

CONSUMER PREFERENCE ELECTRICITY USAGE PLAN FOR DEMAND SIDE MANAGEMENT IN THE SMART GRID

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Abstract: High peak demand is often a challenge to the grid and could result into measures such as procurement of additional plants to meet the peak demand, higher tariffs for consumers, undesirable load shedding or even black-outs. However, these issues can be mitigated by introducing Demand Side Management (DSM) techniques for effective energy management of consumers' peak demand. In this paper, an enhanced Device Operation Knowledge - Electricity Usage Plan (DOK-EUP) is proposed, which applies time independencies of selected smart home appliances for peak demand reduction based on their operation principles and for consumer's benefit. The proposed DOK-EUP technique was tested with the surveyed demand profile of a Time-of-Use (TOU) consumer and results showed lower morning and evening peak demands, lower peak-to-peak difference, shift in peak period to traditional off-peak periods, financial savings for the consumers and utility provider, and a cleaner environment.

Key words: Device Operation Knowledge - Electricity Usage Plan (DOK-EUP), Peak Demand Reduction (PDR), Time Shiftable Smart Appliance (TSSA), Demand Side Management (DSM), Time-of-Use (TOU).

1. INTRODUCTION

The traditional grid is faced with the challenge of meeting ever-increasing demand from residential, commercial and industrial consumers. The smart grid defined by bi-directional communication, information and power flows between utilities and consumers. It introduces higher intelligence into all segments of the grid from generation to transmission, distribution and consumers' premises (e.g. households and business premises). The added intelligence into energy management is made possible by the transformation of traditional consumer premises into smart homes and smart business premises. For example, a smart home consists of smart appliances, smart meters and potentially, Distributed Energy Resources and Storage (DERS), interconnected in a Home Area Network (HAN) [1]. The HAN interfaces smart meters with controllable smart appliances in a smart home. A residential consumer would be able to manage energy consumption through the interconnection of home appliances with the smart meter and through the smart meter to the utility. Some energy management functions of the HAN in the smart grid include in-home displays, responsiveness to price signals based on consumer-centred preferences, setting limits for utility or local control actions, security monitoring, control of loads without continuous consumer involvement and consumer over-ride capability [2, 3]. The HAN has connection with the grid as illustrated in Fig. 1.

The HAN is an essential component of the Advanced Metering Infrastructure (AMI), which comprises systems that monitor, measure, read and analyse energy consumption, expenditure and trading through certain

communication hardware and software in a smart grid. AMI enables two-way communications between utility and the meter. Communication media for AMI are wired (e.g. Ethernet, Power Line Communication), wireless (e.g. WiFi, ZigBee) and/or cellular (e.g. mobile telecommunication). The architecture shown in Fig. 1 is a wireless HAN enabled by Wireless Sensors (WSs) installed on each smart device in the network. The smart meter or an in-home display communicates bi-directionally with the smart home appliances depending on the type energy management programme installed in it.

In the traditional unregulated use of electric power by residential consumers, the morning and evening peak demands can grow beyond installed capacities of peaker plants. This often leads to increased tariffs, undesirable load shedding or even black-outs. Peaker plants are generating sets to assist with peak demand intervals [4-6]. The cost of building new and higher rated peaker plants is often passed unto the consumers through increased electricity tariffs. Hence, it is essential to apply enhanced Demand Side Management (DSM) techniques for Peak Demand Reduction (PDR) from a consumer's perspective. Such enhanced DSM techniques should benefit the consumer, utility and the environment. DSM is a very important energy management tool within a smart grid to enhance the energy control management, liberalise the electricity market, reduce energy consumption, balance electricity demand and supply in real time, increase the feasibility of distributed energy resources and storage, and reduce cost of electricity infrastructure [7].

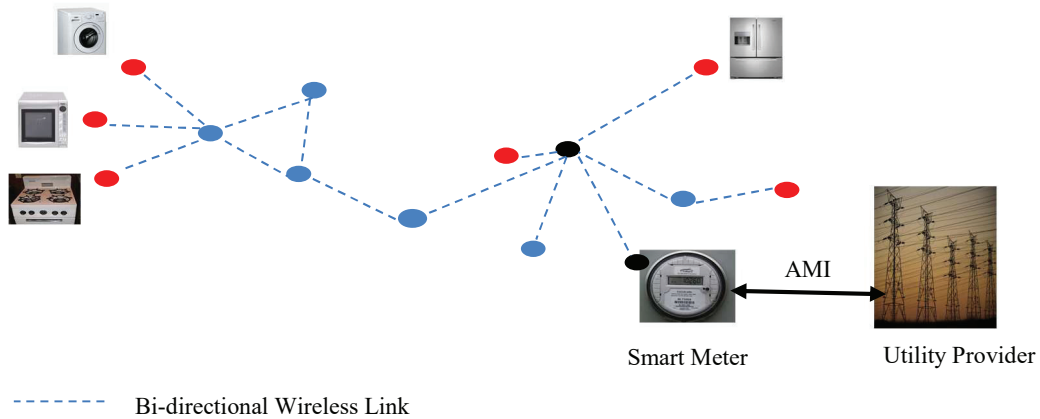


Figure 1: A Typical Topology in a HAN Connected to the Grid

DSM programs are predominantly time-based or incentive-based, with the former shown to impact demand profiles better than the latter [8-12]. Time-based DSM programs include Flat Rate Pricing (FRP), Time of Use (TOU) pricing, Real Time Pricing (RTP) and Critical Peak Pricing (CPP) programs. Incentive-based DSM programs include Direct Load Control (DLC), Interruptible/Curtailable Services (ICS), Power Tariffs (PT) and Locational Marginal Price (LMP) programs. The FRP DSM program employ static time pricing, with a single tariff or pricing applied throughout a 24-hour period and may only change in seasons of high demand such as winter. It is mostly implemented in rural areas and informal settlements of South Africa and some developing countries e.g. Nigeria. TOU programs use electricity tariffs based on time of use of energy in the day and season of the year. Hence, daily peak tariffs are higher than non-peak tariffs and winter tariffs are usually higher than summer tariffs. RTP programs set energy prices dependent on the demand of energy in real time. Hence, the higher the energy demand, the higher the energy price in real time communicated to consumers and vice versa. However, CPP increases normal peak time energy prices to offer system reliability and balance supply prices. DLC implementation have become unpopular, as consumers prefer price-responsiveness DSM programs, since the latter gives the consumers local control over its demand and bill. Classification of common DSM programs are shown in Fig. 2.

Households usually have two daily peak demand intervals, one in the morning peak period and the other in the evening. If residential consumers are able to efficiently manage their energy consumption at peak periods, there would be financial and energy savings for consumers and utilities. Also, there will be safer environment, as less greenhouse gas emissions (e.g. CO₂ emissions) will be generated from peaker plants.

Many residential TOU consumers intend to shift load to off-peak times, but they do it sporadically, so this does not

yield lasting benefit to the consumers and the utility provider as desired. In this paper, a Device Operation Knowledge - Electricity Usage Plan (DOK-EUP) for PDR is introduced based on applied operation knowledge of time-shiftable home appliances. These time-shiftable home appliances are also referred to as Time Shiftable Smart Appliances (TSSAs) in this paper. The proposed DOK-EUP was shown to be efficient for PDR in smart homes. This method also resulted into shifted morning peak demand. In the DOK-EUP algorithm proposed in this paper, the smart meter can schedule the operation of TSSAs for maximized comfort and financial savings. Smart appliances are basically classified as time-shiftable or power-shiftable appliances, but this work focusses only on the former.

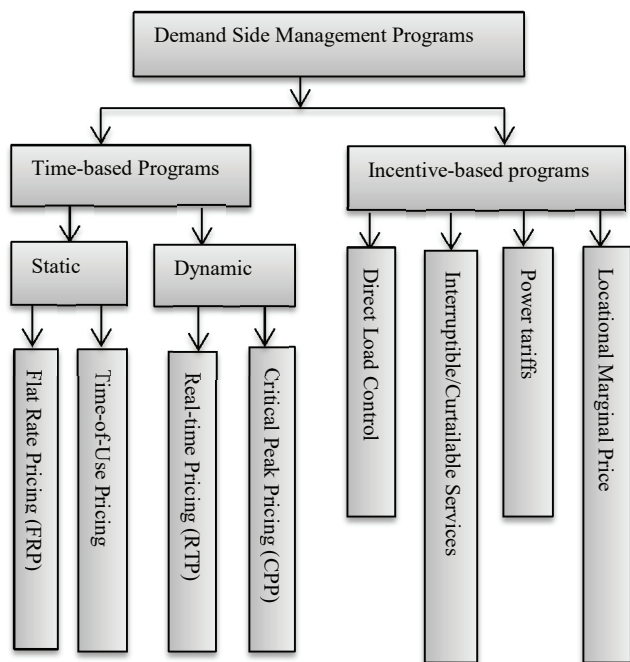


Figure 2: Classification of DSM programs

Some literature, [8-17] have explored different techniques for DSM in residential buildings, mostly block of flats and single-standing homes in some instances. In [13], the authors proposed an optimal load demand scheduling technique for water heaters using Binary Particle Swarm Optimisation (BPSO) for PDR. Also in [14], lazy scheduling and fine-grained coordination of energy demand within a constrained peak was proposed for heating, air quality control and refrigeration in households. The authors in [15] studied the demand response of modifying the elastic load components of common household appliances by decreasing their instantaneous power drawn at the expense of increasing their duration of operation. In [16], load shifting DSM program was proposed for residential, commercial and industrial consumers in a smart grid. However in [17], the DSM opportunities in understanding the load profiles of home appliances were studied and the knowledge was used in building the load profile in this work from survey data.

In [10], the authors investigated time shiftable home appliances, called Time Programmable Smart Devices (TPSDs) for DSM in rural microgrid households. The TPSDs were proposed to have time programmable interface, through which the consumer would input the preferred appliance operation times. However, this work proposed a DOK-EUP algorithm that can be installed into the smart meter or in-home display for effective and autonomous control of household demand. Also in [10], the EUP resides independently in each appliance with neither a local control within the smart home nor external interaction with the utility. Furthermore, the proposed DOK-EUP technique has a local control within the smart home and can also interact with the utility through its smart meter or in-home display. The interactive platform can be in form of an in-home display as shown in [18]. It would further give room for consumers to be compensated for energy savings and PDR as is expected in the smart grid. Also, the DOK-EUP technique gives the consumer the flexibility of participation at will and the consumer can opt in/out as desired at any time.

The rest of the paper is structured as follows: Load shaping DSM techniques and motivation for PDR are discussed in Section 2 with the proposed DOK-EUP technique for PDR described in Section 3. Section 4 includes the simulation results and Section 5 contains the conclusion of the paper.

2. DEMAND SIDE MANAGEMENT TECHNIQUES

One of the major aims of DSM is to level out the daily morning and evening demand peaks and build up valleys for an efficient use of available energy resources and to defer or eliminate, as the case may be, the need to acquire additional peaker plants to meet consumers' peak demand. This can involve the use of power saving technologies, electricity tariffs, monetary incentives, and government policies to mitigate peak load demand [16]. In [7], modification of consumers' load profiles was used to

classify DSM techniques into load shifting, peak clipping, load conservation, load building, valley filling and flexible load as illustrated in Fig. 3 [7, 10].

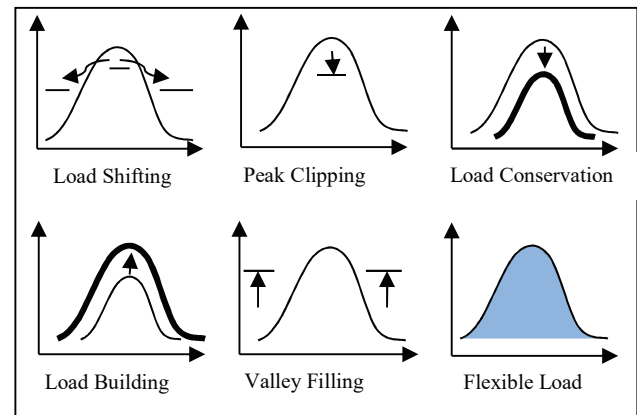


Figure 3: Demand side management techniques

Load shifting technique: It uses the time-independency characteristics of some electrical appliances and shifts their usage from peak time to off-peak time [8, 10-12, 15, 19]. It is a common technique for effective load management in recent distribution networks.

Peak clipping technique: This is employed by utilities to reduce peak demand of consumers' load profile at specific periods by direct control of equipment or use of tariff [12].

Load conservation technique: This technique is used to achieve load shape optimization through application of demand reduction methods at customer premises. It may have a long term effect on utility grid, network planning and operation.

Load building technique: It attempts to optimize the daily response in case of large demand introduction beyond the valley filling technique through contributions from energy conversion, storage systems or Distributed Energy Resources (DERs) [4, 20].

Valley filling technique: It involves the reduction of valley demand depth by building the off-peak demand [10, 13, 21].

Flexible load technique: This technique offers reliability to the smart grid by locating customers with flexible loads, who are willing to be controlled during critical demand periods in return for certain incentives.

Some of the motivations for DSM in the smart grid are briefly presently here.

Firstly, with TOU and dynamic pricing methods prominent among utilities in the world, consumers' demand at peak periods can be scheduled more favourably for energy and financial savings. Secondly, PDR helps to reduce the need to build additional energy network infrastructure to meet consumers' increasing peak

demand. Thirdly, consumers' energy consumption can be optimized by paying less for same energy consumption through the application of DSM techniques such as load shifting. Fourthly, the environment is protected due to a reduction of approximately 1 kg of CO₂ emission from peaker generating plants per kWh energy at peak period [22]. Lastly, efficient DSM techniques will lead to win-win situations for utility providers, consumers and the environment.

3. DOK-EUP DEMAND SIDE MANAGEMENT TECHNIQUE

In this section, a model for the proposed DOK-EUP technique for DSM in smart homes is presented. The DOK-EUP device is proposed to be installed into the smart meter in smart homes as a firmware. The DOK-EUP device is intended to be a Non-Intrusive Load Monitoring (NILM) device in order to offer low cost and installation complexities [21]. The DOK-EUP algorithm installed in the DOK-EUP device aims at Peak-to-Average-Ratio (PAR) energy reduction through PDR by scheduling shiftable appliances not to be used during traditional peak periods. It configures the EUP of TSSAs based on their known working principle with consumer's comfort in consideration. The smart appliances in the home are connected to the smart meter, which has identity for each connected appliance in the home. The proposed DOK-EUP was used to programme the allowable on/off working periods of the TSSAs. Therefore, an efficient and consumer satisfactory DOK-EUP for some TSSAs were considered. The TSSAs are devices whose usage period are largely time-independent and as such can be shifted in time from peak period to off-peak period without trading off consumer's comfort and appliance functionality.

3.1 Classification of household appliances

The household appliances were classified as either shiftable or non-shiftable loads. The TSSAs considered in this work are refrigerator, water heater, room heater, dish washer and washing machine; while radio, television, electric stove, phone, bulbs, electric iron, electric kettle, toaster etc. are non-shiftable appliances. Other appliances that could also be TSSAs, but not studied in this work, include pool pump, vacuum cleaner, tumble dryer etc.

DOK-EUP for TSSA refrigerator: A refrigerator is a common appliance in most households left to operate for 24 hours and hence, a major contributor to base load in residential premises. Leaving a refrigerator in an on-state for 24 hours daily would yield a higher electricity bill at month end than if its usage were scheduled according to DOK-EUP. Most refrigerated food items can remain safe after a power outage for 2 to 4 hours at a time, if the refrigerator doors were not opened and thermostat set at maximum 4.44°C [23]. Therefore, a TSSA refrigerator, set at this temperature, was modelled with this DOK and the on/off working periods of the refrigerator were simulated without negative impact on consumer's comfort, food

items in the refrigerator and the appliance. The TSSA refrigerators for the households were simulated to be without power supply from the smart meter for 2 hours during morning peak (07:00 to 09:00 hours) and 2 hours during the evening peak (18:00 to 20:00 hours) daily. These two off periods were scheduled during the morning and evening peak periods in order to contribute to PDR at such times. In [24], the DSM potential of refrigerators to contribute to reduction of peak demand was also investigated. Taking out refrigerator demand from the grid at peak periods could lead to peak-time grid stability since 70.3% of South African households own a refrigerator [25]. The on and off DOK-EUP scheduling for the TSSA refrigerator cannot damage the appliance since it is thermostatically controlled appliance. A TSSA freezer could also be scheduled similarly, but during 07:00 to 10:00 and 18:00 to 20:00 hrs daily within the morning and evening peaks respectively.

DOK-EUP for TSSA heaters: Domestic hot water heaters and Air-Conditioners contribute to about half of the energy consumption in residential premises. Hot water usage in the home, for bathing, cooking, dishwashing and laundry is about 30 to 50% of a consumer's electricity consumption and bill [26]. Hence, the need for HVAC load management. For instance, a 3 kW 150 litre water heater (geyser) requires 2 hrs 40 mins to heat up water from 20°C to 65°C; and if the water heater is switched off and it stores the water at thermostat set point, the water temperature will only drop by 10°C over 24 hrs [26]. Therefore, the TSSA water heater was scheduled to be allowed switched on for a maximum of 4 hours daily - 04:00 to 06:00 hrs for morning bath and 21:00 to 23:00 hrs for evening bath. However, households using shower are likely to save more energy than those running bath. The consumer can switch on the appliance within these allowable DOK-EUP periods but not restricted to the above duration. However, the DOK-EUP will not allow the appliance to be switched on during any of the peak periods.

In winter, the TSSA space heater, which may be an air-conditioner or conventional room heater, was modelled with a DOK-EUP, which allows the heater to be switched on for 6 hours (22:00 to 04:00 hrs) on weekdays and 10 hours (22:00 to 04:00 hrs and 11:00 to 03:00 hrs) on weekends, if necessary. Also, the consumer can switch on the appliance within these allowable periods but not restricted to the above schedule. The duration of the on state of the TSSA room heater can also depend on the weather conditions, type of building, dimensions of the room, number of occupants and items in the room. However, the DOK-EUP restricts the heater to be switched on only at off-peak times. Any customer that overrides the schedule would be denied incentive as will be later discussed in this paper.

DOK-EUP for TSSA washing machine: Washing machine is not in daily use in most households. The utilisation usually depends on the household size and ages of

occupants. However, this paper recommends that the washing machine usage in the home should follow the DOK-EUP proposal and hence not used during any of the peak periods. Therefore, its usage is restricted from the peak periods, but scheduled for 02:00 to 04:00 hrs. This period close to wake up time was chosen so that the clothes do not stay longer than necessary and unbearable in the machine before being taken out to dry.

DOK-EUP for TSSA dish washer: The TSSA dish washer was also scheduled for usage at off-peak times daily between 23:00 to 01:00 hrs. Dish washer is owned by 7.4% households in South Africa [25]. Therefore, DOK-EUP implementation on dish washers may have little effect on the national grid, but would offer financial savings for the households that possess following the DOK-EUP.

The DOK-EUP for the TSSAs illustrated above implies that the consumer is not allowed to use the specified TSSA appliances during peak periods. However, usage at other times is allowed for the appliances as desired by the consumer. Hence, no matter the type of household, the DOK-EUP will still be applicable.

The DOK-EUP algorithm will also help to reduce standby energy consumption in households. This standby energy is often due to presence of transformers, Light Emitting Diode (LED), Liquid Crystal Display (LCD) for clocks and microcomputers in these appliances [27]. The in-home load control offered by the DOK-EUP algorithm to the TSSAs at peak times ensures no contribution to standby power by these appliances even at peak periods.

Implementation of the proposed DOK-EUP will allow the households' demand to spread more evenly across the day (especially off-peak times) and therefore, reduce peak demand. This proposal could also be extended to other time-shiftable appliances other than the ones considered in this work such as the freezer, swimming pool pump, tumble dryer, vacuum cleaner etc. Smart meters are proposed to have capabilities to detect the different types of load in a household (via sensors or protocols) [1-3] and respond to each according to the scheduling algorithm embedded in them [8-16].

3.2 DOK-EUP model formulation

Let the set of TSSAs for consumer a be denoted by \mathbb{S} and the set of non-shiftable appliances be \mathbb{N} . All the appliances owned by a consumer belongs to \mathbb{Q} : $\mathbb{Q} = \mathbb{S} \cup \mathbb{N}$. In a 24-hour period with equal time slots division, each appliance is used within a time slot $t \in \mathbb{T}$, where $\mathbb{T} = [1, 2, 3, \dots, 24]$ with usage period u_i and u_j for TSSA i and non-shiftable j appliances respectively. In order to ensure that household consumption is reduced during peak periods t_p , the time-shiftable appliances are scheduled not to be used at these times so that PDR can be enhanced both at the individual smart home and neighbourhood levels. Hence, energy consumption of time-shiftable appliances can only take place during off-peak times, $t_{op} \in \mathbb{T}$, while

that of non-shiftable appliances can take place at any time $t \in \mathbb{T}$. The scheduled EUP for the TSSAs, are based on appliance-specific DOK as earlier discussed. Generally, peak periods are not more than 2 to 3 hours at a stretch. For instance, in Johannesburg, South Africa, the duration of the morning peak period lasts 3 hours (07:00 - 10:00 hrs) while the duration for the evening peak period lasts 2 hours (18:00 - 20:00 hrs) [1].

In the proposed system, the TSSAs are restricted from being switched on from the start of each peak period $t_p^{m,s}$ and $t_p^{e,s}$ to the end of each peak period $t_p^{m,f}$ and $t_p^{e,f}$ for morning and evening peak periods respectively, $\forall t_p^{m,s}, t_p^{m,f} \in t_p^m$, and $t_p^{e,s}, t_p^{e,f} \in t_p^e$. Where, $t_p^m = [t_p^{m,s}, t_p^{m,s} + 1, t_p^{m,f}]$ for the morning peak and $t_p^e = [t_p^{e,s}, t_p^{e,s} + 1, t_p^{e,f}]$ for evening peak since $2 \leq t_p^{m,f} - t_p^{m,s} \leq 3$ and $2 \leq t_p^{e,f} - t_p^{e,s} \leq 3$; and $t_{op} \in \mathbb{T} \setminus t_p^m, t_p^e$. Therefore, $\mathbb{T} = [1, 2, \dots, t_p^{m,s}, t_p^{m,s} + 1, t_p^{m,f}, \dots, t_p^{e,s}, t_p^{e,s} + 1, t_p^{e,f}, \dots, 24]$.

At time t , the total energy consumed by consumer $a \in \mathbb{A}$ is given by (1):

$$x_a^t = \sum_{i \in \mathbb{S}} x_a^{t,i} + \sum_{j \in \mathbb{N}} x_a^{t,j}, \forall t \in \mathbb{T}, \quad (1)$$

where $x_a^{t,i}$ and $x_a^{t,j}$ are the energy consumed by TSSA appliance i and non-shiftable appliance j respectively. Therefore, the daily energy consumption vector for consumer a can be expressed as $\mathbf{x}_a = [x_a^1, x_a^2, \dots, x_a^{24}]^T$. The total daily energy consumption X by all the consumers in the neighbourhood is expressed in (2):

$$X = \sum_{a \in \mathbb{A}} \sum_{t \in \mathbb{T}} x_a^t. \quad (2)$$

Each time slot t is further sub-divided into equal time slots, within which an appliance can use electricity. The usage periods are $u_i \in H_i$ and $u_j \in H_j$, where $H_i \triangleq \{u_{i,s}^t, \dots, u_{i,f}^t\}$ and $H_j \triangleq \{u_{j,s}^t, \dots, u_{j,f}^t\}$, for appliance starting times $u_{i,s}^t$, $u_{j,s}^t$ and finish times $u_{i,f}^t$, $u_{j,f}^t$ respectively. Therefore, $H_i \in t_{op} \setminus t_p^m, t_p^e$ and $H_j \in t_{op}, t_p^m, t_p^e$. Therefore, $\mathbb{T} = t_{op} \cup t_p^m \cup t_p^e$. Since,

$$\sum_{i \in \mathbb{S}} x_a^{t,i} = 0, \forall t \in t_p^m, t_p^e, \quad (3)$$

Therefore,

$$x_a^t = \begin{cases} \sum_{i \in \mathbb{S}} x_a^{t,i} + \sum_{j \in \mathbb{N}} x_a^{t,j} & \forall t \in t_{op} \\ \sum_{j \in \mathbb{N}} x_a^{t,j} & \forall t \in t_p^m, t_p^e \end{cases}. \quad (4)$$

Also, it is assumed that no hourly consumption is greater than the daily peak demand as shown in (5):

$$0 \leq x_a^t \leq x_a^{max} \quad (5)$$

However, the energy PAR is expressed in (6):

$$PAR = \frac{\text{Peak energy consumption}}{\text{Average energy consumption}} = \frac{\max_{t \in \mathbb{T}} \sum_{a \in \mathbb{A}} x_a^t}{\frac{1}{T} \sum_{a \in \mathbb{A}} x_a^t}. \quad (6)$$

Since the denominator could be constant as widely assumed in smart grid literature [19, 20], therefore, a lower PAR for the grid can be achieved by minimizing the numerator (peak energy consumption) as in (7).

$$\begin{aligned} \min_{a \in \mathbb{A}} PAR \triangleq & \min_{a \in \mathbb{A}} \max_{t \in \mathbb{T}} \sum_{a \in \mathbb{A}} x_a^t. \\ & \text{subject to (3) – (5)}. \end{aligned} \quad (7)$$

Therefore, the lower the peak demand consumption, the lower the PAR becomes and the better it is for the grid. Hence, the reasons TSSAs were scheduled for usage during off-peak period in this work.

Given that hourly TOU tariff matrix, $\mathbf{F} = [f_1, f_2, \dots, f_t, \dots, f_{24}]$, $\forall f_t \in \mathbf{F}, t \in \mathbb{T}$. The standard tariff period is also considered here as a type of off-peak period so that shiftable appliances can still be operated within this period, if desired by the consumer. However, the vector tariff matrix \mathbf{F} is rightly populated with tariff values corresponding to each time slot according to Table I [28]. Table I shows TOU tariff for different periods of the day and seasons of the year in Johannesburg, South Africa.

TABLE I. TOU TARIFF FOR SINGLE-PHASE DOMESTIC CUSTOMERS

Period	Summer (c/kWh)	Winter (c/kWh)
Peak	109.89	262.09
Standard	86.93	104.65
Off-peak	68.39	73.38

Therefore, the total hourly and daily cost of energy consumption to a consumer C_a is shown in (8) and (9) respectively:

$$C_a^t = f_t x_a^t, \quad (8)$$

$$C_a = \mathbf{F} \mathbf{x}_a. \quad (9)$$

For situations when the consumer decides not to be a DOK-EUP consumer, its hourly energy consumption and consumption costs are found using (10) and (11) respectively:

$$\bar{x}_a^t = \sum_{i \in \mathbb{N}} \bar{x}_a^{t,i}, \forall i = 0, \mathbb{S} = \{\}, \mathbb{Q} = \mathbb{N}, \quad (10)$$

$$\bar{C}_a^t = f_t \bar{x}_a^t, \quad (11)$$

In order to incorporate consumer's preferences into the implementation of the DOK-EUP model, the DOK-EUP algorithm is only activated for a consumer when consent is obtained from the consumer. This consent is sent to the utility's Data Aggregation Point (DAP) within the Neighbourhood Area Network (NAN) of the consumer through the smart meter. These infrastructures (smart

meter, NAN and DAP) are already proposed for the smart grid and upon which the DOK-EUP can leverage, just like other future DSM, Demand Response (DR) and Home Energy Management (HEM) technologies for the smart grid [1, 3]. Also, lower tariff incentive is proposed to be given during winter to every consumer that gives consent for the DOK-EUP implementation in their household due to their contribution towards PDR and consequentially, PAR reduction for the grid. Furthermore, the DOK-EUP algorithm allows the consumer to opt in/out of the DOK-EUP agreement at will. The DOK-EUP algorithm is illustrated with the flow chart in Fig. 4.

Morning peak energy savings, $x_{a,s}^{max,m}$ is given in (12):

$$x_{a,s}^{max,m} = x_{a,ND}^{max,m} - x_{a,DOK}^{max,m}, \forall a \in \mathbb{A}, \quad (12)$$

Where, $x_{a,ND}^{max,m}$ is morning peak demand with Normal Demand EUP (ND-EUP) and $x_{a,DOK}^{max,m}$ is morning peak demand with DOK-EUP. Also, the evening peak energy savings, $x_{a,s}^{max,e}$ is given by (13):

$$x_{a,s}^{max,e} = x_{a,ND}^{max,e} - x_{a,DOK}^{max,e}, \forall a \in \mathbb{A}, \quad (13)$$

Where, $x_{a,ND}^{max,e}$ is the evening peak demand with ND-EUP and $x_{a,DOK}^{max,e}$ is evening peak demand with DOK-EUP. Peak-to-peak energy savings per day in each scenario is given by (14) and (15) respectively:

$$x_{a,s}^{max,ND} = x_{a,ND}^{max,e} - x_{a,ND}^{max,m}, \quad (14)$$

$$x_{a,s}^{max,DOK} = x_{a,DOK}^{max,e} - x_{a,DOK}^{max,m}. \quad (15)$$

4. RESULTS AND DISCUSSION

Results of the simulations are presented in this section. The results include comparisons between ND-EUP load profile based on consumers' traditional usage of home appliances and DOK-EUP load profile based on the proposed DOK-EUP.

A middle-income household in Johannesburg, South Africa was taken as a case study and a detailed survey of the household's demand was carried out in winter and summer for the period of one year. These householders leave home for work in the morning and return in the evening from Monday to Saturday weekly. The household comprises a family of five (5) – father, mother and three children. The survey inquired from the householder on appliance ownership, daily and seasonal usage of appliances and monthly electricity bills to validate the survey data. The survey data was simulated to obtain the ND-EUP hourly load profile for the household in summer, based on traditional usage of electricity. Each appliance hourly load profile was estimated with lessons obtained from [17, 29]. The standby mode energy consumption of appliances was also considered during each appliance load profile design [27, 29].

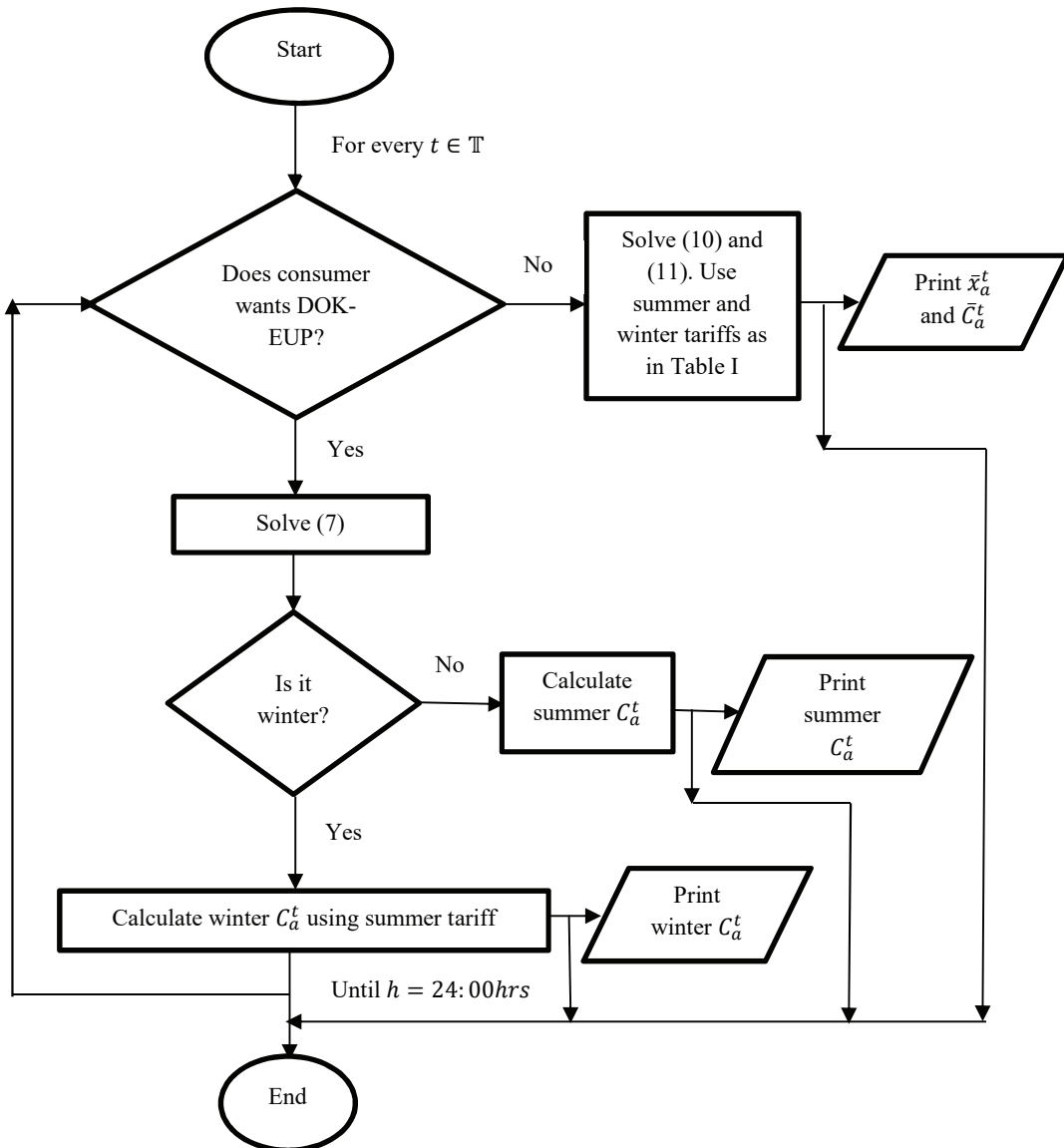


Figure 4: Flow chart illustrating DOK-EUP algorithm

Also, the simulated data was normalised and fed into the DOK-EUP algorithm to obtain the DOK-EUP load profiles in winter and summer. The detailed survey was carried out due to unavailability of appliance hourly consumption data locally as at the time of writing this paper, for residential customers. The data obtained from the utility was hourly aggregate for areas and communities. However, as the nation progresses in smart grid implementation, more useful data for research purposes will be available from utilities. The appliances possessed by the household is resented in Table II.

Therefore, the resultant load profiles for ND-EUP and DOK-EUP DSM simulations are shown in Fig. 5 and Fig. 6 for summer and winter seasons respectively. The proposed DOK-EUP algorithm was observed to have shifted the morning peak demand from traditional peak period to off-peak period in summer and winter due to the proposed DOK-EUP for TSSAs.

TABLE II. HOUSEHOLD ELECTRICAL LOAD

Load	Power P (KW)	Quantity n	Load type
Radio	0.015	1	NS
Television	0.040	1	NS
Stove	2.000	1	NS
Phone	0.010	2	NS
Bulbs (inside and outside)	0.010	6	NS
Iron	1.600	1	NS
Kettle	2.200	1	NS
Fan*	0.080	1	NS
Refrigerator	0.350	1	S
Water heater	3.000	1	S
Room heater*	1.000	1	S

*Seasonal loads, NS – Non-shiftable load, S – Shiftable load

During summer, a better distributed consumption at the evenings was noticed, which is good for grid stability. However during winter, the evening demand was so distributed such that the evening peak was almost completely shifted to off-peak period in the night at around 23:00 hrs (Fig. 6).

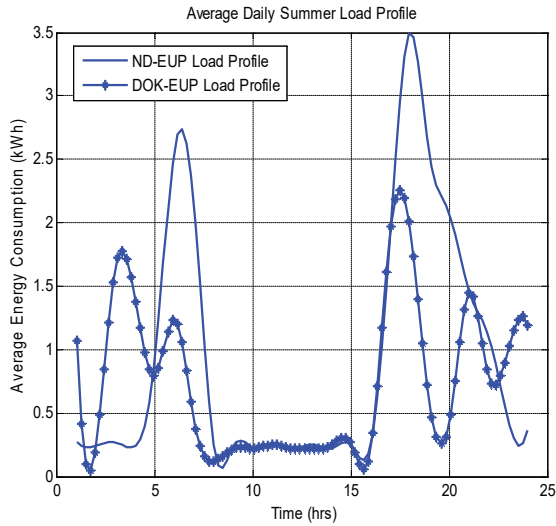


Figure 5: Average daily summer load profile for sample household

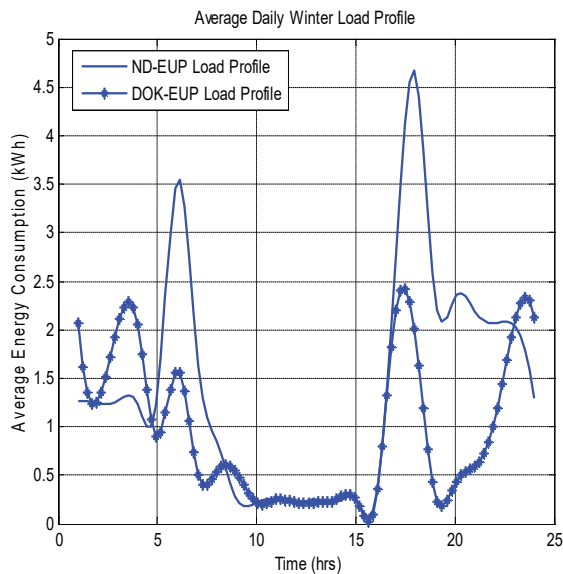


Figure 6: Average daily winter load profile for sample household

Also, PDR was shown to also be a possible advantage of DOK-EUP as the peak demand in DOK-EUP is less than the peak demand in ND-EUP. This order of PDR from many households could lead to lower capital cost incurred on peaker plants by the utility provider, financial savings for consumers and safer environment for all due to reduced associated CO₂ emissions from peaker plants. Therefore, with 1.5348 kWh and 2.4929 kWh PDR from the DOK-EUP household in summer and winter respectively, there will be 1.504 kg and 2.443 kg CO₂ emissions reduction

from the DOK-EUP household tested [22, 30]. The aggregate reduction in CO₂ emissions over many DOK-EUP households could offer a safer environment in South Africa compared to the 8.9 kg/person CO₂ emissions from grid electricity [31].

Furthermore, it was observed that the peak-to-peak difference for daily and seasonal analyses in the DOK-EUP load profiles were lower than in the ND-EUP load profiles. This could also contribute towards a combined near-table overall load profile proposed for the future grid (smart grid). It is worthy to note that although the results obtained were discrete in time, but the *spline* function in MATLAB [32] was used to convert the plots into continuous graph. The summary of the energy savings, financial savings, peak demand and peak-to-peak difference is presented in Table III.

TABLE III. SUMMARY OF COMPARISON BETWEEN THE ND-EUP AND DOK-EUP FOR ONE HOUSEHOLD

	Summer		Winter	
	ND-EUP	DOK-EUP	ND-EUP	DOK-EUP
Energy consumed (kWh)	22.158	19.848	33.973	24.822
Peak-to-peak difference (kWh)	0.898	0.308	1.098	0.363
Peak demand (kWh)	3.5076	1.9728	4.6579	2.1650
Electricity bill (R)	625.92	466.86	1,734.39	570.60
PAR	3.30	2.15	2.79	1.81

R - Rand (South African currency)

It was assumed that the consumer applied DOK-EUP to its consumption throughout summer and hence, got tariff incentive to pay for energy consumption during winter at summer TOU tariff rate. Therefore, the financial savings for the DOK-EUP consumer was 25.41% and 67.10% in summer and winter respectively.

Since the consumer can opt out of the DOK-EUP DSM programme at any desired instance, the effect of such decisions on householder's electricity bill in summer is presented in Fig. 7. This showed that the higher the number of days in a month the consumer opts in for DOK-EUP, the lower its' monthly electricity bill.

Therefore, it can also be inferred that the higher the number of households that opts in for DOK-EUP, the lower the grid PAR would be (as shown from (6) and (7)), since DOK-EUP offered PDR. Technicalities of opting in and out of the proposed DSM programme shall leverage

on the bi-directional communication and information flows that characterise the smart grid.

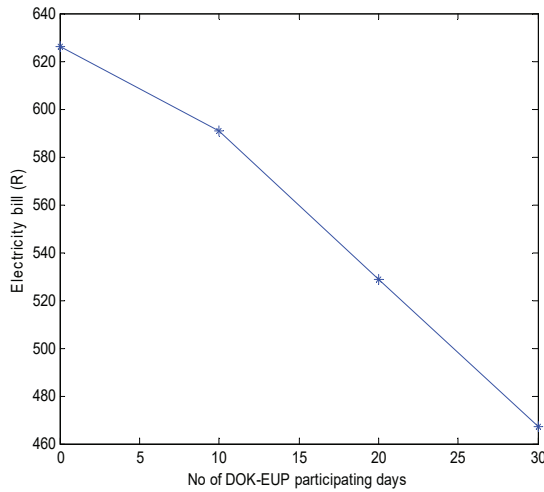


Figure 7: Effect of number of participating days on monthly electricity bills

Co-operation from the householders is expected to be positive towards this DOK-EUP due to the socio-economic effect it would have on them in tariff incentive, energy and financial savings. Also, a survey by the Department of Energy, South Africa [33] showed that 77% of South African consumers will be willing to accept policies on energy-saving initiatives. The authors also in a preliminary survey among residents in Johannesburg, South Africa and found out that 81% of householders will be willing to comply with DSM techniques that can reduce their monthly electricity bills (i.e. financial savings) without trading off their comfort and appliance's lifespan. Also, the algorithm is scalable over as many household as possible that consent.

5. CONCLUSION

The proposed DOK-EUP model for TSSAs in this paper was shown to offer peak demand reduction, peak demand shifting, financial and energy savings and reduced associated CO₂ emissions. This work has also shown the importance of knowing the working principle of an appliance before implementing its' scheduling for DSM optimization. The proposed DOK-EUP DSM technique can also offer grid stability and reduce or eliminate the possibilities of load shedding or blackouts common to peak times. This technology is also autonomous in its operation with local (in-house) load control and is driven by consumer, utility and environmental satisfaction. Also, consumers' privacy is guaranteed due to the opt in/out provision in the algorithm.

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