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Optimal Energy Scheduling of Appliances in Smart Buildings Based on Economic and Technical Indices

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***Abstract* – In this article, optimal energy consumption in the smart houses is studied considering techno-economic indices and demand side management (DSM) in electrical grids. The optimal energy consumption is implemented based on optimal scheduling of the household appliances than energy price and capacity of demand flexibility in DSM. The proposed approach is considered as two-stage optimization. Using first stage, energy consumption is modified by optimal shifting of the appliances subject to DSM and energy price. Thus, modified energy consumption is taken into accounted in second stage optimization to maximizing the consumers comfort and minimizing operation cost, simultaneously. The optimization process is done in the MATLAB software, in which objectives in second stage are optimized via lp-metric method. Finally, the performance of the proposed modelling is validated as case studies using numerical simulation.**

***Keywords* – Demand side management; optimal energy consumption; optimal shifting, lp-metric method; two-stage optimization**

Nomenclature		
t,T	Time index	Hour
si	Solar irradiance	kW/m^2
S_{PV}	Total area of PV	m^2
v, V_R, V_{Ci}, V_{Co}	Wind speed, Rated speed, Cut-in speed, Cut-off speed of WT	m/s
$P_{N,WT}$	Total rated power of WT	kW
α, β, λ	Cost factors of DGs	$/kW
P_d	DG power	kW
η_{pv}	Efficiency of PV	%
D_E, D_{UM}, D_E^B	Electrical demand, Unmet demand and Electrical demand before shifting	kW
η^{ch},η^{dis}	Efficiency of ESS systems in discharge and charge state	%
C_{ESS}, C^{es}_{OP}	ESS cost and operation cost	$
C_{DG},C_{UG}	Cost of the DG and upstream grid	$

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π^{p}_{UG}, P_{UG}	Electrical price and Upstream grid power	€/kW, kW
μ_{ESS}	Binary variable of the ESS	–
Λ	Participation level of the flexible appliances in shifting strategy	%

1. INTRODUCTION

Recently, smart energy systems are used to developing influence of the demand side management (DSM) in the large energy area such as residential building [1]–[4]. The DSM strategy is utilized by energy companies to improve performance of energy systems via persuading demand side using price signals [5]–[8]. The implementation of DSM leads to stimulation of the consumers to control self-energy consumption in high real-time energy price [9]–[12]. On the other side, residential buildings have maximum energy consumption especially electrical energy than commercial and industrial sections [13]–[20]. The optimal energy scheduling in the smart residential building can implement as modern service by energy companies to increase energy systems efficiency and improve consumers comfort level through DSM service [21]–[25].

The residential building energy scheduling have been done in previous researches with different models and approaches. The optimal scheduling of generation units is studied in [26] to minimizing generation cost and emission. In [27] maximization of the energy saving is proposed by demand reduction strategy in high energy price. The energy scheduling in smart autonomous residential building is examined in [28] with consideration of electric vehicle (EV) power generation at peak demand. In [29], minimizing the energy loss and maximizing the profit in residential buildings is discussed using optimal design of the energy resources. The optimal sizing and siting of energy resources in the residential building networks is implemented in [30] for minimizing the installation costs. The load demand scheduling by different strategies in reviewed in [31] using intelligence algorithm. The energy management of the household appliances is studied in [32] for reduction of consumption costs. In [33] scheduling of the household appliances is proposed under uncertain parameters such as energy price and renewable energy resources for increase efficiency of system and minimizing costs. The optimal committee of household appliances is proposed in [34] using discrete and continuous optimization model. In [35] consumption of the household appliances based-economic and environment models is implemented, without consideration of the consumers' comfort index.

In this article, optimal energy scheduling of the household appliances in the smart residential buildings is proposed. The energy scheduling is optimized based on optimal dispatch of consumption using demand shifting. The two-stage optimization model is taken into accounted for proposed approach. The energy consumption is optimized in first stage, and it's applied in second stage optimization in order to maximization of comfort and minimizing the operation costs. The lp-metric is utilized as optimization method for solving objective functions and generation of the non-dominated solutions of objectives. Therefore, contributions in this work can be listed as follows:

- Proposing two-stage optimization for optimal energy scheduling in the residential buildings;
- Utilization of the demand shifting modelling for optimal consumption in first stage;
- Minimizing operation costs and maximizing consumers' comfort in second stage;
- Solving objective functions in second stage using lp-metric method.

2. SMART RESIDENTIAL BUILDINGS OVERVIEW

The overview of the smart residential buildings is studied in this section, which in Fig. 1 graphical description of them in electrical grids is depicted. In this figure, generation side are distributed energy generators and upstream grid. The distributed energy generators including electrical energy storage (ESS), diesel generator (DG), wind turbine (WT) and photovoltaic (PV) [36]–[41]. The upstream grid has diverse price at each time in a day, which these prices from electrical market are applied. The household appliances in the smart residential buildings have various behaviours in electrical energy consumption. These behaviours are depended on different time of appliances usage. For example, electrical consumption of the washing machine, optional lighting, dryer and electrical oven can be moved to other times of a day, which these appliances are named as flexible appliances. On the other side, some of the appliances such as refrigerator and critical lighting have fix behaviours in electrical consumption, and all times or pre-defined times are operated. Therefore, in our work, DSM modelling is implemented to flexible appliances. The energy scheduling centre using flexible appliances can provide optimal level of system based on pre-defined objectives

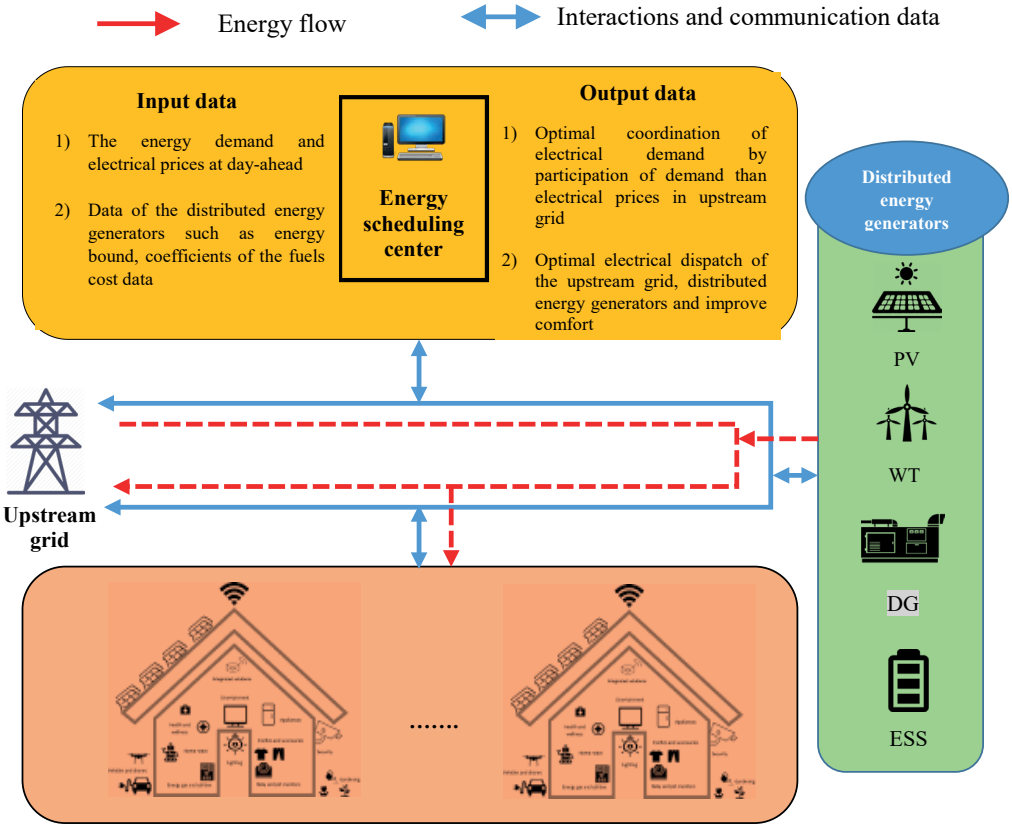


Fig. 1. Overview of smart residential buildings in electrical grids.

3. Economic and Technical Modelling of the Distributed Energy Generators and Upstream Grid

The mathematical modelling of the distributed energy generators based-economic and technical indices is formulated as follows:

3.1. PV Modelling

The modelling electrical generation based on solar irradiance by PV is as follows Eq. (1) [33].

$$P_{PV}(si) = \eta_{\mathrm{PV}} \cdot S_{PV} \cdot si \tag{1}$$

3.2. WT Modelling

The electrical generation using WT subject to wind speed is given by Eq. (2) [34]:

$$P_{WT}(v) = \begin{cases} 0 & \text{if} \quad v \le V_{Ci} \\ P_{N,WT} \cdot \left(\dfrac{v - V_{Ci}}{V_R - V_{Ci}} \right) & \text{if} \quad V_{Ci} \le v \le V_R \\ P_{N,WT} & \text{if} \quad V_R \le v \le V_{Co} \\ 0 & \text{if} \quad V_{Co} \le v \end{cases} \tag{2}$$

3.3. DG Modelling

The mathematical modelling of DG based-fuel cost is formulated by Eq. (3).

$$C_{DG}(t,d) = \left\{ \alpha P_d^2(t,d) + \beta P_d(t,d) + \lambda \right\} \tag{3}$$

3.4. ESS Modelling

Using Eq. (4) and Eq. (5) economic and technical modelling of ESS can be calculated, respectively [30], [31].

$$C_{ESS}(t,ess) = \left\{ C_{OP}^{ess} \cdot P_{ESS}(t,ess) \right\}, \tag{4}$$

$$\begin{cases} P_{ESS}(t) / \eta_{\mathrm{dis}} \le P_{ESS-dis}^{\max} \cdot \mu_{\mathrm{ESS}} & \text{discharge} \quad P_{ESS}(t) \ge 0 \\ P_{ESS}(t) \cdot \left(-\eta_{\mathrm{ch}} \right) \le P_{ESS-ch}^{\max} \cdot (1 - \mu_{\mathrm{ESS}}) & \text{charge} \quad P_{ESS}(t) \le 0 \end{cases}, \tag{5}$$

where Eq. (4) is ESS cost at time operation, and Eq. (5) is ESS status in the discharge and charge modes.

3.5. Upstream Grid Modelling

The economic modelling of the upstream grid in various price of electrical energy is as follows by Eq. (6).

$$C_{UG}(t) = \pi_{\mathrm{UG}}^{\mathrm{p}}(t) \cdot P_{UG}(t) \tag{6}$$

4. Optimization Approach Modelling

In this section, proposed optimization as two-stage is formulated as follows:

4.1. First Stage Optimization

In first stage, optimization of the electrical energy consumption subject to electrical price in the upstream grid is done using Eq. (7). In this optimization, electrical energy consumption is optimized by flexible appliances participation via shifting strategy in all smart buildings [32]–[37].

$$\min f_1^{fs} = \sum_{t=1}^{T} \left\{ D_E(t) \cdot \pi_{\mathrm{UG}}^{\mathrm{p}}(t) \right\} \tag{7}$$

Subject to:

$$\sum_{t=1}^{T} D_E(t) = \sum_{t=1}^{T} D_E^B(t)\,, \tag{8}$$

$$D_E(t) = D_E^B(t) \cdot \Lambda(t)\,, \tag{9}$$

$$1 - \Lambda(t) \le \Lambda(t) \le 1 + \Lambda(t)\,, \tag{10}$$

where Eq. (8) ensure that, total of the electrical demand before shifting strategy is equal to after shifting strategy. The Eq. (9) is value of the demand shifted. And Eq. (10) represented, participation level of the flexible appliances in demand shifting strategy.

4.2. Second Stage Optimization

In this stage, multi-objective functions such as consumers' comfort and operation costs are optimized as follows:

4.2.1. Minimizing Operation Costs

The operation costs of the DGs, ESSs and upstream grid are minimized in first objective of second stage optimization.

$$\min f_1^{ss} = \sum_{t=1}^{T} \left\{ \sum_{d=1}^{D} C_{DG}(t,d) + \sum_{ess=1}^{ESS} C_{ESS}(t,ess) + C_{UG}(t) \right\} \tag{11}$$

4.2.2. Maximizing Consumers' Comfort

The consumers' comfort is modelled based on electrical consumption than optimal level of the consumption and unmet electrical demand [38]–[40].

$$\max f_2^{ss} = 1 - \left[\frac{\sum_{t=1}^{T} \left| \Psi(t) - \Psi^{\mathrm{OP}} \right|}{\sum_{t=1}^{T} \Psi(t)} \right], \tag{12}$$

where

$$\Psi(t) = D_E(t) + D_{UM}(t), \tag{13}$$

$$D_{UM}(t) = \begin{cases} D_{UM}(t) > 0 & D_E(t) > P_{GS}(t) \\ D_{UM}(t) = 0 & D_E(t) < P_{GS}(t) \end{cases}, \tag{14}$$

$$\Psi^{\mathrm{OP}} = \frac{\sum_{t=1}^{T} D_E(t)}{T}. \tag{15}$$

Here Eq. (13) includes electrical demand and unmet electrical demand. Using Eq. (14), unmet demand is calculated with attention to unable of generation side including distributed energy generators and upstream grid in meet demand, and Eq. (15) is optimal level of the consumption.

4.2.3. Constraints

Technical constraints of the system such as power balance, energy generation bound of the DG, upstream grid and unmet demand limit are modelled in Eqs. (16)–(19) for the second stage optimization, respectively [41], [42].

$$P_{UG}(t) + P_{PV}(t) + P_{WT}(t) + \sum_{d=1}^{D} P_d(t,d) \pm \sum_{ess=1}^{ESS} P_{ESS}(t,ess) = D_E(t) - D_{UM}(t) \tag{16}$$

$$0 \le P_d(t,d) \le P_d^{\max} \tag{17}$$

$$0 \le P_{UG}(t) \le P_{UG}^{\max} \tag{18}$$

$$0 \le D_{UM}(t) \le D_E(t) \tag{19}$$

5. Optimization Method

Since, in second stage optimization operation costs is minimized and costumers' comfort is maximized, simultaneously. The lp-metric method is employed as optimization method for solving objective functions in second stage. The lp-metric method modelling is as follows [43]–[48] by Eq. (20):

$$\min lp = \left[\left\{ w \cdot \frac{f_1^{ss} - f_1^{ss,op}}{f_1^{ss,op}} \right\} - \left\{ (1-w) \cdot \frac{f_2^{ss} - f_2^{ss,op}}{f_2^{ss,op}} \right\} \right], \tag{20}$$

and subject to

$$0 \le w \le 1. \tag{21}$$

Here, $f_1^{ss,op}$ and $f_2^{ss,op}$ are optimal value of operation cost and costumers' comfort, respectively. And w is weight for objective functions at interval [0,1]; to finding Pareto frontier solutions. In this method, minimum value of the objective in Eq. (20) is considered as the best solution.

6. NUMERICAL SIMULATION AND CASE STUDIES

In this section, optimization approach is implemented as numerical simulation. The two case studies with attention to flexible appliances participation are provided as follows:

- Case A) Optimization without flexible appliances participation;
- Case B) Optimization with flexible appliances participation.

In Fig. 2 the process of the optimization is depicted. In Table 1, parameters of the PV and WT are listed [49]–[53]. The DGs and ESS parameters are given in Tables 2 and 3. The solar irradiance and wind speed at day-ahead is provided in Fig. 3. Electrical demand and electrical price in the upstream grid is shown in Fig. 4 [54]–[56]. It should be mentioned, that maximum power generation is 500 kWh, and value of the demand shifting by flexible appliances participation is 35 %.

TABLE 1. PV AND WT PARAMETERS

PV		**WT**	
Parameters	**Value**	**Parameters**	**Value**
S_{PV}	55 m^2	V_{Ci} , V_{Co}	3 m/s, 25 m/s
η_{PV}	20 %	V_R	15 m/s
$P_{N,PV}$	180 kWh	$P_{N,WT}$	350 kWh

TABLE 2. DGS DATA

Parameters	**α, €/kWh^2**	**β, €/kWh**	**λ, €**	P^{min}, **kWh**	P^{max}, **kWh**
DG 1	44.2	10.2	124	0	180
DG 2	54.2	15.6	132	0	180

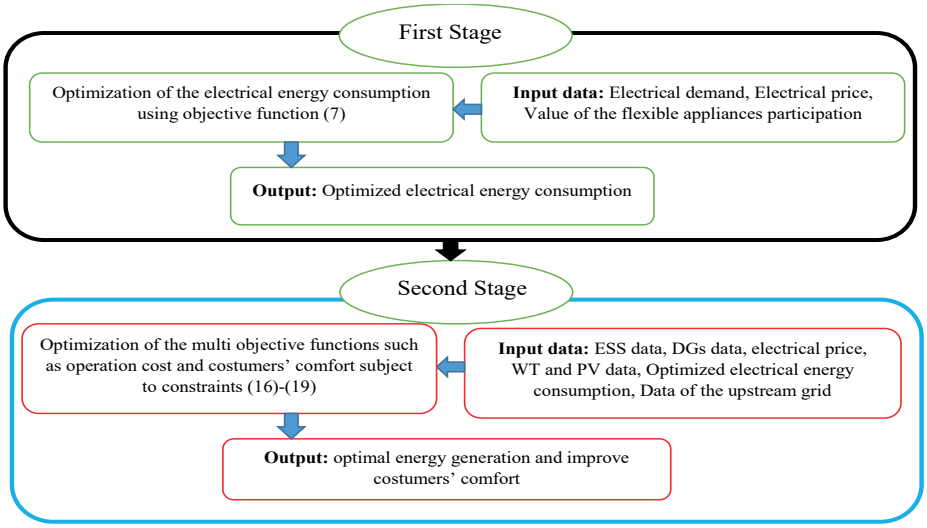


Fig. 2. Optimization process.

TABLE 3. ESS DATA

Parameters	Value
P_{ESS}	80 kWh
η_{ch}	90 %
η_{dis}	95 %
$C^{ESS}{}_{OP}$	€10

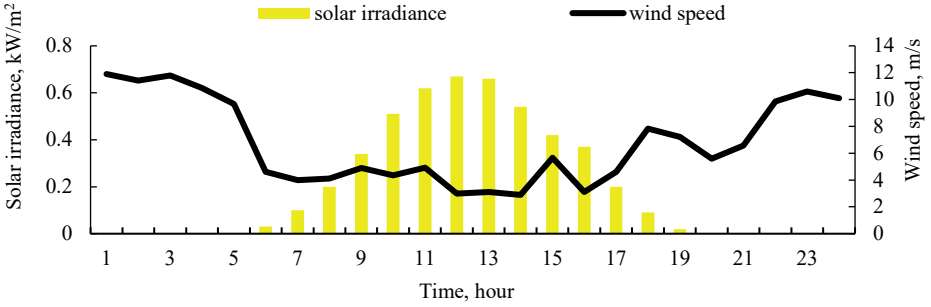


Fig. 3. Solar irradiance and wind speed at day-ahead.

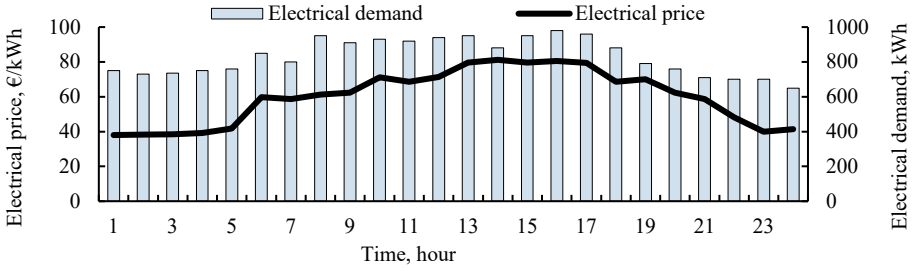


Fig. 4. Electrical demand and electrical price at day-ahead.

7. RESULTS AND DISCUSSION

In this subsection, results of mentioned case studies are discussed as follows:

In Fig. 5. optimized electrical demand in first stage with original electrical demand is depicted. As shown, flexible appliances are shifted from high price to low electrical price, and case studies are implemented subject to original electrical demand (Case A) and optimized electrical demand (Case B). In Fig. 6 Pareto frontier solutions for operation cost and costumers' comfort in second stage for cases A and B are provided. The change step of the weight in lp-metric method is taken by 0.1 for objective functions, and minimum value of the best solutions for Cases A and B are equal to 0.67 and 0.63, respectively.

In case A, amount of the best solution for consumers' comfort and operation cost are respectively 75.1 % and € 692 574.2, which is determine in Fig. 6(a). However, with participation of the flexible appliances in Case B, the best solution in Fig. 6(b) has values 85.2 % and € 558 654.2 for consumers' comfort and operation cost, respectively. Comparing

Case B with Case A, operation cost is minimized by 9.2 % and consumers' comfort 10.1% is increased. In Case A, 62.3 % of the operation cost is associated to upstream grid cost to feed demand; this is while, cost of the upstream grid in Case B is minimized by 5.87 % than Case A.

The optimal energy scheduling in Cases A and B is shown in Fig. 7. In Fig. 7(a) (Case A), power generation of upstream grid is done in high price and peak demand, which leads to increase operation cost. As well, unmet demand is scheduled at hours 12, 13, 15–17 or peak demand. The total unmet demand in mentioned hours is equal to 270 kWh. The charge scheduling for ESS in Case A is at hours 1 and 4, and discharging is scheduled at hour 14 and high electrical price.

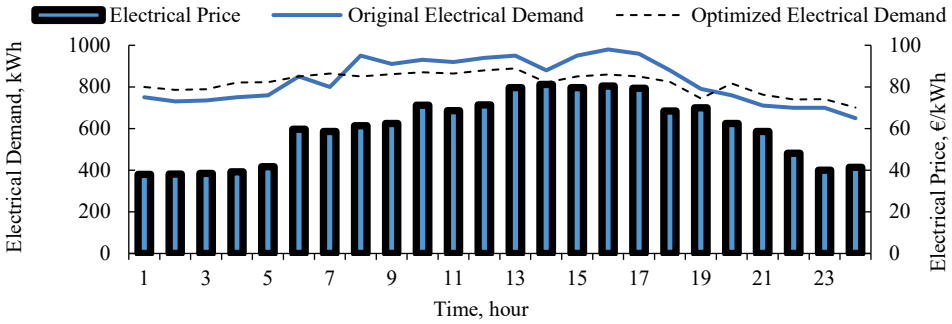


Fig. 5. Original and optimized electrical demand.

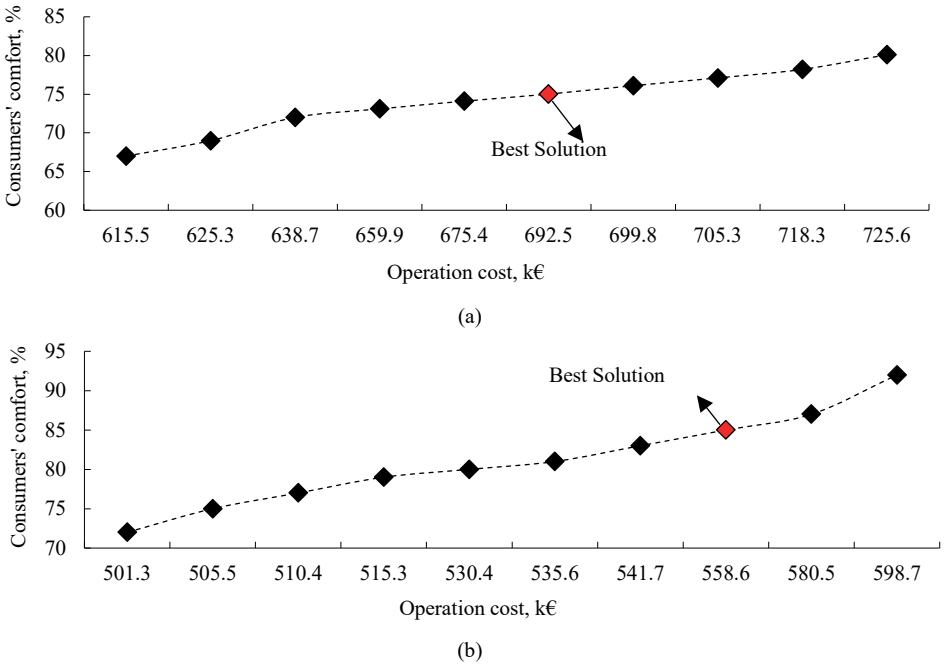


Fig. 6. Pareto frontier solutions. a) Case A and b) Case B.

In Fig. 7(b), scheduling of the electrical power with participation of the flexible appliances (Case B) is depicted. It's visible, optimal level of the electrical demand is provided to generation side at peak demand. In this case, due to implementation of the demand shifting strategy from peak demand to off-peak, unmet demand is reduced by 59.2 % in comparison with previse case. Also, participation of the ESS in meet demand is increased with value 33.3 % than Case A. The electrical power generation by ESS is scheduled at peak demand and high electrical price. It can be concluded that, ESS have major role in minimization of the unmet demand and operation cost. Also, it can be inferred that, with participation of the flexible appliances in energy scheduling, desired level of the operation cost and consumers' comfort is provided.

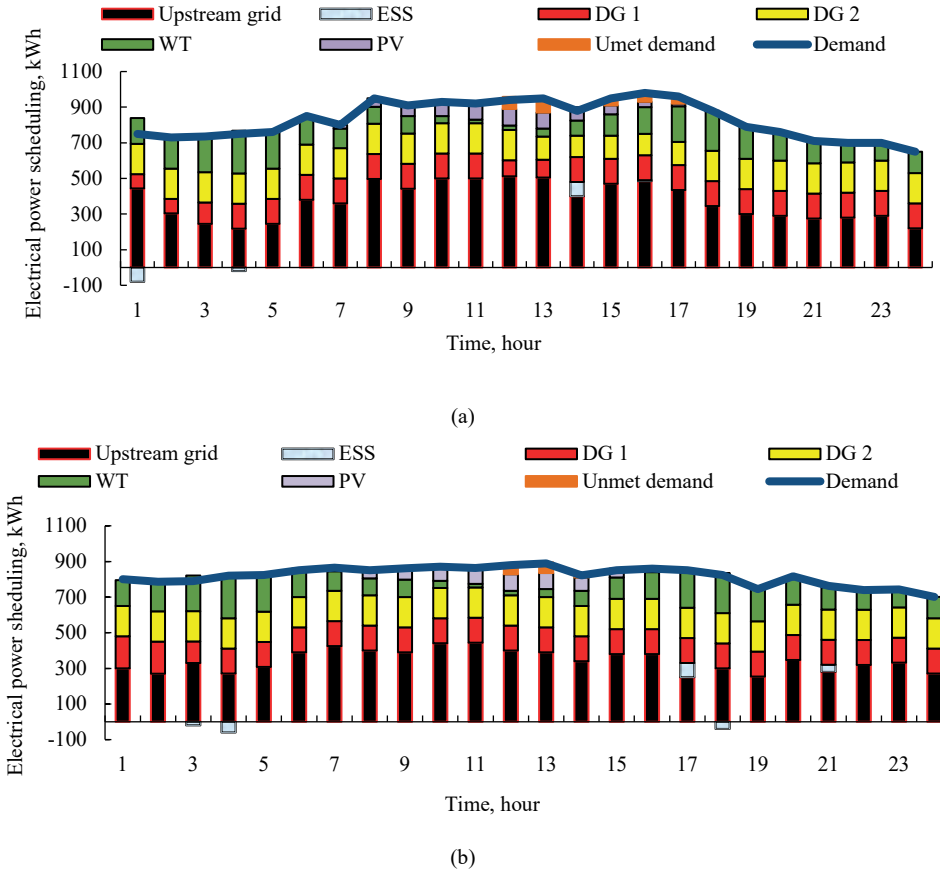


Fig. 7. Electrical power scheduling. a) Case A and b) Case B.

8. CONCLUSION

This article presented two-stage multi objective functions optimization for optimal scheduling of the flexible appliances in smart building. Using first stage optimization, electrical demand is optimized via participation of flexible appliances and electrical price in upstream grid. In second stage, multi-objectives are considered subject to optimized electrical demand. The minimization of the operation cost and maximization of the consumers' comfort

are multi-objectives in second stage optimization. The numerical results in the simulation section as two case studies are implemented to evaluate effectiveness of the proposed approach. In Case A, optimization is done without participation of flexible appliances and in Case B, participation of flexible appliances is taken into accounted. The comparative analysis of the results to case studies is listed in Table 4.

TABLE 4. RESULTS OF CASE STUDIES

	Operation cost, €	**Consumers' comfort, %**
Case A	692574.2	75.1
Case B	558654.2	85.2

The results show that, DSM strategy has provided optimal rate of operation cost and consumers' comfort according to participation of flexible appliances then electrical price.

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