A cost effective trade-off based renewable power augmented energy efficient load model for manufacturing industries for demand side management

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Abstract: Efficient utilization of electrical energy plays a significant role for sustainable development of the industries. Moreover, effective implementation of energy efficiency technology in the industrial infrastructure and production chain is a part of smart grid mission. However, the cost effectiveness of the project is always a constraint for adoption and implementation. In this paper, for demand side management, an appropriate rule based strategy has been proposed which improves the energy efficiency of a production unit in a cost effective manner. Also, an attempt has been made to develop a fair trade-off based captive renewable power augmentation scheme which will further enhance the cost effectiveness of the presented energy efficiency model for the plant. Moreover, this approach can significantly reduce the maximum demand of the plant which will unburden the power utility. The developed model has been applied in a cement-asbestos industry considered for case-study which produces satisfactory results. The proposed model can be suitably customized for other type of production industries. The trade-off mechanism has been validated using HOMER Pro-3.2 software.

Keywords: energy efficiency; production plant; cement asbestos; photovoltaic; distributed generation
1. Introduction

The growing industrialization is considered to be the prioritized missions for national development. In the same time, industrial loads consume almost 40% of total global conventional energy inputs and 30% out of that is simply wasted due to inefficient operation of the systems (www.beeindia.gov.in/content/existing-building). Misuse of energy not only leads to energy shortage but also contribute to the environmental and climate change (Khan, 2002; Yuan, Farnham, & Emura, 2015). Therefore, a systematic, time bound and economical approach is highly essential to save this energy which otherwise wasted in the industrial systems.

Budgetary constraints for implementation of energy efficiency projects in production industries have been highlighted in reference (Palanichamy, Nadarajan, Naveen, SunderBabu, & Dhanalakshi, 2002). However, cost effective and profit oriented energy efficiency projects can overcome such budgetary constraints. Different energy efficiency measures have been suggested in references (Boglietti, Cavagnino, Ferraris, Lazzari, & Luparia, 2005; Brundage, Chang, Li, Arinez, & Xiao, 2014; Le & Canizares, 2015; Mohagheghi & Raji, 2013) for production chain of industrial loads. Similarly, the building energy management techniques suggested in references (Angelo, Spooner, & MacGill, 2010; Corno & Razzak, 2012; Pellegrino, Lo Verso, Blaso, Acquaviva, & Osello, 2016; Wang, Gu, Li, Bale, & Sun, 2013; Zhao, Suryanarayanan, & Simoes, 2013) can be suitably customized to achieve the indoor lighting efficiency of production industries. However, these suggested techniques in references (Angelo et al., 2010; Boglietti et al., 2005; Brundage et al., 2014; Corno & Razzak, 2012; Le & Canizares, 2015; Mohagheghi & Raji, 2013; Pellegrino et al., 2016; Wang et al., 2013; Zhao et al., 2013) are suffering from improper framework in terms of cost effectiveness. In this direction, a suitable simulation based methodology for energy efficient building design for industrial infrastructure has been suggested in reference (Liu, Zhao, Huang, & Zhao, 2012). Though, the design is technically effective for future industrial infrastructures, not effective for already existing production plants. For demand side energy management (DSEM), different energy management systems with the help of roof top solar photovoltaic (PV) have been recommended in references (Guan, Xu, & Jia, 2010; Kapsalis & Karamanis, 2015; Kenjun, Zhou, Allan, & Yuan, 2011; Makhtari, Nourbakhsh, & Ghosh, 2014). The same scheme can be suitably transformed for industrial applications. However, these schemes will be involve with huge storage battery back-up and complex control system which will not be economically viable and environmental friendly. The main features of the proposed energy efficiency model for production industries can be summarized as,

(i) More systematic and easy to follow for the energy auditors.
(ii) Pareto analysis identifies the prioritized loads in stages for replacement so that the energy efficiency project can be implemented in a cost effective manner.
(iii) This paper introduces a fair trade-off based renewable captive generation augmentation system, which not only cost effective and environmental friendly but also significantly unburdens the utility systems.

2. The proposed energy efficiency model

There always exist a huge scope for energy saving options in production industries through intelligent operation of devices and effective energy management policies. Therefore, a methodical energy management initiation is extremely essential to develop an energy efficiency model and adopt the energy management recommendations for implementation in a cost effective manner for production industries. However, the execution of these projects must be carried out through multi dimensional and predefined objectives as shown in Figure 1. In this paper, an attempt has been made to develop a cost effective framework for energy efficiency projects in production industries. The same proposed framework has been applied on a medium scale production plant like cement asbestos production plant.

Identification of active supply feeders and systems receiving power from each identified feeder is highly essential for DSEM. Through appropriate and methodological approach, the computation of
systems operational time is the next step towards finding energy usage pattern of each system. Considering the production plant as the single entity, categorization of the load is the next step of energy auditing process based on their characteristics. Therefore, irrespective of their feeder identity, similar type of energy consuming devices must be grouped to form a load category. This will helpful for prioritization process.

The energy efficient model of the production plant can be developed by identifying the energy efficient replacement of devices belongs to each said category. The next step in this direction is the prioritization of the loads for replacement. Though, there is a scope for energy savings in multiple groups of loads, the energy efficiency project must be implemented in the industry on priority and phase wise manner taking the cost effectiveness of the project into account. In this paper, an attempt has been made to apply the methodology of “Pareto Analysis” to identify the sequence of
prioritized load groups so that the implementation of the energy efficiency project will follow the same to generate optimum benefit for the organization. The next step in this regards can be the maximum demand (MD) management in the electrical energy efficient load model of the organization. In this paper, an attempt had been made to inject renewable power from captive roof top solar PV for said purpose without shifting either vital or non vital loads. The power supply model using solar PV has been strategically outlined based on the triplet trade-off between utility supply, solar PV with storage battery and solar PV without storage battery. For the case-study, part of the load in a suitable feeder has considered for testing of the trade-off process and the same technique can be further extended in a more effective way for better results. Through proper implementation of the proposed model, the production industries will be benefitted in two stages. The first stage of benefits will be resulted from the reduction of electricity bill due to captive generation from renewable sources and the second stage of benefit will be resulted from the scope to renew the allocated MD capacity so that annual cost paid towards the allocated MD to the utility will be reduced.

3. Mechanism for computation of average usage time of devices

The reliability of the data regarding device usage time connected to different feeders must be given highest priority in order to prepare a result oriented energy efficient model for the production unit. For the production plant considered for the case-study, the systems usage pattern by the occupants has been investigated, analyzed through proper data collection mechanism and the analyzed data has been validated through real time measurement tools. The energy usage data collection strategies for the presented case study can be observed from Table 1. The power measurement of each device was accomplished with the help of transportable meters with specifications; make: Yokogawa, model: CW240 and make: Prova Instruments Inc., model: 6,601 3φ-pf power clamp. The energy consumption data was recorded with the help of Fluke: 435 power analyzer. The input power consumption of the premise was recorded with the recording frequency of 20 min. The same frequency was maintained to record the usage pattern of individual devices. It has been found that there was no significant error.

| Users activity | Operation of systems | Electrical energy consumption |
|----------------|----------------------|------------------------------|
| Strategy       | Monitoring through CCTV footage and duty allocation chart available in the production plant | Cross questioning of key workers, plant and site engineers, field supervisors, occupants in a particular premise and validation through portable meters | Investigation of available monthly electricity bill and validation through power analyzer for the year 2014–2015 |
| Duration of field survey | Two weeks during working hours | Two weeks during working hours | One year |
| Data recording frequency | 20 min | 20 min | Monthly for one year |

4. Case-study

4.1. System description

The cement asbestos industry considered for case study is situated at a global positioning of latitude: 25°07′28″ N and longitude: 86°33′20″ E. The place is elevated above sea level with 57 m. For effective and detailed energy audit in the production chain, it is mandatory to understand first the production layout of the plant. The overall production layout of the plant considered for the case-study is shown in Figure 2 which is operated with 24 h mode. This overall layout has been drawn on the basis of plant visit. Beyond two production chains, for the application of the proposed model, the study covers plant offices, indoor plant, outdoor plant, residential complexes and other facilities. For production of the cement asbestos sheets, cement, asbestos fiber and white coal fly ash from...
thermal power plants are considered as the major raw materials. The output of the plant is cement asbestos used for roofing purpose.

4.2. Electrical load description
The feeder wise overall electrical load structure of the cement asbestos plant considered for the case study is shown in Figure 3. The utility supply received through main feeder is distributed within the production plant area through feeder1 to feeder5 from plant substation. The allocated MD for the plant was found to be 4,500 KVA which is 50% higher than the actual MD. As per the management statement, this excess MD allocation is for future expansion of the plant. The connected load with the designated feeders as per the record and followed by field survey and energy meter data loggers output validation was found as follows, feeder1: 595 kW, feeder2: 595 kW, feeder3: 54 kW, feeder4: 132 kW, feeder5: 227 kW and feeder6: 38 kW. The above loading information has been cross validated through the spot measurement using “Fluke: 435” power analyzers during the energy audit within the plant with recording frequency of 30 min and for two weeks.

4.3. Detail feeder wise load study

4.3.1. Load on production chain1 (feeder1)
As it has already been mentioned that feeder1 is a dedicated supply for production chain1, the load on this feeder is basically induction motors of different ratings shown in Table 2. All these motors receive power from machine control centers (MCC panel). It has been observed that the MCC panels are well equipped with proper metering arrangements to measured active power, power factor, voltage, current and frequency operation of each motor. Since the plant is operated for 24 h for 350 days in a year, the hours of operation in Table 2 is accordingly computed. The production chain remains off for 15 days every year for scheduled maintenance of the system.

From Table 2, the annual energy consumption in feeder1 can be computed as,

\[ P^{feeder}_{ec} = \sum_{j=1}^{16} (P^{mot}_{mot}) t^{feeder}_{j} = 4,998,000 \text{ kWh/annum} \]  

4.3.2. Load on production chain2 (feeder2)
The load pattern of production chain2 is exactly same as the production chain1 as both the units have same production capacity of 10,000 MT per month including accessories.
Figure 3. Plant electrical load structure.

Table 2. Detail load pattern on the feeder1

| S. No. | Name of section (type of load)     | Power consumption (kW) | No. of appliances | Total power consumption (kW) | Operation time (h/year) |
|--------|-----------------------------------|------------------------|------------------|----------------------------|-------------------------|
| 1.     | Bag opening device (motor)        | 5                      | 1                | 5 \(P_{\text{mot1}}^1\)     | 8,400 \(t_{\text{f1}}^1\) |
| 2.     | Hydraulic disintegrator (motor)   | 30                     | 1                | 30 \(P_{\text{mot2}}^1\)    | 8,400 \(t_{\text{f1}}^2\) |
| 3.     | Fiber mixing plant (motor)        | 30                     | 1                | 30 \(P_{\text{mot3}}^1\)    | 8,400 \(t_{\text{f1}}^3\) |
| 4.     | Beater tank (motor)               | 30                     | 1                | 30 \(P_{\text{mot4}}^1\)    | 8,400 \(t_{\text{f1}}^4\) |
| 5.     | Mixer/Agitator (motor)            | 50                     | 1                | 50 \(P_{\text{mot5}}^1\)    | 8,400 \(t_{\text{f1}}^5\) |
| 6.     | Dilution tank (motor)             | 30                     | 1                | 30 \(P_{\text{mot6}}^1\)    | 8,400 \(t_{\text{f1}}^6\) |
| 7.     | Suction machine (motor)           | 30                     | 1                | 30 \(P_{\text{mot7}}^1\)    | 8,400 \(t_{\text{f1}}^7\) |
| 8.     | M/C1 (motor)                      | 30                     | 1                | 30 \(P_{\text{mot8}}^1\)    | 8,400 \(t_{\text{f1}}^8\) |
| 9.     | M/C2 (motor)                      | 30                     | 1                | 30 \(P_{\text{mot9}}^1\)    | 8,400 \(t_{\text{f1}}^9\) |
| 10.    | M/C3 (motor)                      | 30                     | 1                | 30 \(P_{\text{mot10}}^1\)   | 8,400 \(t_{\text{f1}}^{10}\) |
| 11.    | Booster pump (motor)              | 15                     | 1                | 15 \(P_{\text{mot11}}^1\)   | 8,400 \(t_{\text{f1}}^{11}\) |
| 12.    | Sticker roller (motor)            | 50                     | 1                | 50 \(P_{\text{mot12}}^1\)   | 8,400 \(t_{\text{f1}}^{12}\) |
| 13.    | Conveyor (motor)                  | 15                     | 3                | 45 \(P_{\text{mot13}}^1\)   | 8,400 \(t_{\text{f1}}^{13}\) |
| 14.    | Translational LD (group of motors) | 120                    | 1                | 120 \(P_{\text{mot14}}^1\)  | 8,400 \(t_{\text{f1}}^{14}\) |
| 15.    | De-stacker (group of motors)      | 60                     | 1                | 60 \(P_{\text{mot15}}^1\)   | 8,400 \(t_{\text{f1}}^{15}\) |
| 16.    | Feed water pump (motor)           | 5                      | 1                | 5 \(P_{\text{mot16}}^1\)    | 8,400 \(t_{\text{f1}}^{16}\) |
The annual energy consumption in feeder2 can be computed as,

\[ P_{\text{ec}}^{2} = \sum_{j=1}^{16} \left( p_{\text{mot}}^{1} \right) t_{j}^{2} = 4,998,000 \text{kWh/annum} \]  \hspace{1cm} (2)

4.3.3. Load on feeder3

The detailed load pattern on the feeder3 is shown in Table 3. The connected load on the feeder3 is either luminaries or cooling devices like cooling fans and heating ventilation air cooling (HVAC). The administrative office working hours for the organization was found between 8 AM and 5 PM in normal working days and remains off on Sunday. The annual energy consumption in case of feeder3 can be computed from Table 3.

\[ P_{\text{ec}}^{3} = \left( p_{\text{lum1}}^{3} \right) t_{1}^{3} + \left( p_{\text{cof1}}^{3} \right) t_{2}^{3} + \left( p_{\text{hvac}}^{3} \right) t_{3}^{3} = 216,876 \text{kWh/annum} \]  \hspace{1cm} (3)

4.3.4. Load on feeder4

The detail of load type connected with the feeder4 is shown in Table 4. The connected loads on the feeder4 are luminaries for indoor plant lighting, workshop lighting and exhaust fans for indoor cooling operated with 3-phase induction motors. The average available illumination level was found in said areas was 300 lumens per meter square plant area. The annual energy consumption in case of feeder4 can be computed from Table 4.

\[ P_{\text{ec}}^{4} = \left( p_{\text{lum2}}^{4} \right) t_{1}^{4} + \left( p_{\text{mot}}^{4} \right) t_{2}^{4} = 1,113,000 \text{kWh/annum} \]  \hspace{1cm} (4)

Table 3. Details of the load connected with feeder3

| S. No. | Name of section (type of load) | Power consumption (kW) | No. of appliances | Total power consumption (kW) | Operation time (h/year) |
|-------|--------------------------------|------------------------|------------------|----------------------------|------------------------|
| 1.    | Luminary (fluorescent lights)  | 0.055                  | 300              | 16.5 \( p_{\text{lum1}}^{3} \) | 3,285 \( t_{1}^{3} \)  |
| 2.    | Cooling fan                    | 0.08                   | 94               | 7.52 \( p_{\text{cof1}}^{3} \) | 3,285 \( t_{2}^{3} \)  |
| 3.    | HVAC                            | 3.5                    | 12               | 42 \( p_{\text{hvac}}^{3} \) | 3,285 \( t_{3}^{3} \)  |

Table 4. Details of the load connected with feeder4

| S. No. | Name of section (type of load) | Power consumption (kW) | No. of appliances | Total power consumption (kW) | Operation time (h/Year) |
|-------|--------------------------------|------------------------|------------------|----------------------------|------------------------|
| 1.    | Luminary (industrial light)    | 0.15                   | 200              | 30 \( p_{\text{lum2}}^{4} \) | 8,400 \( t_{1}^{4} \)  |
| 2.    | Exhaust fan (motor)            | 2.5                    | 41               | 102.5 \( p_{\text{mot}}^{4} \) | 8,400 \( t_{2}^{4} \)  |

The annual energy consumption in case of feeder2 can be computed as,

\[ P_{\text{ec}}^{2} = \sum_{j=1}^{16} \left( p_{\text{mot}}^{1} \right) t_{j}^{2} = 4,998,000 \text{kWh/annum} \]  \hspace{1cm} (2)

4.3.3. Load on feeder3

The detailed load pattern on the feeder3 is shown in Table 3. The connected load on the feeder3 is either luminaries or cooling devices like cooling fans and heating ventilation air cooling (HVAC). The administrative office working hours for the organization was found between 8 AM and 5 PM in normal working days and remains off on Sunday. The annual energy consumption in case of feeder3 can be computed from Table 3.

\[ P_{\text{ec}}^{3} = \left( p_{\text{lum1}}^{3} \right) t_{1}^{3} + \left( p_{\text{cof1}}^{3} \right) t_{2}^{3} + \left( p_{\text{hvac}}^{3} \right) t_{3}^{3} = 216,876 \text{kWh/annum} \]  \hspace{1cm} (3)

4.3.4. Load on feeder4

The detail of load type connected with the feeder4 is shown in Table 4. The connected loads on the feeder4 are luminaries for indoor plant lighting, workshop lighting and exhaust fans for indoor cooling operated with 3-phase induction motors. The average available illumination level was found in said areas was 300 lumens per meter square plant area. The annual energy consumption in case of feeder4 can be computed from Table 4.

\[ P_{\text{ec}}^{4} = \left( p_{\text{lum2}}^{4} \right) t_{1}^{4} + \left( p_{\text{mot}}^{4} \right) t_{2}^{4} = 1,113,000 \text{kWh/annum} \]  \hspace{1cm} (4)

Table 5. Details of the load connected with feeder5

| S. No. | Type of electrical load       | Power consumption (kW) | No. of appliances | Total power consumption (kW) | Operation time (h/year) |
|-------|--------------------------------|------------------------|------------------|----------------------------|------------------------|
| 1.    | Luminary (fluorescent lights)  | 0.055                  | 1,000            | 55 \( p_{\text{lum2}}^{5} \) | 2,555 \( t_{1}^{5} \)  |
| 2.    | Cooling fan                    | 0.08                   | 900              | 72 \( p_{\text{cof2}}^{5} \) | 3,600 \( t_{2}^{5} \)  |
| 3.    | Other devices                  | 0.5 (average)          | 200              | 100 \( p_{\text{mis}}^{5} \) | 730 \( t_{3}^{5} \)  |
4.3.5. Load on feeder5

The detail of load type connected with the feeder5 is shown in Table 5. The connected load on the feeder4 is either luminaries or cooling devices like cooling fans. The annual energy consumption in case of feeder5 can be computed from Table 5.

Therefore, the annual energy consumption for feeder5 can be computed from Table 5 as;

\[ p_{\text{ec}}^5 = \left( p_{\text{lum1}}^5 \right) t_1^5 + \left( p_{\text{cof2}}^5 \right) t_2^5 + \left( p_{\text{mis}}^5 \right) t_3^5 = 832,725 \text{ kWh/annum} \] (5)

4.3.6. Load on feeder6

The details of the loading pattern on the feeder6 are shown in Table 6. The load on the feeder6 is basically the street lighting load fixed at the outdoor plant area, residential colony area and outside plant area for security reasons. The fittings used for street lighting is 150 watt high pressure sodium vapor (HPSV) type. The operational time for said category of load was found between 6 PM and 5 AM throughout the year.

Therefore, the annual energy consumption for feeder5 can be computed with reference to Table 6 as,

\[ p_{\text{ec}}^6 = \left( p_{\text{stl}}^6 \right) t_1^6 = 145,142.25 \text{ kWh/annum} \] (6)

However, there always exists a significant scope for energy savings in almost all the feeders.

4.4. Energy saving actions

Based on the guide lines of the said production plant and with due discussions with the plant management, the energy savings actions has started by discarding the production on production chain1 while production chain2 was operational. As both the production chains are similar, action on one chain will be applicable on the other chain. Since the translational lifting device (TLD) is a key operational device, as per the plant works managers advice, the load on this system not has been considered for any action on energy savings. However, the energy audit and suitable actions has been executed on other electrical systems as a part of energy management. The observations based on appropriate measurement and energy saving options on each load category has been outlined as follows (www.beeindia.gov.in/content/existing-building; Al-Badri, Pillay, & Angers, 2014).

(i) Measurement and energy saving actions on Load1–Load5.
(ii) Measurement and energy saving actions on Load6–Load11.

In Table 7, production chain motors of 5 kW (4 numbers), 15 kW (4 numbers), 30 kW (16 numbers), 50 kW (4 numbers) and 60 kW (2 numbers) is considered as Load1, Load2, Load3, Load4 and Load5 respectively. Similarly, in Table 8, Load6, Load7, Load8, Load9, Load10 and Load11 denotes fluorescent lighting load, cooling fan load, HVAC load, production plant exhaust fan load, plant indoor illumination system load and HPSV lamp load used for plant outdoor lighting load respectively connected at different feeders. For this present case study the loads related to other devices category is not considered for analysis. It can be observed from Table 8 that, there is a significant energy savings options in each category of load connected to different feeders.

| S. No. | Type of electrical load | Power consumption (kW) | No. of appliances | Total power consumption (kW) | Operation time (h/year) |
|-------|------------------------|------------------------|------------------|-----------------------------|------------------------|
| 1.    | Luminary (HPSV)        | 0.15                   | 241              | 36.15 \( p_{\text{ec}}^5 \) | 4,015 \( t_1^5 \)    |

Table 6. Details of the load connected with feeder6

\[ P_{f5}^{\text{ec}} = \left( P_{\text{lum1}}^5 \right) t_1^5 + \left( P_{\text{cof2}}^5 \right) t_2^5 + \left( P_{\text{mis}}^5 \right) t_3^5 = 832,725 \text{ kWh/annum} \]
| S.No. | Load No. | Load type & numbers | Existing status (www.beeindia.gov.in/content/existing-building) (Al-Badri et al., 2014) | Efficient replacement (www.beeindia.gov.in/content/existing-building) (Al-Badri et al., 2014) | Hours of operation/annum | Energy savings/annum (kWh) | Investment ($) |
|-------|----------|---------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|------------------------|--------------------------|---------------|
|       |          |                     | No load power (kW) | Efficiency | No load power (kW) | Efficiency |                           |                           |            |
| 1.    | Load1    | 5 (4)               | 0.78               | 76         | 0.297               | 90.8       | 8,400                      | 16,229                    | 800        |
| 2.    | Load2    | 15 (4)              | 2.33               | 77.4       | 0.873               | 91.2       | 8,400                      | 48,956                    | 2,334      |
| 3.    | Load3    | 30 (16)             | 4.5                | 76         | 1.66                 | 91.2       | 8,400                      | 381,696                   | 16,000     |
| 4.    | Load4    | 50 (4)              | 6.65               | 77.26      | 2.56                 | 92         | 8,400                      | 137,424                   | 5,334      |
| 5.    | Load5    | 60 (2)              | 8.8                | 78.2       | 3.32                 | 92         | 8,400                      | 92,064                    | 2,000      |
Table 8. Load matrix (Load6–Load11)

| S. No. | Load No. | Measured power consumption of each connected device (kW) | Number of devices connected to different feeders |
|--------|-----------|----------------------------------------------------------|-------------------------------------------------|
|        |           | Existing system $P_{Ext}^n$ in kW | Proposed energy efficient system $P_{Eff}^n$ in kW (www.beeindia.gov.in/content/existing-building) (Corno & Razzak, 2012) | Feeder3 $N_3^n$ | Feeder4 $N_4^n$ | Feeder5 $N_5^n$ | Feeder6 $N_6^n$ |
| 1.     | Load6     | 0.055                                                    | 0.014                                           | 300 | 0 | 1,000 | 0 |
| 2.     | Load7     | 0.080                                                    | 0.035                                           | 94  | 0 | 900  | 0 |
| 3.     | Load8     | 3.500                                                    | 1.100                                           | 12  | 0 | 0    | 0 |
| 4.     | Load9     | 2.500                                                    | 2                                               | 0   | 41 | 0    | 0 |
| 5.     | Load10    | 0.150                                                    | 0.08                                            | 0   | 200| 0    | 0 |
| 6.     | Load11    | 0.15                                                     | 0.055                                           | 0   | 0 | 0    | 241 |

Table 9. Energy audit outcome matrix

| Load   | Energy savings (kWh) × 1,000 | Monetary savings ($) | Investment ($) | Payback period (months) |
|--------|-------------------------------|----------------------|----------------|-------------------------|
| Load1 (L1) | 16.229                       | 1,623                | 800            | 6                       |
| Load2 (L2) | 48.956                       | 4,896                | 2,334          | 6                       |
| Load3 (L3) | 381.696                      | 38,170               | 16,000         | 5                       |
| Load4 (L4) | 137.424                      | 13,743               | 5,334          | 5                       |
| Load5 (L5) | 92.064                       | 9,207                | 2,000          | 3                       |
| Load6 (L6) | 145.124                      | 14,513               | 11,917         | 10                      |
| Load7 (L7) | 159.696                      | 15,970               | 13,254         | 10                      |
| Load8 (L8) | 94.608                       | 9,461                | 6,000          | 8                       |
| Load9 (L9) | 172.200                      | 17,220               | 4,784          | 4                       |
| Load10 (L10) | 117.600                     | 11,760               | 6,667          | 7                       |
| Load11 (L11) | 91.924                      | 9,193                | 8,034          | 11                      |

Figure 4. Energy savings in each category of load.
Total energy savings in Load6–Load11 can be computed as,

\[
\sum_{n=6}^{11} E_{\text{savings}}^n = \sum_{n=6}^{11} (P_{\text{Ext}}^n - P_{\text{Eff}}^n) \left[ N_f^3 t_f^3_n + N_f^4 t_f^4_n + N_f^5 t_f^5_n + N_f^6 t_f^6_n \right]
\]  

(7)

Based on the calculations in Section 4.4 and utilizing the information provided in Tables 1–8, the energy savings per annum, investment and payback period for each load has been computed and shown in Table 9 and graphically shown in Figure 4. It can be observed from Figure 4 that there is a significant scope in almost all categories of loads. It can also be observed from Figure 5 that the payback period on initial investment will be less than one year. Thus, the amount of money invested for the implementation of the energy efficiency project will be recovered from cost of energy saved. For remaining period of life span of the device the organization will earn profit.

5. Pareto analysis for prioritization of load
Potential of energy savings in Load1–Load11 has been prioritized by applying Pareto analysis. Pareto analysis is a statistical tool applied on decision-making system used for the segregation of a limited number of tasks that produce significant overall effect on the whole system. Pareto analysis (80/20 rule) states that, by doing 20% of the job, 80% of the benefit can be achieved from the entire system. It can be observed from Figure 6 that the Load3, Load9, Load7, Load6, Load4, Load10, Load8, Load11 and Load5 have almost 97% of potential and have to be replaced with its efficient alternative.

Therefore, out of total numbers of potential loads, nine categories of loads can contribute about 97% scope for energy savings. Hence in this paper, these nine identified loads have been considered for probable replacement (Corno & Razzak, 2012; Guan et al., 2010; Kapsalis & Karamanis, 2015; Liu et al., 2012; Mokhtari et al., 2014).

6. Demand side management (DSM)

6.1. Through energy efficient replacement actions
Load pattern of the existing and proposed efficient model of the organization considered for the case study depicted on hourly basis is shown in Figure 7.

It can be observed from Figure 7 that the load curve for both existing and efficient model is almost leveled. However, there is a huge potential for electrical energy savings if the proposed energy efficiency model will be implemented. Therefore, the proposed efficiency model prepared for the said industry is a feasible project as the total investment involved with the project will be paid back within one year.

6.2. Illumination of plant indoor area with natural light
The month wise average solar insolation level available over roof tops of the industry considered for the case study is shown in Figure 8. It can be observed that the average solar radiation between 8 AM
and 5 PM is sufficient for a work station for fine works. Therefore, it is recommended considering the roof structure of the plant that 3,000 m² of roof area must be provided with transparent roofing sheets. The same has been immediately implemented with one time investment of $834. It has been observed that between 8 AM and 5 PM, the fine works can be executed when 50% of the plant indoor lighting devices remain off.

The total energy savings achieved through this action was found to be almost 25,920 kWh costing $2,592. Therefore, the amount invested for change of roof structure of the plant will be paid back within 4 months. With this action, the modified load pattern can be observed from Figure 9.

7. Trade-off mechanism for captive renewable generation augmentation

The monthly average solar irradiation and the ambient temperatures are shown in Figure 8 and in Table 10 respectively over the production plant premise.

It has been observed that the plat roof is inclined at an angle of 32° to the horizontal surface. Therefore, solar PV panels can be fixed over the plant roof tops with an inclination same as the plant roof (Hong, Lee, Koo, & Kim, in press; Shukla, Sudhakar, & Baredar, 2016). The design specifications of the proposed PV modules that has to be installed are as follows; Type: Multicrystalline; Maximum power: 280 W; Voltage at maximum power: 36.62 V; Current at maximum power: 7.65 A with open circuit voltage of 43.80 V and short circuit current of 8.30 A. For the generation of 100 kW of solar PV power on an average, taking the output voltage and available roof top space into account, a string of six solar PV panels in series and 75 strings in parallel is being proposed. Based on the availability and feasibility, solar PV based renewable power generation has been selected for industrial captive augmentation in this case-study. The possible strategy of power supply to the selected load on the selected feeders can be:
(i) Totally supplied from utility only or 
(ii) Totally supplied from solar PV only or 
(iii) Supplied from utility only when solar PV is not available, otherwise supplied from solar PV.

Each mentioned power supply scheme has been analyzed to identify the suitable alternative for minimum cost of energy (COE) keeping the gap between energy demand and supply as well as environmental issues in mind.

**Case-I: Total load is supplied from utility only**

In this case, the total power demand will be feed from the available utility supply. Considering uninterrupted power supply arrangement, energy cost will be @$0.13/kWh$.

**Case-II: Total load is supplied from solar PV only**

In this option, a roof top solar PV power generation scheme of capacity 100 kW with 80% efficiency has been selected to cater both the average power demand of 50 kW and the charging of storage battery of appropriate capacity. Based on average power demand and generation capacity selected, the charging and discharging cycle of the storage battery is shown in Figure 10 with reference to the Figure 4. Therefore, considering a terminal voltage of 220 V/phase, a storage battery capacity of 3,864 Ah is required for continuity of power supply to the selected load.

As per the market survey on 29th March, 2016, the cost of storage battery will be $5,796 (@ $1.5/ Ah). Moreover, the life period of the storage battery is considered as 5 years. Similarly, the cost of the solar PV module will be $100,000 (@ $1/Watt) and the life of the solar PV will be 20 years. For the
Table 10. Ambient temperature statistics for last three years over the production plant considered for case-study

| Months | January | February | March | April | May | June | July | August | September | October | November | December |
|--------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| 2015   | 27.70   | 30.50    | 34.35 | 35.63 | 37.45 | 33.40 | 32.13 | 33.00  | 33.20     | 32.65   | 30.00    | 27.30    |
| 2014   | 28.50   | 31.26    | 34.83 | 36.20 | 38.00 | 34.31 | 31.90 | 34.33  | 33.56     | 33.15   | 29.43    | 28.10    |
| 2013   | 27.55   | 30.36    | 33.63 | 35.80 | 37.57 | 34.21 | 32.30 | 33.63  | 34.51     | 32.55   | 30.14    | 27.67    |
designed capacity of PV and storage battery, HOMER Pro-3.2 software tool has been used to forecast the cost of energy and the same has been provided in Table 10.

It can be observed from Table 11, the cost of energy is significantly high in comparison to the power supply scheme discussed in case-I. Considering the COE, this scheme can’t be recommended for the type of the load considered in this case-study.

**Case-III: Power supplied from utility only when solar PV is not available, otherwise supplied from solar PV (Proposed)**

In this case, the solar PV will be augmented with the utility supply to supplement the average power demand of the load during the availability of solar power. Otherwise, the supply will be from utility. The significance of the proposed scheme is that it can be realized with no or minimum storage battery back-up.

For this considered load, to generate an average power of 50 kW from solar PV, 55 kW of solar PV generation plant has been recommended with 10 Ah of storage battery. The cost of energy from the designed value of solar PV minimum storage battery to supplement power between 9 AM and 4 PM has been computed using HOMER Pro-3.2 software tool. The same has been presented in Table 12. The COE in this case is $0.121 which is approximately equals to the utility energy cost as discussed in case-I. Moreover, in comparison power supply scheme discussed in case-I, the proposed scheme is more appropriate considering the environmental value addition issues.

| Table 11. Generation cost for case-II | If the power is with solar PV only |
|--------------------------------------|----------------------------------|
| Initial capital required ($)         | 105,796                          |
| Cost of energy ($/kWh)               | 0.454                            |
| Net present cost ($)                 | 112,148                          |
| Operating cost ($/year)              | 21,160                           |

| Table 12. Generation cost for case-III |
|----------------------------------------|-------------------------------------|
| Decisive factors type of the system    | Proposed scheme                     |
| Initial capital required ($)           | 50,150                              |
| Cost of energy ($/kWh)                 | 0.121                               |
| Net present cost ($)                   | 14,442                              |
| Operating cost ($/year)                | 50,155                              |
8. Leveling of the power curve through integration of captive renewable generation

The monthly electricity bill of the said production unit can be further reduced through an appropriate augmentation of renewable generation from solar PV. It has been recommended with reference to solar insolation level available over production unit shown in Figure 8 that a 55 kW (with 80% efficiency) solar PV unit must be installed. It is also decided that the luminary and cooling fan load of feeder3 and only cooling fan load of feeder5 will thrown to solar PV through dedicated service mains between 8 AM and 4 PM.

The total investment for installation and erection of the necessary service mains will be $54,000 with an annual energy generation of 113,880 kWh costing $11,388. Though the solar PV system is almost 20 years, the amount invested for renewable energy integration will be paid back in 5 years. Moreover, the selected supply schedule from solar PV will be realized with minimum storage battery considering the environmental issues. The recommended solar PV augmentation structure can be observed from Figure 11. The computed second modified load pattern of the said production unit after integration of solar PV with the utility supply can be observed from Figure 12.

6. Conclusion

There always exists a significant scope for energy savings in industrial establishments in particular to production industries. The developed energy efficiency model has been successfully implemented on a cement asbestos industry for testing. The output of the proposed model was found satisfactory in terms of significant reduction in power consumption in a cost effective manner. It has been
observed that, at least 1,457,537 kWh of energy can be saved with a cost saving of $145,756. However, to implement the proposed energy efficiency project an initial investment of $77,124 is required which can be paid back in 7 months. Similarly, the proposed scheme for illumination of plant indoor area with natural light can save 25,920 kWh of electrical energy, which can further enhance the profit of the organization costing $2,592 with an initial investment of $834. This investment can be recovered in terms of cost of energy saved within 4 months. The proposed captive renewable power augmentation evaluated through fair trade-off mechanism for industrial infrastructures was found economical and environmentally friendly. The proposed concepts of the captive renewable augmentation for industrial load not only enhance the energy efficiency program but also unburden the power utility.

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