

A Comprehensive Review of Demand-Side Management Based on Analysis of Productivity: Techniques and Applications

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Abstract: Demand-side management (DSM) includes various persuasive measures to improve the use of energy; thus, it has been studied from various perspectives in the literature. Nowadays, the context of productivity has an important role in the evaluation of the electrical energy systems. Accordingly, this paper presents a platform to comprehensively contemplate the DSM from the productivity perspective that features its three aspects. First, the widespread indices of DSM are manifestly redefined, and a plenary index of DSM is introduced, reflecting both energy and investment productivity. Second, the modification of energy efficacy and consumption pattern is discussed, considering a general categorization of DSM modalities based on the pertaining index of each branch. Third, a modified model of demand response (DR) is developed to implement seven DR strategies in the smart microgrids. The simulation results demonstrate that the load factor can improve up to 8.12% with respect to the normal consumption pattern. Moreover, the load factor can be further enhanced at least by 4.22% in comparison with the customary model.

Keywords: demand response; demand-side management; load curve analysis; energy productivity; smart microgrid



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1. Introduction

1.1. A Glimpse into Demand-Side Management (DSM)

DSM is mainly known as an energy-management technique that is employed to improve the consumption pattern of customers in the electrical energy systems [1]. From the energy-system point of view, the DSM can be defined as the implementation of appropriate managerial measures to influence the load-demand characteristics that make the resources on the demand side. Although the DSM refers to various persuasive measures on the demand side, the desirable modification of the load-demand characteristics via DSM improves the energy expenditure from input to consumption that causes the low carbon transition, improvement of the investment productivity, cost reductions, and a greater flexibility for the end-use consumers [2,3]. The resources caused by the DSM programs can be integrated into energy-resource-allocation frameworks or applied for regulating the investment productivity. Accordingly, the concept of DSM implies a correlation between the supply side and demand side that brings about interactive avail [4]. Moreover, the DSM is a key aspect in a smarter energy future to make accurate control over energy service, as well as affordable power utilization. The smart grids facilitate the designing and implementation of the distributed DSM schemes [5,6]. The implementation of DSM in smart grids provides a type of standing reserve that can improve the system's operation via the adjustment of renewable resources' dispatch [7]. The advantages of DSM are enumerated in Table 1.

Table 1. Capabilities and advantages of DSM implementation.

Capability of DSM	Advantage/Importance	Reference(s)
DSM can provide dispatchable loads	Enhancement of demand flexibility	[2,8–10]
DSM influences the operation issues	Enhancement of operational flexibility for the system	[11–14]
DSM can improve the energy resources utilization	Energy-productivity enhancement	[15,16]
DSM can improve the energy-system-asset utilization	Asset-productivity enhancement	[17]
DSM can reduce required generation capacity at peak load periods	Reduction of the generation margin	[18–20]
DSM can lower the exploiting of energy sources	Mitigation in emissions of environmental pollutants	[21–24]
DSM can thriftily provide reserve requirements	Sustainment of energy services	[25]
DSM can mitigate intermittency problem due to renewable energies	Attainment of demand–supply balance	[26–28]
DSM can affect optimal size and control of energy-storage systems	Investment productivity improvement	[29,30]
DSM can improve demand matching	Efficacious energy management	[31–33]
DSM can be coordinated with power quality issues	Integrated techno-economical frameworks	[34]
DSM can facilitate demand-side integration in smart grids	Competitive-markets implementation	[35–37]
DSM can reflect the actual energy price toward end-use customers	Dynamic-pricing implementation	[38,39]
DSM can sustain the corrective actions vs. preventive control	Security-framework improvement	[40–42]
DSM can lower the congestion in the transmission system	Improvement of planning expansion of transmission grids	[43]

1.2. DSM Strategies

Mainly, the DSM includes many diversified strategies [44–46]. The overall demand reductions, along with demand response (DR), were expressed as two general strategies of DSM in Reference [47]. The strategies of DSM are adopted according to the size of electricity grid and energy consumption, technological infrastructure, circumstance of interaction between implementer and participants, deregulation characteristics, and the potential of different load-demand types. The use of efficient appliances and lights, commercial load scheduling, restricting residential appliance use, price incentives, and tariff structure, as well as community involvement, consumer education, and local committees for the mini-grids, was enumerated in Reference [48] as the applicable strategy of DSM. In the active distribution grids, energy efficiency, orderly power utilization, and DR are the primary strategies [49]. In the widespread classification of the DR, time-based (price-based) programs and incentive-based programs are two general categories [50,51]. The time-based programs are based on price-driven strategies. The price-driven DR was studied in Reference [52], where the electricity price signals were used to influence the customers' energy consumption pattern. The effects of price-based and incentive-based DR strategies on the operational cost reduction of a microgrid were scrutinized in Reference [53]. The load-shifting mechanism as a type of orderly power-utilization strategy was focused on in the design of a trilevel energy market model in Reference [54] that was implemented via a time-of-use (TOU) pricing scheme.

1.3. Role of DSM in Energy Management

Practically, the DSM is a main constituent of energy-management frameworks in the smart grids. A game theoretic DSM model for distributed energy management was proposed in Reference [55] to incorporate the energy-storage components while taking into account the supply constraints in the form of power outages that employ emerging blockchain technologies. An optimization model of energy scheduling was suggested in Reference [15] for the microgrids, including responsive loads that adopts the TOU and real-time pricing (RTP) strategies. The application of solitary TOU tariffs has been found to be suitable for long-term modification of the load curve [56]. The solitary RTP strategy was implemented in Reference [57], underlying a Stackelberg-game approach. The RTP strategy for peak load shaving was adopted in Reference [58], such that the reduced load demand can diminish the spinning reserve required for dealing with the uncertainties of renewable resources during the peak load periods, whereas more renewable power outputs can be allocated to the increased load demand during the off-peak load periods. The dynamic pricing strategy in price-based DR is significantly efficient in the smart grids [37–39]. A model for optimal scheduling of microgrids was proposed in Reference [59], where an incentive-based DR strategy was pursued by considering the load, price, and

renewable-energy uncertainties. The concept of online DSM was studied in Reference [60]; it considers an internal RTP strategy of a microgrid by using a combination of supply–demand mismatch power and inclining block rate mechanism to optimize the load profile. The interruptible/curtailable strategy was used in Reference [61] for optimal market-based microgrid operation. The different DSM programs may be implemented simultaneously. An energy-management framework for optimal operation of grid-connected microgrids was developed by Reference [62] that pursues the flexible load-shaping DSM strategy, as well as price-based and incentive-based DR strategies in the presence of non-dispatchable energy resources.

1.4. Motivation, Needs, and Aims

There are several noticeable review papers in the DSM arena. Some of the papers have focused on the flexibility. The electricity grid flexibility solutions for the insular scope via DSM and storage were discussed in Reference [63]. The power flexibility and joint power-heat flexibility potentials in energy-intensive industries were investigated in Reference [64], considering DR programs. Two important features of the existing review papers are the DSM methods' classification and the scope of discussion. A comparison of the present work and some previous reviews is presented in Table 2.

Table 2. Comparison of present work and some previous reviews in the DSM arena.

Paper	Scope/Significant Issue	DSM Categorization	
[65]	- DSM policies, - Implementers, - Implementation strategies.	1.	Demand-side response (including price-based and incentive-payment-based methods),
		2.	Energy-efficiency issue (including energy-efficiency improvement and energy conservation),
		3.	On-site backup involving generation and storage.
[66]	- Main concepts and general subjects from energy-management point of view, - Revised phrases and practical methods through a reconsidered theoretical framework of DSM.	1.	Static DSM (including energy-consumption management, reliability-based load management, and strategic load management),
		2.	Dynamic DSM (including energy-efficiency management, orderly power utilization, and DR).
[67]	The effect of DSM on the power system from four general viewpoints: - Power market, - Three hierarchical level-based reliability, - Environmental issues, - Power system operation (including power system flexibility, transmission congestion, stability, preventive maintenance, facility upgrade, and coordination with renewable energy resources).	1.	DR (including market-based and reliability-based methods),
		2.	Energy efficiency,
		3.	Strategic load growth.
[68]	Assessment of different categories of DR potential, including theoretical, technical, economical, and general achievable potentials.	1.	DR (including price-based and incentive-based methods),
		2.	Energy-efficiency measures.
[69]	Ongoing strategies in the area of the active building of energy-management systems, considering the necessity of the following: - Involvement of energy-consumption prediction models, - Consideration of modern loads, such as electric vehicles, - Employment of real data and methodologies, taking into account all subsystems.	1.	DR,
		2.	Energy efficiency.
This work	- Reconsideration of DSM contexts from the productivity perspective, - Innovation of a general DSM index, - Developing of a modified DR.	1.	Energy-efficiency enhancement,
		2.	Energy-consumption reduction,
		3.	Demand matching,
		4.	Load-profile improvement.

Since the productivity is considered as a fundamental pillar for the evaluation of energy systems, the energy productivity and the pertaining monetary contexts are crucial themes in the DSM [70,71]. Accordingly, this paper tends toward reconsideration of DSM contexts from the productivity perspective. This issue requires the development of a general index for the DSM index by considering the energy efficiencies, the asset productivity, and the investment thrift in the electrical energy system to analyze and model the DSM modalities. Since the most important modality of DSM in the smart grids is DR, a modified DR model is presented so that value of the developed general index for DSM can be enhanced due to the rational payment criteria embedded in the model that determines the incentives and penalties by considering the real-time reaction of the customers regarding electrical energy consumption.

2. DSM Indices

Several indices for DSM have been proposed in the literature. The load factor, peak-to-valley distance, and reduced energy consumption were used in Reference [62]. Moreover, the peak load reduction, peak-to-average ratio, and the energy cost were enumerated in Reference [72].

In order to facilitate the DSM analysis, the DSM indices need to be perspicuously organized. The precise definitions are presented in this section, and a general index is introduced for DSM analysis from the energy-management point of view, called the ‘DSM index’. Moreover, an illustrative implementation is accomplished by which the values of the indices are calculated.

2.1. Demand Factor

The demand factor is defined as the peak load demand divided by the average supplyable electrical power during a specified time span, and it can be formulated as follows:

$$DF \triangleq \frac{P_{\text{peak}}^{(t_i \sim t_f)}}{\frac{1}{t_f - t_i} \int_{t_i}^{t_f} p_G(t) dt}. \quad (1)$$

From the energy-management perspective, the demand factor can be construed as the maximum required energy resource capacity divided by the available energy resource capacity during the time span, and it can be reformulated as follows:

$$DF \triangleq \frac{P_{\text{peak}}^{(t_i \sim t_f)} \times (t_f - t_i)}{E_G}. \quad (2)$$

If the available energy resource capacity is assumed to be constant during the time span, according to Equation (3), the length of time will be ineffectual and the demand factor can be regarded as the peak load demand divided by the maximum supplyable electrical power:

$$DF = \frac{P_{\text{peak}}^{(t_i \sim t_f)} \times (t_f - t_i)}{P_G^{(\text{max})} \times (t_f - t_i)} = \frac{P_{\text{peak}}^{(t_i \sim t_f)}}{P_G^{(\text{max})}}. \quad (3)$$

Theoretically, the value of this index is a real number between zero and one.

2.2. Utilization Factor

The utilization factor is defined as the average supplied electrical power divided by the peak load demand during a specified time span, and it can be formulated as follows:

$$\gamma_{\text{utilization}} \triangleq \frac{\frac{1}{t_f - t_i} \int_{t_i}^{t_f} p_s(t) dt}{P_{\text{peak}}^{(t_i \sim t_f)}}. \quad (4)$$

From the energy-management perspective, this index can be construed as the supplied energy divided by the maximum required energy resource capacity, and it can be reformulated as follows:

$$\gamma_{utilization} = \frac{E_s}{P_{peak}^{(t_i \sim t_f)} (t_f - t_i)}. \quad (5)$$

Theoretically, the value of this index is a positive real number.

2.3. Load Factor

The load factor is an index that is widely used for load-curve analysis [73–75]. This index is defined as the average load consumption divided by the peak load demand during a specified time span ([62]), and it can be formulated as follows:

$$LF \triangleq \frac{\frac{1}{t_f - t_i} \int_{t_i}^{t_f} p(t) dt}{P_{peak}^{(t_i \sim t_f)}}. \quad (6)$$

From the energy-management perspective, this index can be construed as the delivered energy divided by the maximum required energy resource capacity, and it is reformulated as follows ([76]):

$$LF = \frac{E_d}{P_{peak}^{(t_i \sim t_f)} (t_f - t_i)}. \quad (7)$$

Moreover, the load factor can be calculated by the following expression:

$$LF = \frac{E_s}{P_{peak}^{(t_i \sim t_f)} (t_f - t_i)} \times \frac{E_d}{E_s} = \gamma_{utilization} \times \eta_g, \quad (8)$$

where η_g is the grid efficiency. Thus, the load factor is the product of the utilization factor and the grid efficiency. Theoretically, the value of this index is a real number between zero and one. Sometimes the inverse of load factor, namely the ‘peak-to-average ratio’, is used [55].

2.4. Capacity Factor

The capacity factor is defined as the average supplied electrical power divided by the maximum suppliable electrical power during a specified time span, and it can be formulated as follows:

$$\gamma_{capacity} \triangleq \frac{\frac{1}{t_f - t_i} \int_{t_i}^{t_f} p_s(t) dt}{P_G^{(max)}}. \quad (9)$$

From the energy-management perspective, this index can be construed as the supplied energy divided by the available energy resource capacity, and it can be reformulated as follows ([76]):

$$\gamma_{capacity} = \frac{E_s}{P_G^{(max)} (t_f - t_i)}. \quad (10)$$

Theoretically, the value of this index is a real number between zero and one.

2.5. Delivery Factor

The delivery factor is defined as the delivered energy divided by the available energy resource capacity, and it is formulated as follows:

$$\gamma_{delivery} \triangleq \frac{E_d}{P_G^{(max)} (t_f - t_i)}. \quad (11)$$

Moreover, the capacity factor can be formulated as the following expression:

$$\gamma_{delivery} = \frac{E_s}{P_G^{(max)}(t_f - t_i)} \times \frac{E_d}{E_s} = \gamma_{capacity} \times \eta_g. \quad (12)$$

Thus, the delivery factor is the product of the capacity factor and the grid efficiency. Theoretically, the value of this index is a real number between zero and one. Moreover, the delivery factor can be reformulated as the following expression:

$$\gamma_{delivery} = \frac{P_{peak}^{(t_i \sim t_f)}}{P_G^{(max)}} \times \frac{E_d}{P_{peak}^{(t_i \sim t_f)}(t_f - t_i)} = DF \times LF. \quad (13)$$

Thus, the delivery factor is the product of the demand factor and the load factor. Consequently, the delivery factor can be decomposed in two ways, as follows:

$$\gamma_{delivery} = \underbrace{DF \times \gamma_{utilization}}_{\gamma_{capacity}} \times \eta_g \equiv DF \times \underbrace{\gamma_{utilization} \times \eta_g}_{LF}. \quad (14)$$

2.6. Regulation Factor

The regulation factor is defined as the demanded energy divided by the available energy resource capacity, and it can be formulated as follows:

$$\rho \triangleq \frac{E_{demand}}{P_G^{(max)}(t_f - t_i)}. \quad (15)$$

Theoretically, the value of this index is a real number between zero and one for the energy-surplus situation, whereas it will become greater than one for the energy-shortage situation. The regulation factor can be used for daily power markets. If this index is considered for a real-time state, the demanded energy can be replaced by the delivered energy.

2.7. Adequacy Coefficient

This index is a function of the regulation factor, which is defined as follows:

$$\lambda_{P_{peak}^{(t_i \sim t_f)}} \triangleq \tilde{f}_S^{(\rho)} - \tilde{f}_S^{(\rho-1)}, \quad (16)$$

where $\tilde{f}_S^{(\rho)}$ represents the Heaviside step function. Theoretically, this index takes a binary value. It is one for the energy-surplus situation, whereas it will be zero for the energy-shortage situation.

2.8. System Productivity

This index is defined as the adequacy coefficient multiplied by the delivered energy divided by the available energy resource capacity, and it can be formulated as follows:

$$SP \triangleq \frac{\lambda_{P_{peak}^{(t_i \sim t_f)}} \times E_d}{P_G^{(max)}(t_f - t_i)}. \quad (17)$$

Theoretically, the value of this index is a non-negative number less than one. Moreover, the system productivity can be reformulated as the following expression:

$$SP = \lambda_{P_{\text{peak}}(t_i \sim t_f)} \times \frac{E_d}{P_G^{(\text{max})}(t_f - t_i)} = \lambda_{P_{\text{peak}}(t_i \sim t_f)} \times \gamma_{\text{delivery}}. \quad (18)$$

Thus, the system productivity is the product of the adequacy coefficient and the delivery factor.

2.9. Energy Productivity

The arena of energy productivity applications is extremely wide [77–79]. This concept has been evaluated in different countries [80–82]. The energy productivity can be regarded as the inverse of energy intensity that determines the value of produced services for one unit of energy used [83]. In the present paper, this index is defined as the useful energy divided by the available energy resource capacity, and it can be formulated as follows:

$$EP \triangleq \frac{E_u}{P_G^{(\text{max})}(t_f - t_i)} \quad (19)$$

Theoretically, the value of this index is a real number between zero and one. The DSM index can be reformulated as the following expression:

$$EP = \frac{E_d}{P_G^{(\text{max})}(t_f - t_i)} \times \frac{E_u}{E_d} = \gamma_{\text{delivery}} \times \eta_c. \quad (20)$$

where η_c represents the consumption efficiency defined in Reference [66]. Thus, the energy productivity is the product of the delivery factor and the consumption efficiency.

2.10. DSM Index

This index is defined as the adequacy coefficient multiplied by the useful energy divided by the available energy resource capacity, and it can be formulated as follows:

$$DSMI \triangleq \frac{\lambda_{P_{\text{peak}}(t_i \sim t_f)} \times E_u}{P_G^{(\text{max})}(t_f - t_i)}. \quad (21)$$

Theoretically, this index takes a non-negative value less than one. Moreover, the DSM index can be reformulated as the following expression:

$$DSMI = \frac{\lambda_{P_{\text{peak}}(t_i \sim t_f)} \times E_d}{P_G^{(\text{max})}(t_f - t_i)} \times \frac{E_u}{E_d} = SP \times \eta_c. \quad (22)$$

Thus, the DSM index is the product of the system productivity and the consumption efficiency. Accordingly, we obtain the following:

$$DSMI = \lambda_{P_{\text{peak}}(t_i \sim t_f)} \times \underbrace{\gamma_{\text{delivery}} \times \eta_c}_{EP} = \lambda_{P_{\text{peak}}(t_i \sim t_f)} \times EP, \quad (23)$$

which means that the DSM can be evaluated by the adequacy coefficient and the energy productivity. Consequently, the DSM index can be decomposed as follows:

$$DSMI = \lambda_{P_{\text{peak}}^{(t_i \sim t_f)}} \times \underbrace{DF \times \underbrace{\gamma_{\text{utilization}}}_{\gamma_{\text{capacity}}}}_{EP} \times \eta_g \times \eta_c \equiv \lambda_{P_{\text{peak}}^{(t_i \sim t_f)}} \times \underbrace{DF \times \underbrace{\gamma_{\text{utilization}} \times \eta_g \times \eta_c}_{LF}}_{EP} \quad (24)$$

The relationship of the defined indices is illustrated in Figure 1. As a result, the general index of DSM is ‘DSM index’ (DSMI) that includes the energy and economical efficacious. The adequacy coefficient and the energy productivity are two factors that can completely exhibit the circumstance of DSM. Moreover, the latter can be decomposed to three components: the demand factor, the load factor, and the consumption efficiency. For instance, the specific load curves for end-use power consumption and supplied electrical power have been depicted in Figure 2. Also, the specific load curves for end-use power consumption and useful electrical power have been depicted in Figure 3. In this case:

$$\begin{cases} E_s = \int_0^{24} p_s(t) dt = 33935 \text{ [MWh]} \\ P_s^{(\text{max})} = 1966 \text{ [MW]} \\ P_G^{(\text{max})} = P_s^{(\text{max})} + 224 = 2190 \text{ [MW]} \end{cases} \quad \begin{cases} E_d = \int_0^{24} p(t) dt = 24239.25 \text{ [MWh]} \\ P_{\text{peak}}^{(t_i \sim t_f)} = 1404 \text{ [MW]} \\ E_u = \int_0^{24} p_u(t) dt = 19825.6 \text{ [MWh]} \end{cases} \quad (25)$$

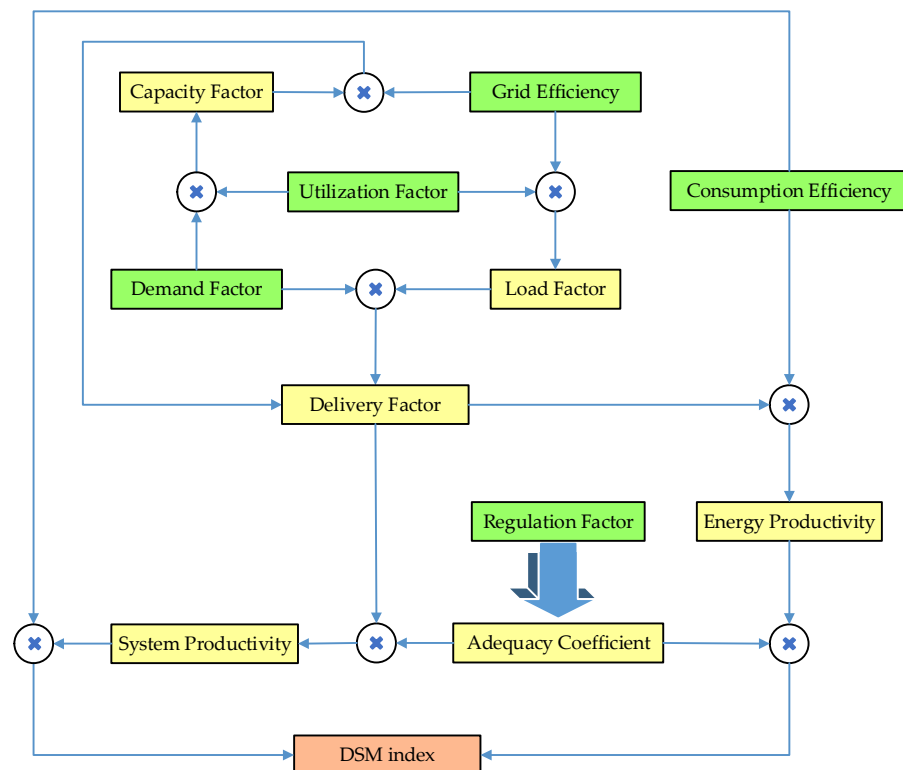


Figure 1. The relation of the different indices for DSM.

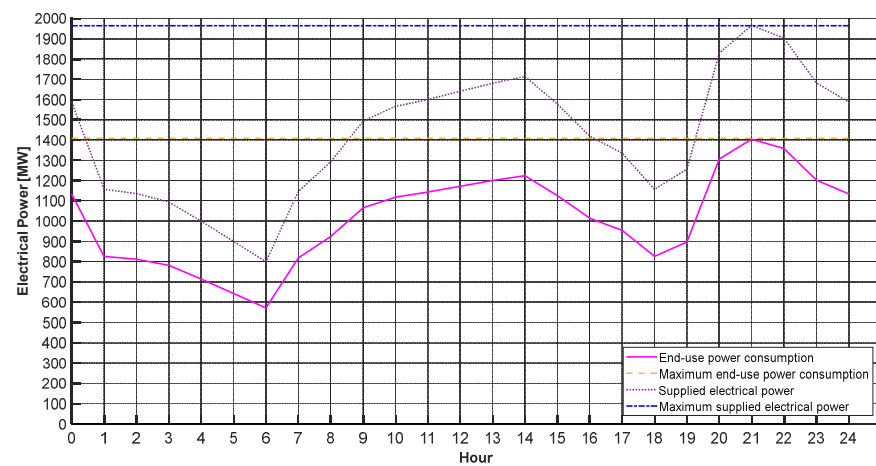


Figure 2. The specific load curves for end-use power consumption and supplied electrical power.

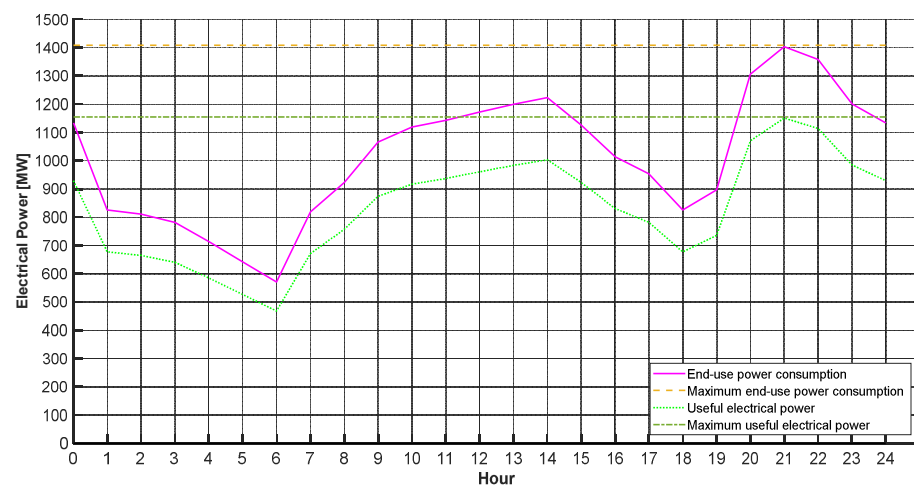


Figure 3. The specific load curves for end-use power consumption and useful electrical power.

Therefore, we have the following:

$$\begin{aligned}
 DF &= \frac{1404}{2190} = 0.64 & \gamma_{utilization} &= \frac{33935}{1404 \times 24} \simeq 1.01 \\
 LF &= \frac{24239.25}{1404 \times 24} \simeq 0.72 & \eta_g &= \frac{0.72}{1.01} \simeq 0.71 \\
 \gamma_{capacity} &= \frac{33935}{2190 \times 24} \simeq 0.65 & \gamma_{delivery} &= \frac{24239.25}{2190 \times 24} \simeq 0.46 \\
 \lambda_{(t_i \sim t_f)} &= 1 - 0 = 1 & SP &= 1 \times 0.46 = 0.46 \\
 P_{peak} &= \frac{19825.6}{2190 \times 24} \simeq 0.3772 & \eta_c &= \frac{0.3772}{0.46} \simeq 0.82 \\
 DSMI &= 1 \times 0.3772 = 0.3772
 \end{aligned} \tag{26}$$

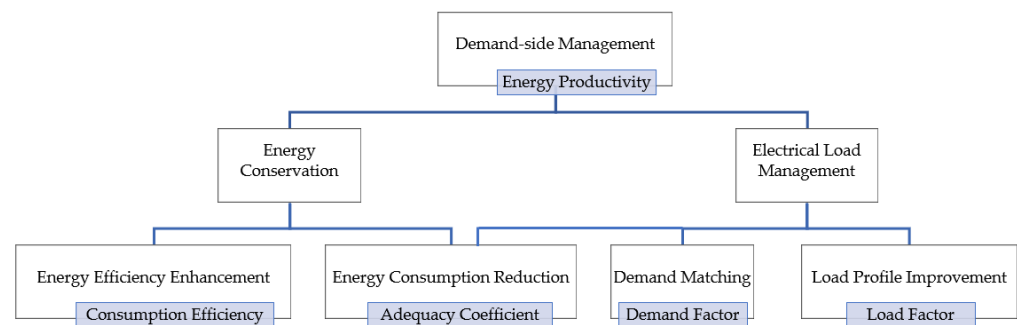
3. Classification and Analysis of DSM

Generally, the DSM can be divided into ‘energy conservation’ and ‘electrical load management’. The energy conservation involves the adequacy coefficient for analyzing the energy consumption reduction in energy-shortage situations, and the consumption efficiency for analyzing the energy-efficiency enhancement. The energy-conservation modalities are elucidated in Table 3.

Table 3. Analysis of energy-conservation techniques.

Energy-Conservation Modalities				
Context	Productivity improvement		Environmental considerations	
Objective	Energy Recovery	Energy Audit	Energy Audit	Energy Saving
Restriction	Useful energy intensification	Energy-efficiency enhancement	Terminal energy reduction	Service withdrawal
Consequence	Fixed terminal energy	Fixed useful energy	Fixed useful energy	Fixed energy efficiency
Evaluation index	Energy-loss decrease	Energy-loss decrease	Energy-loss decrease	Energy-loss decrease
	Delivery factor	Energy efficiency	Utilization factor	Regulation factor

On the other hand, the electrical load management involves the adequacy coefficient for analyzing the energy-consumption reduction when system reliability is jeopardized, the demand factor for analyzing the demand matching, and the load factor for analyzing the load profile's improvement. The general classification of DSM based on the index of each branch is shown in Figure 4.

**Figure 4.** The general classification of DSM based on the index of modality.

The branches are elucidated in the following.

3.1. Load Profile Improvement

The electrical load management involves the techniques of load-profile improvement based on the efficacious strategies for changing the consumption pattern via orderly mechanisms. The load-profile improvement is mainly evaluated via assessment of the load factor index [19,84,85]. There are several mechanisms for the electrical load management divided into three categories. First, strategic saving aims at energy-consumption reduction in a certain time span that includes peak clipping and strategic conservation mechanisms. The peak clipping improves the load profile considered for one hour, whereas strategic conservation improves the system productivity, and the effect of strategic conservation on the load curve is basically evaluated for 24 h. Second, strategic productivity aims at load-profile improvement under the same total energy consumption that involves load shifting and flexible load-shape mechanisms. Third, strategic transfusion aims at load-profile improvement via energy consumption increment and electrification that involves valley filling and strategic load-growth mechanisms.

The change of load factor is given by Equation (27):

$$\left. \begin{aligned}
 LF_{\text{old}} &= \frac{\frac{1}{t_f - t_i} \int_{t_i}^{t_f} p_{\text{old}}(t) dt}{p_{\text{peak}_{\text{old}}}} \\
 LF_{\text{new}} &= \frac{\frac{1}{t_f - t_i} \int_{t_i}^{t_f} p_{\text{new}}(t) dt}{p_{\text{peak}_{\text{new}}}}
 \end{aligned} \right\} \Rightarrow \Delta LF = LF_{\text{new}} - LF_{\text{old}} = \frac{1}{t_f - t_i} \int_{t_i}^{t_f} \left(\frac{p_{\text{new}}(t)}{p_{\text{peak}_{\text{new}}}} - \frac{p_{\text{old}}(t)}{p_{\text{peak}_{\text{old}}}} \right) dt. \quad (27)$$

In the load shifting and flexible load-shape mechanisms, the average load consumption will be unchanged. Therefore, if $P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)} < P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}$, the load factor will rise, but if $P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)} > P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}$, it will drop.

If t_1 and t_2 are two points in $[t_i, t_f]$, the change of load factor will be given by the following:

$$\Delta LF = \frac{1}{t_f - t_i} \cdot \left\{ \int_{t_i}^{t_1} \left(\frac{p_{\text{new}}(t)}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \right) dt + \int_{t_1}^{t_2} \left(\frac{p_{\text{new}}(t)}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \right) dt + \int_{t_2}^{t_f} \left(\frac{p_{\text{new}}(t)}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \right) dt \right\}. \quad (28)$$

It is assumed that the changed load curve is described as follows:

$$p_{\text{new}}(t) = \begin{cases} P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}, & t \in [t_1, t_2] \\ p_{\text{old}}(t), & t \notin [t_1, t_2] \end{cases}. \quad (29)$$

Hence, the change of load factor can be obtained as follows:

$$\Delta LF = \frac{1}{t_f - t_i} \left\{ \left(\frac{1}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{1}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \right) \left(\int_{t_i}^{t_1} p_{\text{old}}(t) dt + \int_{t_2}^{t_f} p_{\text{old}}(t) dt \right) + \frac{1}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \int_{t_1}^{t_2} \left(P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} - p_{\text{old}}(t) \right) dt \right\}. \quad (30)$$

This shows that if $P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)} < P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}$, the change-of-load factor will be positive. This means the following:

- If the local peak clipping occurs in the peak load periods, the load factor will improve,
- If the load consumption is added in off-peak load periods but does not exceed from the old peak, the load factor will improve.

Moreover, considering the linear piecewise load curve that reflects the average load consumption for each hour, it can be concluded that if the load consumption is added in all periods and exceeds from the old peak, the load factor will diminish.

Now, it is assumed that the changed load curve is described follows:

$$p_{\text{new}}(t) = \begin{cases} P_{\text{flat}_{\text{new}}}^{(t_i \sim t_f)}, & t \in [t_1, t_2] \\ p_{\text{old}}(t), & t \notin [t_1, t_2] \end{cases}. \quad (31)$$

Hence, the change of load factor can be obtained as follows:

$$\Delta LF = \frac{1}{t_f - t_i} \left\{ \left(\frac{1}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{1}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \right) \left(\int_{t_i}^{t_1} p_{\text{old}}(t) dt + \int_{t_2}^{t_f} p_{\text{old}}(t) dt \right) + \int_{t_1}^{t_2} \left(\frac{P_{\text{flat}_{\text{new}}}^{(t_i \sim t_f)}}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \right) dt \right\}. \quad (32)$$

This shows that if $P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)} = P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}$, the change of load factor will become negative. This is because of the following:

$$\Delta LF = \frac{1}{t_f - t_i} \times \frac{1}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} \int_{t_1}^{t_2} \left(P_{\text{flat}_{\text{new}}}^{(t_i \sim t_f)} - p_{\text{old}}(t) \right) dt < 0. \quad (33)$$

This means that if the load-consumption reduction occurs in the off-peak load periods, the load factor will diminish.

Considering the stepwise function approximation of the load curve, the following procedure is applicable:

$$\begin{aligned}
 LF_k &\triangleq \frac{\frac{1}{t_{f_k} - t_{i_k}} \int_{t_{i_k}}^{t_{f_k}} p(t) dt}{P_{\text{peak}}^{(t_{i_k} \sim t_{f_k})}} \Rightarrow \int_{t_{i_k}}^{t_{f_k}} p(t) dt = (t_{f_k} - t_{i_k}) \times P_{\text{peak}}^{(t_{i_k} \sim t_{f_k})} \times LF_k \\
 &\Rightarrow \sum_k \int_{t_{i_k}}^{t_{f_k}} p(t) dt = \sum_k \left[(t_{f_k} - t_{i_k}) \times P_{\text{peak}}^{(t_{i_k} \sim t_{f_k})} \times LF_k \right] \\
 &\Rightarrow \int_0^T p(t) dt = \sum_k \left[(t_{f_k} - t_{i_k}) \times P_{\text{peak}}^{(t_{i_k} \sim t_{f_k})} \times LF_k \right] \\
 &\Rightarrow T \times P_{\text{peak}}^{(0 \sim T)} \times LF_{\text{total}} = \sum_k \left[(t_{f_k} - t_{i_k}) \times P_{\text{peak}}^{(t_{i_k} \sim t_{f_k})} \times LF_k \right].
 \end{aligned} \tag{34}$$

It shows that, if the load consumption reduction occurs in the off-peak load periods, the load factor will diminish; this is because the right-hand side is reduced.

From the above expressions, it can be concluded that the load-demand reduction in peak load hours and the limited load-consumption increase in off-peak load periods are desirable in the load-management techniques.

Now, it is assumed that the changed load curve is described as follows:

$$p_{\text{new}}(t) = p_{\text{old}}(t) + P_d. \tag{35}$$

where P_d is a real number. It results in the following:

$$\frac{p_{\text{new}}(t)}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} = \frac{p_{\text{old}}(t) + P_d}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} + P_d} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} = \frac{P_d \left(P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} - p_{\text{old}}(t) \right)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} \times \left(P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} + P_d \right)}. \tag{36}$$

Considering Equation (27), if $P_d > 0$, the load factor will improve, and if $P_d < 0$, the load factor will diminish. In other words, the strategic load growth will correct the load curve, whereas the strategic conservation will deteriorate the load factor. Therefore, the effect of strategic conservation needs to be captured by a different index called adequacy coefficient that is described afterward. It is worth mentioning that the changed load curve is described as follows:

$$p_{\text{new}}(t) = k \cdot p_{\text{old}}(t) + P_d, \tag{37}$$

where k is a positive real number. Moreover, the same result will be obtained because of the following:

$$\frac{p_{\text{new}}(t)}{P_{\text{peak}_{\text{new}}}^{(t_i \sim t_f)}} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} = \frac{k \cdot p_{\text{old}}(t) + P_d}{k \cdot P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} + P_d} - \frac{p_{\text{old}}(t)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)}} = \frac{P_d \left(P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} - p_{\text{old}}(t) \right)}{P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} \times \left(k \cdot P_{\text{peak}_{\text{old}}}^{(t_i \sim t_f)} + P_d \right)}. \tag{38}$$

3.2. Demand Matching

The demand matching refers to the coordination of the required energy resource to satisfy the load demand and the available energy resources. The demand factor is a suitable index for demand matching. In order to show the role of demand matching, two cases are supposed to have the same corrected load curve, as depicted in Figure 5. Thus, the load factors of the two cases are equal. If the strategic conservation is not required for both cases (i.e., the adequacy coefficient is equal to one and the peak load demand does not exceed from the available energy resource capacity for both cases), the load management is more effective for that case in which the available energy resource is less than the other. In other words, although the load factors are equal, the demand factor of case 2 is better according to

(2). Hence, the effective load management supplementally needs to a load growth strategy in the case 1 to match the load demand with the available energy resource capacity.

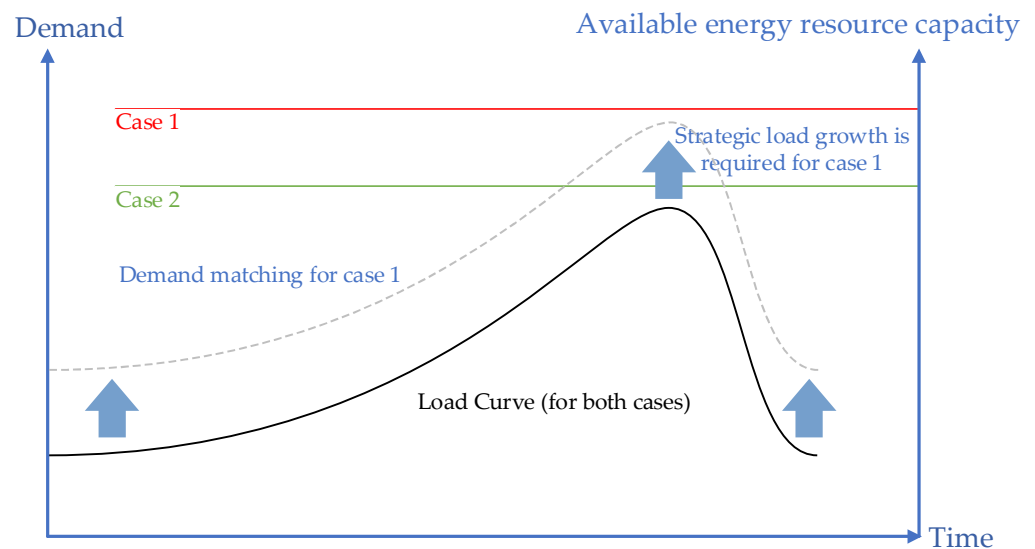


Figure 5. The demand-matching concept.

3.3. Energy-Consumption Reduction

The energy-consumption reduction includes the decrease of terminal energy of end-use customers, as well as strategic conservation. Mostly, the decrease of terminal energy is a result of energy audit modality [86–88]. Therefore, the consumption efficiency improves and the energy productivity is enhanced according to Equation (24). On the other hand, from the load-management viewpoint, if the energy shortage occurs, the strategic conservation will be required. In such conditions (shown in Figure 6), the adequacy coefficient is equal to zero because the value of the regulation factor is greater than one; thus, the DSMI is equal to zero. Although strategic conservation deteriorates the load factor, this action is required so that the actual energy productivity can be improved.

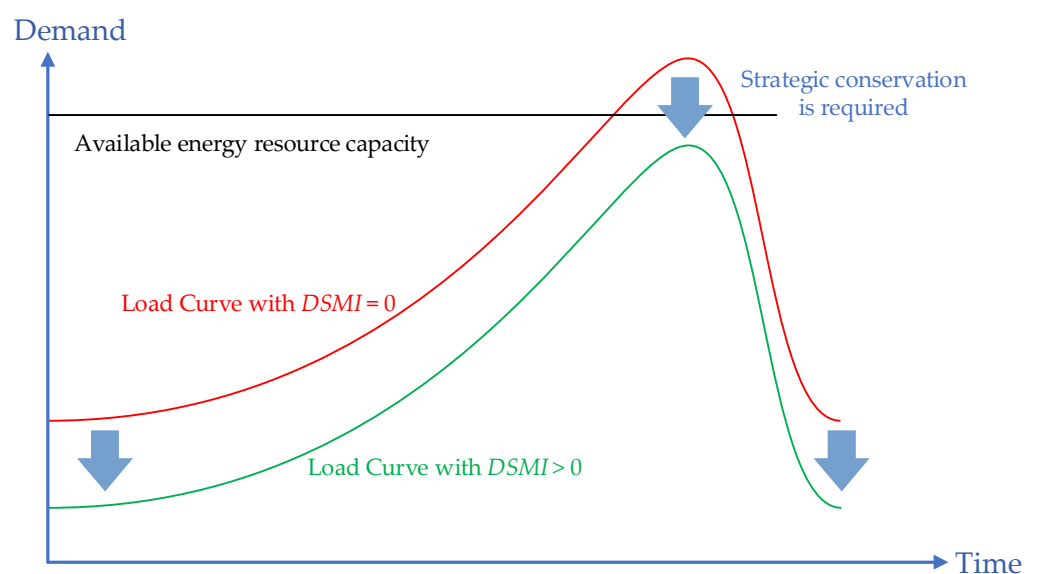


Figure 6. Role of adequacy coefficient in reflection of strategic-conservation necessity in DSM index.

3.4. Energy-Efficiency Enhancement

The energy-efficiency enhancement correlates with the economic issues and environmental concerns [89]. The energy-efficiency investments should be scrutinized to estimate the success of pertaining DSM programs that aim toward electricity-efficiency enhancement [90]. The enhancement of consumption efficiency is feasible via the energy recovery (see Reference [80], for example) and the energy audit (see References [91,92], for example). The efficiency indicators for urban energy systems, including thermodynamic indicators, physical indicators, physical–thermodynamic indicators, economic–thermodynamic indicators, and economic indicators, were used in Reference [93].

4. Comprehensive Model of DR

The DR is the most important modality of electrical load management. Generally, the energy balance of the smart grids can be achieved by implementation of DR. The investigations in the DR arena lack the extensive model by which the prevalent methods can be described distinctly. Moreover, the previous models have mostly focused on the reduction of energy consumption in different time periods, whereas the smart grids provide a useful groundwork to pay attention to energy efficiency from the operator’s point of view, even in short-term and medium-term time horizons. One of the neglected concepts is the load augment in off-peak load periods to improve the energy efficiency of the power system. This section develops an analytic framework for elucidating the load augment in the prevalent DR strategies. To attain this goal, a comprehensive mathematical model for DR is presented considering the different coefficients that specify a prevalent method and the mutual effect of load and the motivational factors. The most common strategies, including seven DR strategies, are simulated in the short-term time horizon. Then the effect of the electrification is investigated in the seasonal load profile. The simulation results demonstrate the improvement of smart grid operation by electrification.

The classic economic model of elastic loads was organized in References [94–96]. The weighting coefficient that was used in Reference [97] was embedded into the DR model to take into account the customers’ reaction in response to the implementation of price-based and incentive-based DR programs. The nonlinear DR models were formulated in Reference [98] based on the concept of the classic economic model of elastic loads. A modified inclusive DR model was developed in Reference [34] that uses six distinctive contexts (i.e., incentive coefficient, penalty coefficient, upfront reservation payment, threefold frame, dynamic pricing, and artificial peak) to form seven DR methods (i.e., time of use, critical peak pricing, real-time pricing, technological direct load control, voluntary response program, capacity market, and contractual indirect load control).

In this section, it is assumed that the load consumption changes from the initial quantity on the basis of the energy requirements, as well as customers’ eventual reaction to the conditions considered in the individual DR contracts:

$$\Delta d_t = d_t - d_t^{(0)}. \quad (39)$$

Equation (39) states that the load demand change for the specified time period is equal to the difference between the real-time load demand and the initial load demand value at that time period.

Although the reactions are impressed by the electricity prices, the quantity of demand can be considered as an independent variable in derivation [94,95,98]. Thus, the change of the electricity price for single-period analysis can be formulated as follows:

$$\Delta \rho_t(d_t) = \rho_t(d_t) - \rho_t^{(0)}. \quad (40)$$

Equation (40) states that the electricity price change for the specified time period is equal to the difference between the real-time electricity price and initial electricity price at that time period. For multi-period analysis, the electricity price change for a specified time

period is regarded as a function of all time periods. The relation between load demand and electricity price is given by $\frac{\rho_{\tau}^{(0)}}{\varepsilon_{t,\tau} d_t^{(0)}} = \frac{\partial \rho_{\tau}}{\partial d_t}$, inclusively [98].

The analysis involves two distinct time periods on the basis of the normal consumption pattern. In order to distinguish the peak load periods and the off-peak load periods, a distinction factor is defined as follows:

$$\gamma_t \triangleq \begin{cases} 1, & t : \text{peak} \\ 0, & t : \text{off-peak} \end{cases} \quad (41)$$

For each type of time period, two payments are assigned: payment for change (PFC) and payment for deviation (PFD). The PFC can be an incentive or penalty, but the PFD is always in the form of a penalty. The calculations of these payments are performed on the basis of the new state of the load demand. For each type of time period, three bands are determined: compensative, permissive, and forbidden bands:

- In the permissive band, an incentive is assigned for efficacious change of load demand (curtailment of load demand for peak load periods and augment of load demand for off-peak load periods). Moreover, a penalty is assigned on based on the value of breach.
- In the compensative band, a fixed incentive was assigned for the efficacious change of load demand (curtailment of load demand for peak load periods and augment of load demand for off-peak load periods). Moreover, a fixed out-of-domain penalty was assigned based on the value of the specified contracted level.
- In the forbidden band, three penalties were determined. The first penalty was assigned to an inappropriate change of load demand (curtailment of load demand for off-peak load periods and augment of load demand for peak load periods). The second penalty was based on the value of breach. The third penalty was assigned to the forbidden load consumption state.

Afterward, the payments for the peak load periods and the off-peak load periods were elucidated.

4.1. Payment for Peak Load Periods

The functions of penalties and incentives for peak load periods were determined and are presented in Figure 7.

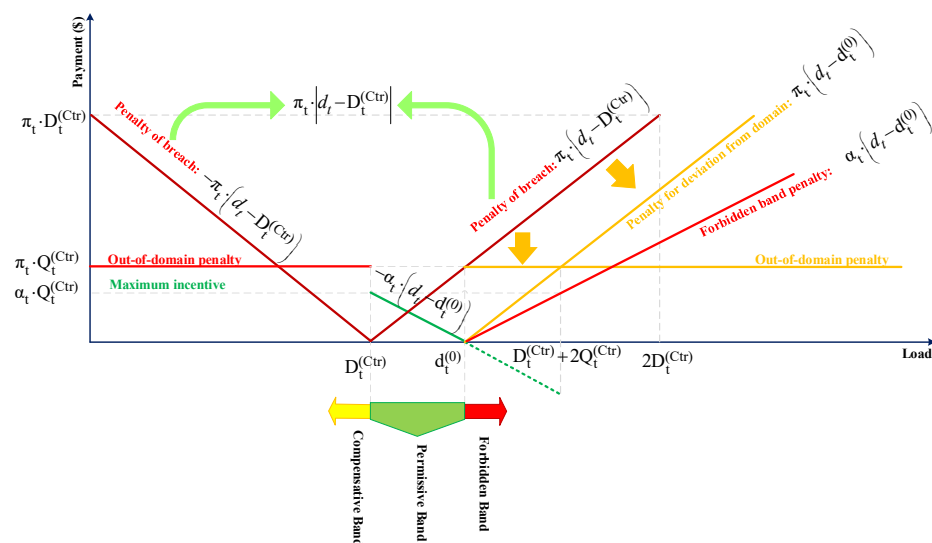


Figure 7. Functions of penalties and incentives for a typical peak load period.

The PFC is calculated as follows:

$$PFC_t(d_t) = \alpha_t \left(Q_t^{(Ctr)} \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})} - \tilde{f}_R^{(d_t - D_t^{(Ctr)})} \right), \quad (42)$$

where $\tilde{f}_R^{(d_t)}$ represents the unit ramp function. The PFD is calculated as follows:

$$PFD_t(d_t) = -pen_t(d_t) = -\pi_t \left[Q_t^{(Ctr)} - (d_t - D_t^{(Ctr)}) + 2\tilde{f}_R^{(d_t - D_t^{(Ctr)})} - Q_t^{(Ctr)} \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})} \right] - \alpha_t \cdot \tilde{f}_R^{(d_t - d_t^{(0)})}. \quad (43)$$

As Figure 7 shows, the penalty of breach can be further categorized as out-of-domain penalty and the penalty for deviation from domain. Thus, the total payment is obtained as follows:

$$TP_t(d_t) = \pi_t (d_t - D_t^{(Ctr)}) - (\alpha_t + 2\pi_t) \cdot \tilde{f}_R^{(d_t - D_t^{(Ctr)})} + (\alpha_t + \pi_t) \cdot Q_t^{(Ctr)} \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})} - \alpha_t \cdot \tilde{f}_R^{(d_t - d_t^{(0)})} - \pi_t Q_t^{(Ctr)}. \quad (44)$$

The quantity of payment rates (incentives or penalties) can be derived from the difference between the microgrid profit before implementing the DR program and its primary projected benefit [99]. The optimal values of the parameters determined in the contracts can be obtained by the approach suggested by Reference [100].

4.2. Payment for off-Peak Load Periods

The functions of penalties and incentives for the off-peak load periods were determined and are presented in Figure 8.

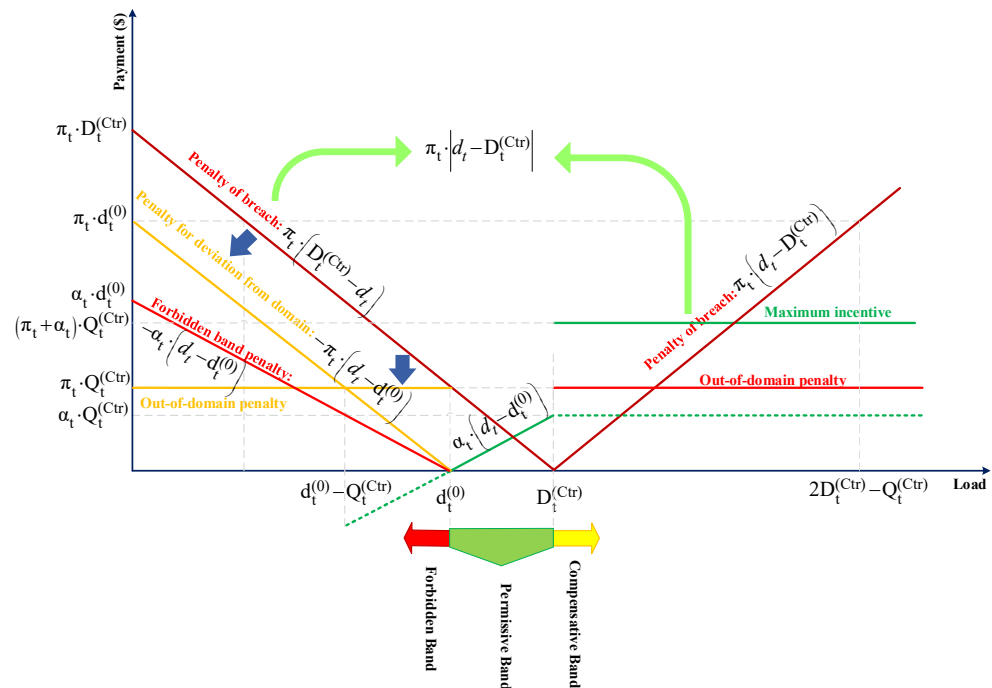


Figure 8. Functions of penalties and incentives for a typical off-peak load period.

The PFC is calculated as follows:

$$PFC_t(d_t) = \alpha_t \left(\Delta d_t - \tilde{f}_R^{(d_t - D_t^{(Ctr)})} \right) + \pi_t \cdot Q_t^{(Ctr)} \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})}. \quad (45)$$

Moreover, the PFD is calculated as follows:

$$PFD_t(d_t) = -pen_t(d_t) = -\pi_t \left[- (d_t - D_t^{(Ctr)}) + 2\tilde{f}_R^{(d_t - D_t^{(Ctr)})} + Q_t^{(Ctr)} \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})} \right] + \alpha_t \left(\Delta d_t - \tilde{f}_R^{(d_t - d_t^{(0)})} \right). \quad (46)$$

As Figure 8 shows, for forbidden band the penalty of breach can be decomposed into the out-of-domain penalty and the penalty for deviation from domain. Thus, the total payment is obtained as follows:

$$TP_t(d_t) = \pi_t \left[\left(d_t - D_t^{(Ctr)} \right) - 2\tilde{f}_R^{(d_t - D_t^{(Ctr)})} \right] + \alpha_t \left[2\Delta d_t - \tilde{f}_R^{(d_t - D_t^{(Ctr)})} - \tilde{f}_R^{(d_t - d_t^{(0)})} \right]. \quad (47)$$

4.3. Individual Payments for Each Band

Figure 9 shows the characteristic of individual payments for each band.

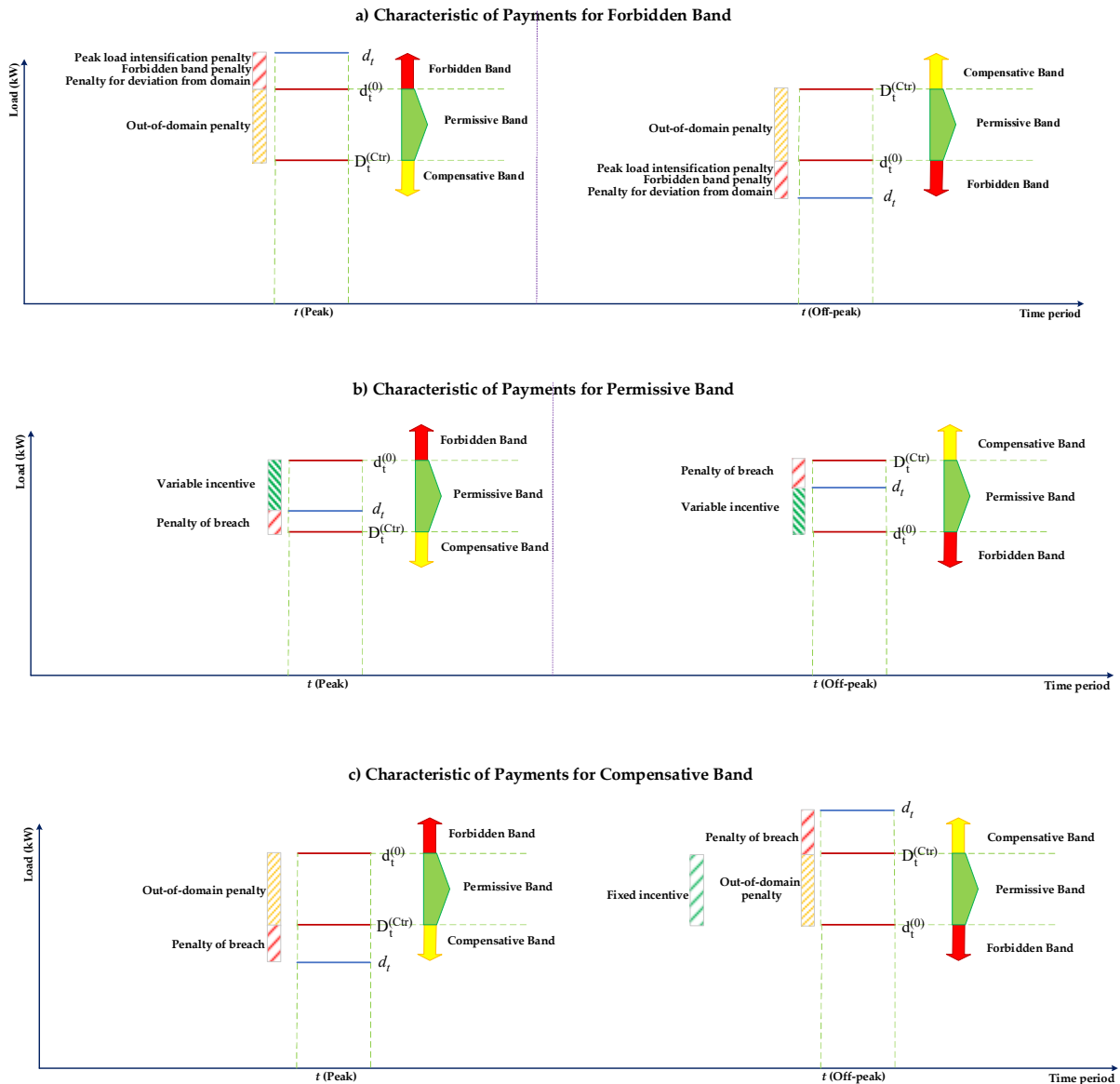


Figure 9. Characteristics of individual payments for each band.

4.4. Unified Function for Total Payment

The unified function of total payment for all periods is given by the following equation:

$$ITP_t(d_t) = \left[2\alpha_t(1 - \gamma_t) \cdot \Delta d_t - \pi_t \gamma_t Q_t^{(Ctr)} \right] + \pi_t \left(d_t - D_t^{(Ctr)} \right) - \alpha_t \cdot \tilde{f}_R^{(d_t - d_t^{(0)})} - (\alpha_t + 2\pi_t) \cdot \tilde{f}_R^{(d_t - D_t^{(Ctr)})} + Q_t^{(Ctr)} \gamma_t (\alpha_t + \pi_t) \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})}. \quad (48)$$

Generally, the payments can be determined as follows:

$$\begin{cases} IPFC_t(d_t) = k_t^{(PFC)} \left(Q_t^{(Ctr)} [\alpha_t \gamma_t + \pi_t (1 - \gamma_t)] \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})} - \alpha_t \cdot \tilde{f}_R^{(d_t - D_t^{(Ctr)})} + \alpha_t (1 - \gamma_t) \cdot \Delta d_t \right) \\ IPFD_t(d_t) = k_t^{(PFD)} \left(-\pi_t \left[-\left(d_t - D_t^{(Ctr)} \right) + 2\tilde{f}_R^{(d_t - D_t^{(Ctr)})} + Q_t^{(Ctr)} (1 - 2\gamma_t) \cdot \tilde{f}_S^{(d_t - D_t^{(Ctr)})} \right] \right. \\ \left. - \alpha_t \cdot \tilde{f}_R^{(d_t - d_t^{(0)})} + [\alpha_t (1 - \gamma_t) \cdot \Delta d_t - \pi_t \gamma_t Q_t^{(Ctr)}] \right) \end{cases} \quad (49)$$

Completely, Table 4 shows the comprehensive overview of payments. Therefore, the final payment is given by the following equation:

$$\begin{aligned} \wp(d_t) = & Q_t^{(Ctr)} \cdot \lambda_t - d_t \cdot \rho_t(d_t) + [\alpha_t (1 - \gamma_t) (k_t^{(PFC)} + k_t^{(PFD)}) \cdot \Delta d_t - k_t^{(PFD)} \pi_t \gamma_t Q_t^{(Ctr)}] \\ & + k_t^{(PFD)} \left[\pi_t (d_t - D_t^{(Ctr)}) - \alpha_t \cdot \tilde{f}_R^{(d_t - d_t^{(0)})} \right] \\ & - (\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)}) \cdot \tilde{f}_R^{(d_t - D_t^{(Ctr)})} + Q_t^{(Ctr)} \left\{ k_t^{(PFC)} \alpha_t \gamma_t + \pi_t [k_t^{(PFC)} (1 - \gamma_t) - k_t^{(PFD)} (1 - 2\gamma_t)] \right\} \cdot \\ & \tilde{f}_S^{(d_t - D_t^{(Ctr)})}. \end{aligned} \quad (50)$$

Table 4. Comprehensive overview of payments.

Period Type	Area of New Demand	Payment Type	Characteristic	Payment Formula
Peak	Forbidden Band	PFC	Peak-load-intensification penalty	$-k_t^{(PFC)} \alpha_t \cdot \Delta d_t $
Peak	Forbidden Band	PFD component	Forbidden-band penalty	$-k_t^{(PFD)} \alpha_t \cdot \Delta d_t $
Peak	Forbidden Band	PFD component	Penalty for deviation from domain	$-k_t^{(PFD)} \pi_t \cdot \Delta d_t $
Peak	Forbidden Band	PFD component	Out-of-domain penalty	$-k_t^{(PFD)} \pi_t Q_t^{(Ctr)}$
Peak	Permissive Band	PFC	Variable incentive	$k_t^{(PFC)} \alpha_t \cdot \Delta d_t $
Peak	Permissive Band	PFD	Penalty of breach	$-k_t^{(PFD)} \pi_t d_t - D_t^{(Ctr)} $
Peak	Compensative Band	PFC	None	0
Peak	Compensative Band	PFD component	Penalty of breach	$-k_t^{(PFD)} \pi_t d_t - D_t^{(Ctr)} $
Peak	Compensative Band	PFD component	Out-of-domain penalty	$-k_t^{(PFD)} \pi_t Q_t^{(Ctr)}$
Off-Peak	Compensative Band	PFC	Fixed incentive	$k_t^{(PFC)} Q_t^{(Ctr)} (\alpha_t + \pi_t)$
Off-Peak	Compensative Band	PFD component	Penalty of breach	$-k_t^{(PFD)} \pi_t d_t - D_t^{(Ctr)} $
Off-Peak	Compensative Band	PFD component	Out-of-domain penalty	$-k_t^{(PFD)} \pi_t Q_t^{(Ctr)}$
Off-Peak	Permissive Band	PFC	Incentive	$k_t^{(PFC)} \alpha_t \cdot \Delta d_t $
Off-Peak	Permissive Band	PFD	Penalty of breach	$-k_t^{(PFD)} \pi_t d_t - D_t^{(Ctr)} $
Off-Peak	Forbidden Band	PFC	Peak-load-intensification penalty	$-k_t^{(PFC)} \alpha_t \cdot \Delta d_t $
Off-Peak	Forbidden Band	PFD component	Forbidden-band penalty	$-k_t^{(PFD)} \alpha_t \cdot \Delta d_t $
Off-Peak	Forbidden Band	PFD component	Penalty for deviation from domain	$-k_t^{(PFD)} \pi_t \cdot \Delta d_t $
Off-Peak	Forbidden Band	PFD component	Out-of-domain penalty	$-k_t^{(PFD)} \pi_t Q_t^{(Ctr)}$

The Model of DR is developed for elastic loads, using Equation (50).

4.5. Model of DR for Elastic Loads

First, it is assumed that $\Psi(d_1, d_2, \dots, d_t, \dots, d_T)$ is the total income of customers during time horizon (T) due to the power utilization; thus, the customers' net profit will be as follows:

$$NP = \Psi(d_1, d_2, \dots, d_t, \dots, d_T) + \sum_{h=1}^T \wp(d_h) \quad (51)$$

4.5.1. Model of Single-Period DR for Elastic Loads

For the single-period modeling, the value of power utilization is considered as the function of conditions in a specified time period that only depends on the electricity price of that time period. Hence, only the self-elasticity emerges in the equations.

According to the optimization framework, in order to maximize the customers' profit, the derivation of the right-hand side of (51) must result in zero; therefore, we obtain the following equation:

$$\frac{\partial NP}{\partial d_t} = 0 = \frac{\partial \Psi(d_t)}{\partial d_t} + \frac{\partial \varphi(d_t)}{\partial d_t}. \quad (52)$$

Consequently, we obtain the following:

$$\begin{aligned} \frac{\partial \Psi}{\partial d_t} = & \rho_t(d_t) + d_t \cdot \frac{\rho_t^{(0)}}{\varepsilon_{t,t}d_t^{(0)}} - \left[\alpha_t(1 - \gamma_t) \left(k_t^{(PFC)} + k_t^{(PFD)} \right) \right] - k_t^{(PFD)} \left[\pi_t - \alpha_t \cdot \tilde{f}_S^{(d_t-d_t^{(0)})} \right] \\ & + \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) \cdot \tilde{f}_S^{(d_t-D_t^{(Ctr)})} \\ & - Q_t^{(Ctr)} \left\{ k_t^{(PFC)} \alpha_t \gamma_t + \pi_t \left[k_t^{(PFC)} (1 - \gamma_t) - k_t^{(PFD)} (1 - 2\gamma_t) \right] \right\} \cdot \tilde{f}_\Delta^{(d_t-D_t^{(Ctr)})}, \end{aligned} \quad (53)$$

and,

$$\begin{aligned} \frac{\partial^2 \Psi}{\partial d_t^2} = & \frac{2\rho_t^{(0)}}{\varepsilon_{t,t}d_t^{(0)}} + k_t^{(PFD)} \alpha_t \cdot \tilde{f}_\Delta^{(d_t-d_t^{(0)})} + \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) \cdot \tilde{f}_\Delta^{(d_t-D_t^{(Ctr)})} \\ & - Q_t^{(Ctr)} \left\{ k_t^{(PFC)} \alpha_t \gamma_t + \pi_t \left[k_t^{(PFC)} (1 - \gamma_t) - k_t^{(PFD)} (1 - 2\gamma_t) \right] \right\} \cdot \tilde{f}_\Delta^{(d_t-D_t^{(Ctr)})}. \end{aligned} \quad (54)$$

The Tylor expansion of the customers' net profit function will result in the following:

$$\frac{\partial \Psi}{\partial d_t} = \frac{\partial \Psi}{\partial d_t} \Big|_{d_t=d_t^{(0)}} + \frac{\partial^2 \Psi}{\partial d_t^2} \Big|_{d_t=d_t^{(0)}} \cdot (d_t - d_t^{(0)}), \quad (55)$$

Therefore, we obtain the following:

$$\begin{aligned} \rho_t(d_t) + d_t \cdot \frac{\rho_t^{(0)}}{\varepsilon_{t,t}d_t^{(0)}} - \left[\alpha_t(1 - \gamma_t) \left(k_t^{(PFC)} + k_t^{(PFD)} \right) \right] - k_t^{(PFD)} \left[\pi_t - \alpha_t \cdot \tilde{f}_S^{(d_t-d_t^{(0)})} \right] + \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) \\ \cdot \tilde{f}_S^{(d_t-D_t^{(Ctr)})} = \rho_t^{(0)} + \frac{\rho_t^{(0)}}{\varepsilon_{t,t}} \\ - \left[\alpha_t(1 - \gamma_t) \left(k_t^{(PFC)} + k_t^{(PFD)} \right) \right] - k_t^{(PFD)} [\pi_t - \alpha_t] + \gamma_t \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) + \left(\frac{2\rho_t^{(0)}}{\varepsilon_{t,t}d_t^{(0)}} + k_t^{(PFD)} \alpha_t \cdot \zeta + \right. \\ \left. \gamma_t \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) \right) (d_t - d_t^{(0)}). \end{aligned} \quad (56)$$

Consequently, we have the following:

$$d_t = \frac{\rho_t - \rho_t^{(0)} + \frac{\rho_t^{(0)}}{\varepsilon_{t,t}} + d_t^{(0)} \cdot \left(k_t^{(PFD)} \alpha_t \cdot \zeta + \gamma_t \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) \right) - k_t^{(PFD)} \alpha_t \left[1 - \tilde{f}_S^{(d_t-d_t^{(0)})} \right] + \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right) \cdot \left(\tilde{f}_S^{(d_t-D_t^{(Ctr)})} - \gamma_t \right)}{\frac{\rho_t^{(0)}}{\varepsilon_{t,t}d_t^{(0)}} + k_t^{(PFD)} \alpha_t \cdot \zeta + \gamma_t \left(\alpha_t k_t^{(PFC)} + 2\pi_t k_t^{(PFD)} \right)}. \quad (57)$$

4.5.2. Model of Multi-Period DR for Elastic Loads

For the multi-period modeling, the value of power utilization is considered as the function of electricity price in all time periods. Hence, considering the concept of the self-elasticity and cross-elasticities, we have the following:

$$d_t = \sum_{\tau=1}^T \left\{ \frac{\rho_t - \rho_\tau^{(0)} + \frac{\rho_\tau^{(0)}}{\varepsilon_{t,\tau}} + d_t^{(0)} \cdot \left(k_t^{(PFD)} \alpha_\tau \cdot \zeta + \gamma_t \left(\alpha_\tau k_\tau^{(PFC)} + 2\pi_\tau k_\tau^{(PFD)} \right) \right) - k_\tau^{(PFD)} \alpha_\tau \left[1 - \tilde{f}_S^{(d_\tau-d_t^{(0)})} \right] + \left(\alpha_\tau k_\tau^{(PFC)} + 2\pi_\tau k_\tau^{(PFD)} \right) \cdot \left(\tilde{f}_S^{(d_t-D_t^{(Ctr)})} - \gamma_t \right)}{\frac{\rho_\tau^{(0)}}{\varepsilon_{t,\tau}d_t^{(0)}} + k_\tau^{(PFD)} \alpha_\tau \cdot \zeta + \gamma_t \left(\alpha_\tau k_\tau^{(PFC)} + 2\pi_\tau k_\tau^{(PFD)} \right)} \right\}. \quad (58)$$

The recent equation formulates the comprehensive model of DR.

5. Illustrative Implementation

Different strategies of DR programs can be obtained from Equation (58) by distinctive factors presented in Table 5. The DR methods can be divided into two general categories, namely price-based programs and incentive-based programs [101–103]. The price-based programs include methods in that the customers are indirectly motivated via the electricity price. This group includes TOU, RTP, and critical peak pricing (CPP). In the incentive-based programs, the contracts and market environment provide the change in customer's power consumption pattern [28,100,104]. The incentive-based programs extracted from the comprehensive model of DR are divided into voluntary programs and mandatory programs [98]. The voluntary programs include the technological direct load control (TDLC) program and voluntary response program (VRP). The mandatory programs include capacity market (CAP) and contractual indirect load control (CILC).

Table 5. Distinctive factors for simulation of modified DR comprehensive model.

DR Factors	DR Strategies						
	Price-Based Programs			Incentive-Based Programs			
	Motivative			Voluntary		Mandatory	
	TOU	CPP	RTP	TDLC	VRP	CAP	CILC
PFC coefficient	0	0	0	1	1	1	1
PFD coefficient	0	0	0	0	0	1	1
Up-front reservation payment	-	-	-	✓	-	✓	-
Threefold frame *	✓	-	-	-	-	-	-
Dynamic pricing	-	-	✓	-	-	-	-
Artificial peak	-	✓	-	-	-	-	-

* TOU tariffs are determined for three windows of the time horizon.

The comparison of customary and modified DR methods mentioned in Table 5 is depicted in Figures 10–16. The customary DR model was used in Reference [34].

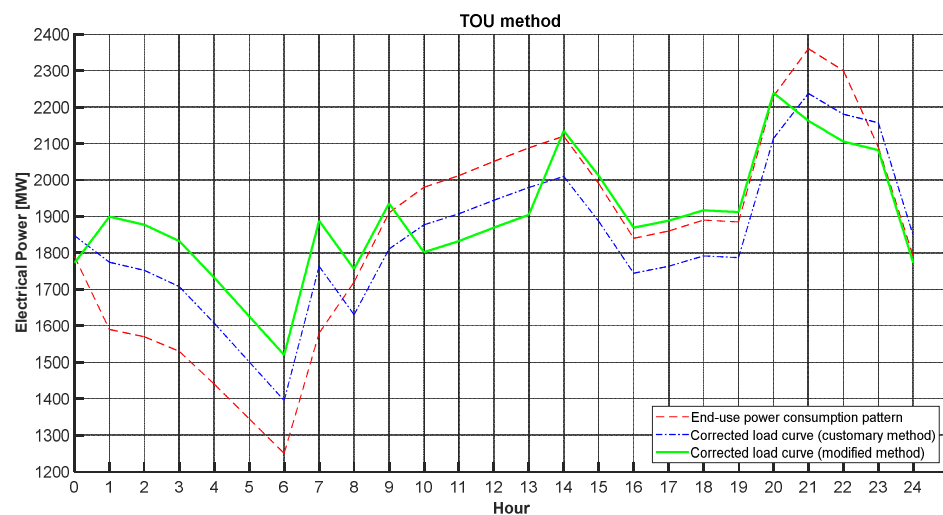


Figure 10. Comparison of customary and modified TOU methods.

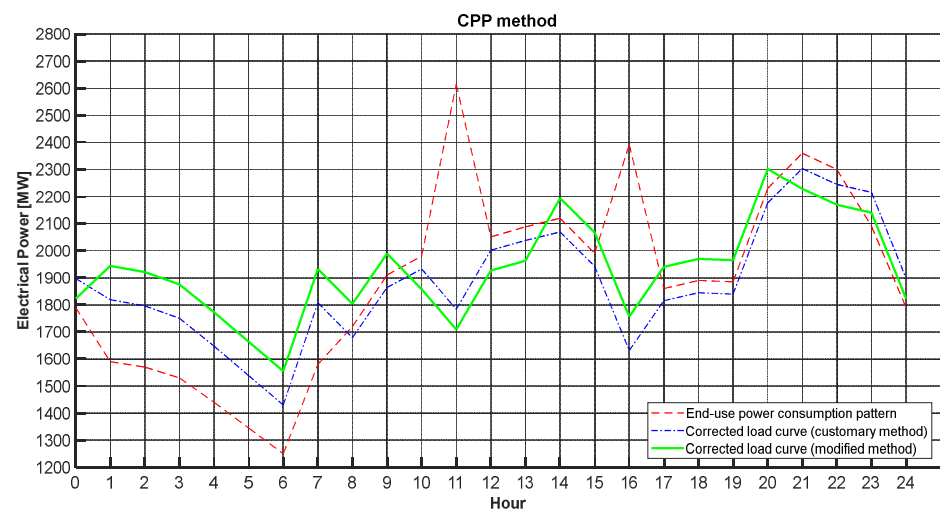


Figure 11. Comparison of customary and modified CPP methods.

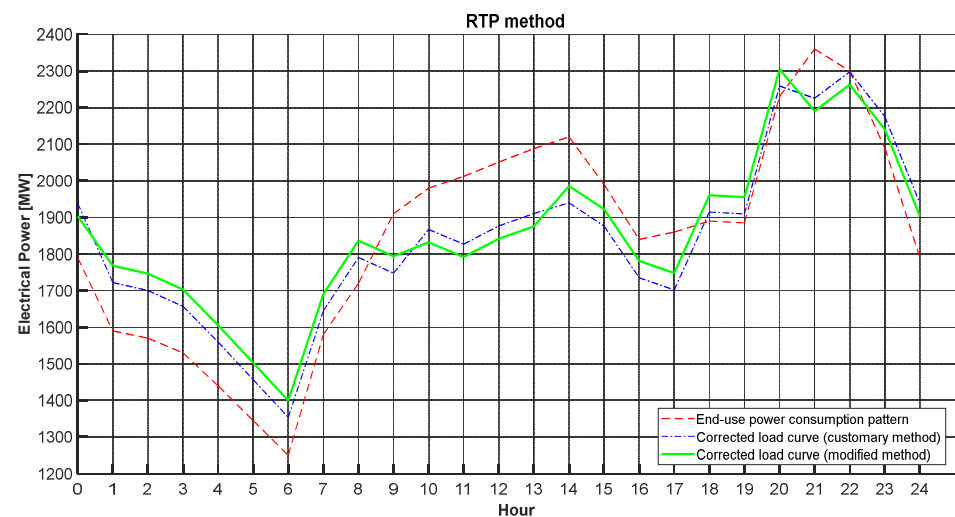


Figure 12. Comparison of customary and modified RTP methods.

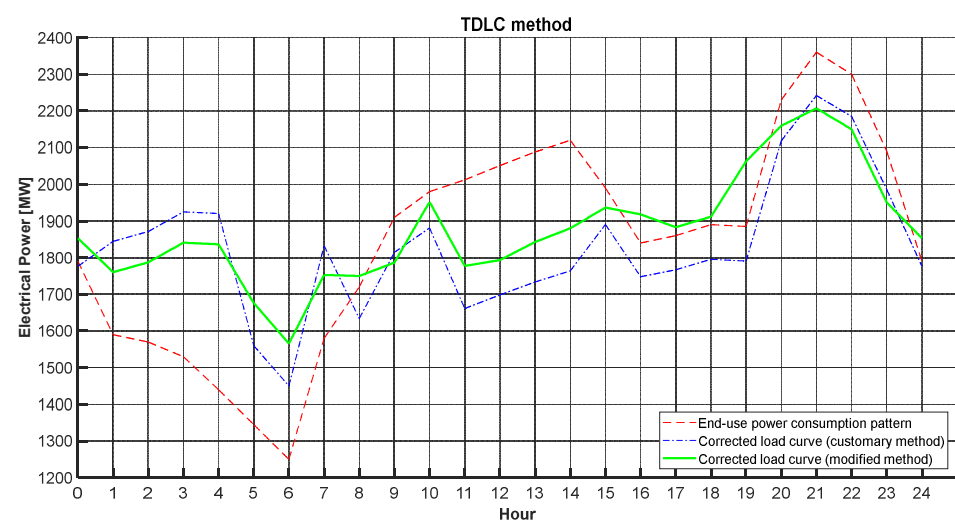


Figure 13. Comparison of customary and modified TDLC methods.

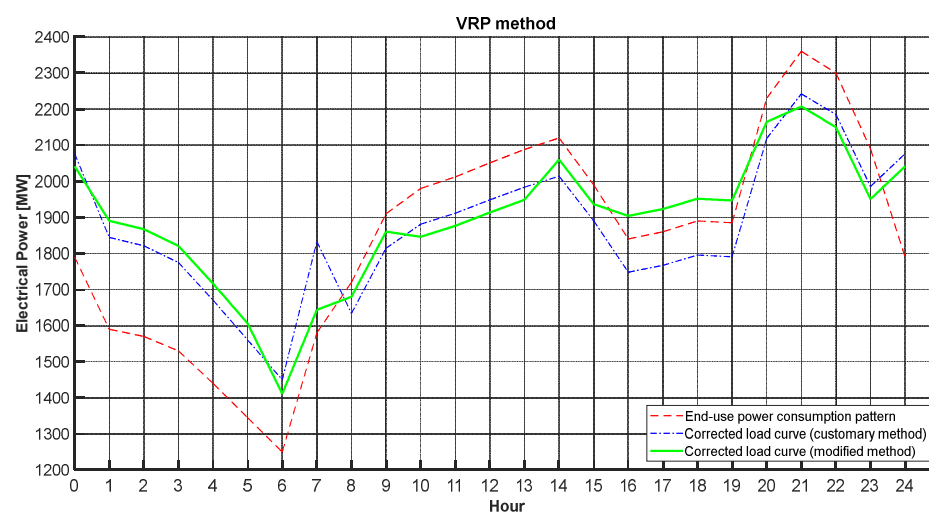


Figure 14. Comparison of customary and modified VRP methods.

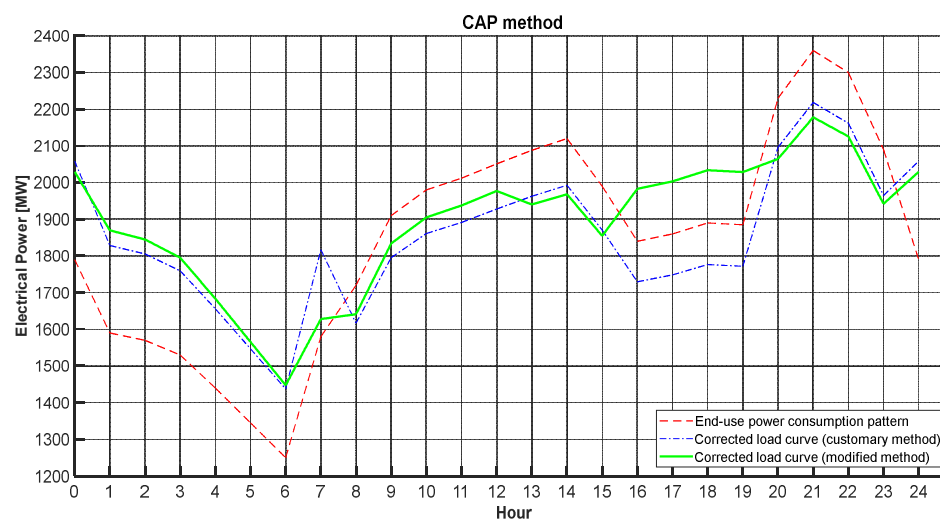


Figure 15. Comparison of customary and modified CAP methods.

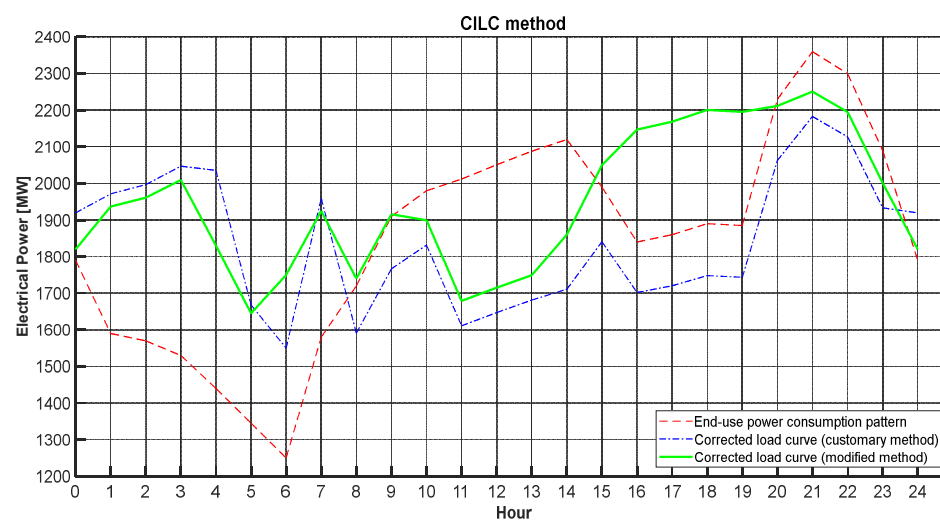


Figure 16. Comparison of customary and modified CILC methods.

The results for the load factors were presented in Table 6. The results demonstrate the improvement of the situation for the modified model.

Table 6. Load factors for simulation of modified DR comprehensive model.

Load Factors	DR Strategies						
	Price-Based Programs			Incentive-Based Programs			
	Motivative			Voluntary		Mandatory	
	TOU	CPP	RTP	TDLC	VRP	CAP	CILC
Primary Pattern	0.7843	0.7260	0.7843	0.7843	0.7843	0.7843	0.7843
Customary Model	0.8226	0.8153	0.7995	0.8157	0.8315	0.8320	0.8408
Modified Model	0.8480	0.8413	0.8052	0.8501	0.8555	0.8662	0.8674

6. Conclusions

This paper focused on the role and importance of productivity in the DSM arena. Foremost, a comprehensive discussion for indices of DSM was accomplished. Meanwhile, an inclusive DSM index was introduced that includes twofold productivity for energy and investment to analyze the productivity in the electrical energy systems. Afterward, a general classification of DSM was presented, and the pertaining modalities were clarified while considering the constituents of the mentioned DSM index. Since DR schemes are the most significant modalities of electrical load management in the smart grids, a DR model was developed that can ensure the implementation of three price-based and four incentive-based DR strategies in the smart microgrids. Moreover, the renovated payment principles were formulated to involve the flexibility of load drop and proliferation simultaneously. The contributions of this paper can be enumerated as follows:

- Reconsideration of DSM contexts from the productivity perspective,
- Innovation of a general DSM index containing the elementary attributes of energy management in the electrical energy systems,
- Developing a modified DR model that enhances the efficacious of load profile improvement in contrast with the conventional model,
- Embedment of rational payment criteria in the modified DR model that precisely determines the incentive and penalties by considering the unforeseeable reaction of the customers in energy consumption.

The simulation results of the DR proposed model show that the load factor can increase between 2.66% and 8.12% than the ordinary load curve. This demonstrates the accuracy and the merit of the modified model compared to the customary DR model because the load factor can be enhanced between 0.71% and 4.22% more than that of the customary DR model.

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Nomenclature

α_t	Payment for change (PFC) rate at time t
$d_t^{(0)}$	Initial load demand value at t -th hour
d_t	Load demand value at t -th hour
Δd_t	Load demand change at t -th hour
DF	Demand factor
$DSMI$	Demand-side management (DSM) index
$D_t^{(Ctr)}$	Contracted load demand
$\varepsilon_{t,t}$	Self-elasticity
$\varepsilon_{t,\tau}$	Cross-elasticity
E_d	Delivered energy
E_{demand}	Demanded energy
E_G	Available energy resource capacity
EP	Energy productivity
E_s	Supplied energy
E_u	Useful energy
$\gamma_{capacity}$	Capacity factor
$\gamma_{delivery}$	Delivery factor
$\gamma_{utilization}$	Utilization factor
γ_t	Distinction factor of hour types
$\tilde{f}_R^{(.)}$	Unit ramp function
$\tilde{f}_S^{(.)}$	Heaviside step function
$\tilde{f}_\Delta^{(.)}$	Dirac delta function
$\tilde{f}_{\Delta^2}^{(.)}$	Unit doublet function
η_c	Consumption efficiency
η_g	Grid efficiency
$IPFC_t$	Unified function of payment for change at t -th hour
$P_{peak_{new}}^{(t_i \sim t_f)}$	Peak load demand after load curve reshaping
$P_{peak_{old}}^{(t_i \sim t_f)}$	Peak load demand before load curve reshaping
$p_G(t)$	Function that describes suppliable electrical load curve
SP	System productivity
$IPFD_t$	Unified function of payment for deviation at t -th hour
ITP_t	Unified function of total payment at t -th hour
$k_t^{(PFC)}$	Payment for change (PFC) coefficient at t -th hour
$k_t^{(PFD)}$	Payment for deviation (PFD) coefficient at t -th hour
$\lambda_{P_{peak}}^{(t_i \sim t_f)}$	Adequacy coefficient
λ_t	Up-front reservation rate at t -th hour
LF	Load factor
LF_{new}	Load factor after load curve reshaping
LF_{old}	Load factor before load curve reshaping
ΔLF	Amount of change in load factor
$P_G^{(max)}$	Maximum suppliable electrical power
$p_s(t)$	Function that describes supplied electrical power curve
$Q_t^{(Ctr)}$	Length of permissive band
ρ	Regulation factor
$\rho_t^{(0)}$	Initial electricity price at t -th hour
ρ_t	Spot electricity price at t -th hour
$\Delta \rho_t$	Electricity price change at t -th hour
π_t	Payment for deviation (PFD) rate at t -th hour
$\wp$	Final payment
PFC_t	Payment for change at t -th hour
PFD_t	Payment for deviation at t -th hour

$p(t)$	Function that describes load curve
$p_{\text{flat}}^{(t_i \sim t_f)}$	Fixed clipped load demand value
$p_{\text{new}}(t)$	Function that describes load curve after load curve reshaping
$p_{\text{old}}(t)$	Function that describes load curve before load curve reshaping
$p_{\text{peak}}^{(t_i \sim t_f)}$	Peak load demand
t_i	Initial time
t_f	Final time
TP_t	Total payment at t -th hour
ζ	Boundary particular value of triplet bands

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