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Multi-Criteria Problems of Energy Consumption in Buildings Considering Technical and Economic Indices

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***Abstract* – This study focuses on economic modelling of the energy consumption in buildings considering controllable appliances scheduling in stand-alone electrical grids. The economic modelling is implemented via coordination of the energy generation of the renewable energies with controllable appliances by using demand shifting strategy (DSS). On the other side, uncertainty and stochastic modelling of the renewable energies are considered in the optimal coordination. Also, optimal coordination is modelled by multi-criteria problems of the technical and economic indices. Solving of the multi-criteria problem is done by fuzzy and augmented epsilon-constraint methods. To investigate the effectiveness of the proposed model, it is applied on a 25-node test system through defining two scenarios. The obtained results show that modelling the optimal coordination to supply the demand of the grid can increase the efficiency of the system.**

***Keywords* – Demand shifting strategy (DSS); multi-criteria problem; stand-alone electrical grids; renewable energies; technical and economic indices.**

Nomenclature		
t, T	Time	Hour
cl, CL	Controllable appliances	–
ESS	Electrical storage system	–
d, D	Diesel generators	–
v, V_R, V_{Ci}, V_{Co}	Wind speed, Rated speed, cut-in speed, cut-off speed of WT	m/s
$P_{N,WT}$	WT power	kW
S_{PV}	PV area	m^2
si	Irradiance of Solar	kW/m^2

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η_{pv}	PV Efficiency	%
η^{ch}, η^{dis}	Efficiency of discharge and charge states in ESS	%
a,b,c	DGs fuel factors	$/kW
P_d	Power of DG	kW
P_{ESS}	Power of ESS	kW
$C^{ess}{}_{OP}$	ESS' Operation cost	$
M^D, M^U	Minimum down and up times for DG	Hour
D_{CL}, D_{NCL}	Load of the Controllable appliances and non-Controllable appliances	kW
R^U, R^D	Ramp up and down for DG	kW
μ_{ESS}	Binary variable for ESS	–

1. INTRODUCTION

In many countries, the global warming and the greenhouse gases emission have been considered as the main critical environmental and social sustainability issues. The Kyoto Protocol has special impact on the electrical generation sectors to reduce the greenhouse gases [1]. To decrease the emission pollution of the power systems in generation and distribution sections, demand side management (DSM) strategies and renewable generators (RGs) are proposed. The international organizations are attempting in increasing the RGs penetration specially wind energy to meet the electrical energy demand with low emission pollution [2]. Employing RGs are developing in power systems regarding their cheap and cleaner electricity generation. The wind energy has the most positive effective on the economic and the environmental issues in comparison with other renewable energy sources [3]. With the establishment of smart grids in electricity industry and utilization of bidirectional communications between demand-side and supply, the new decision-making framework using the DSM strategies is prepared for the system operators in which they are enable to make optimal decisions using coordination between suppliers and consumers. The DSM strategies are employed to change the behaviour of customers in response to energy market price or emergency conditions of the system [4], [5].

The smart residential grids are smart small-scale form of distribution networks, which they integrate non-renewable and renewable sources to supply demand locally based on the optimal conditions. The smart residential grids play an important role in active distribution networks since they meet the demand of the network locally which reduces the purchased power from the main grid, reduces the power losses, and increases the reliability indices [6]. The smart residential grids can use from DSM strategies in the day-ahead scheduling problem to solve its challenges including contingencies problems, the forecast errors of the output power of RGs and high cost of fossil fuel resources [6], [7].

The DSM strategies encourage consumers to change their energy consumption pattern to minimize the total operation cost. These changes are including shifting load regarding the availability of output power of RGs for the decreasing the utilization of fuel fossil sources to minimize the costs.

The structure of the proposed smart buildings is depicted by Figure.1. The main participants in the smart buildings are as follows:

1. Controllable appliances: The controllable appliances can be shifted from peak demand to low demand. The air conditioners, optional lighting, oven and dryer are controllable loads

2. Generators units: The diesel generators (DGs), electrical storage system (ESS) and RGs such as photovoltaic (PV) and wind turbine (WT) are considered as main electrical generators.
3. Home energy management system (HEMS): The HEMS is coordinated with controllable appliances and generators units based on measured data by smart meter to energy management of the controllable appliances.

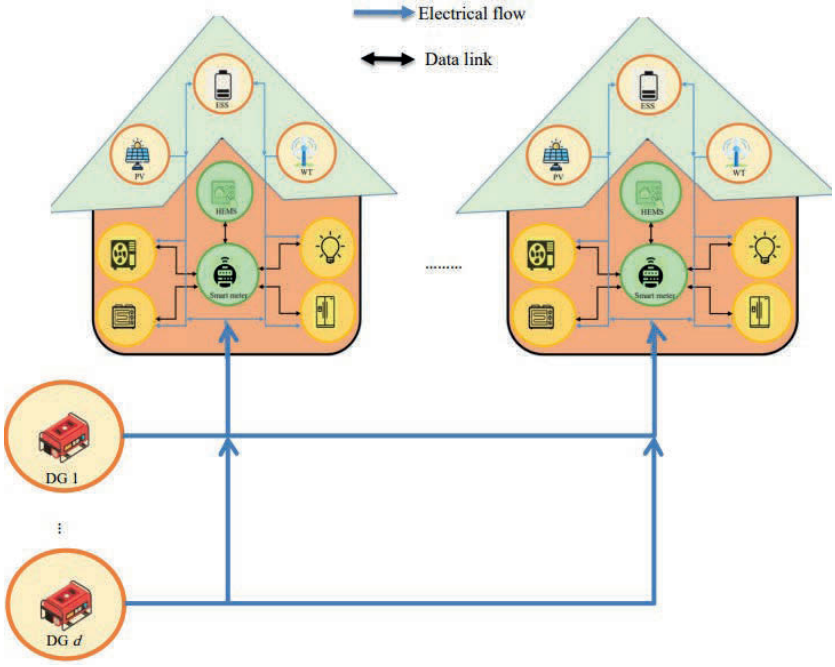


Fig. 1. Structure of the proposed smart buildings.

The studies which have been done on the electrical grids from different viewpoints such as models, optimization approaches and consumer's participation. In [8], a life cycle energy approach is proposed for the autonomous buildings to minimize the energy demand where different design configurations of energy resources such as energy storage capacity and PV systems are done using the post-processed optimization. In [9], the optimum sizing problem of HSS based on maximizing the recovery curtailed power generation of RGs in an autonomous electrical grid is solved using distributed algorithm (DA). The evolutionary particle swarm optimization (E-PSO) approach is used in [10] to minimize the total annual cost (TAC) of an autonomous tri-generation system consisting of RGs, cooling, and heating energy systems without consideration of the consumer's participation. The authors of [11] employed the grasshopper optimization algorithm (GOA) for the optimal design an energy generators-based autonomous system with the aim of minimizing the generation cost. In this study, the ESSs are optimally scheduled to manage the uncertainties of RGs. The net present cost of a system equipped with the PV systems is minimized regarding the uncertain behaviour of PV system in [12]. The HOMER software is used in [13] for the optimal planning of a stand-alone resources energy system. The optimal siting and sizing problem of the generation resources in the electrical system regarding the seasonal energy demand variations is done using the PSO approach in [14]. The authors of [15] proposed a new model

considering the economic and environmental indices to supply the demand of an electrical system using micro hydro systems.

This study presents economic modelling of the energy consumption in buildings considering controllable appliances energy scheduling in stand-alone electrical grids. The economic modelling is implemented via coordination of the energy generation of the renewable energies with controllable appliances by using demand shifting strategy (DSS). On the other side, uncertainty and stochastic modeming of the renewable energies are considered in the optimal coordination. Also, optimal coordination is modelled by multi-criteria problems of the technical and economic indices. The solving multi-criteria problem is done by fuzzy and augmented epsilon-constraint methods. Thus, contributions can be highlighted as follows:

1. Modelling stand-alone smart buildings by using multi-criteria problem.
2. Maximizing penetration of the RGs such as PV and WT by DSS.
3. Minimizing operation cost by DSS via optimal coordination of the controllable appliances with RGs.
4. Solving multi-criteria problem by the augmented epsilon-constraint method.
5. Maximum trade-off of the multi-criteria problem is determined by fuzzy method.

2. RGS FORMULATION

The RGs in this paper include WT and PV considering weather data. Hence, uncertainties of solar irradiance and wind speed in the stochastic approach are analysed [16].

2.1. WT formulation

The WT formulation considering wind speed is as follows [17]. The Weibull probability density function and WT output are modelled by Eq. (1) and Eq. (2), respectively.

$$f^{WT}(v)=\begin{cases}\dfrac{k}{c}\times\left(\dfrac{v}{c}\right)^{k-1}\times e^{-\left(\frac{v}{c}\right)^{k}} & v\geq 0\\ 0 & \text{otherwise}\end{cases} \tag{1}$$

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

2.2. PV formulation

Power generated by PV depends on solar irradiance, which solar irradiance by Beta probability density function is calculated in Eq. (3) and PV output by Eq. (4) [18].

$$f^{PV}(si)=\begin{cases}\dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}si^{\alpha-1}(1-si)^{\beta-1} & 0\le si\le 1,\alpha\ge 0,\beta\ge 0\\ 0 & \text{otherwise}\end{cases} \tag{3}$$

$$P_{PV}(si)=\eta_{\mathrm{PV}}\times S_{PV}\times si \tag{4}$$

For optimal coordination of the controllable appliances with RGs output, power generation of the PV and WT system must be merged in each time. So, merged power output of the RGs is modeled by Eq. (5).

$$P_{PW}(t)=P_{PV}(si,t)+P_{WT}(v,t) \tag{5}$$

3. ESS FORMULATION

The ESS formulation considering power charge and power discharge is modelled in Eq. (6).

$$\begin{cases}P_{ESS}^{dis}(t)/\eta_{\mathrm{dis}}\le P_{ESS}^{\max}\times\mu_{\mathrm{ESS}} & P_{ESS}(t)\ge 0\\ P_{ESS}^{ch}(t)\times\left(-\eta_{\mathrm{ch}}\right)\le P_{ESS}^{\max}\times(1-\mu_{\mathrm{ESS}}) & P_{ESS}(t)\le 0\end{cases} \tag{6}$$

4. MULTI-CRITERIA FORMULATION

In this stage, multi-criteria problem is modelled as operation cost, and RGs penetration maximization in the system. These objectives are optimized subject to constraints and participation of the consumers. The formulation of the modelling multi-criteria problem is as follows:

4.1. Operation costs

Minimizing costs of DGs and ESS is modelled as first objective as follows.

$$\begin{aligned}\min f_1=&\sum_{t=1}^{T}\left[\sum_{d=1}^{D}\left\{aP_d^2(t,d)+bP_d(t,d)+c\right\}\right]\\ &+\sum_{t=1}^{T}\left[\sum_{ess=1}^{ESS}\left\{C_{OP}^{ess}\times P_{ESS}^{dis}(t,ess)\right\}+\sum_{ess=1}^{ESS}\left\{C_{OP}^{ess}\times P_{ESS}^{ch}(t,ess)\right\}\right]\end{aligned} \tag{7}$$

4.2. RGs penetration

The second objective is RGs penetration maximization, which is modelled by (8). This objective is modelled based on coordination of the RGs output power with controllable appliances. By using equation (9), DSS can be done, and by equation (10) level of the DSS can be modelled.

$$\max f_2=1-\left\{\sum_{t=1}^{T}\frac{\left[\left|P_{PW}(t)-\sum_{cl=1}^{CL}D_{CL}(t,cl)\right|\right]}{D_{NRC}(t,ncl)+D_{CL}(t,cl)}\right\}, \tag{8}$$

where:

$$D_{CL}(t,cl) = \sum_{t'}\sum_{cl=1}^{CL} D_{CL}(t',t,cl) - \sum_{t'}\sum_{cl=1}^{CL} D_{CL}(t,t',cl), \tag{9}$$

$$0 \le \sum_{t'}\sum_{cl=1}^{CL} D_{CL}(t,t',cl) \le \Psi(t) \times \sum_{cl=1}^{CL} D_{CL}(t,cl). \tag{10}$$

4.3. Constraints of the system

The optimization of the pre-defined objectives is implemented subject to different constraints. The energy balance constraints between the electrical generation with electrical demand is modelled by Eq. (11), DG power limit, minimum up and down times of the DG, ramp up and down for DG are modelled by constraints (12)–(16), respectively.

$$\left\{\sum_{d=1}^{D} P_d(t,d) + \sum_{b=1}^{B} P_{ESS}^{dis}(t,b) - \sum_{b=1}^{B} P_{ESS}^{ch}(t,b) + \sum_{pw=1}^{PW} P_{PW}(t)\right\} = \left\{\sum_{cl=1}^{CL} D_{CLs}(t,cl) + \sum_{ncl=1}^{NCL} D_{NRC}(t,ncl)\right\} \tag{11}$$

$$0 \le P_d(t) \le P_d^{\max} \tag{12}$$

$$\mu^{\mathrm{On}}(t,d) + \sum_{\tau=t+1}^{\min(T,t-1+M^U)} \mu^{\mathrm{Off}}(\tau,d) \le 1 \tag{13}$$

$$\mu^{\mathrm{Off}}(t,d) + \sum_{\tau=t+1}^{\min(T,t-1+M^D)} \mu^{\mathrm{On}}(t,d) \le 1 \tag{14}$$

$$\sum_{t=1}^{T} P_d(t,d) - \sum_{t=1}^{T} P_d(t-1,d) \le RU \tag{15}$$

$$\sum_{t=1}^{T} P_d(t-1,d) - \sum_{t=1}^{T} P_d(t,d) \le RD \tag{16}$$

5. METHOD OF THE SOLVING PROBLEM

In the optimization process of the multi-criteria problem diverse solutions named as non-dominated solutions or Pareto front regarding the equality and the inequality constraints are generated. On the other hand, since the generated solutions for objective functions have the conflict nature, the decision maker should analyse the solutions considering the importance of objectives. There are many approaches to solve the multi-objective function problems including: 1) global criterion method, 2) weight sum method, and 3) intelligence algorithms such as CSOA, PSO, GA and etc. In this paper, the augmented epsilon-constraint approach is employed to generate the non-dominated solutions. In this approach, at first, the pay-off table or the maximum and the minimum values of each objective function must be calculated. Then, one of the objective functions is considered as the main objective and the others are considered as the constraints. In this case, the objectives range which are considered as the constraints are divided as the equal intervals to generate the grid points. Finally, the non-dominated solutions of objectives are obtained using the grid point of the constraints. The mathematical model of the augmented epsilon-constraint approach is as follows [19]:

$$\min\left\{ f_1(x) - \delta \sum_{n=1}^{N} \frac{s_n}{r_n} \right\} \qquad 10^{-6} \le \delta \le 10^{-3}, \tag{17}$$

where:

$$f_n(x) + s_n - \varepsilon_{\mathrm{n}}^{\mathrm{z}} \qquad n = 2,3,...,N; s_n \in R^+$$

$$\varepsilon_{\mathrm{n}}^{\mathrm{z}} = f_n^{\max} - \left\{ \frac{f_n^{\max} - f_n^{\min}}{q_n - 1} \right\} \times z \qquad z = 0,1,...,q_n \tag{18}$$

Here x, n, and δ are decision variable, nth objective function and the slack variable, respectively. And ε^{z}_{n}, r_n and q_n are zth range of nth objective, objectives range, and the equal intervals, respectively.

5.1. Fuzzy method

In this study, the fuzzy method based on the priority, the importance and the maximum compatibility of the objective functions are employed. The following steps should be implemented to select the best solution [20]:

1. The objective functions must be normalized by fuzzy approach using (19).
2. After normalization of the objectives, the maximum value between the membership functions based on the selected weights is determined as the best trade-off solution using (20).

$$\vartheta_n^m = \begin{cases} 1 & f_n^m \le f_n^{\min} \\ \dfrac{f_n^{\max} - f_n^m}{f_n^{\max} - f_n^{\min}} & f_n^{\min} \le f_n^m \le f_n^{\max} \\ 0 & f_n^m \ge f_n^{\max} \end{cases} \tag{19}$$

$$\vartheta^m = \frac{\sum_{n=1}^{N} \omega_n . \vartheta_n^m}{\sum_{m=1}^{M} \sum_{i=1}^{I} \omega_n . \vartheta_n^m} \qquad \sum_{n=1}^{N} \omega_n = 1, \qquad \omega_n \ge 0 \tag{20}$$

Here m and n are the number of solutions and the number of objectives, respectively; $\vartheta^m{}_n$ and $f^m{}_n$ are the membership function and the objectives value in nth objective and mth solution, respectively; $f_n^{\min}$ and $f_n^{\max}$ are the minimum and the maximum values in nth objective, respectively.

6. CASE STUDIES AND SIMULATION

To investigate the effectiveness of the proposed multi-criteria problem and its solution approach, the 25-node test system is considered as the test system as shown in Fig. 2. The resulted model is a mixed integer non-linear program (MINLP) model which it is solved in the GAMS software environment using the DICOPT solver by PC system Intel^{R} coreTM i5 system with CPU 2.5 GHz and 6 GB of RAM. To investigate the optimal decisions to coordination, two case studies are defined as follows:

– Case A) The optimal coordinating between RGs powers with controllable appliances is not considered.
– Case B) The optimal coordinating between RGs powers with controllable appliances is considered.

In Fig. 3, using the Monte Carlo method solar irradiance and wind speed via random numbers are forecasted for day-ahead. In Table 1, the information of the RGs is listed. Also, information of the ESS and DG is listed in Tables 2 and 3, respectively [21], [22]. In Fig. 4, the load demand in the system is shown.

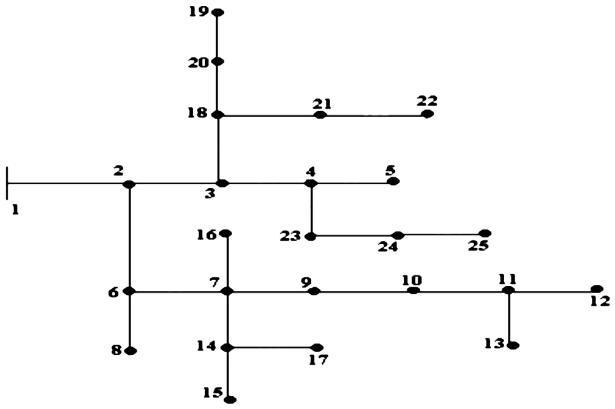


Fig. 2. 25-nodes stand-alone grid.

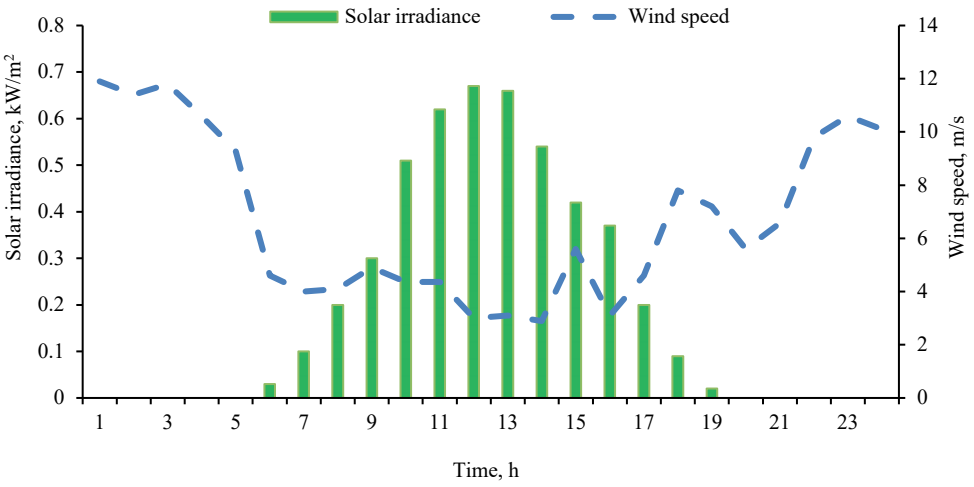


Fig. 3. Wind speed and solar riddance.

TABLE 1. RERS DATA

PV		WT	
Parameters	**Value**	**Parameters**	**Value**
S_{PV}	20 m^2	V_{Ci} , V_{Co}	1 m/s, 12 m/s
η_{PV}	25 %	V_R	4 m/s
$P_{N,PV}$	5 kW	$P_{N,WT}$	5 kW

TABLE 2. ESS DATA

Parameters	**Value**
P^{max}_{EES}	4 kW
η_{ch}	90 %
η_{dis}	95 %
C^{ess}_{OP}	20 $

TABLE 3. DGS DATA

Parameters	**a, $/kW²**	**b, $/kW**	**c, $**	**P^{max}, kW**	**M^U, Hour**	**M^D, Hour**	**Location, Node**
DG 1	47.5	87.8	127	100	15	5	3
DG 2	48.8	87.6	125	100	15	5	5
DG 3	48.3	92.1	128	100	15	5	8
DG 4	49.4	81.6	126	100	15	5	13

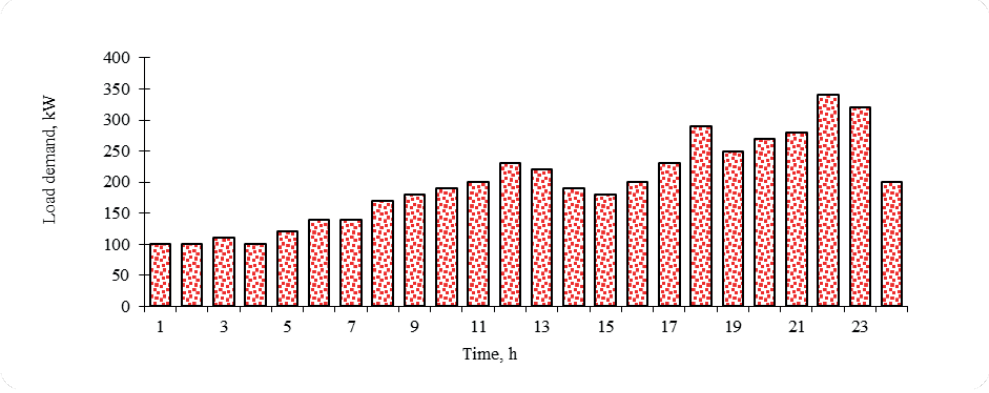


Fig. 4. Load demand in the system.

6.1. Results and discussion

The results of the applying the proposed approach on the test system in two case studies are presented in this sub-section as follows:

Case A) As mentioned before, controllable appliances and power of the RGs in Case A is not coordinated. Thus, costs of the ESS and DGs in first objective are only minimized. The value of the first objective (costs) in Case A is obtained by 587 686.32 $. The contribution of the ESSs and DGs in the total cost in Case A is equal to 2.1 % and 97.9 %, respectively. In following, can be seen excess energy generated of the RGs in Fig. 5, at hours 1:00–4:00 and 7:00 is injected to ESSs. The injected power by RGs to ESS has provided more charge cost

for ESSs at mentioned hours. On the other hand, ESSs at hours 20:00–24:00 are discharged for meet peak demand.

Case B) In this case, coordination of the RGs power output with controllable appliances in second objective function is considered. Hence, multi-criteria problems such as first and second objectives are minimized, simultaneously. The fuzzy and the augmented epsilon-constraint methods are proposed for solving multi-criteria problem. The obtained Pareto solutions from augmented epsilon-constraint method and the best trade-off solution are shown in Fig. 6. In the best trade-off solution, first and second objectives are equal to 569 324.3 $ and 45.1 %, respectively. The total costs for ESSs and DGs are equal to 3941.1 $ and 565 384.1 $, respectively. With coordination of the RGs' power with controllable appliances by using DSS, 3.12 % of the costs is minimized in comparison with Case A. Also, ESSs' costs and DGs' costs are minimized by 68.1 % and 1.73 %, respectively. These reductions of the costs are related to free operation of the RGs and meeting demand with RGs. The power generation in Case B is shown by Fig. 7. By implementing DSS, excess power of the RGs at times 1:00 and 2:00 is supplied to load demand. The DSS leads to maximize RGs' penetration in supplying demand in Case B.

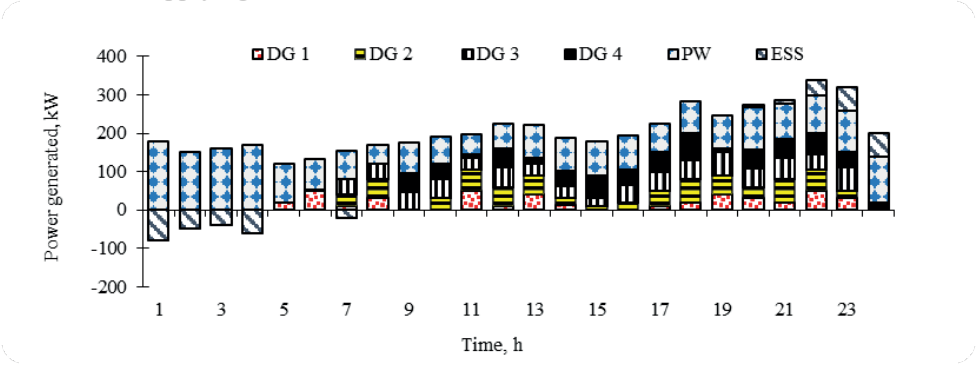


Fig. 5. Power generation in Case A.

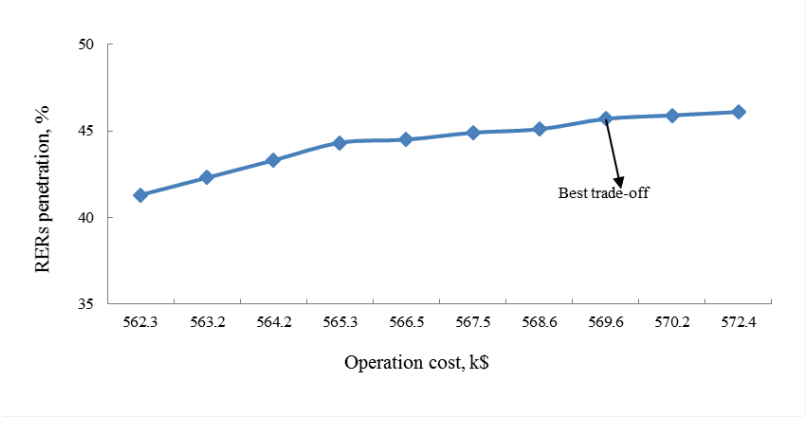


Fig. 6. Non-dominated Pareto solutions.

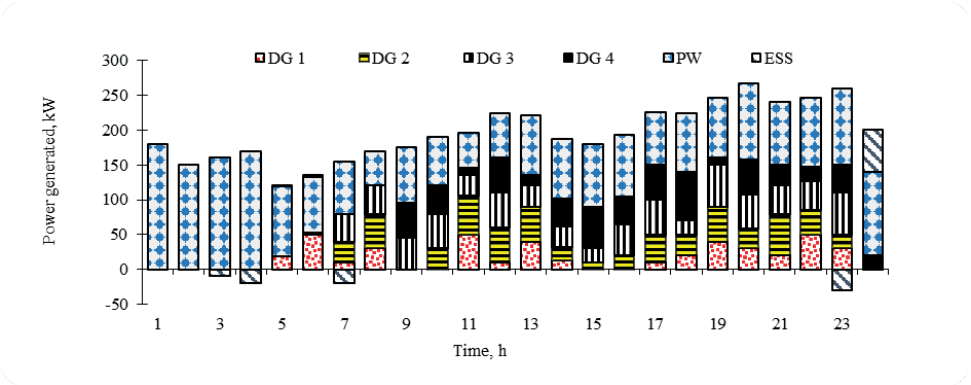


Fig. 7. Power generation in Case B.

7. CONCLUSION

This study presents economic modelling of the energy consumption in buildings considering controllable appliances energy scheduling in stand-alone electrical grids. The economic modelling is implemented via coordination of the energy generation of the renewable energies with controllable appliances by using demand shifting strategy (DSS). On the other side, uncertainty and stochastic modelling of the renewable energies are considered in the optimal coordination. Also, optimal coordination is modelled by multi-criteria problems of the technical and economic indices. Solving of the multi-criteria problem is done by fuzzy and augmented epsilon-constraint methods. According to the results, it can be concluded that participation of DSM can provide optimal state of system based on the RGs power generation which lead to increasing the flexibility of the system.

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