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Demand Side Management potentials for mitigating energy poverty in South Africa

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ABSTRACT

South Africa is severally posited to be Africa's most industrialized nation with an economy heavily reliant on energy. With depleted electricity reserve margin which led to massive load shedding and rationing of electricity in 2008, Eskom has stepped up the construction of additional power plants to cover for growing supply deficits. Emerging trends however favour Demand Side Management (DSM) initiatives as alternatives to building additional supply capacity due to environmental and economic constraints. This research evaluates the electricity per capita for 2007, 2011 and 2016 on provincial basis assuming 100% and 36.8% residential sector consumption of generated electricity to show declining electricity per capita values. A scenario simulation (for 100%, 50% and 30% household participation) of cloth washers and cloth dryers optimal dispatch is then modelled to show the enormous DSM potentials in terms of electricity cost reduction and supply flexibility. A modified genetic algorithm (MGA) is used in the dispatch of participating loads on the Medupi power plant which has been modelled to operate with carbon capture and sequestration (CCS) technology. DSM potentials of 6938.34 MW, 3469.18 MW and 2081.51 MW are computed for 100%, 50% and 30% household participation for cloth washers and cloth dryers.

1. Introduction

South Africa is one of Africa's most industrialized nation and also its highest net electricity producer (about 45%) (Eskom). Most of the electricity consumed by the nine provinces of South Africa is produced by Eskom from 27 major power stations with combined installed nominal capacity of over 42000 MW from various sources including; coal, hydro, liquid fuel, pumped storage, nuclear and wind (Where Eskom's electricity comes from, 2015). The significant growth witnessed in South Africa's electrification drive (rural and urban) which has seen electrification rate move rapidly from less than 33% (in 1990) to 58% (1996) and 90% (2016) has been largely due to various government policy and intervention (Marquard et al., 2007).

According to Marquard et al. (2007), electrification in South Africa which was around 35% of the total population before 1990 had doubled by 2000. The 1996 census conducted revealed that about 58% of the country's population had access to electricity. Continuing, Marquard et al. (2007) further posited that only about one in four non-urban black South African households were electrified compared to 97% electrification of non-urban white South African households before 1990. It could thus be surmised that the major obstacle to increased widening access to electricity was political, which kept electricity access prior to 1990 below 40%. These dismal statistics highlighting low electrification rates for pre-1990 years were further worrisome when compared to countries with similar income levels at the beginning of the electrification program (Argentina – 88%, Venezuela – 86%, Costa Rica – 85%, Thailand – 75% and Brazil – 65%). However, the abolishment of apartheid and subsequent entrenchment of democracy has led to a steady increase in electrification rates in the country. A further observation from the report (Marquard et al., 2007) was the fact that as at 1990, South Africa had an extremely energy intensive economy and possessed in Eskom a world class electricity supply industry with a huge electricity reserve margin.

Table 1 (Where Eskom's electricity comes from, 2015) gives a breakdown of the contribution share of each energy source to Eskom's overall capacity while Table 2 (Eskom power stations from 1926 to 2015, 2014) presents the time-line of the evolution of South Africa's power stations from 1926 to 2015 vis-a-vis their commissioning, decommissioning and recommissioning.

While government's initial efforts at boosting electricity generation

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Nomenclature

$AHHS_{j,k}$	year j, province k average household size
C_{bias}^{cost}	consumer cost biased function
CCS	carbon capture and sequestration
$DEC_{j,k}^{\eta=0.368}/DEC_{j,k}^{\eta=1}$	Daily Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
$HEC_{j,k}^{\eta=0.368}/HEC_{j,k}^{\eta=1}$	Hourly Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
$HWEC_{j,k}$	Normalized value for province k households with electricity connection for year j
$MEC_{j,k}^{\eta=0.368}/MEC_{j,k}^{\eta=1}$	Monthly Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
OP_t^{cost}	Time t operations cost
P_{cost}^{DP}	Daily cost of electricity to consumers using dynamic pricing
P_{cost}^{FP}	Daily cost of electricity to consumers using time of use pricing
$REC_{j,k}$	Residential Electricity Consumption for province k, year j
S_{cost}	Daily operational cost of generating electricity by the utility
$THH_{j,k}$	Total households for province k, year j
U_{bias}^{cost}	Utilization cost biased function
U_{cost}	Daily cost that penalizes generator utilization outside optimal operational limits
$YEC_{j,k}^{\eta=0.368}/YEC_{j,k}^{\eta=1}$	Yearly Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
DLC	Direct Load Control
DSM	Demand Side Management
MGA	Modified Genetic Algorithm
QoL	Quality of Life
TOU	Time Of Use

and access led to a surplus in electricity supply in 1990 which resulted in the mothballing of the Komati, Camden and Grootvlei power stations, inconsistencies in government policies and an initial delay in the construction of additional power stations to compensate for increasing population and industrialization activities, have seen Eskom in recent times implementing load shedding (Kohler, 2014; Loadshedding) to offset supply deficits and prevent grid collapse.

Government has consistently evolved policies to guarantee energy security and sufficiency right from the National Electrification Forum of 1991–1993. Furthermore, the South Africa Government electrification thrust is service delivery based rather than on providing energy for productive services. With an increasing population and rising demand of energy for both residential and non-residential (commercial, transportation, industrial etc.) activities, building additional power plants to boost supply though logical is becoming increasingly expensive as recognised in the United Kingdom by Bradley et al. (2013), Ofgem (2015). In addition, global concerns relating to the negative contribution of fossil based electricity generation to the environment puts further constraints on the design and construction of these additional power plants. Further compounding South Africa's energy (electricity) sector drive issues is the fact that a number of South Africa's coal-powered plants will be decommissioned within the next decade. This presents a problem of energy security as planned replacements may not be able to completely cover the expected shortfalls due to delays in completion or other competing factors.

South Africa in keying into global trends has been increasing its energy base share of renewable energy. Interests has varied from solar (solar water heating) (Eskom) to wind (Eskom) to concentrating solar power (CSP) (Eskom) etc. However, despite the modest contribution of renewable energy sources (RES) to South Africa's generation mix, their availability is both stochastic (with respect to location) and probabilistic (with respect to supply) which means that exactly quantifying their real time capacity via prediction does create some disparity between predicted and actual values. This is however at variance with generation from conventional sources like coal and diesel generator power plants whose capacities are known values and provide exact figures during system operations (SO) and planning.

Table 1
Breakdown of energy category contribution to Eskom's capacity (Where Eskom's electricity comes from, 2015).

Source/Category	Number	Capacity (MW)	% of Eskom's total capacity
Coal power	13	34,952	84.85
Liquid fuel	4	2409	5.85
Nuclear power	1	1830	4.44
Pumped storage	2	1400	3.40
Hydro power	6	600	1.46
Wind power	1	3	0.01

Demand Side Management (DSM) has in recent times been gaining traction as a viable means of curtailing or modifying consumer's consumption pattern by shifting demand/supply imbalance control from the supply side to the demand (consumer) side. A reason for this is based on the fact that significant savings can be achieved from the consumer side that could eliminate the need for grid extension or additional generating capacity (Mishra et al., 2013; Pierce and Paulos, 2012). In the United Kingdom for example, the Energy Efficiency Commitment Phases 1 and 2 (EEC1) and (EEC2) programs which ran from 2002 to 2005 and 2005 to 2008 achieved energy savings of 86.8 TWh and 187 TWh respectively. Similarly, a carbon reduction of about 293MtCO_2 was achieved via the Carbon Emissions Reduction Target (CERT) and Community Energy Saving Programme (CESP) between 2008 and 2012 (Warren, 2014). In similar vein, Eskom in 2008 began a campaign to exchange incandescent bulbs in homes for more energy efficient CFL bulbs with about 65 million of such energy efficient CFL bulbs installed in South African homes to date. The result has been considerable energy savings and reduced electricity bills, job creation and a culture of greater energy efficiency among South Africans. It is estimated that about 11.8 TWh of DSM programs are currently in place in South Africa with expected cumulative savings of 466 MW by 2017/2018 from the additional Residential Mass Roll-out lighting LED program which commenced 2015/2016 (Eskom).

In a recent report SA must reduce power by up to 15: Peters (2013), it was posited that for South Africans to enjoy uninterrupted power supply, there had to be about a 10% reduction in energy consumption (from the residential sector). It can therefore be evidenced and further inferred from the report that energy efficient habits (DSM) can guarantee a balance between electricity demand and supply for residential homes. However, statistics emanating from CSIR (2016) indicate that national electricity demand using the less energy scenario modelling would increase (year-on-year) by 2.3% in 2016 and 2017, 2.5% in 2018, 2.7% in 2019 and 2.8% in 2020. To compensate for increasing electricity demand and diversify the generation mix, DOE (2016) posits that renewable energy planned capacity expansion is 2915 MW for 2016, 3799 MW for 2017, 4864 MW for 2018, 6879 MW for 2019 and

Table 2
Timeline of power plants commissioning, recommissioning and decommissioning (1926–2015) (Eskom power stations from 1926 to 2015, 2014).

Power station	Power source	Commissioned	Decommissioned	Recommissioned	Status
Witbank	Coal	1926	1963		Not operational
Colenso	Coal	1926	1985		Not operational
Salt River 1	Coal	1928	1979		Not operational
Sabie River	Hydro	1928	1964		Not operational
Congella	Coal	1928	1978		Not operational
Klip	Coal	1936	1986		Not operational
Vaal	Coal	1945	1989		Not operational
Pretoria West()	Coal	1952			Operational
Hex River	Coal	1952	1988		Not operational
Vierfontein	Coal	1953	1990		Not operational
Umgeni	Coal	1954	1989		Not operational
Taaios (+)	Coal	1954	1986; 1999	Yes	Not operational
Wilge	Coal	1954	1987		Not operational
Salt River 2	Coal	1955	1994		Not operational
West Bank 2	Coal	1956	1989		Not operational
Kelvin (*O*)	Coal	1957			Operational
Highveld (+)	Coal	1959	1986; 1999	Yes	Not operational
Komati (+,*ES*)	Coal	1961	1990	Yes	Operational
Ingagane	Coal	1963	1990		Not operational
Rooiwal()	Coal	1963			Operational
Camden (+,*ES*)	Coal	1967	1990	Yes	Operational
Grootvlei (+,*ES*)	Coal	1969	1990	Yes	Operational
Hendrina (*ES*)	Coal	1970			Operational
Gariep (*ES*)	Hydro	1971			Operational
Arnot (*ES*)	Coal	1975			Operational
Kriel (*ES*)	Coal	1976			Operational
Acacia (*ES*)	Gas	1976			Operational
Port Rex (*ES*)	Gas	1976			Operational
Vanderkloof Dam (*ES*)	Hydro	1977			Operational
Duvha (*ES*)	Coal	1980			Operational
Drakensberg (*ES*)	Hydro	1981			Operational
Matla (*ES*)	Coal	1983			Operational
Koeberg (*ES*)	Nuclear	1984			Operational
Lethabo (*ES*)	Coal	1985			Operational
Tutuka (*ES*)	Coal	1985			Operational
Kendall (*ES*)	Coal	1988			Operational
Palmiet (*ES*)	Hydro	1988			Operational
Matimba (*ES*)	Coal	1993			Operational
Majuba (*ES*)	Coal	1996			Operational
Ankerlig (*ES*)	Gas	2007			Operational
Gourikwa (*ES*)	Gas	2007			Operational
Newcastle (*)	Gas	2007			Operational
Medupi (*ES*)	Coal	2015			Operational

(*O*) – Aldwyeh International.
(+) – Mothballed.
() – City of Tshwane.
(*) – IPSA Group.
(*ES*) – Eskom.

7867 MW for 2020. Furthermore, it is also observed from the IRP report (DOE, 2016) that capacity projections for DSM techniques remain at a low 500 MW for the short to medium term projections. More emphasis is however placed on new power stations with improved efficiency and lower carbon emissions which require huge investments in construction, operations and maintenance.

A review of available literature to our knowledge has revealed the absence of any research work that has effectively quantified in real terms the contribution of applying DSM on specific household electrical devices with available pricing techniques – time of use (TOU) and a proposed dynamic pricing (DP) regime with additional constraints of peaking limits and carbon emissions for South Africa. Research conducted during the write-up of this work further indicates that majority of existing literature target such areas as efficiency in industrial sectors, renewable energy, electricity intensity, policy, review and access. Table 3 highlights the focus areas of some selected scholarly works as regards South Africa's energy (electricity) sector. From Table 3, a hierarchy of the interests sees associated statistics and policy as the major centre of focus. For example, van Blommestein and Daim (2013) evaluated the decision making process of consumers when purchasing energy efficient devices to determine if there was sync between the technology focus of consumers and current efficiency initiatives. The evaluation was carried out using a hierarchical decision model (HDM). Similarly, Amusa et al. (2009) applied bounds testing approach to co-integration with an autoregressive distributed lag framework to examine South Africa's electricity demand during the period 1960–2007 while Inglesi (2010) forecast electricity demand of South Africa up to 2030 using the Eagle-Granger methodology for co-integration and error correction models.

Works that touched on DSM include (Alix, 2000) where factors inhibiting municipalities from investing in DSM initiatives were investigated, Lombard et al. (1999) where a program for thermal efficiency in the South African residential sector was proposed and Rankin and Rousseau (2008) where the authors described how an improved in line water heating concept could achieve peak load reduction without availability compromise within the specified operating time. Pricing

Table 3
Selected literature and their focus areas relating to South Africa's Energy (electricity) Sector.

Literature	Publication year	Focus area
van Blommestein and Daim (2013)	2013	B, D, H, I
Amusa et al. (2009)	2009	D, F, I, J, K
Azimoh et al. (2015)	2015	A, C, D, I, J
Azimoh et al. (2016)	2016	A, C, D, I
Bekker et al. (2008)	2008	A, D, E, F
Bohlmann et al. (2016)	2016	D, F, H
Alix (2000)	2000	B, D, F, K, J
Inglesi (2010)	2010	B, D, F, H, I, J, K
Inglesi-Lotz and Blignaut (2011)	2011	D, E
Inglesi-Lotz (2011)	2011	D, F, H, I, K
Inglesi-Lotz and Pouris (2012)	2012	B, D, F
Inglesi-Lotz and Blignaut (2012)	2012	B, D, E, F
Inglesi-Lotz and James (2014)	2014	B, D, E, F
Kohler (2014)	2014	B, D, E, F, H
Lombard et al. (1999)	1999	B, F, I
Nakumuryango and Inglesi-Lotz (2016)	2016	D, E
Pereira et al. (2011)	2011	A, C, D, E
Rankin and Rousseau (2008)	2008	B, C
Setlhaolo and Xia (2016)	2016	B, C, G, I, K
Thondhlana and Kua (2016)	2016	B, F, I

A - Electricity access; B – DSM; C – Quality of Life (QoL); D – Associated statistics.
E – Review; F – Policy; G – Optimisation; H – Modelling.
I – Consumer side; J – Supply side; K – Pricing.

and its effect on demand was also studied in Amusa et al. (2009) where the effect of pricing policy on aggregate demand and the magnitude of demand change/response to variation in pricing policy between 1960 and 2007 for South Africa was investigated. Inglesi-Lotz (2011) also employed the Kalman filter in estimating the price elasticity of electricity in South Africa between 1980–2005.

According to Chekired et al. (2017), over 40% of global energy consumption comes from the residential and building sectors. This thus implies that households offer great potentials for DSM initiatives. This work therefore seeks to quantify in real terms the potential DSM capacity of cloth washers and cloth dryers for varying rate of household participation in South Africa. In this work, the Medupi power plant capacity is scaled between (arbitrarily selected) base loads and DSM loads. Simplified statistical derived equations are used in computing per capita electricity values for further discussions while a modified genetic algorithm (MGA) is used in allocating the evolved DSM loads (without optimising dispatch) within the allocated DSM allowance to achieve pre-determined cost functions. The evaluated and simulated results are then used in extending policy discussions on pricing, power plant capacity utilization and load dispatch.

A motivation for this work stems from the fact that in utilizing dynamic pricing schemes, households can take advantage of lower electricity prices during off-peak periods to reduce electricity bills thus freeing up resources (money) for other purposes. Similarly, Eskom using direct load control (DLC) on participating demand response (DR) loads can minimize it's operations cost and ensure a smooth grid operation.

2. Background

In providing insight into declining electricity per capita across the years under consideration, associated statistics for South Africa relating to census (population, average household number, number of houses electrified and provincial electricity supply) would be utilized.

2.1. A brief on Eskom

Eskom is South Africa's major electricity provider, generating over 95% of South Africa's electricity and 45% of Africa's electricity. Aside generation, Eskom also transmits and distributes electricity directly to the residential (5.6%), mining (14.4%), industrial (22.3%), commercial and agricultural (7%) and rail (1.4%) sectors. International exports is about 5.6% while sale to municipalities is about 42.7%. Production sources for its power generation varies from coal (83%), nuclear (5%), open-cycle gas turbine (OCGT, 3%), independent power projects (IPPS, 3%) to imports (4%) (Eskom, 2015a). Imports are from the Southern African Power Pool (SAPP) which is an inter-connected regional transmission network of the Southern African Development Community (SADC).

2.2. A brief on Medupi power station

Medupi power plant is a greenfield coal fired power plant project situated in the Limpopo province and is expected to be the fourth largest coal plant in the world. It has an installed capacity of 4764 MW from its six units each capable of outputting 794 MW. Unit 6 (the first of the 6 units) was synchronized with the grid in 2015. It has a planned operational lifetime of about 50 years (Eskom, 2015b, 2013).

2.3. A brief on data utilized and sources

Data utilized for the computation of per capita electricity consumption was primarily sourced from Statistics South Africa (STATS SA). Population, average household size and number of electrified household per province were gotten from the Community Survey (2007), Census 2011 Provinces at a glance (2012) and Community Survey (2016). Electricity supplied to each province was gotten from the P4141 series from STATS-SA and STATS-SA (2016).

Table 4 presents the population of South Africa's nine provinces from censuses conducted in 1996, 2001 and 2011 (Census 2011 Provinces at a glance, 2012) and community surveys conducted in 2007 (Community Survey, 2007) and 2016 (Community Survey, 2016). It is also observed from Table 4 the national percentage of homes with access to electricity and the growing trend in electricity access for the years under consideration. In trying to establish a justification for DSM, there is a need to present the declining electricity available to the

Table 4
Provincial census/community survey population and national electricity access (Community Survey, 2007, 2016; Census 2011 Provinces at a glance, 2012).

Province	1996	2001	2007	2011	2016
Eastern Cape	6,147,244	6,278,651	6,527,747	6,562,053	6,996,976
Free State	2,633,504	2,706,775	2,773,059	2,745,590	2,834,714
Gauteng	7,834,125	9,388,854	10,451,713	12,272,263	13,399,724
KwaZulu-Natal	8,572,302	9,584,129	10,259,230	10,267,300	11,065,240
Limpopo	4,576,566	4,995,462	5,238,286	5,404,868	5,799,090
Mpumalanga	3,123,869	3,365,554	3,643,435	4,039,939	4,335,964
Northern cape	1,011,864	991,919	1,058,060	1,145,861	1,193,780
North west	2,727,223	2,984,098	3,271,948	3,509,953	3,748,436
Western cape	3,956,875	4,524,335	5,278,585	5,822,734	6,279,730
Total	40,583,572	44,819,777	48,502,063	51,770,561	55,653,654
Household Electricity Access (%)	58.2	69.7	80.1	84.7	90.3

residential sector by computing electricity per capita (yearly, monthly, daily and hourly). This is to provide insight into the prevailing energy poverty occasioned by increasing population and increasing demand for electrical power to meet consumer needs (heating/cooling, lighting, entertainment, cooking etc.).

Table 5 presents the electricity consumed by various sector and their ranking/position. It is observed from Table 5 that the residential sector consumes on average about 36.8% of total electricity supplied and comes second behind the industrial sector (40.9%) (Modise and Mahotas).

Table 6 (STATS-SA) further presents the supply of electricity to the nine provinces for three years (2007, 2011 and 2016) and the residential component of the electricity consumed for each province using the fraction (36.8%) as obtained from Table 5. The provision of this additional column (residential component – YREC) is necessary in obtaining a more accurate value for per capita electricity consumption rather than a generalized value which assumes that 100% of electricity generated is consumed by the residential sector. Furthermore, the computation of the per capita values for electricity consumption also utilizes actual electrified households and the average household size for each province to obtain more accurate results. The method of computing electricity per capita thus employed in this research work is at variance with the generally established norm, as this employed method aims at showing the variation in electricity per capita across the different provinces.

The number of households for years 2007, 2011 and 2016 for each province alongside the average household size and percentage of provincial households with access to electricity is presented in Table 7 (Community Survey, 2007, 2016; Census 2011 Provinces at a glance, 2012).

3. Per capita electricity computation and its implications

The computation of the per capita electricity consumption for each of the nine provinces is shown subsequently. By per capita electricity consumption, we imply the average electricity consumption (Wh/kWh) computed for an individual (hourly, daily, monthly and yearly) based on the total electricity supplied to a province, number of electrified households and average household size. From Tables 5 – 7, the following can be obtained:

$n =$ Residential electricity component weight (0.368) from Table 5

$REC_{j,k} =$ Residential electricity consumption for year j and province k from Table 6

$TEC_{j,k} =$ Total electricity consumption for year j and province k from Table 7

where,

j is the index of year and k is the index of the provinces. Eqs. (1) and (2) present the limits for j and k while Tables 8, 9 present the index description for j and k. That is,

$$1 \le j \le 3 \tag{1}$$

$$1 \le k \le 9 \tag{2}$$

If,

$THH_{j,k}$ is the total households for year j and province k from Table 4

$AHHS_{j,k}$ is the average household size for year j and province k from Table 4 and

$HWEC_{j,k}$ is households with electricity connection for year j and province k

Then,

$$HWEC_{j,k} = \frac{(\%)HWEC_{j,k}}{100}, \quad 0 < HWEC_{j,k} \le 1$$
$$YEC_{j,k}^{\eta=1} = \frac{TEC_{j,k}}{THH_{j,k} \times AHHS_{j,k}} \text{ (kWh/capita)} \tag{3}$$

$$MEC_{j,k}^{\eta=1} = \frac{YEC_{j,k}^{\eta=1}}{12} \text{ (kWh/capita)} \tag{4}$$

$$DEC_{j,k}^{\eta=1} = \frac{MEC_{j,k}^{\eta=1}}{30} \text{ (kWh/capita)} \tag{5}$$

$$HEC_{j,k}^{\eta=1} = \frac{DEC_{j,k}^{\eta=1} \times 1000}{12} \text{ (Wh/capita)} \tag{6}$$

where, $YEC_{j,k}^{\eta=1}$, $MEC_{j,k}^{\eta=1}$, $DEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=1}$ are the yearly, monthly, daily and hourly provincial electricity consumption per capita (per individual) when all electricity supplied is assumed to be consumed by the residential sector ($\eta = 1$) and all households are assumed to be connected to the grid ($HWEC_{j,k} = 1$).

The result obtained from the computation of $YEC_{j,k}^{\eta=1}$, $MEC_{j,k}^{\eta=1}$, $DEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=1}$ for the years 2007, 2011 and 2016 for the nine provinces is shown in Table 10.

Similarly, the computation of the yearly ($YEC_{j,k}^{\eta=0.368}$), monthly ($MEC_{j,k}^{\eta=0.368}$), daily ($DEC_{j,k}^{\eta=0.368}$) and hourly ($HEC_{j,k}^{\eta=0.368}$) provincial electricity consumption per capita when actual residential electricity consumed is taken into consideration ($\eta = 0.368$) with grid connected households ($HWEC_{j,k\neq1}$) is shown in Eqs. (7)–(10).

$$YEC_{j,k}^{\eta=0.368} = \frac{TEC_{j,k}}{THH_{j,k} \times AHHS_{j,k}} \text{ (kWh/capita)} \tag{7}$$

$$MEC_{j,k}^{\eta=0.368} = \frac{YEC_{j,k}^{\eta=0.368}}{12} \text{ (kWh/capita)} \tag{8}$$

$$DEC_{j,k}^{\eta=0.368} = \frac{MEC_{j,k}^{\eta=0.368}}{30} \text{ (kWh/capita)} \tag{9}$$

$$HEC_{j,k}^{\eta=0.368} = \frac{DEC_{j,k}^{\eta=0.368} \times 1000}{12} \text{ (Wh/capita)} \tag{10}$$

Table 11 similar to Table 10 presents the results obtained from the computation of $YEC_{j,k}^{\eta=0.368}$, $MEC_{j,k}^{\eta=0.368}$, $DEC_{j,k}^{\eta=0.368}$, and $HEC_{j,k}^{\eta=0.368}$ for the years 2007, 2011 and 2016 for the nine provinces.

Given $TEC_{j,k}$ as the total electricity supplied province k for year j in GWh, then $YEC_{j,k}^{\eta=1}$ and $YEC_{j,k}^{\eta=0.368}$ are the average yearly electricity (kWh/capita) consumed by an individual, with 100% and 36.8% consumption of electricity supplied province k for $\eta = 1$ and $\eta = 0.368$ respectively by the residential sector. $MEC_{j,k}^{\eta=1}$ and $MEC_{j,k}^{\eta=0.368}$ are the average monthly electricity (kWh/capita) consumption per capita for 100% and 36.8% residential consumption of province k supplied electricity. $HEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=0.368}$ are the average hourly electricity (Wh/capita) consumption per capita for province k.

A basis for the evaluation of the values presented in Tables 10, 11 is to highlight the following:

(a) That while electricity access might have been increasing, electricity available for consumption by the residential sector has been decreasing rapidly across the years under consideration. For example, in Table 11, $HEC_{j,k}^{\eta=0.368}$ for Eastern Cape has declined from 72.42 Wh (in 2007) to 66.67 Wh (in 2011) and 63.39 Wh (in 2016). This trend is witnessed in all the provinces (except for Limpopo) for the years under consideration.

(b) That the evaluation of electricity consumption per capita for each

Table 5
Electricity usage/consumption by sector (Modise and Mahotas).

Sector	Percentage of total consumption (%)	Position/Ranking
Residential	36.8	2nd
Commercial	11.4	3rd
Transport	2.7	5th
Others	8.1	4th
Industrial segment	40.9	1st

Table 6
Provincial yearly electricity consumption (GWh) and residential component (STATS-SA).

	2007		2011		2016	
Province	TYEC	YREC	TYEC	YREC	TYEC	YREC
Eastern Cape	7290	2682.72	7726	2843.168	8790	3234.72
Free State	10,446	3844.128	9765	3593.52	10,240	3768.32
Gauteng	62,549	23,018.03	62,113	22,857.58	57,106	21,015.01
KwaZulu-Natal	47,271	17,395.73	46,150	16,983.2	41,336	15,211.65
Limpopo	12,306	4528.608	13,904	5116.672	13,514	4973.152
Mpumalanga	34,072	12,538.5	33,704	12,403.07	34,049	12,530.03
Northern cape	5243	1929.424	5330	1961.44	5114	1881.952
North west	30,606	11,263.01	30,573	11,250.86	28,944	10,651.39
Western cape	23,836	8771.648	23,495	8646.16	22,516	8285.888

TYEC – Total yearly electricity consumed (GWh).
YREC – Yearly residential electricity component (GWh).

province has shown the varying disparity among the provinces which is usually masked when electricity consumption per capita is computed for the whole nation. For example, from Table 11, while Mpumalanga has $HEC_{j,k}^{\eta=0.368}$ of 370.39 Wh in 2016, Eastern Cape has $HEC_{j,k}^{\eta=0.368}$ of about 63.39 Wh for 2016. An importance of this result is the fact that it affects the ownership of electrical appliances of residential houses which is useful in evaluating the Quality of Life (QoL) of household dwellers.

From Table 11 therefore, three classes (tiers) of residential consumers can be observed from the $HEC_{j,k}^{\eta=0.368}$ column in 2016. These are:

Tier 1: this tier consists of all residential consumers of electricity whose hourly consumption $HEC_{j,k}^{\eta=0.368}$ is less than 200 Wh, i.e. $0 < HEC_{j,k}^{\eta=0.368} < 200$ Wh. It is observed from the Table 11 that in 2016, Eastern Cape, Limpopo, Western Cape, Free State and KwaZulu-Natal provinces were all tier 1 electricity consumers.

Tier 2: this tier consists of all residential electricity consumers with $200\text{ Wh} \le HEC_{j,k}^{\eta=0.368} < 300$ Wh. It is also observed from the Table 11 that in 2016 only Gauteng and Northern Cape residences was into this category.

Tier 3: this tier consists of residential users of electricity with $HEC_{j,k}^{\eta=0.368} \ge 300$ Wh. North West and Mpumalanga residences were in this category as observed from the Table 11 in 2016.

3.1. Justification for tier classification

According to Monyei et al. (2017), there is a direct relationship between electrical appliance ownership and electrical consumption. In justifying the tier classifications (Tier 1, Tier 2 and Tier 3), Table 12 presents the ownership of electrical appliances by an individual used in meeting needs (lighting, entertainment, heating/cooling, and others).

Table 8
Index description for j.

Year	Index (j)
2007	1
2011	2
2016	3

Table 9
Index description for k.

Province	Index (k)
Eastern Cape	1
Free State	2
Gauteng	3
KwaZulu-Natal	4
Limpopo	5
Mpumalanga	6
Northern cape	7
North west	8
Western cape	9

The classification of provincial residential houses into the various tiers is thus done to accurately depict the extent of ownership of electrical appliances by residences during the optimisation process of DSM.

The implication of the computed electricity per capita values for the provinces (when $\eta = 0.368$) is best evaluated using scenario planning. Based on already adopted values of average house size per province, the typical electricity consumption per household is thus determined for each province. A fraction of the values determined are optimally allocated among competing DSM needs (cloth washers and cloth dryers) for a typical urban and typical rural house (both grid connected) with the ensuing statistics (cost and utilization) computed for both cases.

Table 13 presents a quick comparison between the yearly electricity per capita for the years under consideration as presented in the Tables 10, 11 along with the World Bank value for 2007 and 2011 (IEA). The disparity across the various scenarios raises doubts as to the viability of ensuing planning done using these values. Furthermore, the declining electricity per capita concerns earlier raised is further reinforced by STATS-SA (2016). According to STATS-SA (2016), electricity consumption decreased by 1.2% and 1.5% in 2016 and 2015 respectively despite a 0.9% increase in electricity generation in 2016 over 2015.

4. The DSM optimisation process

In applying and optimising DSM, there is the need to justify its application. Fig. 1 (Save electricity, we'll show you how: Eskom) presents the distribution of South AFrica's residential electricity usage

Table 7
Provincial household electricity access indicators (Community Survey, 2007, 2016; Census 2011 Provinces at a glance, 2012).

	2007			2011			2016		
Province	THH	AHHS	%HWEC	THH	AHHS	%HWEC	THH	AHHS	%HWEC
Eastern Cape	1,586,739	4.1	65.9	1,687,385	3.9	75	1,773,395	3.9	85.4
Free State	802,872	3.5	86.6	823,316	3.3	89.9	946,639	3	93.8
Gauteng	3,263,712	3.3	83.2	3,909,022	3.1	87.4	4,951,137	2.7	89.7
KwaZulu-Natal	2,234,129	4.6	71.5	2,539,429	4	77.9	2,875,843	3.8	88.5
Limpopo	1,215,935	4.3	81.2	1,418,102	3.8	87.3	1,601,083	3.6	93
Mpumalanga	940,425	3.9	82.2	1,075,488	3.8	86.4	1,238,861	3.5	90.3
Northern Cape	264,653	4	86.8	301,405	3.8	85.4	353,709	3.4	88.8
North west	822,964	3.7	83	1,062,015	3.3	84	1,248,766	3	89
Western cape	1,369,180	3.8	93.9	1,634,000	3.6	93.4	1,933,876	3.2	96.6

THH – Total households.
AHHS – Average household size.
HWEC – Households with electricity connection.

Table 10
Computed $YEC_{j,k}^{\eta=1}$, $MEC_{j,k}^{\eta=1}$, $DEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=1}$ for 2007, 2011 and 2016.

Province	2007				2011				2016			
	$YEC_{j,k}^{\eta=1}$	$MEC_{j,k}^{\eta=1}$	$DEC_{j,k}^{\eta=1}$	$HEC_{j,k}^{\eta=1}$	$YEC_{j,k}^{\eta=1}$	$MEC_{j,k}^{\eta=1}$	$DEC_{j,k}^{\eta=1}$	$HEC_{j,k}^{\eta=1}$	$YEC_{j,k}^{\eta=1}$	$MEC_{j,k}^{\eta=1}$	$DEC_{j,k}^{\eta=1}$	$HEC_{j,k}^{\eta=1}$
Eastern Cape	1116.77	93.06	3.10	129.26	1177.38	98.11	3.27	136.27	1256.26	104.69	3.49	145.40
Free State	3766.96	313.91	10.46	435.99	3556.61	296.38	9.88	411.65	3612.36	301.03	10.03	418.10
Gauteng	5984.57	498.71	16.62	692.66	5061.25	421.77	14.06	585.79	4261.73	355.14	11.84	493.26
KwaZulu-Natal	4607.66	383.97	12.80	533.29	4494.85	374.57	12.49	520.24	3735.66	311.31	10.38	432.37
Limpopo	2349.24	195.77	6.53	271.90	2572.50	214.37	7.15	297.74	2330.37	194.20	6.47	269.72
Mpumalanga	9351.62	779.30	25.98	1082.36	8342.70	695.23	23.17	965.59	7852.69	654.39	21.81	908.88
Northern cape	4955.30	412.94	13.76	573.53	4651.52	387.63	12.92	538.37	4283.87	356.99	11.90	495.82
North west	9354.06	779.51	25.98	1082.65	8710.37	725.86	24.20	1008.15	7721.62	643.47	21.45	893.71
Western cape	4515.60	376.30	12.54	522.64	4035.05	336.25	11.21	467.02	3585.50	298.79	9.96	414.99

among various competing needs. A sector ranking of Fig. 1 shows that the Geyser, space heating, cold storage, others and the pool pump offer considerable potential for DSM application. However, DSM application is best suited for sectors that offer minimal discomfort to home owners and would not significantly impact negatively on the comfort level/QoL of home owners. Furthermore, the complexities involved in optimising user specific preferences for such complex sectors as cooling, heating etc. defeat the purpose for this research paper which is to show in simplest forms and without much significant investments the DSM potentials from residential homes. For this work therefore, two primary components of the laundry sector – cloth washer and cloth dryer would be considered in the DSM optimisation process.

4.1. Justification for choice of sectors for DSM application

A justification for the choice of the laundry sector for DSM application and optimisation stems from the fact that the current DSM initiatives being undertaken by Eskom are efficiency based and not price-based. For example, Eskom has already initiated DSM for the lighting sector through the distribution of energy efficient bulbs across the country (Eskom). Furthermore, the laundry sector (cloth washer and cloth dryer) has also received significant appraisal in reviewed articles (Klaassen et al., 2013; Hakimi, 2016; Shipman et al., 2013) due to its ability to have its functionality remotely monitored and controlled. Also, its operation can also be dispatched in real time without hitches. Additionally, data obtained shows that over 40% of South African homes have a washing machine (Community Survey, 2016), which cumulatively offers great potential for DSM.

Table 14 depicts the associated statistics (ratings and number) to be used in the optimisation process for both the cloth washer and the cloth dryer. For the purpose of this research, 60% of the 40% of residential homes with washing machine are assumed to have a cloth dryer. It is observed from Table 15 the possible periods of dispatch for the washing machine and cloth dryer for the week. Also observed is the fact that the washing machine and cloth dryer are capable of being dispatched all through the day. Hence, DSM would be optimally scheduling and dispatching the washing machines and cloth dryers within a 24-h period to show the flexibility of its dispatch and also achieve the aim of the

Table 12
Tier classification based on ownership.

Needs	Devices	Tier ownership			Average duration (h)	Unit rating (W)
		1	2	3		
Lighting	Light bulb	1	2	>2	8	16
Entertainment	TV	–	1	≥ 1	5	150
	Satellite decoder	–	1	1	5	10
	VCD/DVD player	1	1	1	5	35
Heating/cooling	Heater	–	1*	≥ 1**	8	1000/ 2000
	AC	–	–	≥ 1	–***	–***
Others	Dishwasher	–	–	1	1	1200
	Cloth washer	–	–	1	0.75	500
	Cloth dryer	–	–	1	1	700
	Cooker	–	–	1	2.5	750/ 1500

*– ≤ 1000 W ** – >1000 W *** – not evaluated since summer season is assumed.
AC – Air conditioner, TV – Television.
All values used are assumed for justification of Tier classification.

Table 13
Electricity per capita comparison for selected years.

Year	World Bank (IEA)	$\eta = 1$	$\eta = 0.368$
2007	4875.108	5111.308	2302.098
2011	4590.547	4733.581	2039.192
2016	–	4293.34	1750.944

Table 11
Computed $YEC_{j,k}^{\eta=0.368}$, $MEC_{j,k}^{\eta=0.368}$, $DEC_{j,k}^{\eta=0.368}$ and $HEC_{j,k}^{\eta=0.368}$ for 2007, 2011 and 2016.

Province	2007				2011				2016			
	$YEC_{j,k}^{\eta=0.368}$	$MEC_{j,k}^{\eta=0.368}$	$DEC_{j,k}^{\eta=0.368}$	$HEC_{j,k}^{\eta=0.368}$	$YEC_{j,k}^{\eta=0.368}$	$MEC_{j,k}^{\eta=0.368}$	$DEC_{j,k}^{\eta=0.368}$	$HEC_{j,k}^{\eta=0.368}$	$YEC_{j,k}^{\eta=0.368}$	$MEC_{j,k}^{\eta=0.368}$	$DEC_{j,k}^{\eta=0.368}$	$HEC_{j,k}^{\eta=0.368}$
Eastern Cape	625.75	52.15	1.74	72.42	576.05	48.00	1.60	66.67	547.66	45.64	1.52	63.39
Free State	1579.67	131.64	4.39	182.83	1471.23	122.60	4.09	170.28	1414.62	117.88	3.93	163.73
Gauteng	2568.73	214.06	7.14	297.31	2158.19	179.85	5.99	249.79	1752.54	146.02	4.87	202.84
KwaZulu-Natal	2367.39	197.28	6.58	274.00	2146.28	178.86	5.96	248.41	1572.84	131.07	4.37	182.04
Limpopo	1066.67	88.89	2.96	123.46	1087.63	90.64	3.02	125.88	927.75	77.31	2.58	107.38
Mpumalanga	4158.96	346.58	11.55	481.36	3512.58	292.72	9.76	406.55	3200.18	266.68	8.89	370.39
Northern cape	2099.77	174.98	5.83	243.03	2005.32	167.11	5.57	232.10	1762.26	146.86	4.90	203.97
North west	4456.50	371.37	12.38	515.80	3821.75	318.48	10.62	442.33	3194.58	266.22	8.87	369.74
Western cape	1795.44	149.62	4.99	207.81	1573.70	131.14	4.37	182.14	1386.06	115.51	3.85	160.42

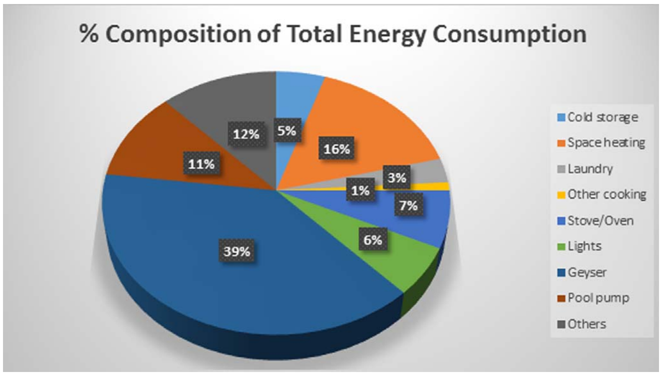

Fig. 1. Residential home electricity usage distribution among various needs (Save electricity).

Table 14
Washing machine and cloth dryer statistics.

Equipment	Device rating (W)	Number per household	Total power (W)
Washing machine	500	1	500
Cloth dryer	1000	1	1000

Table 15
Weekday dispatch of proposed DSM loads.

	Time slots		
Device	00–02	02–22	22–24
Washing machine	✓	○	✓
Cloth dryer	✓	○	✓

✓ – dispatch possible within the time slot.
○ – possible DSM window.

objective functions.

4.2. Electrical power load optimisation and dispatch

An electricity network broadly consists of generation (supply) stations, transmission/distribution network and the utilization/consumers. At the supply/generation side, the aim of the supply side energy management system (SSEMS) is to minimize operations and emissions cost (Gunda and Djokic, 2016). The transmission line management system (TLMS) ensures that line ampacity limits are not exceeded. Ampacity limits for transmission lines could be static or dynamic (Cong et al., 2016). Home energy management systems (HEMS) aim at reducing the electricity bills of homes (while improving their comfort) by smartly dispatching loads during periods of low electricity cost (Althaher et al., 2015). The general grid operation thus aims at optimally scheduling generation and load dispatch to ensure demand-supply balance while meeting the individual objectives of SSEMS, TLMS and HEMS.

5. Modelling and scenario description

In providing a basis for policy arguments, the Medupi power plant is modelled as to utilize carbon capture and sequestration (CCS) technology and used in dispatching the combined washing machine and cloth dryer loads for a 24-h cycle. Table 16 presents the DSM potentials for the three scenarios under consideration – 100%, 50% and 30% household participation. Furthermore, 60% of households in all three cases are assumed to own a cloth dryer. The specific modelling properties of the Medupi power plant such as its operating range, emissions value and capacity are shown in Table 17.

Table 18 presents the distribution of DSM potentials among various dispatch time schedules. It is important to point out that the values have been stochastically evaluated based on the cumulative values presented in Table 16. This has been achieved by generating random values that cumulatively add up to the total number of houses in Table 16. For example, in Table 18, 100% household participation for the cloth washer results in 1,261,518 houses for 15 min duration, 2,207,656 houses for 30 min duration, 946,138 houses for 45 min duration and 1,892,277 houses for 60 min duration. The sum of the houses adds up to 6,307,589 (as shown in Table 16).

5.1. Cost function definition and description

In dispatching the evaluated loads based on their dispatch time, two cost functions - the utilization biased cost function (U_{bias}^{cost}) and the consumer biased cost function (C_{bias}^{cost}) are evaluated simultaneously. While U_{bias}^{cost} aims at reducing the utilization cost which is the cost associated with operating the Medupi power plant outside its optimal operating limits as specified in Table 17, C_{bias}^{cost} aims at reducing the associated cost of electricity to the consumers using dynamic pricing. The description of the cost functions are defined as:

$$U_{bias}^{cost} = min(U_{cost}^{t}) \tag{11}$$

$$C_{bias}^{cost} = min(DP_{cost}^{t}) \tag{12}$$

where,

$$U_{bias}^{cost} = \begin{cases} 0.2 \times Op_t^{cost}; & otherwise \\ 0; & G^{norm} \le Util^t \le G^{max} \end{cases} \tag{13}$$

$$DP_{cost}^{t} = DP^{t} \times E_{MWh}^{t} \times 1000 \tag{14}$$

$$Op_t^{cost} = a + (b \times \xi^t) \tag{15}$$

${E_{MWh}}^{t}$ is the real time/slot (t) energy to be utilized (MWh). DP^t is the real time/slot dynamic price (ZAR/kWh). 1000 from Eq. (14) is the scaling factor for converting the price in (ZAR/kWh) to ZAR/MWh. ξ^t is the loading factor is the fraction of the power plant currently being utilized (as a percentage). a and b are defined in Table 17. G^{norm} and G^{max} are defined from Table 17 as the normal (norm) and maximum (max) operating capacity of the Medupi power plant respectively.

5.2. Dynamic price modelling

The computation of the dynamic price DP^t follows the time of use (TOU) pricing being used by Eskom. As seen in Fig. 2, the daily average dynamic price is equivalent to Eskom's spot price (excluding the peak

Table 16
DSM potential across various household participation rate.

	Cloth washer			Cloth dryer		
Percentage participation	100%	50%	30%	100%	50%	30%
Number of houses	6,307,589	3,153,795	1,892,277	3,784,553	1,892,277	1,135,366
DSM capacity (MW)	3153.79	1576.90	946.14	3784.55	1892.28	1135.37

Table 17
Modified Medupi power plant modelling parameters.

	LCOE model values		Operating range (%)			Carbon emissions	Capacity
Technology	a	b	min	max	norm	(kg/MWh)	(MW)
CCS	2815.21	− 14.80	66	88	85	136.2	1588

LCOE – Levelized cost of energy.
CCS – Carbon capture and sequestration.

Table 18
DSM household potential across various time schedules.

	Cloth washer			Cloth dryer		
	100%	50%	30%	100%	50%	30%
15 min	1,261,518	441,531	908,293	378,455	321,687	90,829
30 min	2,207,656	851,525	189,228	2,081,504	473,069	681,220
45 min	946,138	883,062	321,687	1,173,211	8704,47	317,902
60 min	1,892,277	977,676	473,069	151,382	227,073	45,415

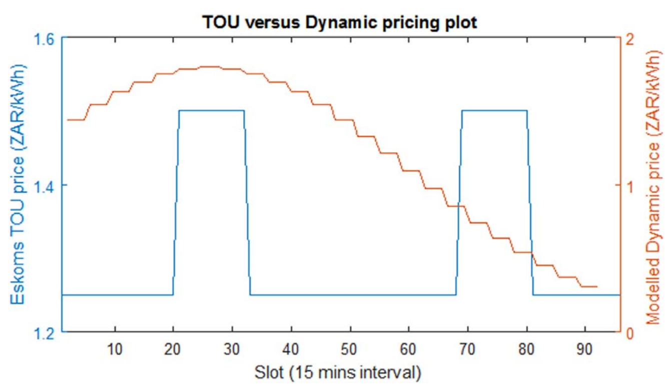

Fig. 2. TOU pricing and dynamic pricing profiles.

periods). Given FP^t as the real time TOU pricing electricity spot price, then $\frac{1}{24}\sum_{t=1}^{t=24}(DP^t) = \overline{FP^t}$.

5.3. Time of use price modelling

The selected Eskom TOU pricing scheme is for a household whose monthly electricity consumption is less than 600 kWh. The cost for off-peak periods is about ZAR 1.25/kWh and is exclusive of the peak period prices. For the purpose of this research, 20% has been added to the spot price during off-peak periods to generate the peak period (6–8 a.m. and 6–8 p.m.) TOU price. Weekdays and weekend peak periods have been assumed to be similar. The generated pricing profile is also shown in Fig. 2.

5.4. Optimisation algorithm description

The first step involved modelling the behaviour of the Medupi power plant. MANN (Monyei et al., 2014) was applied on data plot describing the evolution of the levelized cost of energy for various power plants (DOE, 2016) to generate constants a and b as shown in Table 17. The modified genetic algorithm (MGA) proposed and used in dispatching the loads to meet the already defined cost functions is described in Table 19. MGA is a variant of Monyei et al. (2014) and is modified to accommodate the variation in input data and optimisation objective. The modifications introduced include: modifying the binary strings of the population matrix to generate integer numbers that determine the start time for dispatching load and constraining dispatch of cloth washers to precede cloth dryers. This is done by scaling the start time of cloth washers and cloth dryers. The modification of the binary bits is at variance with MIGA (Monyei et al., 2014) where the binary bits are actual solutions. The cross-over employed is similar to Ogunjuyigbe et al. (2015) while the environmental cost was computed as shown in Lau et al. (2014). The prevailing exchange rate was gotten from SARB.

6. Results and discussion

In dispatching the participating DSM loads, the Medupi power plant has its capacity (power) allocated between the base loads and the DSM loads. While the base power has been arbitrarily selected to match an actual scenario, the proposed MGA dispatches the DSM loads within the DSM allowance on the power plant. In achieving an optimal allocation that meets the cost functions, the MGA ensures that the plant capacity is not over-utilized. The values chosen for the base and DSM loads allowance are shown in Table 20 for the various household participation rate. The area plot shown in Fig. 3(a) presents the 24-h (96-slots) power dispatch for the cloth washers, cloth dryers and base load demand for 100% participation of households. The real values for the cloth washer are gotten by deducting the base load value from the actual cloth washer value on the plot. Similarly, the real values for the cloth dryer are gotten by deducting the sum of the base load value and the corresponding cloth washer value (on the plot) from the actual cloth dryer value on the plot. While average utilization for both ${C_{bias}}^{cost}$ and ${U_{bias}}^{cost}$ is about 48%, over-utilization of the power plant is not observed for both cases. The ${C_{bias}}^{cost}$ option achieves a daily savings of about ZAR

Table 19
Modified genetic algorithm description.

Input:(${P_{cost}}^{DP}$, ${P_{cost}}^{FP}$, Tables 17, 18, ${U_{bias}}^{cost}$, ${C_{bias}}^{cost}$, **limit)**
Start:
Step 1: Generate MWh equivalent of Table 18
Step 2: Generate possible time slots to allocate MW and MWh vales respectively into time/slot matrices.
Step 3: Randomly select time slots for application of genetic algorithm
Step 4: Convert randomly selected time slots to binary equivalent
Step 5: Perform Cross-over (Monyei et al., 2014)
Step 6: Mutate random bits
Step 7: Convert mutated string to decimal values
Step 8: Update time matrix
Step 9: For each complete time allocation of MW values compute ξ.
Step 10: For each complete time allocation of MWh values, compute ${P_{cost}}^{DP}$ and ${P_{cost}}^{FP}$ (${P_{cost}}^{FP}$ is the equivalent fixed price cost for electricity).
Check:
For ${U_{bias}}^{cost}$
If current ${U_{bias}}^{cost}$ is smaller than preceding ${U_{bias}}^{cost}$,
Update ${U_{bias}}^{cost}$
For ${C_{bias}}^{cost}$
if current ${P_{cost}}^{DP}$ is smaller than preceding value and is greater than current S_{cost},
Update ${P_{cost}}^{DP}$
If limit is reached, exit loop
Note:
$S_{cost}^t = U_{cost}^t + e_{cost}^t + Op_t^{cost}$
Where
${S_{cost}}^t$ is the real time supply cost
${U_{cost}}^t$ is the real time utilization cost
${e_{cost}}^t$ is the real time environmental cost computed as shown in Lau et al. (2014)
End

Table 20
Power allocation for base and DSM loads.

Household participation (%)	Base load allowance (MW)	DSM allowance (MW)
100	588	1000
50	1000	588
30	1238	350

3,115,047 using dynamic pricing over the TOU pricing scheme for the same energy dispatch. This translates to about a 9.2% reduction in electricity cost using dynamic pricing over TOU pricing on average. The $U_{bias}{}^{cost}$ option dispatch shown in Fig. 3(b) achieves a utilization cost of ZAR 5920 which is about 20% lower than the utilization cost obtained from the $C_{bias}{}^{cost}$ option.

The 24-h (96-slots) power dispatch for the washing machines, cloth dryers and base load demand for a 50% participation of households is shown in the area plots depicted in Fig. 4(a and b) for both cost functions. The computation of real values for the cloth washer and cloth dryer is similar to the description provided for reading Fig. 3(a and b). Differing from the 100% household participation, convergence of values is noticed between the $C_{bias}{}^{cost}$ and $U_{bias}{}^{cost}$ options. With a higher average plant utilization of 68.97%, a 4.6% reduction in electricity cost for the participating households using dynamic pricing over TOU pricing is observed for both cost function options. The utilization cost for both cases is ZAR 23,794.87.

Fig. 5(a and b) presents the 24-h dispatch of the power demand from the washing machine, cloth dryers and base loads for 30% household participation for both the $C_{bias}{}^{cost}$ and $U_{bias}{}^{cost}$ cost functions respectively. Similar to the 50% household participation, a convergence of the dispatch allocation for both cost functions is also observed. However, a higher average utilization of the power plant (81%) is observed for both cost function options. Similar to the preceding household participation rates, electricity cost savings of about 5.1% by the dynamic pricing scheme over the TOU pricing scheme is further observed for both cost functions. The convergent utilization cost is about ZAR 29,017.88. The computation of the real cloth washer and cloth dryer values is similar to the explanation provided in reading Fig. 3(a and b).

The savings accrued from 100% household participation translates to 247 Wh/day per household. Similarly for 50% household participation it is 299 Wh/day per household and 577 Wh/day per household for 30% household participation. The implication of this is that the application of DSM is capable of extending the duration of comfort for 100% household participation by Tier 2 capacity. Similarly, 50% household participation results in the comfort of participating households being extended by Tier 2 capacity while for 30% household participation, household comfort duration is extended by Tier 3 capacity. The relevance of this stems from the fact that the contribution of electrical appliances to comfort and QoL is not only a function of ownership but also of duration of usage. In mitigating poverty, the results obtained show that on average, households' monthly electricity bill (for DSM application on cloth washer and cloth dryer only) is reduced by 1.24%, 1.5% and 2.9% for 100%, 50% and 30% household participation respectively. This implies that resources could be freed up to consume more electricity for improved QoL.

6.1. Policy discussion

Table 21 presents corresponding daily values for S_{cost}, $P_{cost}{}^{DP}$, $P_{cost}{}^{FP}$ and U_{cost} for 100%, 50% and 30% household participation and $C_{bias}{}^{cost}$ and $U_{bias}{}^{cost}$ cost functions. In presenting policy discussions, values would be used from Table 21 to highlight alternatives on pricing, utilization and dispatch of DSM loads for the residential sector (particularly washing machines and cloth dryers).

6.1.1. Policy discussion on pricing

According to Alix (2000), Eskom's distribution tariff does not always make local sense. This is because it penalizes usage during peak periods. The consequence of this is that home owners are thus made to consciously reduce or totally avoid electricity consumption during these periods. Furthermore, this method is particularly worrisome to illiterate home owners who might have no clue as to the variation in electricity prices across the day. The proposed dynamic pricing scheme obviates the need for monitoring of price signals. With smart regulators attached to the washing machines and cloth dryers, all that home owners have to do is load their devices and indicate duration and turn over control to the utility. The utility updates its database to accommodate the new entrant and re-runs the proposed optimisation algorithm to obtain the optimal dispatch profile that meets the pre-determined cost objective. The benefits of incorporating the dynamic pricing scheme include the following:

(i) A possible reduction in household expenditure on electricity. As seen from Table 21, across all scenarios for 100%, 50% and 30% household participation, electricity cost is reduced using dynamic pricing over TOU pricing. According to Chakravarty and Massimo (2013), Kanagawa and Nakata (2007), Pachauri et al. (2004), there is a nexus between poverty and energy poverty which implies that a reduction in electricity bill for home owners frees up money that can be deployed for other activities capable of improving their QoL.

(ii) More flexibility in dispatch as the utility is able to more accurately optimise the grid and balance demand/supply. This is particularly useful in meeting grid constraints since the utility has more control over the entire electricity movement chain.

(iii) Optimisation of electrical load dispatch to meet pre-determined constraints (reduced emissions, reduced electricity cost, reduced operational costs etc.).

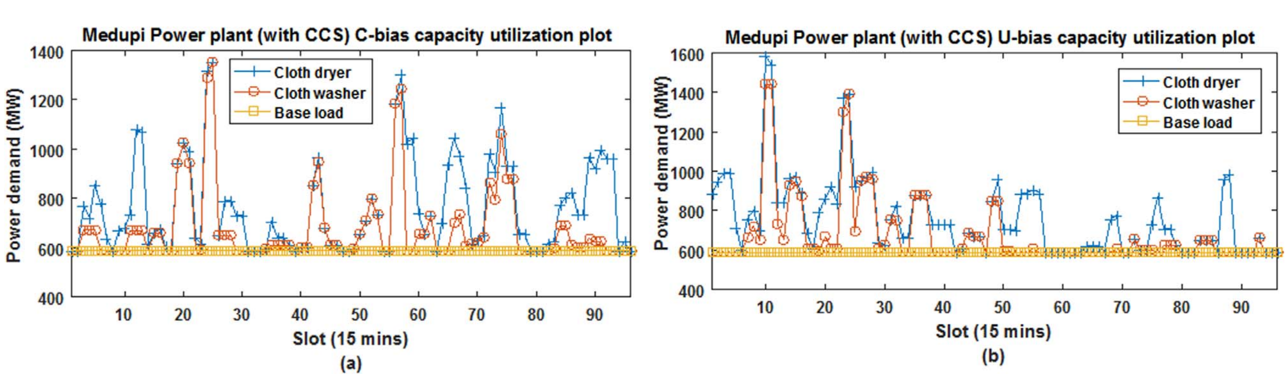

Fig. 3. 100% Household participation power dispatch for $C_{bias}{}^{cost}$ and $U_{bias}{}^{cost}$ options.

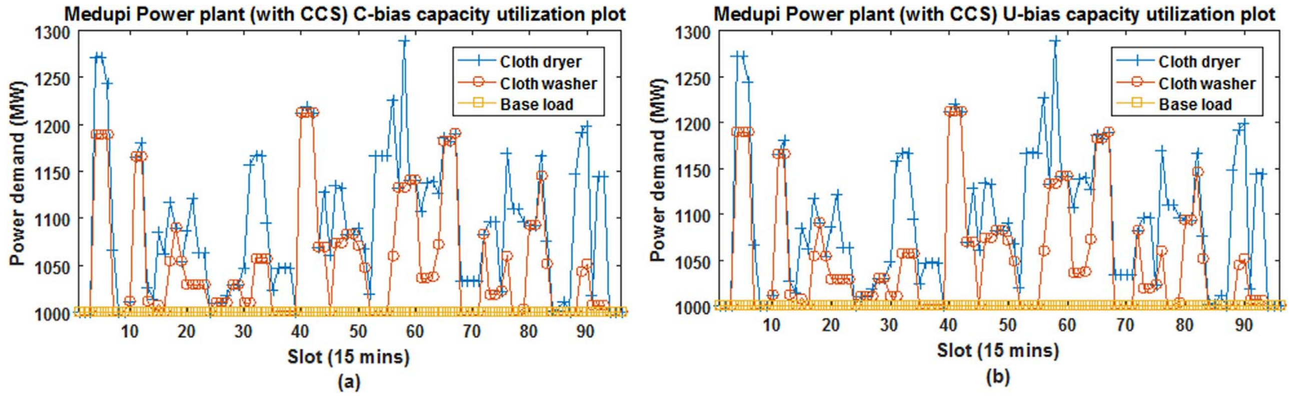

Fig. 4. 50% Household participation power dispatch for C_{bias}^{cost} and U_{bias}^{cost} options.

6.1.2. Policy discussion on utilization

Spinning and supplemental reserves are important constituents in the electricity sector as they help in preventing grid collapse in the case of sudden upsurge in electricity demand. However, lack of participation of the electricity supplier in the demand sector could lead to over-compensation and large values of spinning/supplemental reserves leading to more operational losses for non-utilization of their capacity. The incorporation of DSM however provides the electricity supplier with more information which is useful in optimally sizing spinning/supplemental reserve capacities which leads to reduced operational costs. Furthermore, the incorporation of DSM as seen from Figs. 3–5 helps in determining the optimal dispatch profile that could achieve the best average utilization of power plants. A critical observation of Table 21 shows a growing utilization cost despite increasing average utilization across the various household participation rate. This trend is due to a decreasing utilization of the allocated DSM capacity. The participation of the utility in influencing electricity end use could provide electricity demand data which can be used in optimally allocating DSM capacity for dispatch, thus freeing up more capacity for base loads.

6.1.3. Policy discussion on dispatch

A demerit of the application of Eskom's TOU pricing scheme is the fact that pseudo-peaks could be created during periods of cheaper electricity rates which is capable of disrupting the operation of the grid in case of demand exceeding supply capacity. A consequence of this has seen Eskom implementing load shedding to limit demand. Furthermore, dynamic pricing (especially when users are pre-informed of proposed spot prices) is capable of leading to pseudo-peaks (Safdarian et al., 2014). The scheme being proposed here only assures home owners of a reduction in their electricity prices (for loads participating in DSM). This thus ensures that the utility is in control of the dispatch and is capable of managing demand surge. The dispatch of the DSM loads could be classified as:

(i) Without time constraint – here, the users do not specify any constraint as to when their loads should be dispatched. The decision of the time of dispatch is entirely left to the utility. However, an override function is provided to enable the home owners remove control from the utility at any time and dispatch their loads using the current TOU spot price. A penalty could also be included to the home owners electricity bill to reduce the repetition of such actions.
(ii) With time constraint – here, the users specify a window within which their loads should be dispatched. The pricing scheme here is more rigid since the utility is given a shorter time frame for flexibility.

6.1.4. Policy discussion on energy poverty mitigation

As earlier posited, energy poverty is related to ownership of electrical appliances (Monyei et al., 2017). However, monthly electricity bill is not just a function of ownership but duration of consumption. From Table 21, the application of dynamic pricing for 100% household participation results in a daily savings of about ZAR 3,115,047 over TOU pricing. This translates to about 2.5 GWh at ZAR 1.25/kWh (247 Wh/day per household). The savings accrued can be used for extended electricity consumption or other activities that contribute to improving the QoL of the household occupants. Similarly, for 50% and 30% household participation, dynamic pricing achieves daily savings of ZAR 1,888,028 and ZAR 2,183,429 over TOU pricing. This translates to extra daily power of 299 Wh and 577 Wh respectively per household. In terms of electricity cost reduction, dynamic pricing achieves 1.24%, 1.5% and 2.9% monthly reduction per household respectively.

6.1.5. Policy discussion on supply capacity expansion

According to Eskom (2015a), plant availability for the period under review was 74.4% with average utilization of 84.77%. With a nominal

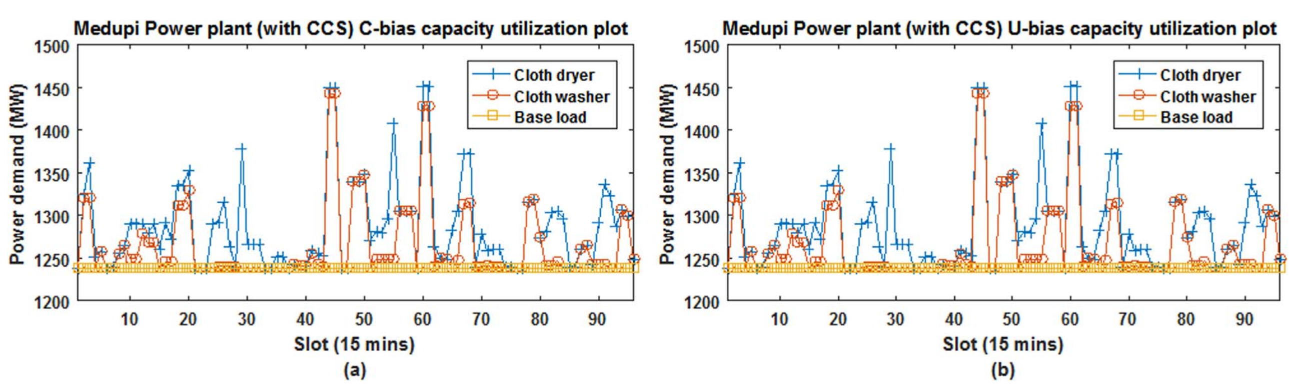

Fig. 5. 30% Household participation power dispatch for C_{bias}^{cost} and U_{bias}^{cost} options.

Table 21
Associated dispatch values for C_{bias}^{cost} and U_{bias}^{cost} options.

Household participation	100%		50%		30%	
Cost function	C_{bias}^{cost}	U_{bias}^{cost}	C_{bias}^{cost}	U_{bias}^{cost}	C_{bias}^{cost}	U_{bias}^{cost}
S_{cost}	8,442,025	8,434,699	10,239,392	10,239,392	10,922,049	10,922,049
P_{cost}^{FP}	33,869,750	33,708,250	40,397,500	40,397,500	43,007,000	43,007,000
P_{cost}^{DP}	30,754,703	34,951,081	38,509,472	38,509,472	40,823,571	40,823,571
U_{cost}	7390.13	5920	23,794.87	23,794.87	29,017.88	29,017.88

installed capacity of 42,000 MW, this translates to about 26,500 MW in terms of actual capacity utilization. According to Eskom (2016–2025), while 3516 MW is expected to be lost due to the decommissioning of ageing plants between 2021 and 2024, over 19,000 MW is expected to be added to the grid generation capacity between 2017 and 2024. This translates to a net increase of about 15,484 MW. Furthermore, additional costs are expected to be spent in increasing the transmission capacity, on reactors, capacitors and transformers, to improve electricity supply. The expected addition to the grid capacity between 2017 and 2024 is over 5 times the capacity to be lost. Demand increase within 2017 and 2024 using the high (less energy intensive) forecast from CSIR (2016) is about 55,078 GWh. Assuming a 70% utilization (of net increase) at 35% availability, this translates to a net production of about 131,106 GWh between 2017 and 2024. The huge difference between demand and supply capacity is to ensure that system operators have a wide-margin of operation allowance to accommodate for sudden increase in demand or loss of generation unit. However, an advanced metering infrastructure (AMI) that supports DSM through direct load control (DLC), provides the utility with advanced information that can enable it efficiently schedule generator and load dispatch under constraints such as maintenance and outages. This thus ensures that enormous resources do not have to be spent in over-sizing generation capacity in anticipation of an increase in demand.

7. Policy implementation and its challenges

Considering the current grid structure, a scaled-up pilot study approach is advocated for implementation of proposed policy. In the scaled-up pilot study approach, a network of willing houses cutting across the three tiers within a distribution network is established. Specific devices within the houses are then fitted with the appropriate switches and controllers for communication with the household meter which communicates with the utility. On a micro-scale level, the utility is able to evaluate response of each tier members to real-time feedback on their consumption. This is in line with Iwafune et al. (2017) where a 3.4% reduction in energy consumption was reported for households that received feedback on their electricity consumption. Some of the challenges to the proposed policy implementation include cost (due to the current grid structure which is centralized and the technical requirements for implementing an AMI), manpower (considering the high technical expertise needed and the low technical skill shortage in South Africa (Reddy et al., 2016)) and security/privacy concerns.

8. Conclusion

This research work has critically examined the electricity sector of South Africa and highlighted the fact that despite increasing investments in electricity generation, there is growing electricity poverty. Rather than taking the general approach in computing electricity per capita (assuming 100% consumption of generated electricity and using national averages), per capita electricity consumption has been computed on provincial basis taking into consideration provincial electricity supply values, residential sector consumption rate, electrified houses and average household sizes on provincial basis. The results obtained are in contrast to the usually evaluated values and show the growing disparity in electricity per capita across the various provinces. Furthermore, DSM has been thoroughly investigated for cloth washers and cloth dryers only in South Africa assuming 100%, 50% and 30% household participation for two cost functions (C_{bias}^{cost} and U_{bias}^{cost}). A major reason for this research work is to show that DSM has a huge potential in mitigating energy (electricity) poverty in South Africa by reducing electricity cost and freeing up more money for either more electricity purchases or other activities that have the potential of improving their QoL. The results obtained show first that DSM potential of 6938.34 MW, 3469.18 MW and 2081.51 MW exits for 100%, 50% and 30% household participation (for cloth washer and cloth dryers combined). Secondly, the application of DSM has been shown to mitigate poverty by reducing household electricity bills by 1.2%, 1.5% and 2.9% on monthly basis for 100%, 50% and 30% household participation. The savings accrued could then be utilized in activities that would contribute to the improvement of the household's QoL. In tackling energy poverty, the application of DSM on cloth washers and cloth dryers has shown that households' electricity consumption could be extended by 247 Wh/day, 299 Wh/day and 577 Wh/day for 100%, 50% and 30% household participation. This implies that already owned electrical appliances can have extended usage on a daily basis as a result of lower electricity bills. The dispatch of the considered DSM loads has been carried out (using the Medupi Coal Power Plant which has been modelled to include CCS technology) to show that consumers electricity cost can be reduced using dynamic pricing when compared to the existing TOU pricing scheme used by Eskom. A modified genetic algorithm (MGA) has been designed specially for this research to optimally dispatch the participating households' loads based on the earlier highlighted cost objectives. Furthermore, this research has been able to show that the incorporation of DSM into grid operation beyond electricity cost reduction, offers the utility more control in managing the grid operation due to their increased control of electricity from generation to distribution. This becomes very useful during systems operations and planning as it ensures that the utility is capable of mitigating grid collapse and reducing operational and associated expenditure costs. Other DSM potential sectors that could be exploited include heating, ventilation and cooling (HVAC), dish washers etc.

9. Future research

Considering the results obtained from the computation of electricity per capita, future work would consider electricity per capita distribution among the various population groups (blacks, coloured, Indians/coloured) across the provinces to understudy the impact of Eskom's electrification thrust in ensuring equitable energy access across the various population groups. This would be important in formulating policy on electrification that would ensure energy access for all in line with the United Nations Sustainable Development Goals (UN-SDGs) by 2030.

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