Energy Consumption Modeling of Production Process for Industrial Factories in a Day Ahead Scheduling with Demand Response

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Abstract

Industrial electricity demand is growing rapidly, whereby, energy consumption modelling and optimization techniques in industries has attracted significant attention in recent years. In this paper, a new model of energy consumption in the production process of aluminum, steel and cement is presented in accordance with a linear piece-wise approximation (LPWA) method. The proposed model is subsequently implemented in the day ahead energy management scheduling of a Microgrid (MG) (involving industrial factories). In order to increase efficiency and give industries an opportunity to contribute in the energy and ancillary services markets, demand response (DR) programs are implemented. The proposed scheduling model considers all the constraints of industrial factories and the MG to maximize their revenue. The performance of the proposed model is evaluated using three case studies. The first and second case studies respectively investigate the effectiveness of the proposed model with and without the implementation of DR programs. In the third case study, the coordination between industrial factories and a MG is investigated. Finally, the results show that the implementation of DR programs and participation of industrial factories in the energy and ancillary services markets, have improved the demand curve, hence increasing the revenue of the MG and industrial factories.

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Demand response, Energy market, Ancillary services market

Nomenclature

Acronyms

AF	Aluminum factory
CF	Cement factory
CS	Case study
DR	Demand Response
LPWA	Linear piece-wise approximation
MG	Microgrid
PR	production revenue
PV	phtovoltaic
SF	Steel factory
WF	wind farm

Indexes

l	Number of aluminum smelting lines ($l \in \{1,2,\cdots,n\}$)
h	Time ($h \in \{1,2,\cdots,24\}$)
k	Number of furnaces in SF ($k \in \{1,2,\cdots,n\}$)
n	Number of processes in CF ($n \in \{1,2,3,4\}$)
j	Number of operation methods in each factory ($j \in \{1,2,3\}$)

$j=1$: controlable load demand, $j=2$: shaftable load demand, $j=3$: non-shiftable load demand

b, m	Number of buses (b, $m \in \{1,2,\cdots,9\}$)
M	Number of uncertain variables ($k \in \{1,2,\cdots,n\}$)
Z	Random variable output
ν	Wind speed

Parameters

ω_h	The offer price of MG to the market in time h (\$/MWh)
ρ_h	The offer price of spinning reserve by MG to the market in time h (\$/MWh)
μ	Mean value of random variable X

σ	Standard deviation of random variable X
ξ	Standard location of each concentration
W	Weight of each concentration
λ	Skewness of each concentration

Decision variables

P^{G}_{bh}	Active power generation at bus b in time h (MW)
P^{D}_{bh}	Active power demand of load at bus b in time h (MW)
Q^{G}_{bh}	Reactive power generation at bus b in time h (MVAR)
Q^{D}_{bh}	Reactive power demand of load at bus b in time h (MVAR)
V_{bh}	voltage magnitude at bus b in time h (KV)
δ_{bh}	voltage angle at bus b in time h (rad)
P^{AF}_{lh}	Consumed power of smelting line l of AF in time h (MW)
P^{AF}_{h}	Consumed power of each AF in time h (MW)
ΔP^{AF}_{ilh}	the excess value of P^{AF}_{ilh} over the segment i of smelting line l of AF in time h (MW)
P^{SF}_{kh}	Consumed power of furnace k of SF in time h (MW)
P^{SF}_{h}	Consumed Power of SF in time h (MW)
ΔP^{SF}_{ikh}	the excess value of P^{SF}_{ikh} over the segment i of each furnace k of SF in time h (MW)
P^{CF}_{nh}	Consumed power of process n of CF in time h (MW)
Pn^{X}	Penalty binary variable of X (1 means penalty has been imposed, otherwise it has not) (X∈{AF, SF, CF})
Aw^{X}	Reward binary variable of X (1 means reward has been imposed, otherwise it has not) (X∈{AF, SF, CF})
N^{CF}_{jnh}	Binary variable of energy section j of process n in CF in time h (1 means this energy section has been chosen, otherwise not)
N^{AF}_{ilh}	Binary variable of AF energy sections (1 means the i^{th} energy section of line l at time h has been chosen, otherwise it has not)
N^{SF}_{ikh}	Binary variable of SF energy sections (1 means the i^{th} energy section of line k in time h has been chosen, otherwise it has not)

Constants

β^X	Penalty and reward coefficient of cost in X (X∈{AF, SF, CF})
$\overline{P}^{WF}$	Capacity of WF (MW)
$\underline{P}_l^{AF}$ / $\overline{P}_l^{AF}$	Min/ max consumed power of each Smelting line l of AF (MW)
α_{il}^{AF}	Value of the segment i of AF in smelting line l (MW)
α_{ik}^{SF}	Value of the segment i of SF in furnace k (MW)
C_{ik}^{SF}/ b_{ik}^{SF}	Constant/ Variable revenue of product sale of the segment i of SF in furnace k ($)
c_{il}^{AF}/ b_{il}^{AF}	Constant/ Variable revenue of product sale of the segment i of AF in each smelting Line l ($)
$\underline{E}_d^{SF}$ / $\overline{E}_d^{SF}$	Min/ max required energy of SF to produce products in each Day (MWh)
a_{jn}^{CF}	Value of segment j of CF in each process n (MW)
C_{jn}^{CF}	Constant revenue of product sale of segment j of CF in each process n ($)
E_l^{τ}	Minimum required energy of smelting line l of AF to maintain temperature balance at hour τ (MWh)
$\underline{E}_d^{AF}$ / $\overline{E}_d^{AF}$	Min/ max required energy of AF to produce products in each day (MWh)
$\alpha_{(i+1)k}^{SF}$	Different energy sections of SF (MW)
$\underline{E}_d^{CF}$ / $\overline{E}_d^{CF}$	Min/ max required energy of CF to produce products in each day (MWh)
P_h^{WF}	Output power of WF (MW)
$\underline{P}_k^{SF}$ / $\overline{P}_k^{SF}$	Min/ max consumed Power of furnace k of SF (MW)
A^{WF}/ B^{WF}	Variable/ Constant cost of energy generation of WF ($/MW)
Y_{bm}	Magnitude of admittance matrix element
$\mho_{bm}$	Angle of admittance matrix element (rad)

Functions

R	Total reward ($)
P_h^{AF-}	Salable energy of AF to the market in time h (MW)
V_h^{AF}	Available spinning reserve of AF to the market in time h (MW)
R^{AF}	Participation in market revenue of AF ($)

Pr^{AF}	Product sale revenue of AF ($)
$P_h^{AF, dec}$	Base power difference to consumed power of AF in time h (MW)
P_h^{SF-}	Salable energy of SF to market in time h (MW)
V_h^{SF}	Available spinning reserve of SF in time h (MW)
R^{SF}	Participation in market revenue of SF ($)
Pr^{SF}	Product sale revenue of SF ($)
$P_h^{SF, dec}$	Base power difference to consumed power of SF in time h (MW)
P_h^{CF-}	Salable energy of CF to market in time h (MW)
V_h^{CF}	Available spinning reserve of CF in time h (MW)
R^{CF}	Participation in market revenue of CF ($)
Pr^{CF}	Product sale revenue of CF ($)
$P_h^{CF, dec}$	Base power difference to consumed power of CF in time h (MW)

1. Introduction

1.1. Aim

The last decade has been an era of economic and industrial development. The overall progression process was quick, which resulted in an increase in the demand for electrical energy. According to statistical data, energy consumption in developing countries is greater than in industrial countries. This raises concerns that in the next twenty years production may not meet domestic demand in underdeveloped countries. As a result, there is a need for extra energy production or energy import to satisfy the growing demand of the power network [1]. Therefore, given the process and energy consumption patterns, the formulation of scientific methods for optimization and energy saving measures, these are essential indicators to be considered in every organization and industry [1]. In order to increase the exploitation of the available resources and participation of end-users in the electricity market, demand response (DR) has been considered as an effective strategy to balance power demand and supply [2]. The active participation of consumers especially in industry and specifically in power system performance, creates opportunities for them to increase their efficiency and revenue. Therefore, this paper aims at proposing a new model of energy consumption in the production process of the main industrial factories manufacturing aluminum, steel and cement. The proposed model is then implemented in the day ahead scheduling of the production process of the named industries and the MG is connected to the factories to maximize their revenue.

1.2. Literature Review

According to IEEE reports [3], approximately 2% to 10% of industrial consumers of electricity account for 80% of the total energy produced. Therefore, industrial consumers are expected to implement more accountability programs as compared to subscribers in residential and commercial sectors [4]. However, recent research suggests that the situation is exactly the opposite [4]. Any causes of electricity interruption in an industrial factory may result in production stoppage, decrease in daily operations, and violation of production constraints. In some cases, these processes are interdependent which makes it difficult to interrupt them. Occasionally, material is saved for each disruption process making the operation strenuous and costly. Therefore, it is evident the that effect of the industrial sector's participation in DR programs has not been fully exhausted. Available infrastructure such as control equipment, measurement and communication systems, contribute to the successful implementation of DR programs. Most industrial consumers are able to set their load profile, while creating a quick and accurate change in their peak load times, in order to increase their profitability and participation in DR [5]. A group of industries with the potential of participating in DR programs are aluminum, steel, and cement. The participation of these industrial loads in the energy management network, using load-response programs, has not only led to a shift in energy consumption, but also actively provides ancillary services such as the spinning reserve [6].

The work in [7] expounds on the modeling and optimization of energy consumption in an aluminum factory (AF), its profit through DR program participation and addresses imbalances between supply and demand using ancillary support services. In this study, high-energy consuming processes of an AF is modeled using LPWA method. Preparation of the optimal setting in an AF using automatic gain control is presented in [8]. The results show a profitability increase in setting services, nonetheless, they do not explain the contribution of the factory using other ancillary functions. The production process of a cement factory (CF) using a time-of-use DR program is discussed in [9]. The results show how to shift the factory load in order to reduce the grid load peak, however, a complete model of the industrial processes has not been presented. The authors in [10] present the scheduling of a steel factory (SF) considering energy constraints. In [11] a novel structure for industrial demand response aggregators, that is used to provide operational power system flexibility is proposed. The proposed structure satisfies the demand of the customer order with the lowest energy cost. In [12] a new approach has been proposed to assist industrial demand response to participate in operational markets. This approach uses physical-mathematical modelling of an industrial demand response to maximize the profit. In [13], an optimization framework is introduced to account for different load conditions in steel factories. In this framework, dependencies among industrial factories, time of use, frequent operation and energy simulation management are discussed. Furthermore, real-time-pricing DR programs were analyzed for CFs in [14]. The results show grid load profile improvements in comparison with other pricing strategies. The work in [15] optimizes Shadaab industrial MG in Tehran and its main goal is to reduce cost and increase renewable energy penetration. However, a complete model of the industrial processes has not been presented. The optimization problem of a virtual power plant is assessed in [16], while considering different solving methods and DR programs. Virtual power plant's contain large industrial loads, whereby the load profile has been considered for the entire grid and not for each individual factory. However, its constraints have not been mentioned. A day ahead pricing is used for analyzing the energy management program in [17] and assessing both on-grid and off-grid conditions. Nonetheless, the type of industries invested in MG's, industrial process models and constraints have not been considered.

1.3. Contribution

Industrial energy consumers are usually located around the city outskirts, whereby implementing a MG would affect the grid both economically and security wise. However, none of the aforementioned research individually considers finished models of CF, AF, and SF in their participation in DR programs for they are all presented together. In order to make the DR program efficient and the situation more realistic, a complete model of the 3 factories has been presented. Concurrently, a day ahead pricing energy management program is also implemented. The main contributions of this paper are:

- Complete modeling of a MG and industrial factories, while considering technical and economic constraints.
- Preposition of an optimization model based on the industrial factories' cooperation.
- Participation of the aforementioned industries in the energy and ancillary service market by implementing DR programs.

1.4. Paper Organization

The remaining sections of this paper are organized as follows: in Section 2, a complete model of a MG using DR program is provided. Section 3 presents a mathematical formulation of energy management optimization. In Section 4, the proposed model is analyzed using previous studies, whereby the effects of DR programs are assessed and compared to other case studies. Subsequently, technical and economic indices are discussed, while considering the effects of production sales and the demonstration of energy purchase prices in industrial factories' revenue using sensitivity analysis. Lastly, Section 5 concludes the paper.

2. Microgrid components

The MG design presented in this paper consists of aluminum, steel, and cement factories connected together with local loads and includes two wind farms (WF) as shown in Figure 3.

2.1. Industries

In order to assess the contribution of aluminum, steel, and cement factories in DR programs and ancillary services, the processes and equipment of industrial factories are divided into three groups. The first group consists of a non-displaceable process, whereby the loads cannot be scheduled for a different time and the required demand must be met under any circumstances. The second group considers a scenario where the peak loads can be shifted to a different time to better match the electricity demand with the supply. The equipment in this category can be either turned on or off based on the available power grid network. The third set of the process is itemized as a controllable factory, where in addition to time displacement, energy demand is adjustable and can be varied according to operational occurrences.

2.1.1. Modeling of Aluminum factories processes

The aluminum melting process converts alumina into aluminum, which is the primary material for various industries, such as canning and car manufacturing [18]. The process is initiated using DC voltage on the cell plates. In addition to alumina, other materials were added to increase the rate of chemical reactions. Hundreds of cells are connected in series to form a melting line or several melting lines. The total power consumption of each melting line is approximately hundreds of megawatts [7].

Furnace flexibility in AF's makes it an appropriate source for DR. In this paper, similar to [7], the melting point is regulated and controlled using a rectifier. The power consumption of each melting line at the AF is given by Eqs. (1)- (3).

$$P_{lh}^{AF} = \sum_{i=1}^{n} (\alpha_{il}^{AF} N_{ilh}^{AF} + \Delta P_{ilh}^{AF}) \quad \forall l, h \tag{1}$$

$$0 \leqslant \Delta P_{ilh}^{AF} \leqslant (\alpha_{l(i+1)}^{AF} - \alpha_{il}^{AF}) N_{ilh}^{AF} \tag{2}$$

$$\sum_{i=1}^{n} N_{ilh}^{AF} = 1 \quad \forall l, h \tag{3}$$

In order to simplify the equation, it is assumed that $\sum_{l} \overline{P}_l$ is the power in a long-term contract with the upstream grid. Consequently, the factory is able to sell power to the grid in the case its consumption is lower than the amount defined by $\sum_{l} \overline{P}_l$. The marketable power to the grid P_h^{AF-} demonstrated in Eq. (4).

$$P_h^{AF-} = \sum_{l} (\overline{P}_l^{AF} - P_{lh}^{AF}) \quad \forall l, h \tag{4}$$

The amount of spinning reserve, given in Eq. (5), is dependent on the ability of the furnace to reduce the consumed power. However, the cost of connecting the spinning reserve is neglected.

$$V_h^{AF} = \sum_{l} (P_{lh}^{AF} - \underline{P}_l^{AF}) \quad \forall l, h \tag{5}$$

The revenue obtained from the participation in the energy markets is calculated in Eqs. (6)- (8). The factory is penalized for exceeding the base power consumption. In this case, the penalty binary variable is equal to 1 and is penalized in proportion to the difference between the base and consumed power of an AF, given as $P_h^{AF,\,dec}$. Likewise, when the load is less than the base power, the factory receives a proportional reward.

$$R^{AF} = \sum_{h} \omega_h (P_h^{AF-} + \rho_h V_h^{AF} + \beta^{AF} (Aw^{AF}) P_h^{AF,\,dec} + \beta^{AF} Pn^{AF} P_h^{AF,\,dec}) \quad \forall l, h \tag{6}$$

$$P_h^{AF} = \sum_{l} P_{lh}^{AF} \quad \forall l, h \tag{7}$$

$$P_h^{AF,\,dec} = P^{base} - P_h^{AF} \tag{8}$$

It should be noted that P^{base} is the rated power of the aluminum factory. This power is sufficient for normal manufacturing processes of this type of unit. On the other hand, $\underline{P}_l^{AF}$ and $\overline{P}_l^{AF}$ show the minimum and maximum power demand of the factory, respectively. Therefore, P_h^{AF-} is the power that can be sold to the upstream grid and is calculated by subtracting P_{lh}^{AF} from $\overline{P}_l^{AF}$ as shown in Eq. (4). Moreover, P_h^{AF} is calculated by subtracting power demand of the factory from P^{base} during each hour as shown in Eq. (8). The result shows that the power reduced during each hour by the factory participating in the DR program had an aim of obtaining a reward.

According to Eq. (9), the revenue from selling aluminum products is modeled using LPWA.

$$Pr^{AF} = \sum_{h} \sum_{l} \sum_{i=1}^{n_l} (c_{il}^{AF} N_{ilh}^{AF} + b_{il}^{AF} \Delta P_{ilh}^{AF}) \tag{9}$$

The revenue gained from product sales is assumed to be constant in each energy section. In the energy section i, the revenue from excess products of production line l, is the left limit of the same energy sector. Thus, the difference in the revenue of products at different powers of each melting line can be modeled.

It is worth mentioning that the temperature equilibrium is the most important aspect in melting-line flexibility, and cell temperature to improve the high melting efficiency and security operation. For this purpose, as shown in Eq. (10), the power consumption in each hour τ_l must be higher than E_l^{τ}.

$$\sum_{h'=h}^{h+\tau_l-1} (P_{lh'}^{AF} - V_{h'}^{AF}) \leqslant E_l^{\tau} \quad \forall l, h \tag{10}$$

It is assumed that the factory has its own storage capability, adding system flexibility, and is proportional to the production of units during the day as given in Eq. (11). Consequently, the minimum and maximum power consumption is proportional to the minimum and maximum factory production.

$$\underline{E}_d^{AF} \leqslant \sum_{hl} P_{lh}^{AF} \leqslant \overline{E}_d^{AF} \tag{11}$$

2.1.2. Modeling of steel factories processes

Steel factories are considered as one of the most complex industries, experiencing high energy consumption levels with numerous energy constraints operating at multi-level and multiple production [10]. Power consumption required for steel products include the necessary energy for iron extraction (iron ore), iron smelting and steel heating (to form the final product).

It is important to mention that smelting of steel scrap requires high energy consumption [19]. In this process, the heat is created by a spark of an electric furnace or induction, which causes the steel to melt. The first method suggests the mitigation of this process, however, it must be restarted if load shedding is experienced over half an hour. The steel scrap then starts to cool down which incurs additional costs. It has been reported that the melting time of steel scrap is 45 minutes and about 15 minutes to replenish the furnace for the next melting period. In addition, the factory has the option to completely stop the process of selling contractual power in energy regulatory markets. The second method proposes that the power consumption rate can also be adjusted quickly and accurately using a tap changer.Therefore, this makes steel factories a reliable DR source to supply the spinning reserve. The supplied spinning reserve is dependent on the furnace power consumption rate and the minimum power of the furnace, in order to avoid the cooling of melted steel.In this paper, the second method is used to supply the spinning reserve, whereby the load demand of the melting furnace is a controllable process. The factory is assumed to have storage capability and flexibility while producing steel products, which is proportional to the amount of goods produced in a day. The consumed power of each smelting line in steel factories is described using Eqs. (12)- (14).

$$P^{SF}_{kh} = \sum_{i=1}^{n_l} (\alpha^{SF}_{ik} N^{SF}_{ikh} + \Delta P^{SF}_{ikh}) \quad \forall k, h \tag{12}$$

$$0 \leqslant \Delta P^{SF}_{ikh} \leqslant (\alpha^{SF}_{(i+1)k} - \alpha^{SF}_{ik}) N^{SF}_{ikh} \tag{13}$$

$$\sum_{i=1}^{n_l} N^{SF}_{ikh} = 1 \quad \forall k, h \tag{14}$$

The combined limit of each smelting line in steel factories is represented by Eq. (15).

$$\underline{E}^{SF}_{d} \leqslant \sum_{hk} P^{SF}_{kh} \leqslant \overline{E}^{SF}_{d} \tag{15}$$

It is assumed that $\sum_{l} \overline{P}_k$ is a long-term power contract and thus, industrial factories can sell power to the network, if its power consumption is lower than $\sum_{l} \overline{P}_k$. Consequently, the salable power P^{SF}_{h} is modeled according to Eq. (16).

$$P^{SF}_{h} = \sum_{k} (\overline{P}^{SF}_{k} - P^{SF}_{kh}) \quad \forall k, h \tag{16}$$

The amount of spinning reserve is dependent on the ability of the furnace to reduce its energy consumption. The amount of spinning reserve is modeled as shown in Eq. (17).

$$V^{SF}_{h} \leqslant \sum_{k} (P^{SF}_{kh} - \underline{P}^{SF}_{k}) \quad \forall k, h \tag{17}$$

The advantage of participating in the energy markets is calculated as highlighted in Eq. (18). The factory is penalized for exceeding the base power consumption. In this case, the penalty binary variable is 1; which is proportional to the consumed factory power. Conversely, in the case the factory significantly reduces the load , it will receive a substantial reward.

$$R^{SF} = \sum_h \lambda_h (E_h^{SF} + \rho_h V_h^{SF} + \mu_f Aw^{SF} P_h^{SF, dec} + \mu_f Pn^{SF} P_h^{SF, dec}) \quad \forall h \tag{18}$$

The production revenues of SF's are expressed in Eq. (19).

$$Pr^{SF} = \sum_h \sum_k \sum_{i=1}^{n_l} (C_{ik}^{SF} N_{ikh}^{SF} + b_{ik}^{SF} \Delta P_{ikh}^{SF}) \tag{19}$$

2.1.3. Modeling of cement industrial factory processes

The electricity cost in a typical CF accounts for nearly 30% of its total cost [20]. In general, the furnace must be continuously active during the production process. However, the operation time of raw materials, ores and the final CF can be set as desired.

In order to provide a full model of processes and constraints of CF's, a new model of production is demonstrated using LPWA method. In this paper, the process has been categorized into 4 stages: i) cement stone chopping, ii) preparation of raw material, iii) furnace preparation and iv) packaging of cement products. The consumed energy in other parts of this industry has been neglected. It is also assumed that there is sufficient capacity for storing inventory. The power consumption of the factory per hour is represented by Eqs. (20) and (21). As shown in Table 6, j is equal to 1 in non-shiftable programs, 2 in shiftable programs, and 3 in controllable programs.

$$P_{nh}^{CF} = \sum_{j=1}^{n_l} (a_{jn}^{CF} N_{jnh}^{CF}) \quad \forall n, h \tag{20}$$

$$P_h^{CF} = \sum_n P_{nh}^{CF} \quad \forall n, h \tag{21}$$

As shown in Eq. (22), N_{cjnh} binary variable demonstrates the operating conditions of each system.

$$\sum_{j=1}^{n_j} N_{jnh}^{CF} = 1 \quad n, h \tag{22}$$

Eq. (23) represents the maximum and minimum CF production during the day.

$$\underline{E}_d^{CF} \leqslant \sum_{h,n} P_{nh}^{CF} \leqslant \overline{E}_d^{CF} \tag{23}$$

The factory will be penalized for exceeding the maximum base power, exactly similar to the AF and SF, as shown in Eqs. (24)- (27).

$$R^{CF} = \lambda_h(E_h^{CF} + \rho_h V_h^{CF} + \beta_c Aw^{CF} P_h^{CF,\,dec} + \beta_c Pn^{CF} P_h^{CF,\,dec}) \quad \forall h \tag{24}$$

$$P_h^{CF} = \sum_n (\overline{P}_n^{CF} - P_{nh}^{CF}) \quad \forall n, h \tag{25}$$

$$V_h^{CF} \leqslant \sum_n (P_{nh}^{CF} - \underline{P}_n^{CF}) \quad \forall n, h \tag{26}$$

$$P_h^{CF,\,dec} = P^{CF,base} - P_h^{CF} \tag{27}$$

The CF production revenues are expressed in Eq. (28).

$$Pr^{CF} = \sum_h \sum_n \sum_{j=1}^{nj} (C_{jn}^{CF} N_{jnh}^{CF}) \tag{28}$$

2.2. *Wind as a renewable energy resource*

2.2.1. *Wind farm*

A wind farm (WF) is used to convert wind energy into electricity. The amount of power produced is highly dependent on the weather variability taking into consideration the hour, day, and different seasons. In order to estimate electricity generation and ensure coordinated grid planning, wind patterns need to be assessed in a specific geographical location. It is noted that there is a nonlinear relationship between the output power and wind speed. This relation can be expressed using WF operation parameters, that include connection, disconnection and wind speed [21]. This paper describes the relation between wind speed and the WF's output power, as shown in Eq. (29).

$$P^{WF} = Cap^{WF} \times \begin{bmatrix} 0 & 0 \leqslant v \leqslant v_i \\ a + bv^3 & v_i \leqslant v \leqslant v_r \\ 1 & v_r \leqslant v \leqslant v_0 \\ 0 & v \leqslant v_0 \end{bmatrix} \tag{29}$$

v_i, v_r, and v_o are cut in, rated, and cut out wind speed, while a and b parameters are calculated as follows:

$$a = \frac{v_i^3}{v_i^3 - v_r^3} \tag{30}$$

$$b = \frac{1}{v_r^3 - v_i^3} \tag{31}$$

2.2.2. Wind farm uncertainty model

Implementing renewable based distributed generations like WFs creates uncertainty, which is a critical challenge in power system planning. Two renowned probabilistic methods of uncertainty modeling are Mont Carlo and point estimation method. An advantage of point estimation method is that it requires less calculation and less probability data functions as compared to Mont Carlo.

In addition, it presents high-level simplicity, accuracy, and uses uncomplicated mathematical operations (such as mean value and standard deviation). In this paper, two point estimation method is implemented as a special case of a point estimate method. To model m random variables using two point estimate method, only solving $2\times m$ scenarios is needed to gain the intrinsic uncertainty of m random variables [22]. Assume $X=\{x_1, x_2, \cdots, x_m\}$ is a random variable with a mean value of μ_{xl} and standard deviation of σ_{xl}. Z is a random quantity and a function of X as $z=f(x)$. Each concentration of random variable x_1 can be defined with a weight (w_{ls}). The concentration of x_{ls} is defined as:

$$x_{ls} = \mu_{x_l} + \xi_{ls}\sigma_{x_l} \tag{32}$$

$$\xi_{l1} = \frac{\lambda_{l3}}{2} + \sqrt{m + (\frac{\lambda_{l3}}{2})^2}, \quad \xi_{l2} = \frac{\lambda_{l3}}{2} - \sqrt{m + (\frac{\lambda_{l3}}{2})^2} \tag{33}$$

$$w_{l1} = -\frac{\xi_{l2}}{m(\xi_{l1} - \xi_{l2})} \quad w_{l2} = \frac{\xi_{l1}}{m(\xi_{l1} - \xi_{l2})} \tag{34}$$

$$\lambda_{l3} = \frac{E(x_l - \mu_{x_l})^3}{\sigma_{x_l}^3} \tag{35}$$

At each time, a variable concentration point considering the mean value of other probabilities is taken into account and calculates the probabilistic information of the output variable shown in Eq. (36).

$$Z_{l3} = F(x_{l1}, x_{l2}, \cdots, x_{ls}, \cdots, x_{ms}) \tag{36}$$

The initial condition of the output is demonstrated in Eq. (37).

$$E(Z) \cong E(Z) + \sum_{s} w_{ls} Z_{ls} \tag{37}$$

Finally, the output is presented in the form of the expected value and standard deviation. The flowchart of this method is presented in Figure 1.

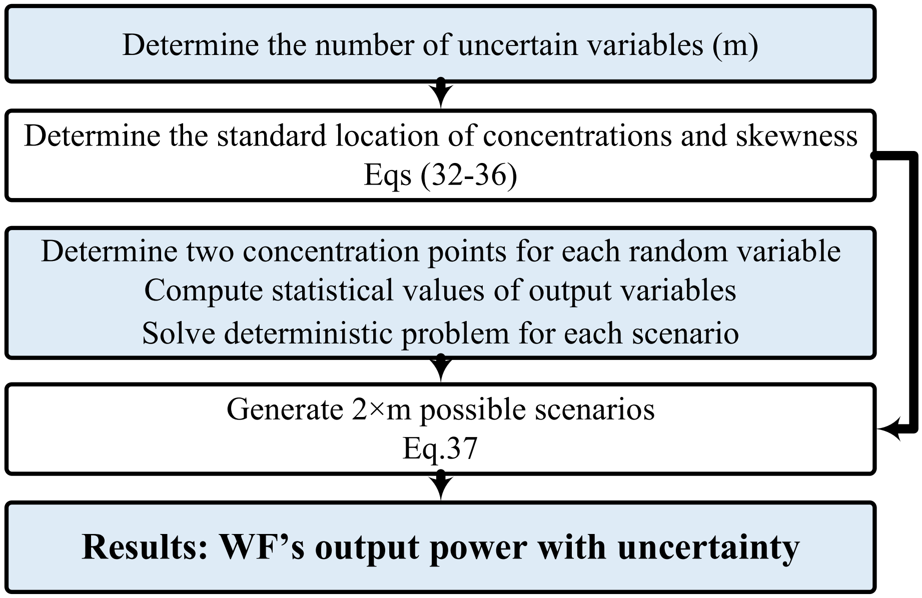

Figure 1: Flowchart of two point estimation method

3. Problem Formulation

3.1. Objective Function

The objective function represents the revenue generated from aluminum, steel and cement factories connected to the grid, with a goal of maximizing it. According to Eqs. (38)- (40), the revenue is the summation of the participation revenues in electricity markets using DR and returns gained by selling the manufactured products (Eq. (38)). Eq. (39) highlights the participation revenues from all the industries using DR including aluminum, Steel, and cement. Eqs. (40) shows the overall revenue attained by selling aluminum, Steel, and cement.

$$\text{Max} \;\; R + \text{Pr} + \sum_{h} \sum_{b} (\omega_h \times p_{bh}^{WF} - (p_{bh}^{WF} \times A_b^{WF} + B_b^{WF})) \tag{38}$$

$$R = R^{AF} + R^{SF} + R^{CF} \tag{39}$$

$$\text{PR} = \text{Pr}^{AF} + \text{Pr}^{SF} + \text{Pr}^{CF} \tag{40}$$

The main idea of this paper is demonstrated in Figure 2. The flowchart is outlined as follows:

In this paper, the MG consists of three industrial factories, namely cement, aluminum, and steel. The MG net revenue is calculated by the summation of the product and energy sales to the upstream grid. The MG energy management system is set to operate at optimal conditions in order to maximise revenues, while considering industrial factory constraints. This is achieved by analyzing input data of the aforementioned factories, forecasting day ahead energy prices, and considering renewable energy generation using WFs.

Considering the production process of each industrial factory, the MG energy management system categorizes each operation as: 1. non-shiftable 2. shiftable 3. controllable. In non-shiftable processes, the load cannot be shifted at one time to another. Hence, the energy demand must be met at all costs and conditions for this process. Therefore, this process will be unable to provide power and spinning reserve to the upstream grid. Shiftable processes are flexible and allow the load to be deferred to a different time. This process helps to balance the supply and demand in a timely manner, however, the energy demand remains constant. In summary, the shiftable process of each machine can either be on or off. If the machine is on, it consumes maximum energy and the power sales to the upstream grid is zero. However, the spinning reserve of this process is equal to the energy consumption of the machine, as it can be turned off at anytime. If the machine is off, the generated energy for the upstream grid is equal to the power consumption of the machine. Meanwhile, the spinning reserve is zero. In controllable processes, just like shiftable processes, energy consumption can be increased or decreased according to the MG operating conditions. If the demand operates in the maximum power region, the energy provided by this process is zero. Moreover, the spinning reserve is equal to the difference between the maximum and minimum power consumption. If power consumption is less than its maximum value, the MG supplied energy is equal to the difference between its consuming and maximum power. In addition, the spinning reserve is equal to the difference between its consuming and minimum power. Towards the end, the MG energy management system determines the expected energy consumption, the MG peak load, the expected MG net revenue, the energy sold to the upstream grid, and the spinning reserve.

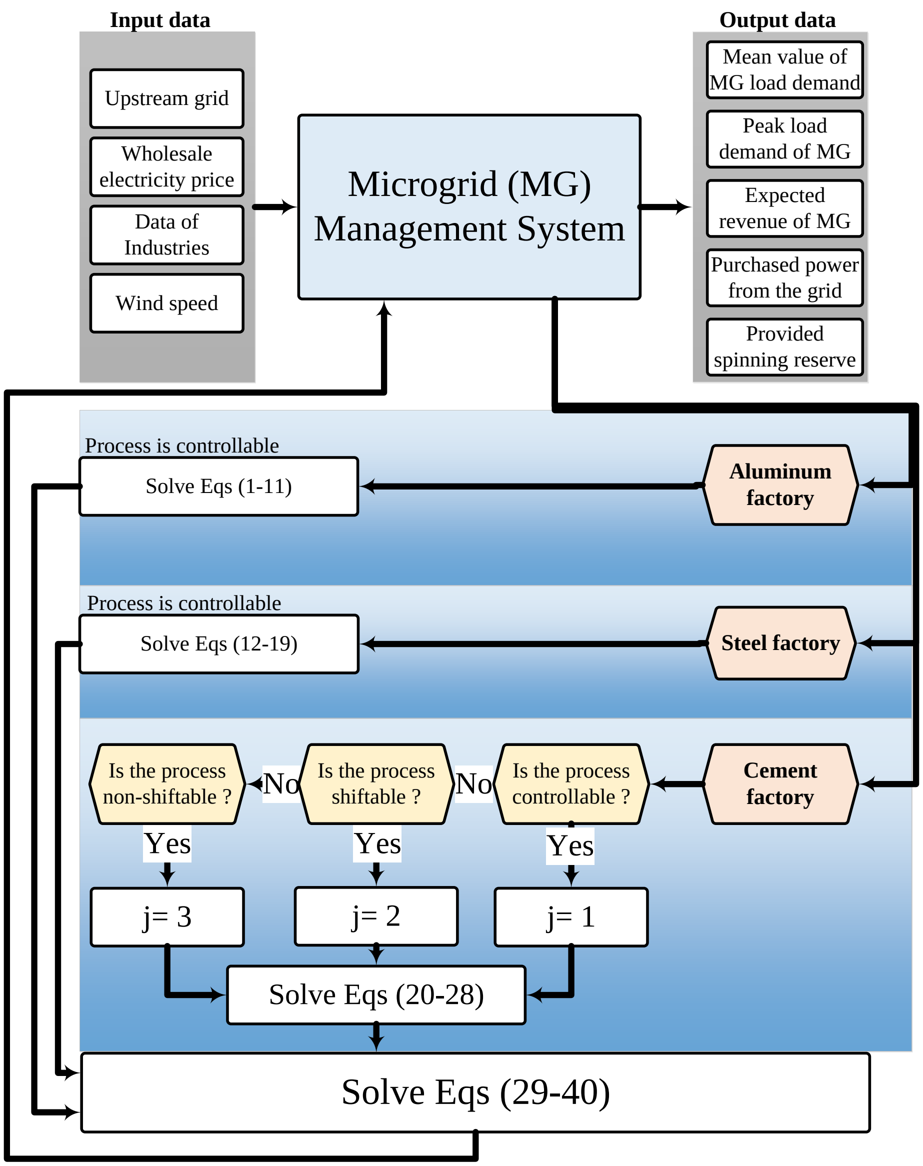

Figure 2: Day ahead scheduling flowchart for industrial factories considering wind energy and DR

3.2. Constrains

In order to increase the reliability and participation in DR programs, a MG is connected to the upstream grid. Eqs. (41) and (42) represent the MG's active and reactive power constraints, respectively. These equations show that the injected active and reactive power to bus, P_{bh}^{inject} and Q_{bh}^{inject} respectively, must be equal to the difference of generated and consumed active and reactive power.

$$P_{bh}^{G} - P_{bh}^{D} = \sum_{m} V_{bh} \times V_{mh} \times Y_{bm} Cos(\theta_{bm} + \delta_{mh} - \delta_{bh}) \tag{41}$$

$$Q_{bh}^{G} - Q_{bh}^{D} = \sum_{m} V_{bh} \times V_{mh} \times Y_{bm} Cos(\theta_{bm} + \delta_{mh} - \delta_{bh}) \tag{42}$$

The voltage and power constraints at each bus are demonstrated in Eqs. (43)-(44). The voltage and consumed power at each bus must not exceed or be less than a certain specified value.

$$\underline{V}_{b} \leqslant V_{bh} \leqslant \overline{V}_{b} \tag{43}$$

$$\underline{P}_{b} \leqslant P_{bh}^{G} \leqslant \overline{P}_{b} \tag{44}$$

4. Simulation and results

To test the proposed model and DR programs, a case study with 9 buses at 132kV is considered. This grid is a modified version of the IEEE 30 bus system, which only considers its transmission network (Figure 3). The MG is connected to an upstream grid via 3 grid supply points (bus 1, 2, and 6). This network has three industrial factories, two WFs, and seven other independent loads, shown in detail in Table 1-8 and Figure 4- 6.

Table 1: Characteristics of WF

WF	Bus No.	Min. generation (MW)	Max. generation (MW)	A_{b}^{WF} (MWh/$)	B_{b}^{WF} ($)
1	4	0	11	15	9
2	9	0	8	11	5

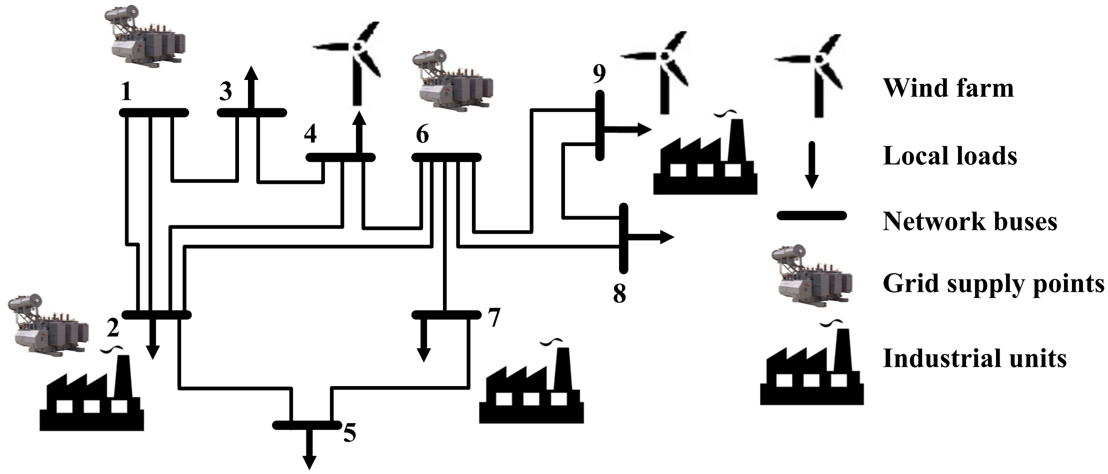

Figure 3: Microgrid network diagram

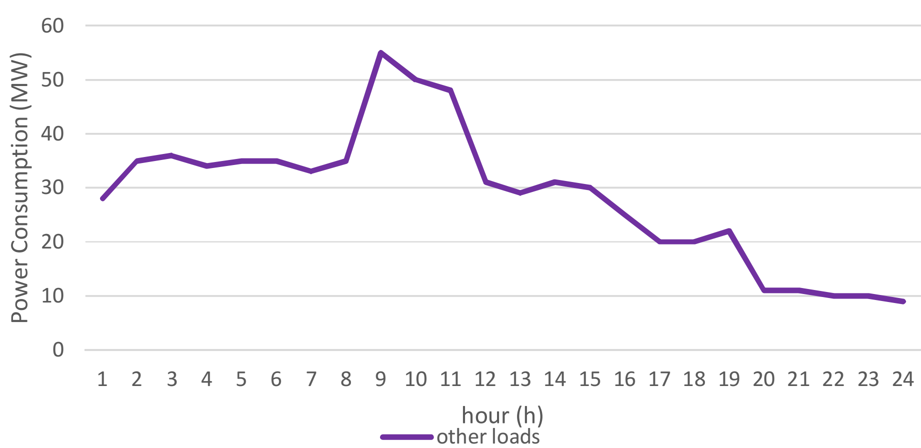

Figure 4: Load duration curve of other loads

Table 2: Mean value and standard deviation of WFs' power generation

Hour	WF 1 mean value (MW)	WF 1 standard deviation (MW)	WF 2 mean value (MW)	WF 2 standard deviation (MW)
h=1,...,6	5	0.1	4	0.1
h=7,...,12	7	0.3	6	0
h=13,...,18	9	0.4	7	0.3
h=19,...,24	8	0.2	7	0.2

Table 3: Smelting line parameters of AF

Line	$\underline{P}_l^{AF}[MWh]$	$\overline{P}_l^{AF}[MWh]$	η_l [h]	E_l^{η} [MWh]
1	30	70	4	185
2	40	60	3	130

4.1. Problem data

In this study, the energy purchase price of a MG from an upstream grid is considered separate from the energy selling price to the upstream grid. The cost of the energy purchase price from the upstream grid is accounted for in the net production revenue of each industrial factory. This means that to calculate the net production revenue (PR), the energy purchase price has been subtracted from product sale revenues. The data collected from the electricity purchase price is demonstrated in Figure 5 [23]. The optimization program is executed using day ahead pricing at 60 minute intervals. The output power and cost parameters of WFs are shown in Figure 6 and Table 1, respectively. The standard deviation of the WF is summarised in Table 2. The input data for AF, SF and CF is shown in Table 3 to Table 8. The AF has two smelting lines. A number of uncontrollable industrial loads is considered in the MG to make the operation more realistic. The proposed model is simulated in general algebraic modeling system (GAMS), using a standard branch and bound solver. The runtime for CS1, CS2 and CS3 are 0.092, 0.094 and 0.097 seconds respectively, which run by a PC with 2.5GHz, Core i7 CPU, and 6GB RAM.

4.2. Case Studies

Case Study 1: **CS1**

In CS1, the energy consumption of a MG and industrial factories has been calcu-

Table 4: revenue parameters of AF

L= 1	α_i [MW]	$\{30, 40, 50, 60, 70\}$
	b_i [MW/$]	$\{56, 58, 60, 62\}$
	c_i [$]	$\{1680, 2240, 2820, 3420\}$
L= 2	α_i [MW]	$\{40, 45, 50, 55, 60\}$
	b_i [MW/$]	$\{66, 68, 70, 72\}$
	c_i [$]	$\{2640, 2970, 3310, 3660\}$

Table 5: revenue of CF

Process Name	Process type	Device revenue ($)		
		Demand 1	Demand 2	Demand 3
Cement stone chopping	Controllable	0	2400	2750
Raw material preparation	Displaceable	0	1800	1800
Furnace preparation	Non-displaceable	2480	2480	2480
Cement products packaging	Displaceable	0	1950	1950

lated, without considering DR. As depicted in Figure 7, the energy consumption of aluminum, Steel, cement, small industrial factories and the overall load of the MG are shown. The expected value of the net revenue of aluminum, steel and cement factories summarised in Table 9 are 188112, 151551/87, and 104400 dollars respectively. The net revenue highlighted in Table 9 is only gained by selling the manufactured products and does not account for DR programs.

Case Study 2: **CS2**

In CS2, a DR program is considered to reduce the peak energy consumption and to increase industrial factory revenues. The expected energy consumption of the MG and industrial factories are demonstrated in Figure 8. It is shown in Table 10, that by implementing the DR program in CS2, the expected energy consumption is significantly reduced while the net revenue of the industrial factories is increased, as compared to CS1; for DR was not implemented in CS1. It is noted that all three industrial factories reduced their production sale revenues for more participation in the DR program. However, SF and CF gained most of its revenue increase via

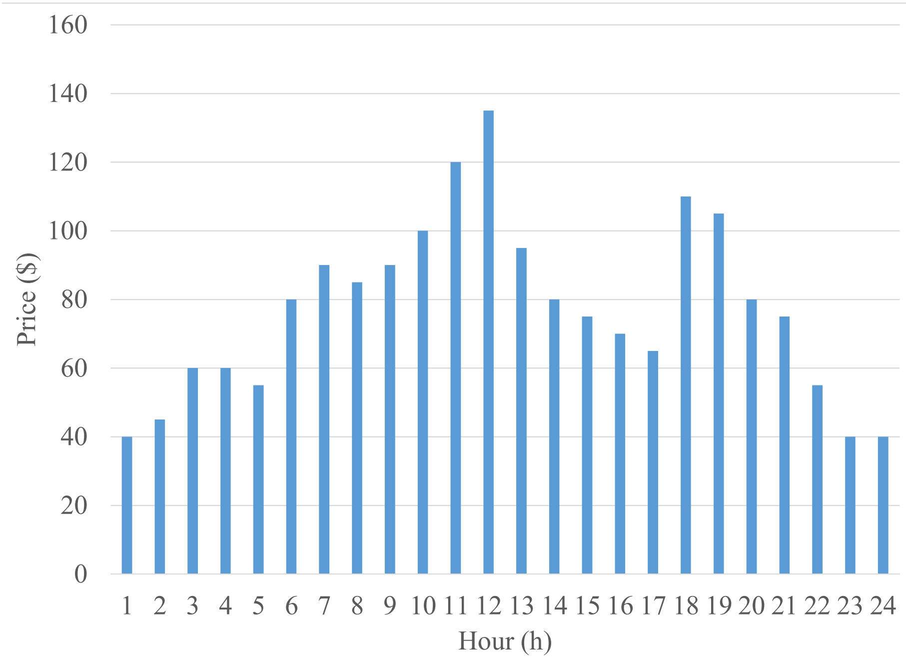

Figure 5: Energy purchase price

participation in energy markets, while AF gained revenue mostly by providing energy to the spinning reserve. Thus, all industrial factories increased their revenues, while reducing their energy consumption. Likewise, according to Figure 9, the peak load was decreased by 19% (96MW).

Figure 10 and Figure 11 illustrate the technical and financial indexes of industrial factories in both case studies. In CS2, as compared to CS1, the overall MG load, MG peak load, and peak energy consumption of each industrial factory has decreased significantly. The CF shows more flexibility compared to the other factories, due to its greater reduction in energy consumption. The expected revenue of the MG in CS1 and CS2 is 470533.9 and 828709.5 respectively. The standard deviation is 589.6 for both cases.

Case Study 3: **CS3**

CS3 aims for an overall load peak reduction of industrial MGs during emergency situations, whereby each factory is mandated to reduce its load by 25%. This regula-

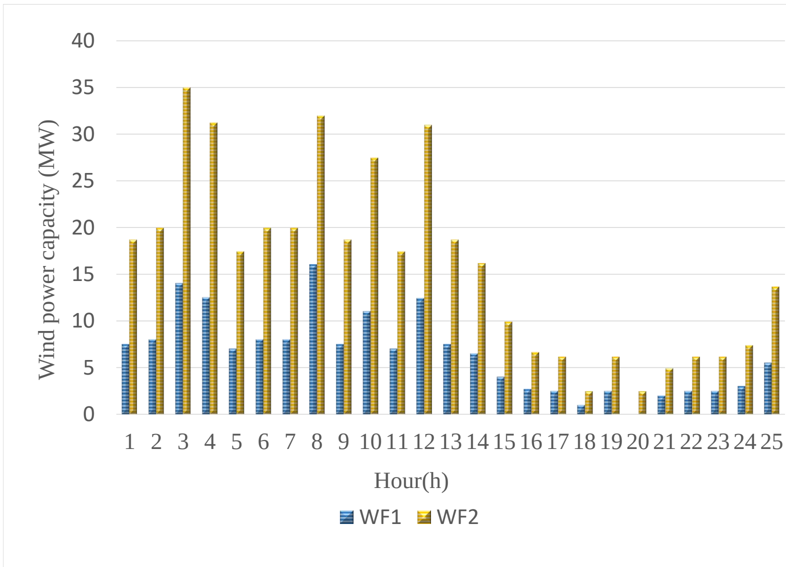

Figure 6: The power produced by WFs

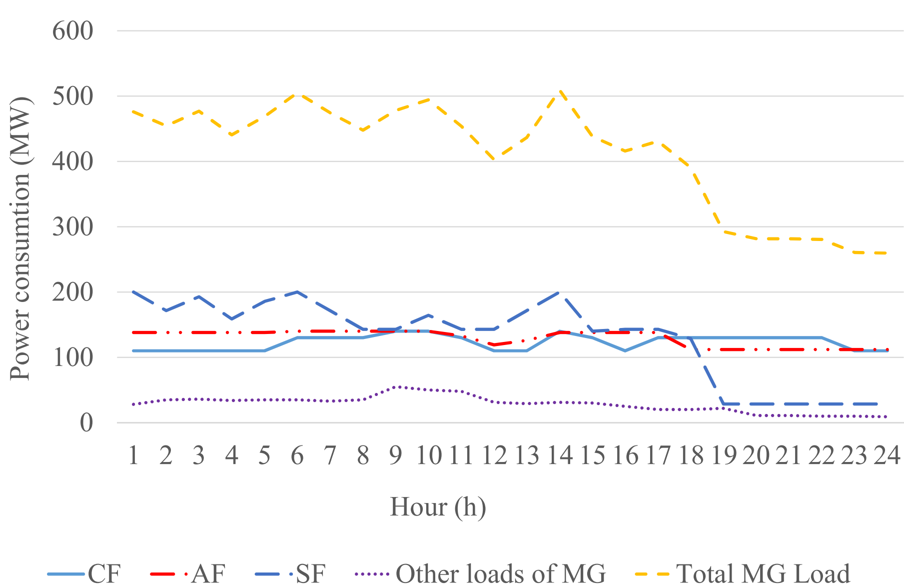

Figure 7: The expected of MG Load and industrial factories in CS1

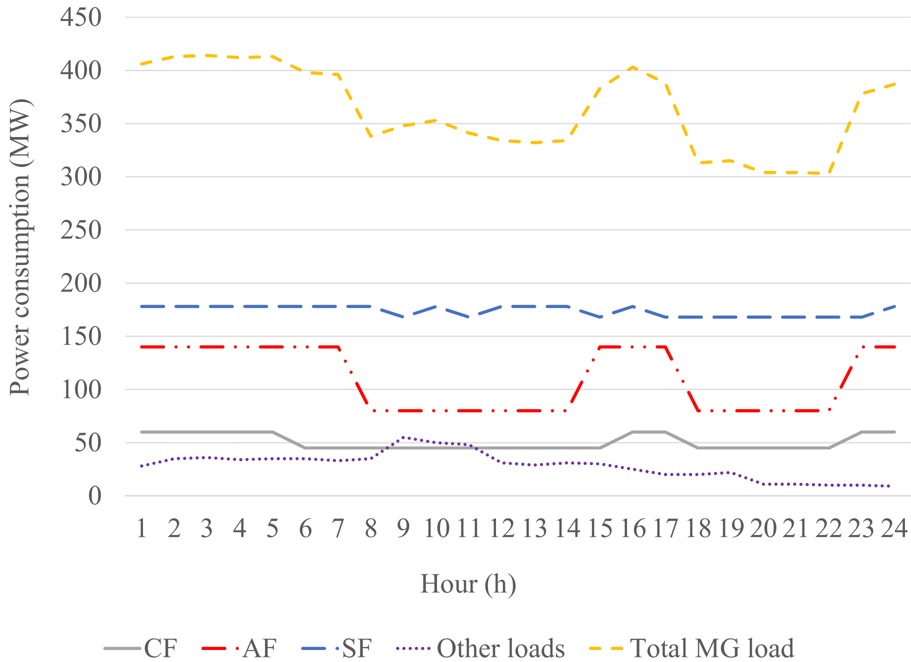

Figure 8: The expected value of MG and industrial load in CS2

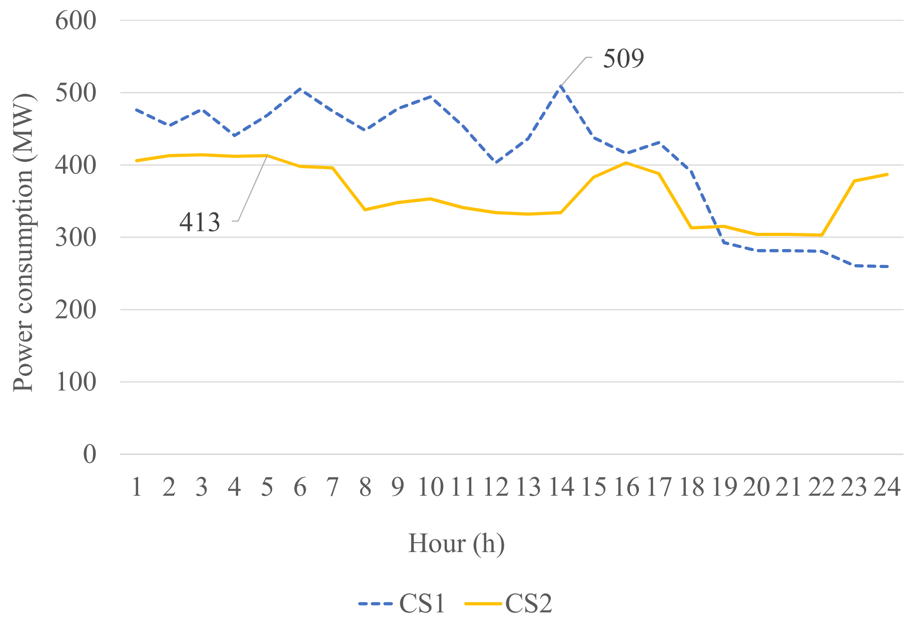

Figure 9: The expected value of MG load in CS1 and CS2

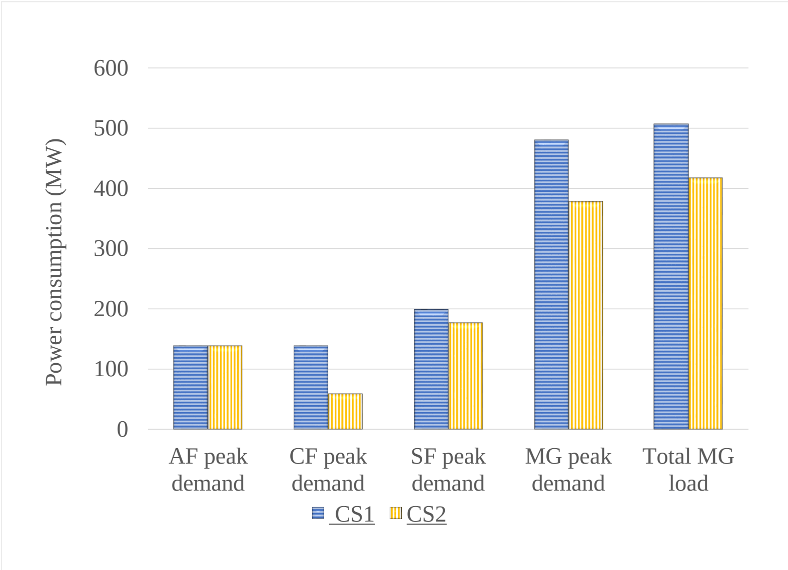

Figure 10: The expected value of Technical Indexes in CS1 and CS2

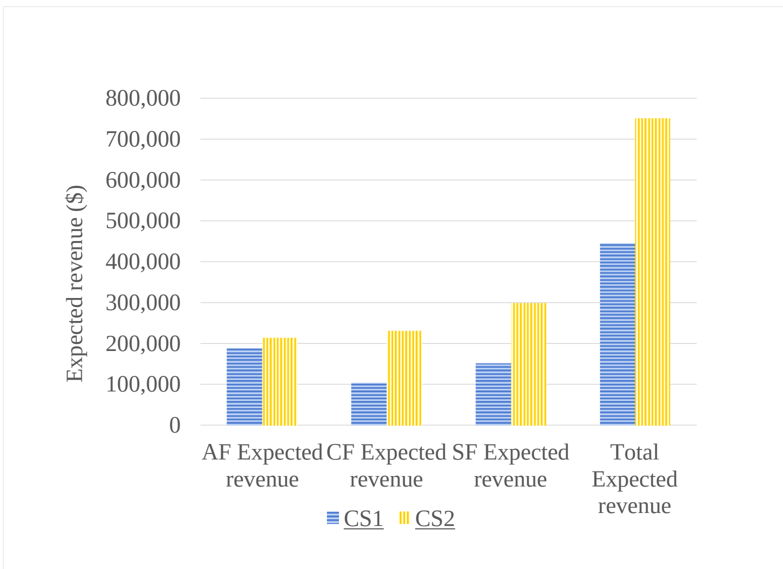

Figure 11: The expected value of Economical Indexes in CS1 and CS2

Table 6: Energy Demand of CF

Process Name	Energy Demand (MW/h)		
	Demand 1	Demand 2	Demand 3
Cement stone chopping	0	40	50
Raw material preparation	0	30	30
Furnace preparation	45	45	45
Cement products packaging	0	15	15

Table 7: revenue Parameters of SF

L= 1	α_i [MW]	{48, 68, 88, 108}
	b_i [MW/$]	{50, 55, 60, 65}
	c_i [$]	{1440, 2440, 3540, 4740}
L= 2	α_i [MW]	{50, 60, 70, 80}
	b_i [MW/$]	{66, 68, 70, 72}
	c_i [$]	{2510, 3170, 3850, 4550}

tion decreases the MG revenue by 0.67%, which is demonstrated in Table 11. Due to the flexibility of steel and cement factories, their product remains unchanged, while the AF product is reduced. In addition, the spinning reserve has consequently decreased due to mandatory peak load reduction. In order to show the advantages of the factories coordinated operation, it is assumed that factories cooperate to reduce their combined peak load by 25% instead of reducing the peak load by 25% for each individual factory. According to Table 12, in this case they gain about 10% more revenue. Moreover, the AF products are increased and its mandatory load peak reduction is compensated by the steel and cement factories. Therefore, the revenues of the AF and the MG is increased in this case. This revenue can be shared between factories based on some agreements, which is beyond the scope of this paper. Table 12 also shows that in the case of coordinated operation more spinning reserve is provided by the MG.

Table 8: Smelting Line Parameters of SF

Line	$\underline{E}_l$ [MW]	$\overline{E}_l$ [MW]
1	30	128
2	40	90

Table 9: Expected daily revenue of industrial factories and MG in CS1

	Overall Expected revenue ($)	Product Sale revenue ($)	DR revenue ($)	Provided Power to the grid (MW)	Provided Spinning Reserve (MW)
AF	188112	188112	0	0	0
SF	151551.87	151151.87	0	0	0
CF	104400	104400	0	0	0
Overall	444063.9	444063.9	0	0	0
MG	470533.9	292512	0	0	0

4.3. Sensitivity Analysis

In this section, the sensitivity of net revenue for industrial factories, the energy purchase prices and product sale revenues is analyzed for both CS1 and CS2. The sensitivity of the MG's net revenue to the change of energy purchase prices from -40% to 40% is shown in Figure 12. In figure 12, CS1 does not show considerable sensitivity to the change in the energy purchase price for it does not have any contribution towards DR programs. The slight sensitivity experienced is due to the existence of WF's which sell electricity to the network. However, as the CS2 network revenue increases as the energy purchase price. The sensitivity of the industrial factories' revenues to energy purchase prices is indicated in Figure 13. As previously mentioned, CS1 presents no sensitivity to energy price changes. However in CS2, cement and steel factories show more sensitivity to price changes as compared to AF's. The sensitivity of the MG's revenue to product sale, as illustrated in Figure 14, shows that CS1 has more sensitivity due to its direct dependency on product sales. Whereas in CS2, both the product sale and energy purchase price affect the net revenue.

Furthermore, Figure 15 depicts the sensitivity of industrial revenue to the product sale. Among the three factories, AF shows more sensitivity towards the change because of less flexibility in reducing the products and the implementation of spinning reserves to maintain revenues.

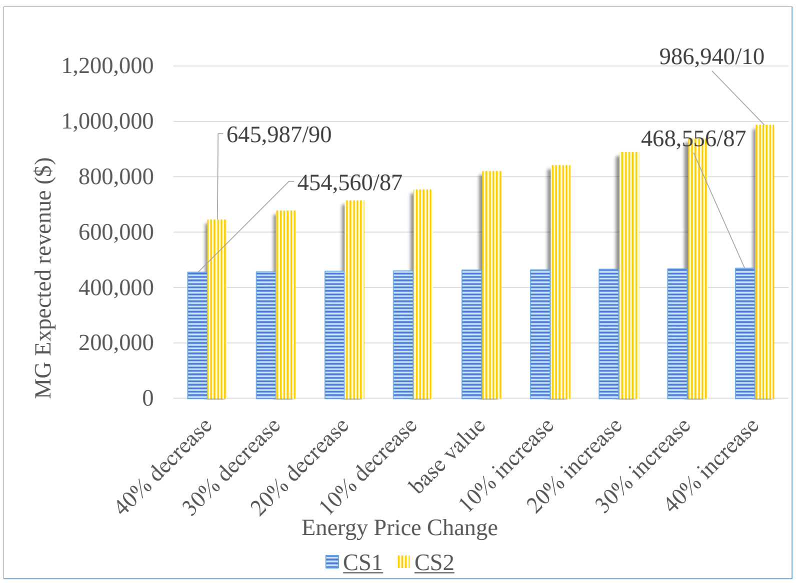

Figure 12: Sensitivity analysis of expected revenue of MG to energy purchase price change

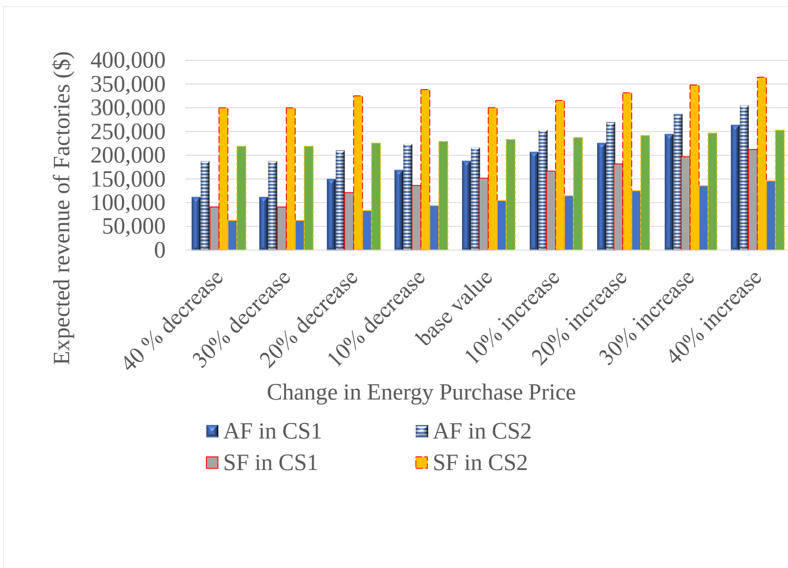

Figure 13: Sensitivity analysis of expected revenue of industrial factories to energy purchase price change

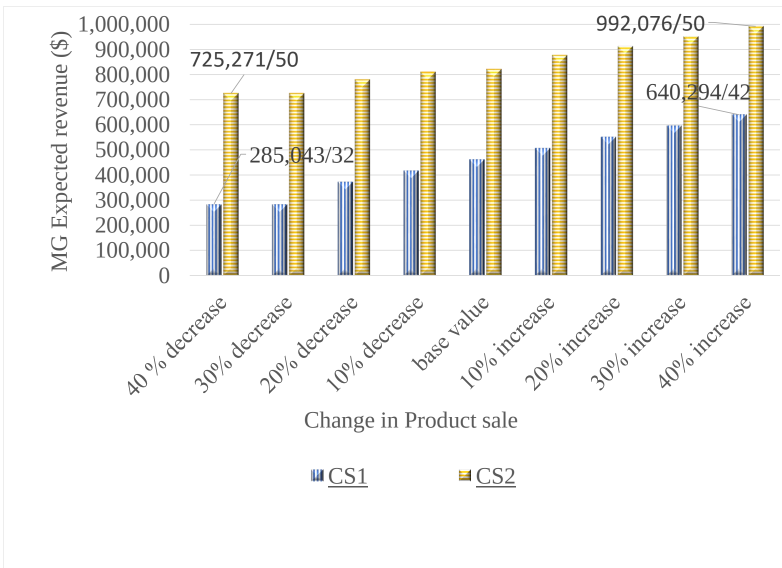

Figure 14: Sensitivity analysis of MG expected revenue to product Sale

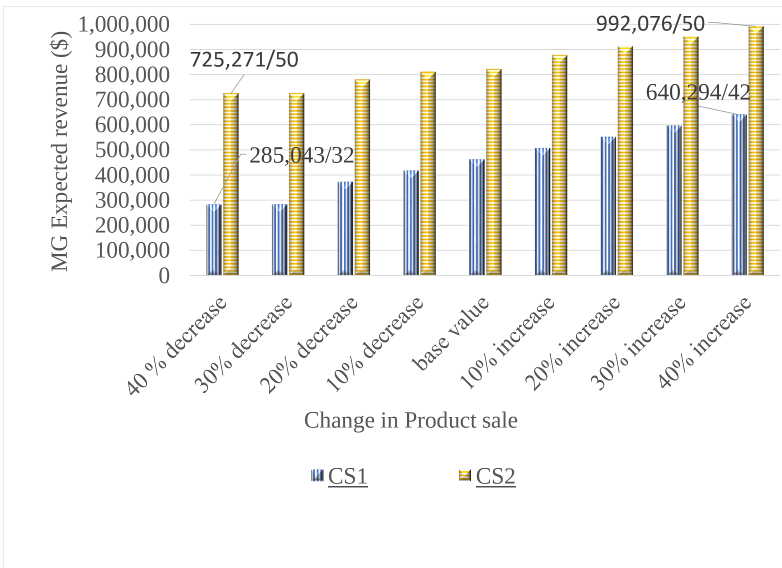

Figure 15: sensitivity analysis of industrial factories expected revenue to Product Sale

It should be mentioned that the production and energy costs have been taken into account. Therefore, the results presented in tables 4, 5 and 7 is the net revenue obtained from selling the manufactured products from the different industrial factories.

Table 10: Expected daily revenue of MG and Industrial factories in CS2

	Overall revenue ($)	Product Sale revenue ($)	DR revenue ($)	Provided Power to the grid (MW)	Provided Spinning Reserve (MW)
AF	216326	148560	67766	480	720
SF	352710	145200	207510	2340	540
CF	233203.5	40800	192403.5	2145	135
Overall	802239.5	334560	391484.5	4965	1395
MG	828709.5	334560	467679.5	4965	1395

Table 11: Expected revenue of MG and industrial factories in CS3

	Overall revenue ($)	Product Sale revenue ($)	DR revenue ($)	Provided Power to the grid (MW)	Provided Spinning Reserve (MW)
AF	210866	116940	93926	1005	195
SF	352710	145200	207410	2340	540
CF	233203.5	40800	192403.5	2145	135
Overall	796779.5	302940	493839.5	5490	870
MG	815384.5	302940	493839.5	5490	870

Table 12: Expected revenue of MG and industrial factories in Cooperation Mode in CS3

	Overall revenue ($)	Product Sale revenue ($)	DR revenue ($)	Provided Power to the upstream grid (MW)	Provided Spinning Reserve (MW)
AF	211306	125520	85786	840	360
SF	352710	145200	207510	2340	540
CF	233203.5	40800	192403.5	2145	135
Overall	802239.5	334560	391484.5	5325	1035
MG	815824.5	311520	485699.5	5325	1035

5. Conclusion

In this paper, a complete model of the day ahead energy management of an industrial MG including aluminium, steel and cement factories, with a high energy consumption using LPWA has been presented. In order to make this study more pragmatic, the MG included a number of uncontrollable processes and industrial loads. The aim of the proposed model is to increase the efficiency of the industrial factories using DR programs and to give an opportunity to the aforementioned industries to participate in the energy and ancillary service markets. In order to assess and demonstrate the positive impact the model has on the factories, three cases were studied and analyzed with and without DR programs. Implementing DR programs depicts a 17.75% decrease in the MG overall load and 31.67% decrease in its peak load. In addition, the revenue obtained from the MG increased by 41.32%. In addition, the sensitivity of the industrial factories to the change in the energy purchase price, and the product sales has also been assessed. It has been highlighted that by using DR programs, the revenue sensitivity of the MG to the energy purchase price increases. Furthermore, it is evident that DR program implementation causes a decrease in the overall revenue sensitivity to the product sales. It has also been noted that the AF shows a high revenue sensitivity to product sales in both cases. Overall, the implementation of DR programs and the participation of industrial factories in the energy and ancillary services markets improve the demand curve, while concurrently increasing the revenue of the MG and industrial factories.

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