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Multi-objectives Optimal Scheduling in Smart Energy Hub System with Electrical and Thermal Responsive Loads

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Abstract **– In this study, multi-objective optimal scheduling of smart energy Hub system (SEHS) in the day ahead is proposed. A SEHS is comprising of interconnected energy hybrid system infrastructures such as electrical, thermal, wind, solar, natural gas and other fuels to supply many types of electrical and thermal loads in a two-way communication platform. All objectives in this paper, are minimized and consist of 1) operation cost and emission polluting in generation side, 2) loss of energy supply probability (LESP) in demand side, and 3) deviation of electrical and thermal loads with the optimal level of electrical and thermal profile in the day ahead. The third objective to flatten electrical and thermal demand profile using Demand Side Management (DSM) by the optimal shifting of electrical and thermal shiftable loads (SLs) is proposed. Also, stochastic modelling of renewable energy sources (RESs) and electrical and thermal loads by Monte Carlo technique is modelled. Using GAMS optimization software, proposed approach by ε-constraint method for obtaining to non-dominated Pareto solutions of objectives is implemented. Moreover, by the decision-making method, the best solution of non-dominated Pareto solutions is selected. Finally, two case studies and sensitivity analysis in case studies for confirmation of the proposed approach are analysed.**

Keywords **– Decision-making method, Demand Side Management (DSM), Multi-objectives optimal scheduling, Smart energy Hub system (SEHS), ε-constraint method.**

Nomenclature

Indices and sets

b, B	Index/set of Boiler
d, D	Index/set of DG
ess, ESS	Index/set of ESS
EG	Index/set of Electrical grid
m, M	Index/set of CHP units
NGG	Index/set of Natural gas grid
pv, PV	Index/set of Photovoltaic (PV)
t, T	Index/set of time period

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TG	Index/set of Thermal grid
tss, TSS	Index/set of TSS
s, S	Scenario indices
w, W	Index/set of Wind turbine (WT)
Parameters	
a, b, c	Cost factors of DGUs, which by other fuels are supplied
d, e, f	Emission factors of DGUs, which by other fuels are supplied
c_w	Scale index of WT
CO_2, SO_2, NO_x	The greenhouse gases consisting of carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x)
$D_E(s, t)$	Electrical demand in Scenario s and at time t (MW)
$D_T(s, t)$	Thermal demand in Scenario s and at time t, MW
$D_G(s, t)$	Natural gas demand in Scenario s and at time t, m^3
$D_E^{NRC}(s,t)$, $D_E^{RC}(s,t)$	Electrical demand of non-responsive customers and responsive customers in Scenario s and at time t, MW
$D_T^{NRC}(s,t)$, $D_T^{RC}(s,t)$	Electrical demand of non-responsive customers and responsive customers in Scenario s and at time t, MW
D_E^{OP}, D_T^{OP}	Optimal level of electrical and thermal demands, MW
$C_{ESS}^{OP}, C_{TSS}^{OP}$	Operating cost of ESS and TSS systems
$P_{N,WT}$	Total rated power of WT, MW
S_{PV}	Total area of PV, m^2
si	Solar irradiance, kW/m^2
v	Wind speed, m/s
V_R, V_{Ci}, V_{Co}	Rated speed, cut-in speed, cut-off speed of WT, m/s
α, β	Beta distribution function of PV
ξ_E, ξ_T	Participation level of RCs in electrical and thermal SLs shifting, %
η_{PV}	Efficiency of PV, %
π_p^{EG}	Electrical price in EG, $/MW
π_p^{TG}	Thermal price in TG, $/MW
π_p^{gas}	Natural gas price in NGG, $/$m^3$
$\eta_{dis}^{ESS}, \eta_{ch}^{ESS}$	Efficiency of ESS in discharge and charge state, %
$\eta_{dis}^{TSS}, \eta_{ch}^{TSS}$	Efficiency of TSS in discharge and charge state, %
σ_d, μ_d	Standard deviation and mean for the demand values

Decision variables	
C_B	Operation cost of boiler, $
C_m	Operation cost of CHP, $
C_{DG}	Operation cost of DG, $
C_{ESS}	Operation cost of ESS, $
C_{TSS}	Operation cost of TSS, $
C_{EG}	Operation cost of EG, $
C_{TG}	Operation cost of TG, $
C_{NGG}	The cost of purchased natural gas, $
$D_E^{RC}(s,t,t')$	Demand shifted of electrical SLs by RC at time t to t' in Scenario s, MW
$D_T^{RC}(s,t,t')$	Demand shifted of thermal SLs by RC at time t to t' in Scenario s, MW
E_B	Emission pollution of boiler, kg
E_m	Emission pollution of CHP, kg
E_{DG}	Emission pollution of DG, kg
E_{EG}	Emission pollution of EG, kg
E_{TG}	Emission pollution of TG, kg
E_{ESS}, E_{TSS}	Energy of ESS and TSS, MW/h
T_b	Thermal generated by boiler, MW
T_m	Thermal generated by CHP, MW
T_{TG}	Thermal generated by TG, MW
$P_{ESS}^{dis}, P_{ESS}^{ch}$	Electrical generated by ESS, MW
$T_{TSS}^{dis}, T_{TSS}^{ch}$	Electrical generated by ESS, MW
P_{PV}	Electrical generated by PV, MW
P_{WT}	Electrical generated by WT, MW
P_d	Electrical generated by DG, MW
P_m	Electrical generated by CHP, kW
P_{EG}	Electrical generated by EG, kW
G_{NGG}	Purchased natural gas by SEHS, m^3
$\rho_s^{PV}, \rho_s^{WT}, \rho_s^{L}$	Probability of PV, WT and demand in Scenario s
p_s	Probability of Scenario s
$\mu_{EES-dis}, \mu_{EES-ch}$	Binary variable of ESS in discharge and charge state
$\mu_{TSS-dis}, \mu_{TSS-ch}$	Binary variable of TSS systems in discharge and charge state
μ_{PST}, μ_{TST}	Binary variable of electrical and thermal shortage

1. INTRODUCTION

The bilateral dependence between energies and social sustainability matters, such as economic, environmental and supply demand issues, have stimulated energy operators to evaluate many types of investigations on an energy scheduling issue [1]. Hence, utilization of energy hybrid system can have an impact on economic, environmental and reliability indices of system based on customer's behaviour in the energy consumption. However, one of the best advancements in the smart grids, establishing Smart Energy Hub System (SEHS) as multi-applications to supply the demand side [2], [3]. The SEHS, using bilateral communication link between customers and generation units, is able to provide optimal coordination between units and customers participating in load profile transformation. The changing in load profile has directed the effect on optimal energy dispatch, and can increase the flexibility of system such as minimization of the generation cost, emissions and improving reliability. The Demand Side Management (DSM) has encouraged customers to manage their consuming at peak time in order to flatten the demand curve, and can balance the generation pattern and demand in optimal operation. Actually, using DSM generation side can be managed by the demand side, and increasing energy operator's authority on optimal energy management of system [3], [4].

Also, DSM strategies can decrease generation costs in energy markets and coordinate the activities of the energy operator and customers to control the demand loads for the prevention of employing of extra units. With the advent of diverse loads such as electrical and thermal loads DSM strategies will be fundamental tool and potentially in the future energy management. The loads shaping by DSM have several strategies, such as load shifting, flexible load shape, strategic load building, valley filling, strategic conservation and peak clipping. In Fig. 1. DSM strategies are shown [3], [4]. The mentioned strategies can be utilized with attention to high energy pricing, improving load factor and reliability, reducing emissions etc.

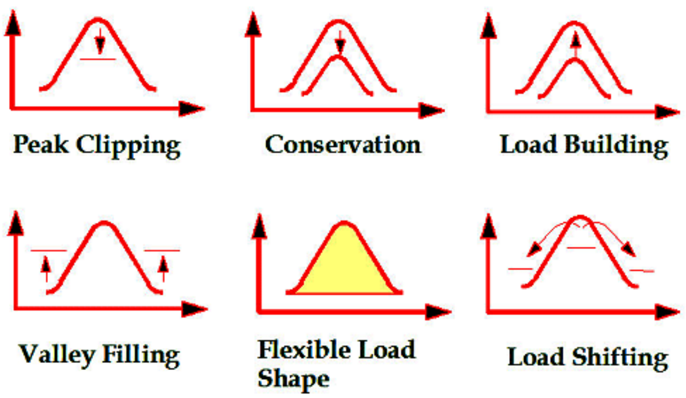


Fig. 1. Demand Side Management strategies [3].

1.1. Related Works

In this subsection a number of previous works on energy hybrid systems perspective have been introduced as a literature review; many of the namely on scheduling, management, operation, planning, design of energy systems. In [5], short-term optimal scheduling of SEHS with consideration of the risk constraints, in order to minimise operation costs is studied. In [6], the optimal energy management of micro-scale energy hybrid as available resources, prices and demand for minimum energy cost, using iterative algorithm (IA) is proposed. In [7], scheduling of the SEHS based on multi-step standardized modelling, and DSM by multiplying the coupling matrix by graph theory (GT) are investigated. The optimal operation-based probabilistic optimization in the SEHS in order to maximize the SEHS profit is studied in [8]. In [9] scheduling strategy of SEHS under conditional value-at-risk (CVaR) with attention to DSM modelling for reducing generation costs is presented. The optimization of SEHS in Canadian buildings' archetypes for minimizing costs and emissions is analysed in [10]. The optimal energy management of energy hybrid system in order to increasing security of the demand supply by converting power to gas (P2G) technology is proposed in [11]. In [12] using online dictionary-learning approach (ODLA), probabilistic energy flow of energy hybrid systems for management of total energy costs in a SEHS is studied. In [13] optimization model of SEHS with consideration peak clipping of thermal and electrical curtailable loads (CLs) and reducing costs, customers' payments are investigated. The load flow analysis of electrical and thermal networks by Newton-Raphson iterative method (NRIM) in the energy hybrid systems in order to optimal design of SEHS is evaluated in [14]. In [15] optimal scheduling model of the SEHS under chance-constrained optimization of the renewable energy sources (RESs) uncertainties to minimize the costs and system investment is proposed. The multi quintessential schemes as cluster of demand side, sharing market, and aggregation in the energy hybrid systems under probabilistic load forecasts for maximum-utility perspective is studied in [16]. In [17] stochastic optimization of SEHS with attention to energy market prices and wind generation uncertainties for maximization of expected benefit is investigated. In [18] two-stage stochastic optimization framework in the SEHS with consideration risk-constrained scheduling is studied. The short-term scheduling framework of SEHS based on stochastic pricing in energy market by information gap decision theory (IGDT) is proposed in [19]. The design of sustainable SEHS in order to obtaining optimal size of resources with consideration RESs uncertainty using Benders decomposition algorithm (BDA) is studied in [20]. In [21] multi-period operation optimization of the energy hybrid systems by Particle Swarm Optimization (PSO) algorithm and interior-point approach (IPA) is analysed. The co-optimization modelling of the energy hybrid system as two-stage robust planning-operation and with attention to lifetime of the electrical storage systems (ESSs) is studied in [22]. In [23] a SEHS based micro energy grid in presence of the electrical responsive loads as optimal operation in day-ahead is analysed. In [24] cooperative trading framework of the SEHS as game theory approach (GTA), and with attention to stochastic characteristics of the RESs is proposed. In [25] optimal operation of the energy hybrid system in presence of the plug-in hybrid electric vehicles (PHEVs) uncertainty and risk-seeking constraints is investigated. The scheduling of the electrical SLs and PHEVs in the energy hybrid system in order to minimization of generation costs is studied in [26]. In [27] optimal scheduling and planning in the SEHS with consideration and assessment of operation cost, emission polluting and energy not supplied (ENS) in single objective is focused. The stochastic economic optimization under uncertainties of wind energy, electrical and thermal market prices is proposed in [28]. In [29] multi-energy scheduling of SEHS in the building users by alternating direction method of multipliers (ADMM) algorithm with consideration customer's satisfaction and maximizing social welfare is studied. The bi-level scheduling optimization of the energy hybrid system as power and gas system integration in order to minimizes the operational cost is investigated in [30]. In [31] optimal co-scheduling for P2G units and natural gas-fired distributed power generators (NGDG) in the power system is studied. The bi-objectives scheduling optimization of the SEHS as minimization of the operation cost and emission without DSM strategy is evaluated in [32]. The multi-objective hybrid location with consideration *M/M/C* queuing framework and non-dominated sorting genetic algorithm

(NSGA-II) is proposed in [33]. The economic and reliability indices of the SEHS as bi-objectives by weight sum method (WSM) is presented in [34]. In [35] using Genetic Algorithm (GA), operation cost and emission of the energy hybrid system are optimized. In [36] and [37] by fuzzy satisfying techniques (FST), the best solution of the non-dominated solutions in economic and environmental objectives of the SEHS is selected. The impact of electrical load shifting on operation cost and emission in the SEHS is proposed in [38] [39]. Using modified teaching-learning based optimization (MTLBO) algorithm, economic and environmental issues of the energy hybrid system is optimized in [40]. The optimization of the energy use, operation cost and emission in the energy hybrid system using GA and WSM is studied in [41]. A multi-objectives problem as energy efficiency, environmental and economic in order to optimization operation in the SEHS is evaluated in [42], [43]. The optimal design of the energy hybrid system, with attention to economic, environmental and installation area problems is analysed in [44].

1.2. Contributions

In this paper, a new multi-objective of the SEHS day ahead scheduling with minimization of operation cost is proposed, as well as emission polluting in generation side as first objective, minimizing loss of energy supply probability (LESP) in demand side as a second objective; and flatten demand profile curve of electrical and thermal with minimization of deviation between total demand and optimal level as a third objective. Using electrical and thermal shiftable loads (SLs) deviation in third objective with optimal level can be minimized. Moreover, non-dominated Pareto solutions of objectives by ε-constraint method is generated, and by Decision-making method the best solution is selected. The main contributions of this study are listed as follows:

- Tri-objectives scheduling of the SEHS with consideration economic, and environmental issues, reliability and demand optimal scheduling is proposed.
- Scheduling of electrical and thermal shiftable loads (SLs) as objective function in order to flatten electrical and thermal demand profile is modelled.
- The ε-constraint method as solution method to generating non-dominated Pareto solutions is employed.
- The best solution is selected by Decision-making method.

1.3. Outline of the paper

The remaining sections of this paper are classified as follows: in section 2 SEHS overview is explained. The Uncertainty modelling of PV, WT and demand is proposed in section 3. The mathematical modelling of the proposed SEHS, including objective functions and constraints is presented in section 4. The ε-constraint method as the solution method and decision-making method are explained in section 5. The numerical simulation, case studies and sensitivity analysis are carried out in section 7. Finally, in section 8, conclusion is provided.

2. SEHS OVERVIEW

The overview of the SEHS is expressed in this section. The SEHS has several main elements, including distributed generation units (DGUs), electrical grid (EG), thermal grid (TG), natural gas grid (NGG), other fuels and the customers. All elements are connected to a bilateral communication link with system operator in order to optimal coordination between generation side and demand side at the time of operation. For example, an operator can inform the demand side or customers based on pricing in the electricity, thermal and natural gas in energy markets to appropriate react of the customers with attention to current status. The elements of SEHS discussed in this paper are as follows.

2.1. DGUs

Generally, DGUs are divided into three types: 1) dispatchable units such as combined heat and power (CHP) units, diesel generator (DG) units and boiler units, which are supplied by fuels fossil and have operation cost and emission in energy generation, 2) non-dispatchable units consist of wind turbines (WT) and photovoltaics (PV) system that power output of them depend on weather status, and 3) storage systems comprising electrical storage systems (ESSs) and thermal storage systems (TSSs), which only have operation cost in charge and discharge cycles [9].

2.2. EG, TG and NGG

The purchased energy from EG, TG and NGG can have diverse price at the time of operation, which operator is able to coordinating demand side with attention to energy price.

2.3. Customers

In this paper, two types of customers in demand side are considered: 1) responsive customers (RCs) that based on the status of the system have suitable reaction, 2) non-responsive customers, which have no reaction in the system. Since in this paper load shifting of DSM strategies is used for demand scheduling, RCs can be shifted, as well as electrical and thermal SLs such as washing machines, electric vehicles (EVs), dryers, heating and cooling loads in the diverse time operation, in order to provide optimal state of the system [45]. SEHS overview is shown in Fig. 2.

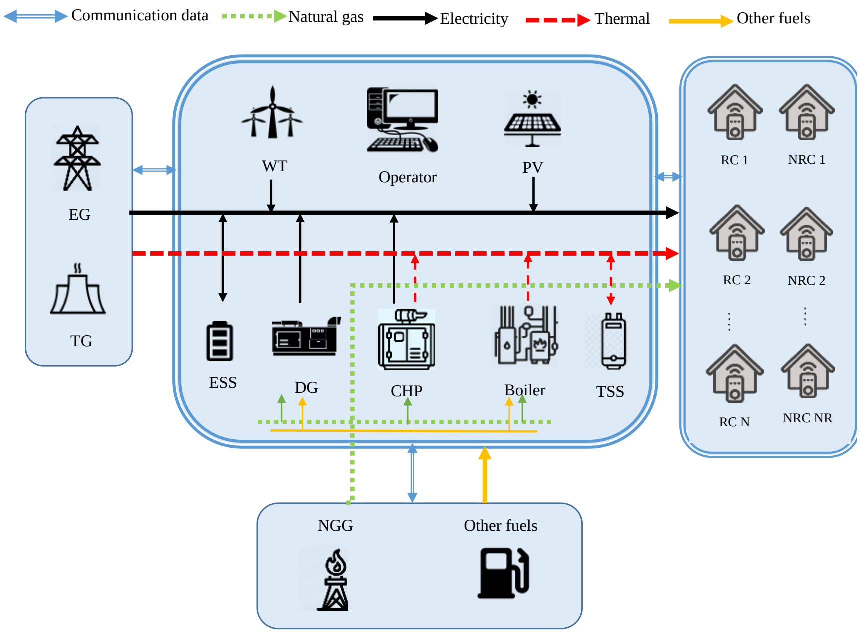


Fig. 2. Smart Energy Hub System overview.

3. UNCERTAINTY MODEL

In this paper, forecast of RESs output, electrical and thermal demands as scenario-based probabilistic modelling by Monte Carlo technique is used. Also, probability in each state, using Probability Density Function (PDF) is obtained.

3.1. PV model

The energy output of the PV based on solar irradiance is measured, and using Beta PDF solar irradiance is modelled, which is expressed by (1) [46], [47].

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

and energy output of PV is as follow:

$$P_{PV}(si) = \eta_{PV} S_{PV} si \tag{2}$$

3.2. WT model

The wind speed forecast by Weibull PDF is modelled, which by is given by (3) [47].

$$f^{WT}(v) = \begin{cases} \dfrac{k}{c_w}\left(\dfrac{v}{c_w}\right)^{k-1} \cdot e^{-\left(\frac{v}{c_w}\right)^k} & v \ge 0 \\ 0 & otherwise \end{cases} \tag{3}$$

and energy output of WT is as follow:

$$P_{WT}(v) = \begin{cases} 0 & if \quad v \le V_{Ci} \\ P_{N,WT}\left(\dfrac{v - V_{Ci}}{V_R - V_{Ci}}\right) & if \quad V_{Ci} \le v \le V_R \\ P_{N,WT} & if \quad V_R \le v \le V_{Co} \\ 0 & if \quad V_{Co} \le v \end{cases} \tag{4}$$

3.3. Demand model

Using Gaussian PDF, uncertainty of electrical and thermal demands is expressed as follow [47]:

$$L(d) = \frac{1}{\sqrt{2\pi\sigma_d^2}} e^{-\frac{(d-\mu_d)^2}{2\sigma_d^2}} \tag{5}$$

Therefore, the probability of PV, WT and demands in each scenario can be integrated as follow [48]:

$$\rho_s = \rho_s^{PV} \rho_s^{WT} \rho_s^{L} \tag{6}$$

4. OBJECTIVE FUNCTIONS

The main objectives in the SEHS are classified as tri-objectives and expressed as follow.

4.1. First objective

The minimization of operation cost, and emission polluting in generation side by first objective are modelled, as follows:

$$\begin{aligned} \min f_1 = & \sum_{s=1}^{S} \rho_s \sum_{t=1}^{T} \left(\sum_{d=1}^{D} C_{DG}(s,t,d) + \sum_{b=1}^{B} C_B(s,t,b) + \sum_{m=1}^{M} C_M(s,t,m) + C_{EG}(s,t) + C_{TG}(s,t) + \right. \\ & \left. C_{NGG}(s,t) + \sum_{ess=1}^{ESS} C_{ESS}(s,t,ess) + \sum_{tss=1}^{TSS} C_{TSS}(s,t,tss) \right) + \\ & \sum_{t=1}^{T} \left(\sum_{d=1}^{D} E_{DG}(t,d) + \sum_{b=1}^{B} E_B(t,b) + \sum_{m=1}^{M} E_M(t,m) + E_{EG}(t) + E_{TG}(t) \right) \end{aligned} \tag{7}$$

where

$$C_{DG}(s,t,d) = \left\{ aP_d^2(s,t,d) + bP_d(s,t,d) + c \right\} + \left\{ \pi_p^{gas} \times P_d(s,t,d) \right\} \tag{8}$$

$$C_B(s,t,b) = \left\{ aT_b^2(s,t,b) + bT_b(s,t,b) + c \right\} + \left\{ \pi_p^{gas} \times T_B(s,t,b) \right\} \tag{9}$$

$$C_m(s,t,m) = \left\{ \pi_p^{gas} \times (T_m(s,t,m) + P_m(s,t,m)) \right\} \tag{10}$$

$$C_{EG}(s,t) = \pi_p^{EG} P_{EG}(s,t) \tag{11}$$

$$C_{TG}(s,t) = \pi_p^{TG} T_{TG}(s,t) \tag{12}$$

$$C_{NGG}(s,t) = \pi_p^{gas} G_{NGG}(s,t) \tag{13}$$

$$C_{ESS}(s,t,ess) = \left\{ C_{ESS}^{OP} \cdot P_{ESS}^{dis}(s,t,ess) \right\} + \left\{ C_{ESS}^{OP} \cdot P_{ESS}^{ch}(s,t,ess) \right\} \tag{14}$$

$$C_{TSS}(s,t,tss) = \left\{ C_{TSS}^{OP} \cdot T_{TSS}^{dis}(s,t,tss) \right\} + \left\{ C_{TSS}^{OP} \cdot T_{TSS}^{ch}(s,t,tss) \right\} \tag{15}$$

$$E_{DG}(t,d) = \left\{ dP_d^2(t,d) + eP_d(t,d) + f \right\} + \left\{ \left(\mathrm{CO}_2^d + \mathrm{SO}_2^d + \mathrm{NO}_X^d \right) \cdot P_d(t,d) \right\} \tag{16}$$

$$E_B(t,b) = \left\{ dT_B^2(t,b) + eT_B(t,b) + f \right\} + \left\{ \left(\mathrm{CO}_2^b + \mathrm{SO}_2^b + \mathrm{NO}_X^b \right) \cdot T_b(t,b) \right\} \tag{17}$$

$$E_m(t,m) = \left\{ \left(\mathrm{CO}_2^m + \mathrm{SO}_2^m + \mathrm{NO}_\mathrm{X}^m \right) \cdot P_m(t,m) \right\} \tag{18}$$

$$E_{EG}(t) = \left\{ \left(\mathrm{CO}_2^{EG} + \mathrm{SO}_2^{EG} + \mathrm{NO}_\mathrm{X}^{EG} \right) \cdot P_{EG}(t) \right\} \tag{19}$$

$$E_{TG}(t) = \left\{ \left(\mathrm{CO}_2^{TG} + \mathrm{SO}_2^{TG} + \mathrm{NO}_\mathrm{X}^{TG} \right) \cdot T_{TG}(t) \right\} \tag{20}$$

The operation cost of DG units, boiler units, CHP units using (8)–(10) can be calculated, respectively. The purchased electrical power, thermal power and natural gas from EG, TG and NGG by (11)–(13) are expressed, respectively. The operation cost of ESS and TSS in discharging and charging states using (14) and (15) are modelled, respectively. The emission equations of DG units, boiler units, CHP units, the EG and the TG by (16)–(20) are modelled, respectively. The first parts of (8) and (9), some of DG units and boilers units by other fuels are supplied, and second parts by natural gas are supplied. Also, first parts of (16) and (17) emission generation by DG units and boilers units using other fuels are modelled, and second part is modelled by natural gas.

4.2. Second objective

In second objective, LESP is minimized, which in this objective based on shortage of electrical and thermal power to supplied demand in each scenario and time is modelled.

$$\min f_2 = \sum_{s=1}^{S} \rho_s \left\{ \left(\frac{\sum_{t=1}^{T} P_{ST}(s,t)}{\sum_{t=1}^{T} D_E(s,t)} \right) + \left(\frac{\sum_{t=1}^{T} T_{ST}(s,t)}{\sum_{t=1}^{T} D_T(s,t)} \right) \right\} \tag{21}$$

Here, first and second part of (21) are shortage of electrical and thermal powers in each scenario and time, respectively.

4.3. Third objective

The flatten electrical and thermal demand profile using minimization of deviation rather than an optimal level by third objective is modelled. In this objective, shifting of electrical and thermal SLs by RCs can be done.

$$\min f_3 = \sum_{s=1}^{S} \rho_s \left\{ \left(\sum_{t=1}^{T} \left| D_E(s,t) - D_E^{OP} \right| \right) + \left(\sum_{t=1}^{T} \left| D_T(s,t) - D_T^{OP} \right| \right) \right\} \tag{22}$$

where

$$D_E(s,t) = D_E^{NRC}(s,t) + D_E^{RC}(s,t) \tag{23}$$

$$D_T(s,t) = D_T^{NRC}(s,t) + D_T^{RC}(s,t) \tag{24}$$

$$D_E^{RC}(s,t) = \sum_{t'} D_E^{RC}(s,t',t) - \sum_{t'} D_E^{RC}(s,t,t') \tag{25}$$

$$D_T^{RC}(s,t) = \sum_{t'} D_T^{RC}(s,t',t) - \sum_{t'} D_T^{RC}(s,t,t') \tag{26}$$

$$0 \le \sum_{t'} D_E^{RC}(s,t,t') \le \xi_E \cdot \sum_{t=1}^{T} D_E^{RC}(s,t) \tag{27}$$

$$0 \le \sum_{t'} D_T^{RC}(s,t,t') \le \xi_T \cdot \sum_{t=1}^{T} D_T^{RC}(s,t) \tag{28}$$

$$D_E^{OP} = \frac{\sum_{t=1}^{T} D_E}{T} \tag{29}$$

$$D_T^{OP} = \frac{\sum_{t=1}^{T} D_T}{T} \tag{30}$$

Using (23) and (24) new electrical and thermal demand profile are obtained, respectively. The shifting of electrical and thermal SLs by RCs from time t to t' in (25) and (26) are modelled, respectively. In (27) and (28) the participation level of RCs in electrical and thermal shifting are given, respectively. The optimal level of electrical and thermal demand profile in day ahead by (29) and (30) are modelled, respectively.

5. CONSTRAINTS

Several constraints in SEHS are considered, which are as follow.

5.1. Energy balance

The energy balance constraint in order to covering of generation-side with demand-side in each scenario and time by (31)–(33) for electrical energy, thermal energy and natural gas are expressed, respectively.

$$\begin{aligned} &\sum_{d=1}^{D} P_d(s,t,d) + \sum_{m=1}^{M} P_m(s,t,m) + \sum_{ess=1}^{ESS} P_{ESS}^{dis}(s,t,ess) + P_{EG}(s,t) + \\ &\sum_{pv=1}^{PV} P_{PV}(s,t,pv) + \sum_{w=1}^{W} P_w(s,t,w) + P_{ST}(s,t) = \\ &D_E(s,t) + \sum_{ess=1}^{ESS} P_{ESS}^{ch}(s,t,ess) \end{aligned} \tag{31}$$

$$\sum_{b=1}^{B} T_b(s,t,b) + \sum_{m=1}^{M} T_m(s,t,m) + \sum_{tss=1}^{TSS} T_{TSS}^{dis}(s,t,tss) + T_{TG}(s,t) + T_{ST}(s,t) = T_D(s,t) + \sum_{tss=1}^{TSS} T_{TSS}^{ch}(s,t,tss) \quad (32)$$

$$G_{NGG}(s,t) - \sum_{d=1}^{D} P_d(s,t,d) - \sum_{m=1}^{M} P_m(s,t,m) - \sum_{b=1}^{B} T_b(s,t,b) = D_G(t) \quad (33)$$

5.2. Energy limitations

The constraints (34)–(41) indicate lower and upper energy limitation of DEGs, including DG units, boiler units, CHP units, ESSs and TSSs, respectively.

$$P_d^{\min} \le P_d(s,t,d) \le P_d^{\max} \quad (34)$$

$$T_b^{\min} \le T_b(s,t,b) \le T_b^{\max} \quad (35)$$

$$P_m^{\min} \le P_m(s,t,m) \le P_m^{\max} \quad (36)$$

$$T_m^{\min} \le T_m(s,t,m) \le T_m^{\max} \quad (37)$$

$$P_{dis}(s,t,ess) / \eta_{dis}^{ESS} \le P_{dis}^{\max} \cdot \mu_{ESS-dis}(s,t,ess) \quad (38)$$

$$P_{ch}(s,t,ess) \times \eta_{ch}^{ESS} \le P_{ch}^{\max} \cdot \mu_{ESS-ch}(s,t,ess) \quad (39)$$

$$T_{dis}(s,t,tss) / \eta_{dis}^{TSS} \le T_{dis}^{\max} \cdot \mu_{TSS-dis}(s,t,tss) \quad (40)$$

$$T_{ch}(s,t,tss) \times \eta_{ch}^{TSS} \le T_{ch}^{\max} \cdot \mu_{TSS-ch}(s,t,tss) \quad (41)$$

Using (38)–(41) discharge and charge state of ESSs and TSS can be obtained, respectively. In addition, ESSs and TSSs are not able to discharge and charge at same time; these constraints are expressed by (42) and (43).

$$\mu_{ESS-dis}(s,t,ess) + \mu_{ESS-ch}(s,t,ess) \le 1 \quad (42)$$

$$\mu_{TSS-dis}(s,t,tss) + \mu_{TSS-ch}(s,t,tss) \le 1 \quad (43)$$

The constraints of electrical and thermal energy shortage to supplied demand are as follow:

$$0 \le P_{ST}(s,t) \le D_E(s,t) \cdot \mu_{PST}(s,t) \quad (44)$$

$$0 \le T_{ST}(s,t) \le T_E(s,t) \cdot \mu_{TST}(s,t) \quad (45)$$

Here μ_{PST} and μ_{TST} are binary variable, and when they are equal to 1, energy shortage is occurred.

5.3. ESS and TSS technical constraints

Using (46) and (47) technical constraints of ESSs and TSSs including energy dynamic limitation are expressed [49]:

$$E_{ESS}^{\min} \leq E_{ESS}(s,t,ess) \leq E_{ESS}^{\max} \tag{46}$$

$$E_{TSS}^{\min} \leq E_{TSS}(s,t,tss) \leq E_{TSS}^{\max} \tag{47}$$

where

$$E_{ESS}(s,t,ess) = E_{ESS}(s,t-1,ess) + \left[P_{ESS}^{dis}(s,t,ess) / \eta_{dis}^{ESS} - P_{ESS}^{ch}(s,t,ess) \cdot \eta_{ch}^{ESS} \right] \tag{48}$$

$$E_{TSS}(s,t,tss) = E_{TSS}(s,t-1,tss) + \left[T_{TSS}^{dis}(s,t,tss) / \eta_{dis}^{TSS} - T_{TSS}^{ch}(s,t,tss) \cdot \eta_{ch}^{TSS} \right] \tag{49}$$

6. SOLVING THE PROBLEM

In order to solve the proposed multi objective functions, ε-constraint method is used in this paper. The mathematical modelling of ϵ-constraint method is used to introduce one of the objectives as main objective, and other objectives are divided into several segments; they are considered as inequality constraints. Then, the main objective is optimized in the inequality constraints and non-dominated Pareto solutions in each segment are obtained. In ε-constraint method, the optimization of the single objective is guaranteed with attention to other objectives that are assumed to inequality constraints. The step length in each segment is varied with consideration of different applications of the optimization modelling and the solving time. The modelling of the ε-constraint method is as follow [50]:

$$\min_{x \in X} f_j(x),$$

subject to

$$f_z(x) \leq \varepsilon_z \qquad z = 1, 2, ..., Z \qquad z \neq j, \tag{50}$$

where x, j and z are decision variable, main objective and other objectives in optimization process.

6.1. Decision-making method

Decision-making is a major tool for operators in order to achieve the optimal operation of systems. Since in this paper tri-objectives are optimized simultaneously, different non-dominated Pareto solutions in output of the problem are generated. Hence, the decision-making method is employed for selecting the best solution in the non-dominated solutions [51]. Fig. 3. has shown the selection of the best solution in bi-objective by decision-making method. The following steps should be performed in order to select the best solution:

1) Non-dominated Pareto solutions by (51) should be normalized;
2) Using (52), the minimum value of normalized non-dominated solutions is considered as ideal point (P_{Ideal}).

Equation (53) selects the minimum distance of k^{th} solution from the ideal point as best solution.

$$\Gamma_z^k = \frac{f_z^{\max} - f_z(k)}{f_z^{\max} - f_z^{\min}} \tag{51}$$

$$P_{Ideal} = \left\{ \min \Gamma_1^1 \quad \min \Gamma_2^2 \quad \ldots \quad \min \Gamma_z^k \right\} \tag{52}$$

$$\min Dis(k) = \sqrt{\left[\Gamma_1^1 - \min \Gamma_1^1\right]^2 + \left[\Gamma_2^1 - \min \Gamma_2^2\right]^2 + \ldots + \left[\Gamma_z^k - \min \Gamma_z^k\right]^2}, \tag{53}$$

where Γ_z^k and $f(k)$ are normalized of z^{th} objective in the k^{th} solution and value of objective in k^{th} solution, respectively.

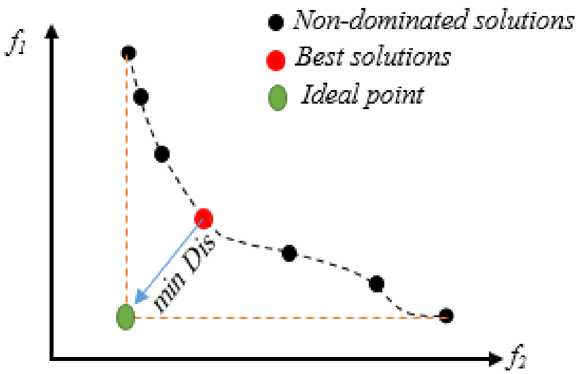


Fig. 3. Selecting the best solution by decision-making method.

7. CASE STUDIES AND NUMERICAL SIMULATION

In this section, case studies and numerical simulation in order to validation of proposed approach in the SEHS scheduling at 24-ahead by mixed integer non-linear program (MINLP) and DICOPT solver in GAMS software are implemented. The DGUs in the proposed SEHS are comprised three DG units, two boiler units, two CHP units, five WT, five PV, one ESS and one TSS, and also SEHS is connected to EG, TG and NGG. Two case studies based on the presence of objectives in the SEHS are considered:

- Case I – Optimization of first and second objectives,
- Case II – Optimization of first, second and third objectives (flatten electrical and thermal demand profile).

Since in this paper wind speed, solar irradiance, and electrical and thermal demand have uncertain nature, 10 scenarios to forecast of WTs output, PVs output and demand have been generated by Monte Carlo technique. On the other hand, in order to prohibit of exhibiting and large number, in tables and figures in total scenarios, results accosted with scenario 6 have been analysed. In Fig. 4 wind speed and solar irradiance is depicted. It should be noted, all WTs and PVs have same data, and data of WTs and PVs is listed in Table 1. Fig. 5 has shown electrical, thermal and natural gas price. In Table 2, the ESS and TSS data are provided. The demand of electrical, thermal and natural gas is shown in Fig. 6. It is worth mentioning that some of dispatchable units, such as DG 1, DG 2 and Boiler 1 by other fuels are supplied, the economic and environmental data of which is listed in Table 3. The environmental data of DG 3, Boiler 2, CHPs 1 and 2, EG and TG based on greenhouse gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) is provided in Table 4 (DG 3, Boiler 2, CHP 1 and 2 by natural gas are supplied). In Table 5, energy limitations of dispatchable units are listed. The participation level of RCs for shifting electrical and thermal SLs are considered equal to 70 % and 60 %, respectively.

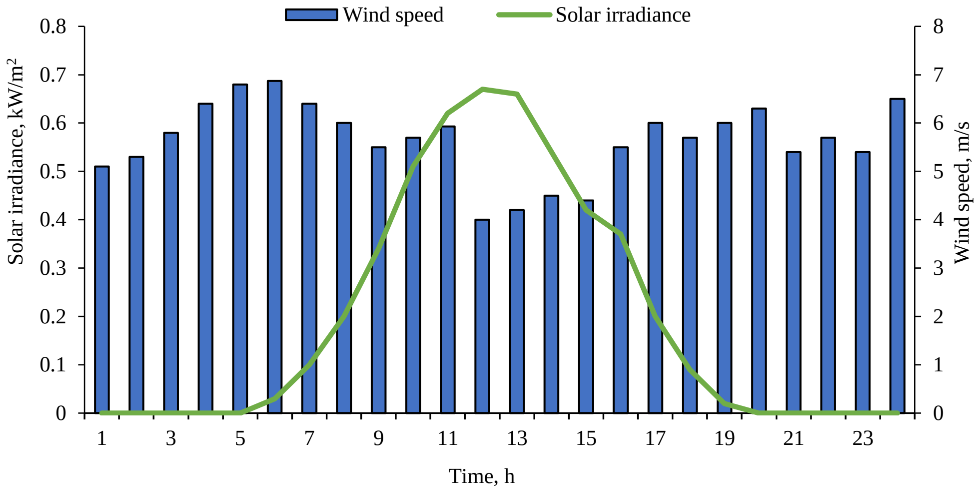


Fig. 4. Forecast of wind speed and solar irradiance in day ahead.

TABLE 1. WTS AND PVS DATA

PV		WT	
Parameters	**Value**	**Parameters**	**Value**
N_{PV}	5	N_{WT}	5
S_{PV}	45 m^2	V_{Ci} , V_{Co}	3 m/s, 20 m/s
η_{PV}	25 %	V_R	15 m/s
$P_{N,PV}$	0.5 MW	$P_{N,WT}$	1.2 MW

TABLE 2. ESS AND TSS DATA

ESS		TSS	
Parameters	**Value**	**Parameters**	**Value**
N_{ESS}	1	N_{TSS}	1
$P^{max}{}_{dis}$	1 MW	$T^{max}{}_{dis}$	0.5 MW
$P^{max}{}_{ch}$	1 MW	$T^{max}{}_{ch}$	0.5 MW
$E^{min}{}_{ESS}$	10 %	$E^{min}{}_{TSS}$	10 %
$E^{max}{}_{ESS}$	100 %	$E^{max}{}_{TSS}$	100 %
$\eta^{ESS}{}_{ch}$	90 %	$\eta^{TSS}{}_{ch}$	90 %
$\eta^{ESS}{}_{dis}$	95 %	$\eta^{TSS}{}_{dis}$	95 %
$C^{OP}{}_{ESS}$	140 $	$C^{OP}{}_{TSS}$	120 $

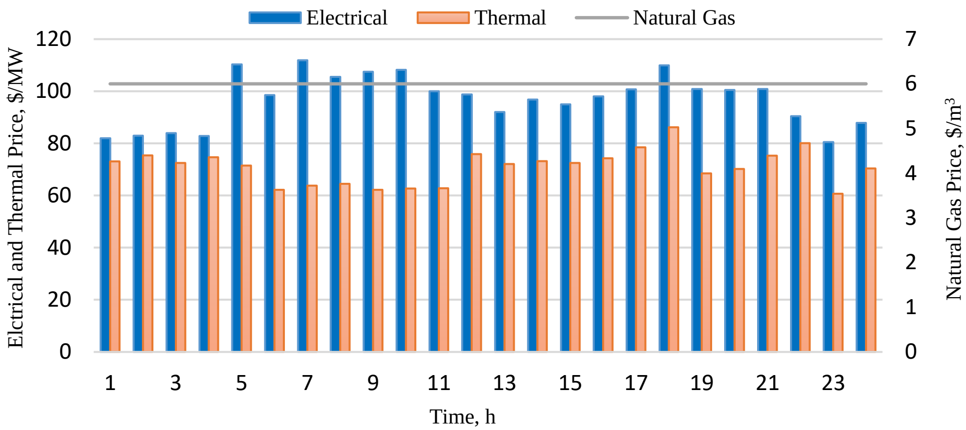


Fig. 5. Energy price in day ahead.

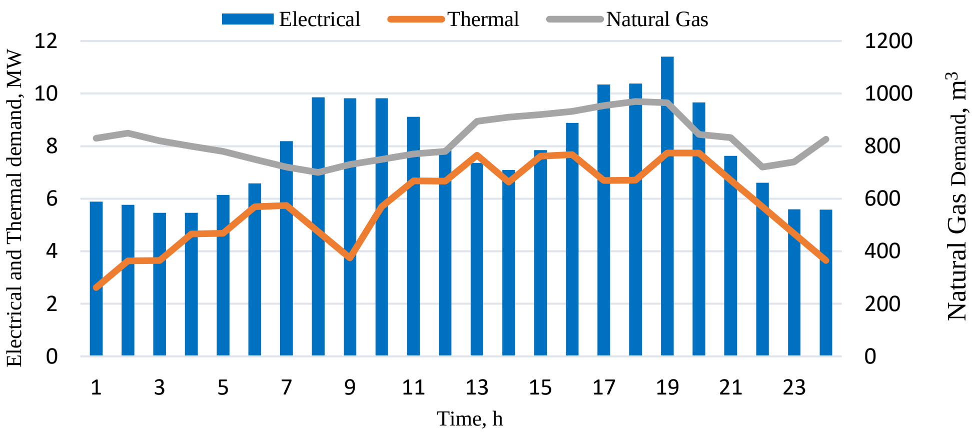


Fig. 6. Energy demand in SEHS.

TABLE 3. ECONOMIC AND ENVIRONMENTAL DATA OF DG 1, DG 2 AND BOILER 1

Parameters	***a*, $/MW²**	***b*, $/MW**	***c*, $**	***d*, kg/MW²**	***e*, kg/MW**	***f*, kg**
Units						
DG 1	25.5	140	102	21	154	108
DG 2	25.5	141	102	21	154	108
Boiler 1	20.5	95.7	100	21.5	90	105

TABLE 4. ENVIRONMENTAL DATA OF UNITS

Emission type	CO_2, kg/MW	SO_2, kg/MW	NO_x, kg/MW
Units			
DG 3	475.5	3.42	1.94
Boiler 2	490.3	3.54	1.26
CHP 1	468.5	3.21	0.79
CHP 2	469.2	3.15	0.15
EG	970.5	7.25	2.75
TG	951.4	7.31	1.69

TABLE 5. ENERGY LIMITATIONS OF DISPATCHABLE UNITS

Parameters	P^{min}, MW	P^{max}, MW	T^{min}, MW	T^{max}, MW
Units				
DG 1	0	0.7	–	–
DG 2	0	0.7	–	–
DG 3	0	0.53	–	–
Boiler 1	–	–	0	0.65
Boiler 2	–	–	0	0.54
CHP 1	0	0.55	0	0.51
CHP 2	0	0.53	0	0.51

7.1. Results analysis

In this subsection, results of numerical simulation in each case studies are discussed and case studies are compared with each other.

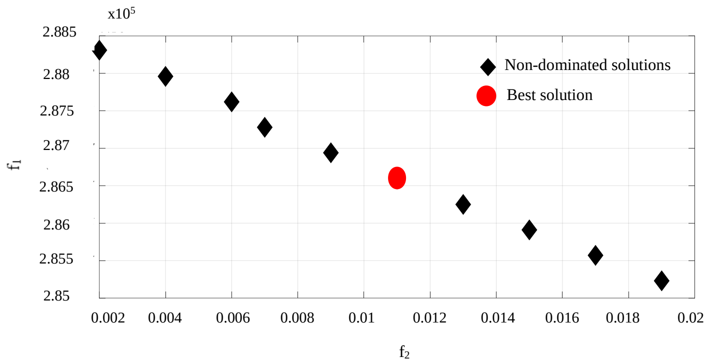
Case I) In Case I, first objective, including operation costs and emission polluting in scheduling of generation side, and also LESP as a second objective are minimized. Fig. 7(a) depicts generated non-dominated solutions using ε-constraint method. Using the decision-making method, the best solution of non-dominated solutions with minimum distance 0.7142 from ideal point is selected. The value of first and second objectives in the selected solution are equal to 286 595.27[†] MW and 0.011 MW, respectively. The operation costs of DG 1, DG 2, DG 3, Boiler 1, Boiler 2, CHP 1, CHP 2, ESS, TSS, purchased electrical from EG, purchased thermal from TG and purchased natural gas from NGG are equal to 3740.53 $, 3742.46 $, 64 $, 2193.6 $, 77.12 $, 152.64 $, 145.77 $, 3360 $, 1440 $, 3126.45 $, 5764.32 $ and 118 225 $, respectively. Also, emission generated by DGs, boilers, CHPs, EG and TG are 12 816.33 kg, 13 714.73 kg, 11731.62 kg, 30 331.33 kg and 75 969.37 kg, respectively. It is clear that maximum operation cost and emission polluting are related to natural gas purchased from NGG and TG, respectively. It can be said that high natural gas demand has direction effect on the operation cost. On the other hand, due to an uncertain nature of RESs and demand, energy shortage for meet demand, only occur in electrical power generation.

The generated electrical power of DGUs and EG to supply electrical demand is shown in Fig. 7(b). The shortage of electrical power at hours 17:00 to 19:00 is done, and total value of it at mentioned hours is equal to 2.1 MW. On the other hand, after RESs in meet electrical demand,

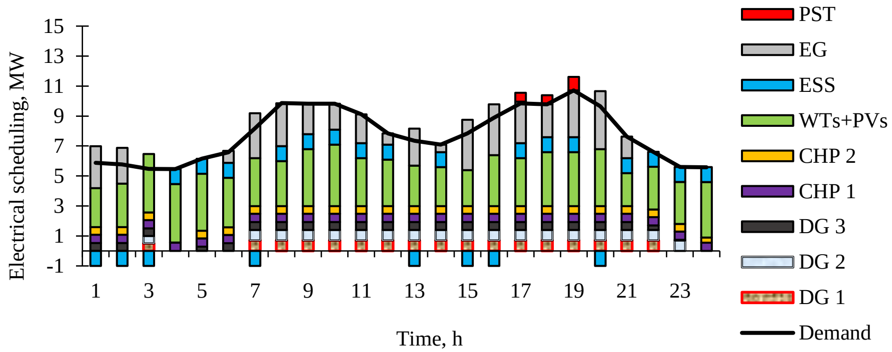
[†] First objective function including cost, and emission, therefore we are not considering unit for it.

EG has maximum participation covering electrical demand compared with dispatchable units, which power purchased from EG is 30.934 MW.

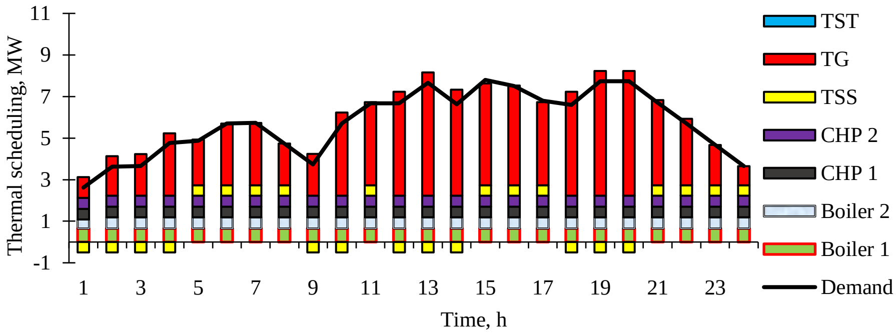
The thermal power generation of DGUs and TG in Fig. 7(c) is shown. As figure illustrates, maximum participation to meet thermal demand is related to TG, which total generated thermal by TG is 79.101 MW.



(a)



(b)



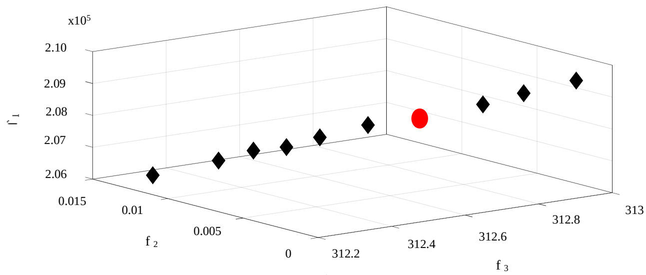
(c)

Fig. 7. (a) Selection of best solution in Non-dominated solutions in Case I, (b) Electrical power generated in Case I and (c) Thermal power generated in Case I.

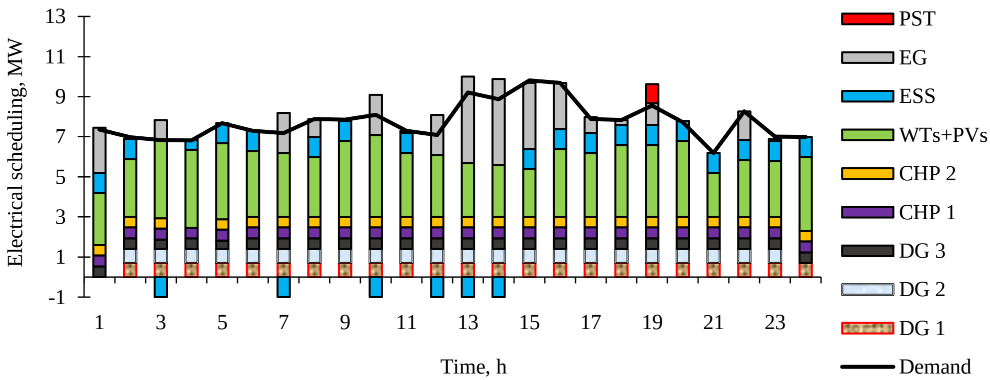
Case II) In this case, all objectives comprising scheduling of generation side, reliability and demand side as simultaneous in the SEHS are optimized. Fig. 8(a) illustrates ten generated non-dominated solutions of objectives by ε-constraint method, in which seventh solution with minimum distance 0.7731 from ideal point, using the decision-making method is determined. The operation cost and emission polluting in generation side in this case study are 140 510.75 $ and 67 124.98 kg, respectively. The LESP, only in electrical energy is done, and total value of it, is equal to 0.005 MW. The deviation of third objective, in order to flatten electrical and thermal demand curve in selected solution, is 312.11 MW. The respective operation costs of boilers, TSS, EG and TG are reduced with quantity 5.16 %, 0.97 %, 34.26 % and 79.9 % than Case I, respectively. In addition, the reduction of emission polluting production in boilers, EG and TG, are 21.05 %, 29.71 % and 81.48 % in comparison with Case I.

The schedulling of electrical demand and electrical power generated by DGUs and EG is depicted in Fig. 8(b). As shown, the electrical demand has more flattened curve than Case I, the total electrical power shortage is 0.95 MW and only occurs at hour 19:00. The purchased electrical power from EG in this case 9.05 % is less than Case I.

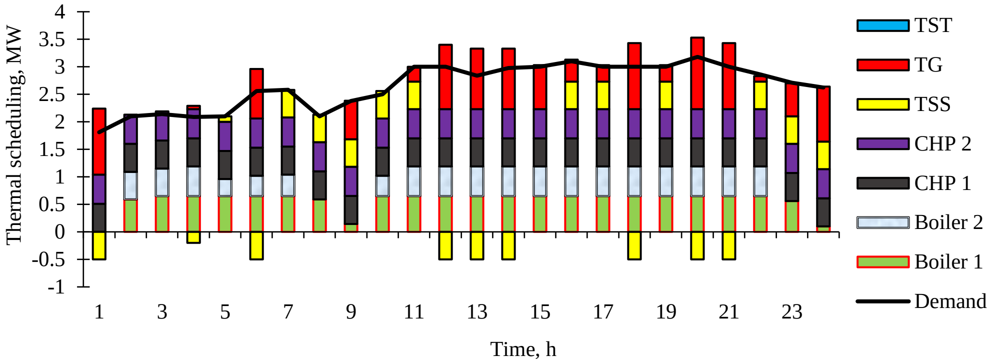
In Fig. 8(c), scheduling of thermal demand and generated thermal power by DGUs and TG is shown. The thermal generated by TG in this case is equal to 14.1 MW, which 82.17 % is less than Case I. On the other hand, participation of Boilers 1 and 2 in order to meet thermal demand, 12.71 % and 26.38 % are reduced in comparison with Case I, respectively.



(a)



(b)



(c)

Fig. 8. (a) Selection of best solution in Non-dominated solutions in Case II, (b) Electrical power generated in Case II and (c) Thermal power generated in Case II.

7.2. Sensitivity analysis in case studies

In this subsection, sensitivity analysis in each case study is investigated. Hence, changing in parameters can have an impact on the objectives, and operator in SEHS must have appropriate decisions with attention to changes in these parameters. Therefore, case specifications such as sensitivity analysis based on increasing electrical, thermal and natural gas pricing are listed in Table 6. In the meantime, in Case II, participation level in shifting of electrical and thermal SLs by RCs, 25 % and 20 % are increased, respectively.

TABLE 6. SENSITIVITY ANALYSIS IN EACH CASE STUDY

	Case I		**Case II**		
Case Specifications	f_1	f_2	f_1	f_2	f_3
Base Case	286 595.27	0.011	207 635.73	0.005	312.11
50 % increasing electrical price	288 511.57	0.011	207 553.11	0.003	312.25
50 % increasing thermal price	290 300.54	0.011	207 501.01	0.003	312.47
100 % increasing gas price	406 230.79	0.011	326 723.37	0.003	312.57

It is clear that the first objective in Case I, 0.66 %, 1.27 % and 29.45 % is increased, in 50 % increasing electrical price, 50 % increasing thermal price and 100 % increasing gas price in comparison with base case, respectively. On the other hand, Case II has optimal value in its objectives than Case I.

8. CONCLUSION

In this study, economic, environmental and reliability scheduling, as well as demand performance appraisal with DSM strategy of a SEHS in day ahead have been analysed. The multi-objectives are minimized and classified as 1) operating cost and emission polluting, 2) LESP; and 3) deviation of electrical and thermal SLs with optimal level in day ahead. The third objective in order to flatten electrical and thermal demand curve with participation of RCs and by load shifting of DSM is modelled. Hence, to solving objectives, using the ε-constraint method, non-dominated solutions are generated and the best solution by decision-making method is selected. Two case studies are taken into account in order to perform a validation of the proposed modelling and approach in numerical simulation, the results of which are demonstrated as follow:

Case I. First and second objectives are optimized, which means operation cost, emission and LESP in selected solution are equal to 142 031.89 $, 144 563.38 kg and 0.011 MW, respectively.

Case II. First and second objectives beside third objective is optimized, and 1.07 % of operation costs, 53.56 % of emission and 54.54 % of LESP are decreased in comparison with Case I, respectively.

Also, sensitivity analysis is studied in Cases I and II, in which Case II with attention to changing parameter such as energies price has more optimal level than Case I.

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