Effective Energy Consumption Scheduling in Smart Homes

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***Abstract* – Monthly expenditure on electricity by most households in South Africa take beyond acceptable percentage of their income. In order to keep the household energy expenditure below the energy poverty threshold, a daily electricity optimization problem is formulated using mixed integer linear programming (MILP) method. The energy optimization scheduling was carried out by a device called the Daily Maximum Energy Scheduling (DMES) device proposed to be incorporated into smart meters of households. The DMES algorithm was tested with household data set and was shown to be capable of ensuring that households spend less than 10% of their income on electricity bill monthly. This technique therefore, would be beneficial to consumers (for better financial savings and planning), utility (for effective energy and financial savings, and energy network planning) and cleaner environments as proposed for smart grid. Also, number of households in the nation living below the energy expenditure-based poverty threshold would increase.**

***Key words* - Smart meter; Daily Maximum Energy Scheduling (DMES); smart home appliances; low-income households; electricity consumption.**

I. INTRODUCTION

The future of smart grid is proposed to be facilitated by bi-directional power, information and communications flow between utility providers and consumers. Advanced Metering Infrastructure (AMI) had recently gained attention from the industry and academia because it involves consumers' participation in the smart grid through Demand Response (DR) and Demand Side Management (DSM). The components of AMI system include smart meters, Home Area Network (HAN), wide area communications infrastructure, Meter Data Management Systems (MDMS) and operational gateways [1]. AMI is therefore essential for effective energy management in the smart grid, alongside the Internet of Things (IoT).

Electricity bill is a recurrent monthly expenditure for households and the demand for electricity to residential consumers is generally inelastic. However, the percentage of household income spent on energy is one of the indicators of energy poverty [2]. Also, the percentage of household income spent on monthly electricity bills by most residential customers in South Africa is beyond the energy poverty threshold set by the Department of Energy, South Africa. Hence, DSM and energy management techniques can be introduced to enhance reasonable consumption of electricity as desired and government threshold for energy poverty. Therefore in this work, Daily Maximum Energy Scheduling (DMES) technique is proposed to attempt to help households spend more reasonably on electricity bills and government to also have more households living below the energy poverty threshold.

Monthly electricity bill comes from cumulative daily consumption. Therefore, daily energy consumption by smart home appliances connected in a HAN to a smart meter is investigated in this work to ensure that electricity bills are within the limit desired according to their income class. This was carried out by setting maximum daily energy consumption limit for households through the DMES device. This work assumes existing HAN in the homes where the DMES device will be deployed.

Generally, linear programming has been a useful tool in solving many optimization problems in economics, science and engineering. In smart grid, it has been proposed useful in implementing many algorithms for DSM [3,4] and DR [5,6]; among others. Mixed Integer Linear Programming (MILP) is proposed in this work to formulate the problem for optimized daily energy consumption in smart homes.

This study has shown that incorporating the DMES device into smart meters will further enhance energy and financial planning and saving for both consumer and utility providers. The consumer would pay for electricity within their desired budget. The utility can also effectively plan for their energy networks especially the generation and distribution. Furthermore, the government would have lesser number of energy poor households in the country. Also, this work is novel to using DSM techniques to mitigate household-level energy poverty.

The rest of this work is organized as follows. Section II contains the relationship between households' income, household electricity expenditure and energy poverty; while the use of DMES device for daily energy consumption scheduling in smart homes is presented in Section III. Results and discussions are found in Section IV and the conclusion in Section V.

II. HOUSEHOLDS INCOME AND ENERGY EXPENDITURE

Electricity consumption by households is largely affected by household income and appliances owned [7], but what percentage of income is spent on electricity bill is of interest in this study. Some energy efficiency technologies are also being introduced to reduce the quantity of energy consumed by households. This includes awareness on the use of energy efficient appliances, opening of windows during summers instead of using fan or air-conditioner, constructing energy efficient buildings etc. However, these come with a cost to customers.

Energy expenditure-based indicator of energy poverty varies from country to country, but is widely 10% - 15% threshold. The Department of Energy (DoE), South Africa, chose 10% as its threshold [8]. This implies that households that spend more than 10% of their income on energy are considered energy-poor households. The DoE through a nationwide survey found that South African households spend an average of 14% of their income on energy expenditure, but low-income households spend an average of 17% of their income on energy bills [8]. This work therefore, attempts to ensure that low-income residential consumers of electricity only pay ≤ 10% of their income on electricity by using the DMES device. The classes of consumers considered as low income households are those in LSM1 – LSM3, according to the South African Living Standard Measurement (LSM) [9].

III. SMART HOMES DAILY CONSUMPTION SCHEDULING

A. HAN DMES System Description

The electricity scheduling in smart homes was carried out by the proposed DMES device to be incorporated into customers' smart meter (SMs). The DMES-SM serves as a link between the HAN and the Data Aggregation Point (DAP). The proposed system is illustrated in the Fig. 1.

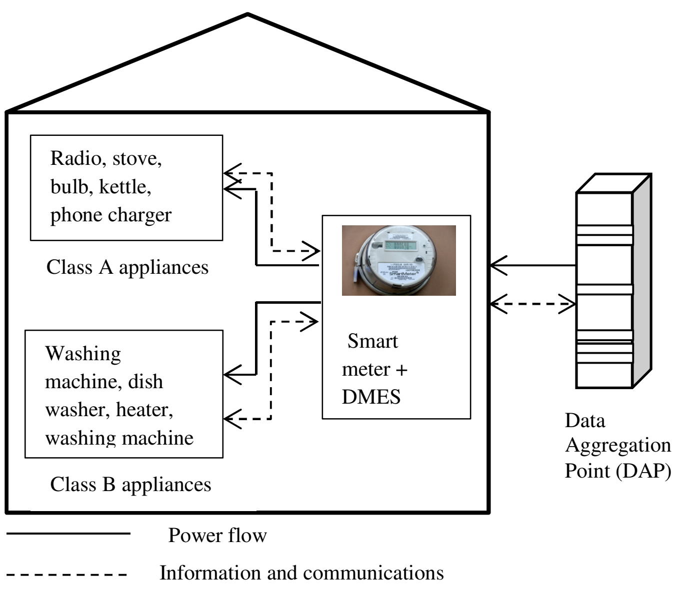

Fig. 1. Illustration of a DMES-HAN

Monthly household electricity bill can be kept within a tolerable range and below energy poverty threshold by monitoring and controlling what is daily consumed in the household. Therefore, a daily maximum electricity consumption technique is proposed in this work. According to [10], low income households in South Africa consume an average of 2666.67 kWh/annum (222.23 kWh/month). The power utility in South Africa, Eskom has a tariff called Home Power Standard classification [11] where block 1 consumers are those that consume 0 to 600 kWh monthly, and block 2 consumers use more than 600 kWh monthly. This block classification is used in this work. This implies that low income households would fall into block 1 energy tariff.

A survey of fifteen low income households was carried out in this work. The average household income for low-income households is R1955 according to the South African Advertising Research Foundation (SAARF) [9]. Since a threshold on energy expenditure had been set as 10% of household income by DoE [8], R200 was chosen as the proposed budgeted energy expenditure for low income households respectively. For a scenario where all customers were connected to non-local authority rates of Eskom, average energy tariff of R1.20/kWh was chosen taking other charges and VAT into consideration [11]. Some information about the initial and DMES consumption systems are presented in Table I.

TABLE I. INFORMATION ON INITIAL AND PROPOSED DMES SYSTEMS

Description	**Low income Household**
Initial average monthly electricity consumption	190 kWh
Initial average monthly electricity bill	≥R228
Initial average maximum daily consumption	6.33 kWh
Proposed average monthly electricity bill	R200
Proposed average maximum daily consumption, $\boldsymbol{E_{max_d}}$	5.56 kWh

B. Daily Electricity Consumption Scheduling for Smart Homes

The proposed daily energy consumption model can be described as a linear optimization problem that sets maximum daily energy consumption for each household through their smart meters according to the proposed monthly budget for electricity bill. The smart home appliances in the low-income households were categorized into class A (priority) appliances and class B (non-priority) appliances as shown in Table II.

TABLE II. LIST OF HOUSEHOLD APPLIANCES

Appliance	**Appliance class and ID**	**Power (kW)**
Radio	A_1	0.015
TV	A_2	0.040
Stove	A_3	1.500
Inside Bulbs	A_4	0.040
Outside bulbs	A_5	0.040
Kettle	A_6	1.000
Fan *	A_7	0.080
Phone charger	A_8	0.010
Refrigerator	A_9	0.250
Iron	B_1	1.000
Room heater*	B_2	2.000
DVD player	B_3	0.025
Laptop	B_4	0.050

* Seasonal appliance

The proposed electricity bill of a consumer is used to calculate how much of monthly electricity that can be purchased from the utility, and hence, a maximum daily consumption is set.

Let $\mathbb{A} = \{A_1, A_2, \dots, A_9\}$ and $\mathbb{B} = \{B_1, B_2, \dots, B_4\}$. The classification of appliances can also be effected based on customer's preferences. Laptop was considered as a class B appliance because it is a battery-assisted appliance and shifting its demand up to an average of 3hrs would not discomfort the user. Since energy is the product of power p and time t, variable q is included to represent the quantity of a particular appliance being used at a particular time in a household. Therefore, electrical energy consumed by an appliance in a household is expressed in (1) as:

$$E = qpt \quad \forall q, p > 0 \; and \; t \geq 0 \tag{1}$$

Whereas, the total hourly energy consumed at time h by all class A and class B appliances is given by equations (2) and (3) respectively:

$$E_{A,h} = E_{A_1,h} + E_{A_2,h} + \dots + E_{A_9,h} = \sum_{A_n \in \mathbb{A}, h \in \mathbb{H}} E_{A_n,h} \tag{2}$$

$$E_{B,h} = E_{B_1,h} + E_{B_2,h} + \dots + E_{B_4,h} = \sum_{B_m \in \mathbb{B}, h \in \mathbb{H}} E_{B_m,h} \tag{3}$$

where E_{A_n} is the energy consumed by class A appliance with ID, $n \; \forall 1 \leq n \leq 9$ and E_{B_m} is the energy consumed by a class B appliance with ID, $m \; \forall 1 \leq m \leq 4$ at a time h for $h \in \mathbb{H}$, where $\mathbb{H} = [1, 2, 3, \dots, 24]$. However, each appliance's period of usage within t, may also be less or greater than one hour. For instance, a kettle would boil water within a few minutes whereas, a refrigerator may be operated for 24 hours.

The energy consumption plan of a smart appliance in a household is expressed as $\mathbf{E}_{A_n} = [E_{A_n,1}, E_{A_n,2}, E_{A_n,3}, \dots, E_{A_n,24}]^T$ $\forall A_n \in \mathbb{A}$ and $\mathbf{E}_{B_m} = [E_{B_m,1}, E_{B_m,2}, E_{B_m,3}, \dots, E_{B_m,24}]^T$ $\forall B_m \in \mathbb{B}$ for class A and B smart appliances respectively.

A household total hourly energy consumed, E_h at every time, h where $h \in \mathbb{H}$ by all the smart appliances connected to the DMES device is expressed in (4):

$$E_h = E_{A,h} + E_{B,h} = \sum_{A_n \in \mathbb{A}, h \in \mathbb{H}} E_{A_n,h} + \sum_{B_m \in \mathbb{B}, h \in \mathbb{H}} E_{B_m,h} \tag{4}$$

The cumulative energy consumed in the household E_h^* at a time h is given by (5):

$$E_h^* = \left(E_{A_n,h-1} + E_{B_m,h-1}\right) + \left(E_{A_n,h} + E_{B_m,h}\right) \tag{5}$$

The consumption pattern per household for each class A appliances, according to the survey carried out, is expressed by the diagonal matrix in (6):

$$\mathbf{C}_{A_n} = \left[\mathbf{E}_{A_n,1} \; \mathbf{E}_{A_n,2} \dots \; \mathbf{E}_{A_n,24}\right] = \begin{bmatrix} E_{A_n,1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & E_{A_n,24} \end{bmatrix} \tag{6}$$

Also, for class B appliances, the consumption pattern is given as (7):

$$\mathbf{C}_{B_m} = \left[\mathbf{E}_{B_m,1} \; \mathbf{E}_{B_m,2} \dots \; \mathbf{E}_{B_m,24}\right] = \begin{bmatrix} E_{B_m,1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & E_{B_m,24} \end{bmatrix} \tag{7}$$

Probability of usage was considered during data mining for appliances not on daily usage (iron and DVD player).

Maximum daily household energy consumption E_{max_d} is found by (8):

$$E_{max_d} = \frac{E_m}{number \; of \; days \; in \; the \; month} = \frac{0.1I/p}{n} \tag{8}$$

Where n represents the number of days in the month, E_m is the proposed maximum monthly household energy consumption, which is a function of the household income, I and flat tariff, p.

The daily consumption of all appliances is expected to continue as scheduled until the time when household daily energy threshold is reached (i.e. $E_h = E_{TH}$), after which switching off of class B appliances begin to further ensure that $E_h \leq E_{max_d}$ every day. The value of E_{TH} is chosen such that $E_{TH} = 0.9E_{max_d}$. At time $h_{E_{Th}} \in \mathbb{H}$ when energy threshold is reached, switching OFF of connected class B appliances in decreasing order of energy consumption sets in such that $\sum_{B_m \in \mathbb{B}} E_{B_m,h} \leftarrow 0$. However, if the consumer is awake, manual switching OFF of desired appliances can be also done. At 24:00 hrs, the timer resets and the same process are repeated again for the next day until month ends and $E_{24} = E_{d_{DMES}}$ is saved in the energy logger of the DMES device. However, for households with consumptions such that $E_{24} < E_{TH}$, then priority plan algorithm does not sets in at all.

C. Energy Savings Decision

The energy savings decision is meant to give the consumers the ability to decide how to spend $E_{max_d} - E_{24}$. Firstly, the consumers can have their E_{max_d} updated daily, $E_{max_{d+1}}$ with the difference of $E_{max_d} - E_{24} = E_s$ from the previous day added to the E_{max_d} of the next day. Once E_{max_d} is updated, E_{TH} is also automatically updated. Secondly, E_s can also be saved during hot months from first day d_1 to last day d_l and used during cold months by the consumer as energy paid back, E_{pb}. The E_{pb} is added to the E_{max_d}; and the cold months E_{max_d} and E_{TH} are updated accordingly. Hence, the consumer can choose between optimizing the energy savings, E_s for the month continuously, *opt1* or for demand in cold months, *opt2*. All the households in this phase of the work chose *opt2* that is to use energy saved E_s in cold months to cater for the usual high demand in cold months.

The optimization problem and algorithm are presented in the next section.

D. DMES Energy Optimization Problem and Algorithm

The linear optimization problem to minimize the total daily energy consumption per household can be formulated in (9) as follows from (1) – (8):

$$\min_{E_h, E_{A_n,h}, E_{B_m,h} \in \mathbb{R}} E_h$$

$$\begin{aligned}
\textbf{s.t.} \quad & E_h \leq E_{max_d}, \\
& \textstyle\sum_{A_n \in \mathbb{A}} E_{A_n,h} + \sum_{B_m \in \mathbb{B}} E_{B_m,h} \leq E_{max_d} \\
& \textstyle\sum_{A_n \in \mathbb{A}} E_{A_n,h} + \sum_{B_m \in \mathbb{B}} E_{B_m,h} = E_h, \quad \forall h \in \mathbb{H}, \\
& \mathbf{1}^T \mathbf{E}_{A,h} + \mathbf{1}^T \mathbf{E}_{B,h} = E_h, \quad \forall h \in \mathbb{H}, \\
& E_{A_n,h} \geq 0, \; E_{B_m,h} \geq 0, \; \forall A_n \in \mathbb{A}, \forall B_m \in \mathbb{B}
\end{aligned} \tag{9}$$

Where $\mathbf{1}^T = [1,1,..,1]$ was introduced to obtain scalar result for the total energy consumption at every time h. The proposed algorithm is as shown in Algorithm 1.

Algorithm 1: Executed by each DMES smart meter device

input: Consumption plan, $\boldsymbol{E_{max_d}}$, $\boldsymbol{E_{TH}}$.
output: total $\boldsymbol{E_h}$ for the day.
repeat
 if time $\boldsymbol{h} \in \mathbb{H}$ **then**
  Solve $\sum_{A_n \in \mathbb{A}} \boldsymbol{E_{A_n,h}} + \sum_{B_m \in \mathbb{B}} \boldsymbol{E_{B_m,h}} = \boldsymbol{E_h}$, $\forall \boldsymbol{h} \in \mathbb{H}$
  Update $\boldsymbol{E_h}$ according to the solution.
   if $\boldsymbol{E_h = E_{TH} = 0.9E_{max_d}}$ **then**
    $\sum_{B_m \in \mathbb{B}} \boldsymbol{E_{B_m,h}} \leftarrow \boldsymbol{0\ at\ h_{E_{Th}}} \in \mathbb{H}$ but class A consumption continues
   end if
 end if
until $\boldsymbol{h = 24{:}00hrs}$
At $\boldsymbol{h = 24{:}00hrs}$,
 if $\boldsymbol{E_{24} < E_{max_d}}$ **then**
 savings optimization decision sets in to determine how $\boldsymbol{E_s = E_{max_d} - E_{24}}$ is used by household
  if *opt1* is chosen **then**
   $\boldsymbol{E_{max_{d+1}} = E_{max_d} + E_s}$
  else *opt2* is chosen **then**
   $\boldsymbol{E_{pb} = \sum_{d_1}^{d_l} E_s}$ for cold months
  end if
 end if
Timer resets and repeats same process next day until month ends and bill is generated.

IV. RESULT OF DMES CONSUMPTION IN SMART HOMES

The result of the survey on household usage of electricity was used to develop the consumption pattern for the households, and it was fed into the DMES algorithm as earlier illustrated. Only fifteen low-income households' consumption data were each considered. The survey inquired from household on possession of household appliances, period of day appliances are used and seasonal usage of appliances. The information was used to build hourly and seasonal load profile data for all the households considered. The data generated was fed into the algorithm and the results obtained for the four seasons of the year are shown in Figs. 2 to 5.

From the annual electricity consumption obtained for all the households considered, it was discovered that only 33% of low-income households, on average, were below the desired DoE energy expenditure threshold initially. This implies that majority of low income householders are spending more than 10% of their income on monthly energy expenditure. The average monthly energy expenditure for the fifteen households was R173.38, which is less than R200 as proposed. Nevertheless, with the DMES technique households can learn to be more energy efficient and saving to keep their consumption below the desired consumption.

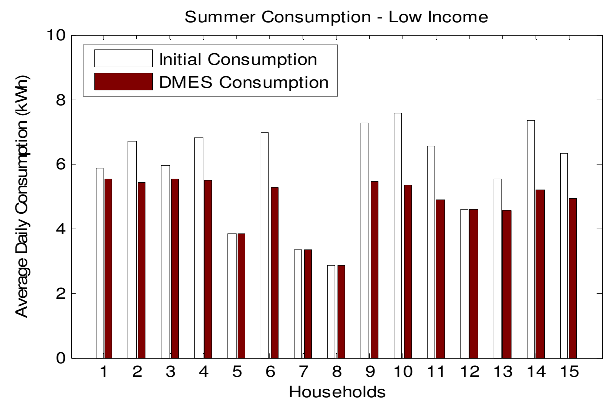

Fig. 2. Result of initial and DMES consumption during summer

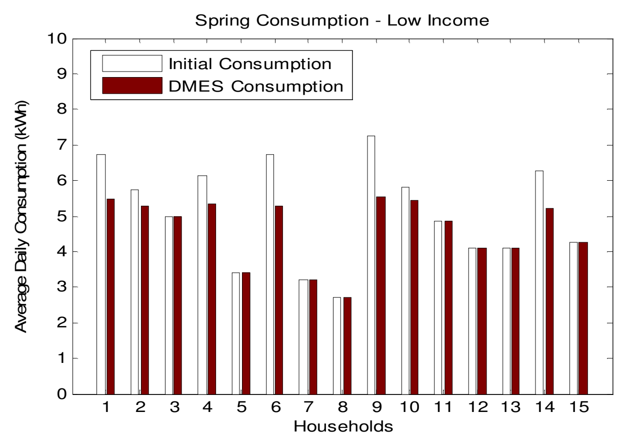

Fig. 3. Result of initial and DMES consumption during spring

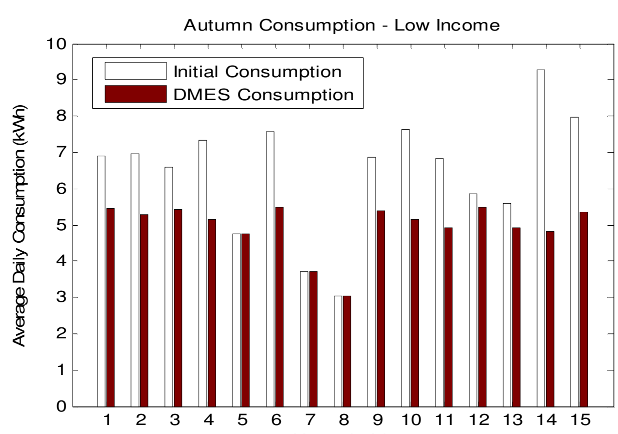

Fig. 4. Result of initial and DMES consumption during autumn

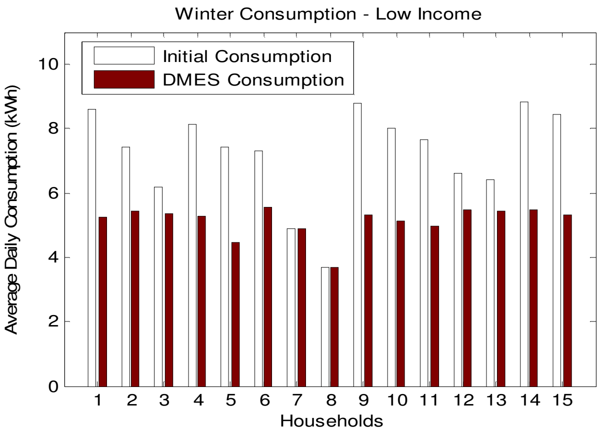

Fig. 5. Result of initial and DMES consumption during winter

In order to ensure that the consumer's energy needs is adequately taken care of, there is an energy request algorithm also incorporated into the DMES device. For instance, households at the upper bound of the low-income class (LSM3) can request for a higher E_{max_d} to be able to meet its energy needs.

Also, it was shown that the DMES device can be used to maintain electricity bills at the amount the household desire and still give the households some comfort. With time, the consumers are expected to adjust better and get used to the DMES technique for monitoring their consumption. This will enhance financial and energy savings for the consumers. This could also mean energy savings, financial savings and better planning for the power utilities.

In [8] it was shown that 77% of South African households are willing to accept government initiatives towards energy saving. Also, apart from the installation of the DMES device on their smart meters, they would also need application of other DSM consumer behavioural techniques as presented in an earlier work [12] so that the comfort of the consumer is further enhanced.

Although this idea was tested for low-income households, middle and high income customers can also find it applicable to them, if desired.

V. CONCLUSION

The DMES device, through daily electricity consumption scheduling, has been shown in this work as a device that can be used to ensure that consumers do spend on electricity bills within a desired limit. Consequentially, it would help both the utility provider and the customers towards better energy savings, financial savings, planning and budgeting for a more reliable and sustainable grid. The DoE, South Africa would also be able to have more households in South Africa spend <10% of their income on monthly electricity bills. The DMES device can be incorporated into smart meters not only in South Africa, but also in other countries of the world, where smart grid is being envisioned. This can be achieved by putting the country's energy expenditure threshold into account, rather than $energy\ expenditure\ threshold = 0.1$ used in this work for South Africa. Peak demand reduction capabilities shall also be investigated using the DMES device to make it more robust for DSM in smart grid.

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