Modelling of Integrated Energy Management Program for Efficient Consumption Reduction

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Abstract:
The need to significantly reduce end users' energy demand and energy bills have been a global concern. This study aims to propose a better and more effective means of reducing end users' energy bills. Energy efficiency and demand response programs were modelled, and the resulting demand was used to model an on-site generation to achieve an effective and better improvement in the end user's peak demand and energy bill. For the energy-efficient model, when compared with the presently installed loads, 12.7% of the annual energy was saved. The optimization carried out on a Primary Health Care (PHC) load improved the load factor from 0.4376 to 0.8280 and the peak demand from 2.2kW to 0.70 kW. Thus, saving about 41.65% of the end user's yearly energy cost. Considering an on-site generation program, there will be a user's annual cost savings of about 54% for 8 years which is the payback period, after which the yearly savings will increase drastically. The results obtained from this study showed a significant advantage of integrating energy management programs to better combat the challenges of energy management by greatly reducing users' energy demand and energy bills.

Keywords: Demand side management, energy management, energy efficiency, supply side management.

1.0 INTRODUCTION

A large share of the energy efficiency enhancement measures available for industrial and residential remains unimplemented due to the existence of various obstacles to energy efficiency. One of the main means of overcoming those barriers to energy efficiency is via energy management operations (Sannö et al., 2019). United Nations Industrial Organization, (2005) mentioned cost reduction among other factors put forward for promoting or undertaking demand side management (DSM) programs. Considering the application of the DSM program to optimize cost reduction, there is a need to review developed mathematical models for demand-side management programs by Attia (2010), the study identified the means of implementing the demand-side management (DSM) programs to be either by direct load control or indirect load control. By direct load control, the utility can modify a customer's load pattern by either switching off the power supply to some customers at a specific time or ensuring the customer did not use some specific type of electrical load at a particular time interval. The paper described the indirect load control method as a means of modifying customers' load patterns using the following methods: Time of use tariff rate, thermal energy storage, efficient end-use technology, electric tariff system, and electrification technologies.

The study was able to formulate mathematical models for Peak clipping, valley filling, load shifting, energy conservation, and load building. The objective function was to maximize the load factor and minimize cost, thus, the load factor was improved by 38.5% and 24.2% for load shift and peak clipping respectively. And in terms of cost minimization, the study displayed a cost saving of 2.6% and 18.1% from the customer's energy cost for load shift and peak clipping respectively. Attia et al. (2018) did a comparative analysis and simulation of load shaping techniques, this was intended to provide insight into the control of customers' total energy consumption and utilities load factor. Load shaping techniques were formulated as a constrained

optimization problem for direct load control processes. The study implemented peak clipping, load shifting, valley filling, strategic conservation, and strategic load growth in which after comparing the outcome of all these programs, Peak clipping was identified as the better program to achieve a reduction of electricity bill cost and increment of utility revenue. The load factor was improved by 18.18% and the cost was reduced by 6% after implementing the peak clipping technique. Kanchev et al. (2014) worked on a microgrid central energy management system that relies on day-ahead operation planning and an online adjustment process during the operation. The study used a dynamic programming-based algorithm with a multi-objective function to reduce the economic cost and CO_2 equivalent emission. The objective function was to ensure an uninterrupted power supply while maximizing renewable generators in the grid and minimizing the economic cost and CO_2 equivalent.

In Ansar et al. (2018), a meta-heuristic technique was used to balance the load for a whole day to avoid peak creation in an hour, while a smart meter performs electricity cost calculation for energy consumption based on usage time. The focus of the study was to reduce customer demand, reduce the peak-average demand (i.e., increase load factor), and electricity cost minimization. The study also stated that the technique employed does not guarantee an optimal solution, though peak consumption was successfully eliminated by shifting some loads to the off-peak period and thus reducing the user's electricity bill. Part of the challenges of this technique was the customer waiting time for load scheduling.

The importance of an Intelligent Residential Energy Management System (IREMS) as the reduction of electricity bills while maintaining the power demand lower than the maximum demand limit subjected to the various constraints governing the operation of household loads and renewable energy resources was explained by Arun & Selvan (2018). The objective was achieved by scheduling the schedulable loads during low energy pricing periods while considering the operational dynamics of non-schedulable loads and the availability of renewable energy resources. IREMS also manages the battery energy storage when excess power is available from renewable energy resources due to the utility-defined power export limit to the grid. An optima resources sizing algorithm was used to size the renewable energy sources and battery storage.

Ganesh et al. (2020) discussed the installation and implementation of an Energy management system in the residential building for sustainable development. The article used a web-based building energy management system (BMS) to continuously monitor electrical load demand and reduce the peak demand. A multi – leader – multi – follower Stackelberg game theoretic model was used to study the problem of distributed home energy management systems with storage. The proposed distributed scheme with a storage system was able to increase the earned profit of the grid by up to 55% (Mondal et al., 2017). Wang et al. (2018) proposed a distributed energy storage planning scheme based on the game algorithm in demand-side management, which helps users select the appropriate size of storage units for balancing the capital and operation costs. Mahin et al. (2019) employed three DSM techniques: using a solar system, load limiting, and deliberate load reduction for residential users to balance the energy demand and supply. The results of the study showed that by using the solar system at home a significant amount of electrical energy can be saved

Most available literature within which few were reviewed in this paper focused on peak demand reduction, cost/bill reduction, load factor improvement, CO_2 reduction and system stability as part of the major problems or challenges of energy management. Attia (2010) was able to

improve load factor by 38.5% and 24.2% and reduces customer energy cost by 2.6% and 18.1% using load shift and peak clipping techniques, also we could see an 18.18% improvement in load factor and 6% cost reduction after implementing the peak clipping technique by Attia et al. (2018). Also, other reviewed literature showed that most researchers focused on the reduction of peak demand, load factor and energy bill, and they either implemented demand response techniques or implemented supply-side management techniques. This paper will serve as an improvement on Attia (2010) and Attia et al. (2018), and also as a follow-up on Mahin et al. (2019)'s recommendation for cost and peak demand reduction as a challenge of energy management. This paper will focus on the reduction of peak demand, load factor improvement and reduction of customers' energy bills. The demand response techniques results will be used to implement on-site generation for the users, this is to have better cost reduction alongside improved load factor and reduced peak demand.

2.0 MATERIALS AND METHOD

2.1 Theoretical framework

The model of Attia (2010) was considered for the demand side management techniques. Demand response techniques were formulated as a constrained optimization problem for direct load control processes, an energy-efficient building modelling was used for an energy efficiency program while an on-site generation using a stand-alone solar system was considered for supply-side management.

2.2 Demand Side Management

Demand side management or Demand response refers to end users' actions towards their regular energy/electricity usage or changes in their consumption in response to variations within the price of electricity over time, or to incentive payments planned to inspire lower energy use during peak periods or when system reliability is vulnerable (National Action Plan for Energy Efficiency, 2010).

2.2.1 Demand Side Management (DSM) Programs

Peak Clipping:

Means of implementation: To reduce peak demand, direct control on customer appliances or end-use equipment can be implemented to limit peak demand periods.

Objective function: The objective function is formulated either to maximize the system load factor (Attia, 2010)

$$Max\ L.F. = \left[\left[\sum_{j=1}^{J} P_{TO(j)} \times t_{(j)}\right] / \sum_{j=1}^{J} t_{(j)}\right] / P_{TO(K)} \quad (1)$$

$Subject\ to\ the\ following\ constaints;$

i. Equality constraint: $P_{new(i)} = P_{old(i)}\ \forall to \rightarrow tk,\ th \rightarrow TD$

ii. Inequality constraints: $P_{new\ (i)} \leq P\ (value_1)\ \forall tk \rightarrow th,\ P_{new\ (i)} \geq P\ (value_2)\ \forall tk \rightarrow th$

$P\ (value_2) \leq P\ (value_1)$

Where; $P_{new\ (i,j)}$: is the demand of load type i at time interval j after applying Peak clipping, $P_{old\ (i,j)}$: is the demand of load type i at time interval j before applying Peak clipping, The $P_{new(i,j)}$: is

not permitted to increase the P (value) which is an extremely limiting value given by the planner, P (value): is limiting value proposed by the planner for to limit load demand after applying for DSM program, k: is the time interval at which the total demand of all load types P_{TO} (k) is at peak. $P_{TO\ (k)}$: is the maximum demand for all the load types over all time intervals, $P_{TO\ (k\ )} \rangle\ P_{To(\ j)} \forall j$ = 1,....., J ; j ≠ k, TD: is the sum of all time intervals; $TD = \sum_{j=1}^{J} t_{(j)}$

Valley Filling: *Means of implementation:* This can be achieved by the creation of new off-peak electric loads such as the charging of electric cars and thermal energy storage. To achieve the valley filling DSM program, control of load demand is the major implementation technique.
Objective function: The objective function is formulated to maximize the system load factor (Attia, 2010)

$$Max.L.F. = \left[\left[\sum_{j=1}^{J} P_{TO(j)} \times t_{(j)}\right] / \sum_{j=1}^{J} t_{(j)}\right] / P_{TO(K)} \quad (2)$$

Subject to the following constraints;

i. Equality constraint: *P new (i, j) = Pold (i, j) ∀tk →th*
ii. Inequality constraints: *Pnew (i, j) ≥ Pold (i, j) ∀to →tk,th →TD, Pnew(i, j) ≤ P(value) ∀to→tk,th→TD*

Load Conservation/ Energy Efficiency: *Means of implementation:* Appliance efficiency improvement and weatherization are some examples of energy conservation.
Objective function: The objective function is formulated to minimize the cost of the customer's electricity bill (Attia, 2010)

$$Min\ C. = \left[\sum_{i=1}^{M}\sum_{j=1}^{J} P_{(i,j)} \times t_{(j)} \times ce_{(i,j)}\right] + \left[\sum_{i=1}^{M}\sum_{j=1}^{J} P_{(i,j)} \times cd_{(i,j)}\right] \quad (3)$$

Subject to the constraint;

i. Inequality constraint: *Pnew (i) ≤ P(old (i)) ∀to→ TD*

Appliance Efficiency Improvement: As treated by Ewesor (2021), the following mathematical expressions are used in designing efficient lighting systems:

Maintenance Factor (Mf) = $\frac{1}{Depreciation\ factor}$ (4)

Spacing (S) = $1\frac{1}{2}\ hm$ (5)

Where hm is the mounting height.

Number of light fittings required (N) = $\frac{Ea\ X\ A}{\emptyset\ X\ Mf\ X\ Cu} = \frac{(L\ X\ W)}{(Ms)^2}$ (6)

Where;
A = Area planned for illumination in m^2, Ea = The desired illuminance in Lm/m^2 (Lux)
Cu = Coefficient of utilization, Mf = Maintenance Factor, L = Length of room, W = Width of the room, and Ms = Maximum spacing between fittings.

$$PES\ (\%) = \frac{E_{actual} - E_{ee}}{E_{actual}} \times 100 \quad (7)$$

E_{actual} is the actual load, E_{ee} is the load when energy-saving equipment is used
Percentage energy efficiency ratio (EER) given by

$$\%EER = \frac{P_{ee}}{P_{actual}} \times 100 \quad (8)$$

P_{ee} = Power demand using energy saving components, P_{actual} = Actual power demand

2.3 Methods

This research work examines a few energy management programs, in this paper, Microsoft excel solver was used to solve the optimization problem, and the targeted peak demand after the application of the DSM program was set to 0.7. This study will check one of the demand side management programs, and the peak clipping program was a choice because this study is aim at reducing peak demand. Another sampled residential load was used to model energy-efficient building using an appliance efficiency improvement program to examine efficient consumption reduction by deducing the percentage energy efficiency ratio and percentage energy savings. The PHC's original load profile and the PHC's load profile after the application of peak clipping were used to model an on-site generation using PVSyst energy modelling software. This is to observe the effect of integrating different energy management programs for efficient consumption reduction.

3.0 RESULTS AND DISCUSSION

3.1 Results

The results obtained from energy efficiency, peak clipping and on-site generation programs are presented and discussed in this section. Table 1 shows the percentage of energy saved after implementing the energy efficiency program, while Table 2 summarizes the cost analysis before and after the energy efficiency program. Table 3 shows the summary of the results obtained from the optimization of the peak clipping program using Microsoft excel solver. Figure 1 shows the actual load and the load after the implementation of the energy efficiency program, Figure 2 represents the load profile before and after the implementation of the peak clipping technique and Table 4 summarizes the cost analysis before and after the implementation of peak clipping. Table 5 shows the results obtained after using PVSYST to model an on-site generation for the PHC.

3.1.1 Result of energy efficient building model for a sampled load used as a case study:

Table 1: Percentage of energy saving (PES) for the sampled load

	ENERGY CONSUMPTION (kWh)			
	Daily (kWh)	**Weekly (kWh)**	**Monthly (kWh)**	**Yearly (kWh)**
E_{actual} (kWh)	363.53	1890.356	7561.424	132979.274
E_{ee} (kWh)	317.5	1651	6604	116141.5
Energy saved (kWh)	46.03	239.356	957.424	16837.674
% Energy saved	**12.7%**	**12.7%**	**12.7%**	**12.7%**

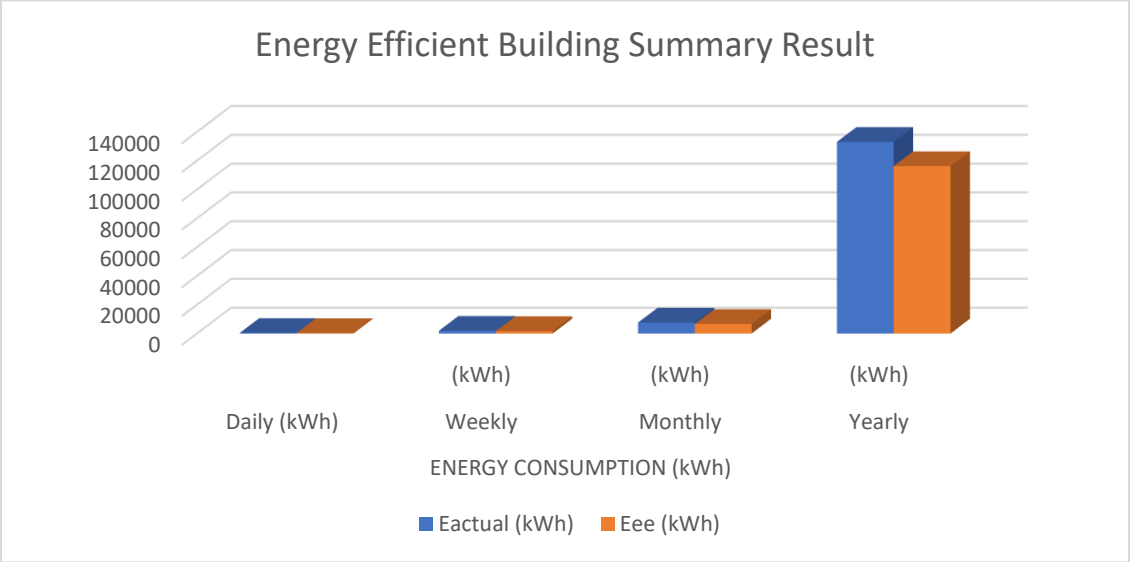


Figure 1: Energy efficiency result, showing the summary of the actual load and the load after the application of the energy efficiency program

The energy consumption cost is calculated at the present charge of 14 cents per kWh ($0.14 per kWh) as shown in Table (2).

Table 2: Cost Analysis of Energy Consumption for the sampled load

	E_{actual}	E_{ee}	Energy saved
Monthly Consumption (kWh)	7561.424	6604	957.424
Cost = $ (kWh × 0.14)	**1058.60**	**924.56**	**134.04**
	E_{actual}	E_{ee}	**Energy saved**
Yearly Consumption (kWh)	132979.274	116141.5	16837.674
Cost = $ (kWh × 0.14)	**18617.10**	**16259.81**	**2357.24**

3.1.2 Result obtained after implementing peak clipping program

Table 3: Result of the Peak Clipping optimization program

Time (Hour)	Load Profile before DSM	Load Profile after the application of DSM
1	0.42	0.42
2	0.42	0.42
3	0.42	0.42
4	0.42	0.42
5	0.42	0.42
6	0.42	0.42
7	0.54	0.54
8	0.54	0.54
9	0.69	0.69
10	0.73	0.7
11	2.15	0.7
12	2.27	0.7
13	2.27	0.7
14	2.27	0.7
15	2.14	0.7
16	2.02	0.7
17	1.12	0.7
18	0.96	0.7
19	0.91	0.7
20	0.79	0.7
21	0.54	0.54
22	0.54	0.54
23	0.42	0.42
24	0.42	0.42

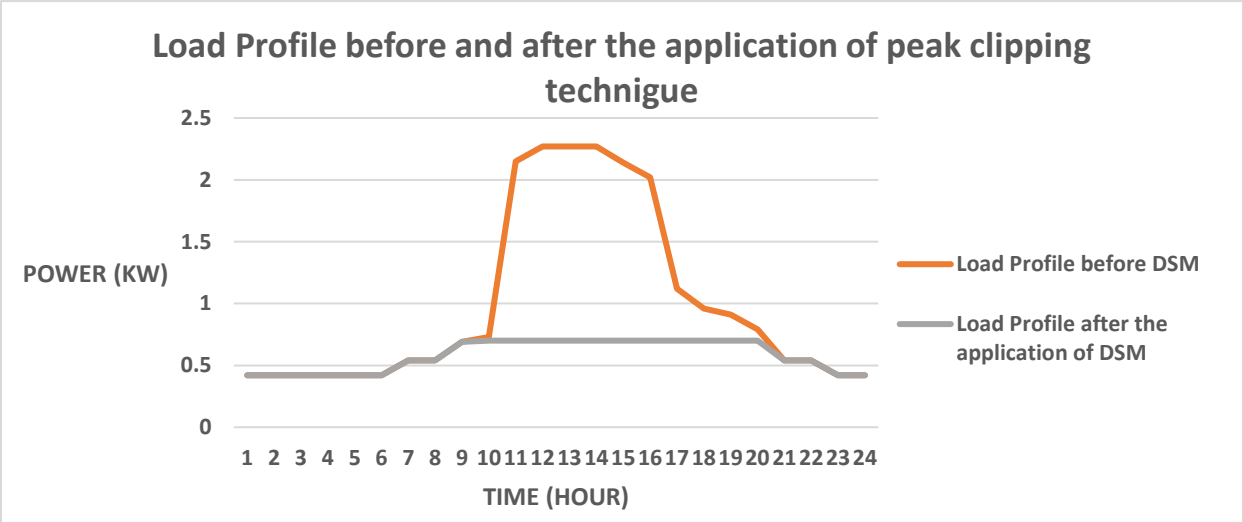


Figure 1: Load profile before and after the application of peak clipping

Table 4: Cost analysis of the DSM technique (peak clipping)

Items	Before Applying DSM Techniques	After Applying DSM Techniques
P_{max} (kW)	2.27	0.70
Energy per day (kWh/day)	23.84	13.91
Energy per year (kWh/year)	8701.6	5077.15
P_{av}	0.9933	0.5796
L.F= P_{av}/P_{max}	0.4376	0.8280
Energy Cost/day ($)	3.34	1.95
Cost/Year	1218.22	710.80
Cost/Month	102.47	59.79
End user savings per year %	-	41.65%

3.1.3 Modelling of on-site generation for the PHC load demand before and after the application of the DSM technique using PVSYST

Table 5: PVSYST on-site generation modelling results

Items and results of PVsyst software	Before the application of the DSM technique	After Applying DSM Techniques
P_{max} (kW)	2.27	0.70
Energy per day (kWh/day)	23.84	13.91
Required generation capacity (kWp)	8.4	4.8
Required storage capacity (kWh)	23.7	11.9
Total generated energy per year (kWh/year)	11343	6568
Investment cost (capital cost)	$9740.58	$5691.82
Running / Operation Cost per year (including an inflation rate of 2.8% per year)	$40.85	$13.62
Excess Energy Per year (kWh/year)	2496	1512
Net present value (NPV)	$1909.12	$1074.23

3.2 Discussion

Presently, as seen in Table 1, the energy consumed per day for the residential load is 363.53 kWh and after implementing the energy efficiency program, the energy demand was reduced to 317.5 kWh, therefore saving 43.06 kWh of energy daily. Thus, a monthly energy cost saving of $134.04 and a yearly cost saving of $2357.24 was achieved via an energy efficiency program as shown in Table 2. After applying the peak clipping technique for the PHC's load, the Load factor improved from 0.4376 to 0.8280. Also, the yearly energy bill was decreased by about 41.65% as presented in Table 4. The objective function was formulated to maximize the system load factor and reduce the customer's energy bill.

Considering the PHC's load demand after the application of the DSM technique, using PVSYST to model an on-site generation self-sufficient system, a 4.8kWp photovoltaic power generator and a storage capacity of 14.4kWh is required to self-power the PHC load. The results of the simulation showed that the site will experience a total energy generation of 6568kWh/year whereby the site's yearly energy use was modelled to be 5077.15kWh/year, the project was simulated for ten (10) years and the estimated investment cost was $5691.82(i.e., $569.18 per year) while the yearly operating cost was also estimated to be $13.62. Thus, the yearly total energy cost for the on-site generation using PHC's load after DSM implementation will be $582.80, and the estimated payback period on this investment was simulated to be 8.4 years as shown in Table 5. Considering the load before the application of Peak clipping, an 8.0kWp

photovoltaic power generator and a storage capacity of 28.8kWh is required to self-power the PHC load. The results of the simulation showed that the site will experience a total energy generation of 11343kWh/year whereby the site's yearly energy use was modelled to be 8701.6kWh/year, the project was simulated for ten (10) years and the estimated investment cost was $9740.58(i.e., $974.06 per year) while the yearly operating cost was also estimated to be $40.85. Thus, the yearly energy cost for the on-site generation using PHC's load before the DSM implementation will be $1014.91, and the estimated payback period on this investment was simulated to be 8.4 years as presented in Table 5 above. Given that the PHC's present yearly energy cost is $1218.22 according to Table 4, the above analysis showed that if the load demand after the implementation of the DSM technique is considered for an on-site generation using a solar stand-alone solution, for the next 10 years the PHC will be saving $635.42 yearly which is about 52% cost reduction while after the payback period of eight (8) years and four (4) months, the PHC will be saving massively on the energy cost. Attia (2010) was able to achieve 2.6% and 18.1% reduction from the customer's energy cost for load shifting and peak clipping programs respectively and also Attia et al. (2018) achieved 6% cost reduction after implementing peak clipping program. A 53% energy cost reduction was achieved in this study after applying peak clipping program on the load demand and using the resulting load profile to model an on-site stand-alone system. This shows the significant positive effect of integrating different energy management programs.

4.0 CONCLUSION

The results obtained from this work revealed a significant reduction in customers' peak demand and customers' cost of energy if multiple energy management programs are implemented. In this study, a higher percentage of yearly energy consumption was saved, and the customer's electricity bill was reduced greatly with the advantage of making an extra profit if the excess generated energy could be fed into the utility grid via a net metering device. Previous studies showed a minor improvement in load factor and a small reduction in customer's energy bills as reviewed in the introductory part of this paper, this was because a single energy management program was used, while in this study, the integration of energy efficiency, peak clipping and on-site generation proved to be more efficient and effective in reducing energy consumption and energy bills. To have an appreciable reduction in end users' energy bills, as seen in the results obtained from this study, it is recommended that a complete energy management program is implemented instead of implementing just a single program that might not have a significant effect. The significant yearly energy cost reduction obtained when the energy demand after applying peak clipping was used to model an on-site stand-alone system proves the significance of the recommendation given above. However, grid feed-in and net metering should be encouraged to reward end users who implemented on-site generation.

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