-91. n.d.

Xia, X., D. Setlhaolo, and J. Zhang. 2012. “Residential Demand Response Strategies for South Africa.” In *IEEE Power and Energy Society Conference and Exposition in Africa: Intelligent Grid Integration of Renewable Energy Resources (PowerAfrica)*, 1–6. Johannesburg, South Africa: IEEE. https://doi.org/10.1109/PowerAfrica.2012.6498654.

Yan, Ye, Yi Qian, Hamid Sharif, and David Tipper. 2013. "A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges." *IEEE Communications Surveys & Tutorials* 15 (1): 5–20. https://doi.org/10.1109/SURV.2012.021312.00034.

Ye, Yuxiang, and Steven F. Koch. 2021. "Measuring Energy Poverty in South Africa Based on Household Required Energy Consumption." *Energy Economics* 103 (November): 105553. https://doi.org/10.1016/j.eneco.2021.105553.

Zahavi, Jacob, and David Feiler. 1980. "The Economics of Load Management by Ripple Control." *Energy Economics* 2 (1): 5–13. https://doi.org/10.1016/0140-9883(80)90040-7.