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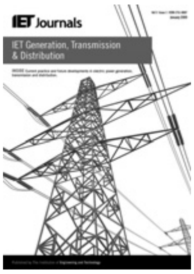

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Environmental/economic dispatch incorporating renewable energy sources and plug-in vehicles

Amin Gholami[1], *Javad Ansari*[1], *Mahdi Jamei*[2], *Ahad Kazemi*[1]
[1]*Centre of Excellence for Power System Automation and Operation, School of Electrical Engineering, Iran University of Science & Technology, Tehran, Iran*
[2]*College of Engineering & Computing, Electrical and Computer Engineering Department, Florida International University, USA*
E-mail: amin_gholami@elec.iust.ac.ir

Abstract: Transportation and electricity industries are considered as major sources of greenhouse gases (GHGs) emission. Different methods have been proposed to deal with the increasing rate of the emission, such as employing plug-in electric vehicles (PEVs) and integrating renewable energy sources (RESs). However, it is important to scrutinise different scenarios of incorporating the mentioned elements to decrease the concerning emission rate while considering the economic constraints. In this study, a combined economic emission dispatch (CEED) is employed to investigate the effectiveness of using PEVs and RESs from different aspects. A sensitivity analysis is executed to survey the influence of emission and cost coefficients. Two test cases each including different scenarios are simulated to determine the efficacy of different types of integration in the proposed model. To have a more accurate and realistic survey, an extended model of the wind farm's cost function is employed in economic dispatch calculations. The particle swarm optimisation algorithm is applied to solve the CEED non-linear problem. The obtained results indicate that the integration of PEVs cannot necessarily reduce the net emission of two industries. In fact, the optimum solution should include the incorporation of PEVs along with RESs to return the desired results.

Nomenclature

Variables and functions

OF	objective Function
TC	total Cost
TE	total Emission
$D(t)$	demand of network at hour t
$P_i(t)$	generating power of ith unit at hour t
$P_{\mathrm{loss}}(t)$	active power losses at hour t
w_i	scheduled wind power of ith wind farm
$W_{i,\mathrm{av}}$	available wind power of ith wind farm
$C_{w,i}(w_i)$	cost function for ith wind farm
$C_{p,w,i}(W_{i,av} - w_i)$	penalty cost because of underestimation of wind power for ith wind farm
$C_{r,w,i}(w_i - W_{i,\mathrm{av}})$	reserve cost because of overestimation of wind power for ith wind farm
v	wind speed
$f_w(w)$	PDF of the WECS output power
$\Psi_{\mathrm{pre}}/\Psi_{\mathrm{dep}}$	present/departure state of PEVs' battery charge
$P_j^{\mathrm{PEV}}(t)$	power of jth vehicle
$N_{\mathrm{PEV}}(t)$	number of PEVs connected to the grid at hour t

Constants

ω_c	cost coefficient
ω_e	emission coefficient
a_i, b_i and c_i	positive fuel cost coefficients of ith unit
α_i, β_i, γ_i, ξ_i and λ_i	GHGs emission coefficients of ith unit
A	emission curve coefficient
$P_{i_{\min}}$	minimum generating power of ith unit
$P_{i_{\max}}$	maximum generating power of ith unit
N_{WF}	number of wind farms
N	number of thermal units
$w_{r,i}$	rated wind power of ith wind farm
B	symmetric loss coefficient matrix
B_0	loss coefficient vector
B_{00}	constant loss coefficient
d_i	direct cost coefficient for ith wind farm.
$k_{p,i}$	penalty cost coefficient because of the underestimation of wind power for ith wind farm in \$/MW
$k_{r,i}$	reserve cost coefficient because of the overestimation of wind power for ith wind farm in \$/MW
$\rho = w/w_i$	ratio of wind power output to rated wind power
$l = (v_r\text{-}v_i)/v_i$	ratio of linear range of wind speed to cut-in wind speed
k, c	Weibull shape and scale factors
η	system efficiency
$N_{\mathrm{PEV}}^{\max}$	maximum number of PEVs at a certain period of time

1 Introduction

In recent years, the power industry has faced many economic and environmental issues. Increasing fossil fuels' cost and environmental laws, such as the Kyoto Protocol [1] and Low Carbon Transition Plan [2], have forced governments to move towards wide utilisation of renewable energy sources (RESs). Depletion of the global energy reserves is another critical issue in the field of energy. As a result, many plans such as '20-20-20' by the European Union have been enacted around the world [3]. Deployment of the next-generation of plug-in electric vehicles (PEVs), which includes plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) with vehicle to grid (V2G) capability, seems to be an appropriate solution to this problem. PEVs are rapidly developing and penetrating to the fleet transportation. From 2008 to 2013, more than 116 000 plug-in-electric cars have been sold in the United States [4]. In 2011, President Barack Obama set the goal for the U.S. to become the first country to have 1 million EVs on the road by 2015 [5]. Consequently, the U.S government started investing a lot of money on this section to accomplish the aims. For example, it has pledged US $2.4 billion in federal grants to support the development of next-generation electric cars and batteries, and US$115 million for the installation of electric vehicle charging infrastructure [5]. The first nationwide detailed analysis of PHEVs probable impacts on greenhouse gases (GHGs) emission is performed in [6]. The potential quota of PHEVs and battery electric vehicle (BEV) in GHG reduction over the next decade in Canada is studied in [7] under some assumptions. The influence of PHEVs fleet relative on production cost and emission of the electricity sector is surveyed in [8]. The results illustrate a notable regional difference between the cost impacts and the CO_2 emissions [8].

The effects of EVs are studied in the past literature from different aspects. In [9], a new smart load management approach for the coordination of multiple PEV chargers in distribution feeders is proposed. In [10, 11], PEVs operate as a reserve to help the load shaving and regulation. In [12], the effect of PHEVs on the load curve, generation capacity and cost has been analysed. In [13], two studies are conducted to quantify the impact of PHEVs on the power grid. The first study quantifies this impact in terms of (i) primary fuel utilisation shifts, (ii) pollution shifts and (iii) total cost for consumers. In the second study, the impact on distribution transformers is quantified through a loss-of-life (LOL) calculation that is based on the transformers hot-spot temperature. In [14], an intelligent method has been proposed to schedule the usage of available energy storage capacity from PHEVs and EVs.

This paper challenges the common conclusion obtained by the literature that PEVs reduce GHGs emission significantly in all modes of integration [6, 7, 15]. However, a few studies have alluded to this issue briefly but did not go through the details to explain the reasons for this claim [8, 16]. Actually, in this paper, it is indicated that the net emission produced by two industries can be increased in the presence of PEVs depending on the network topology and operation planning. The reason is the extra demand for the electricity imposed on the grid by connecting PEVs and consequently consuming more fossil fuels by conventional units to supply the added load. The incremental emission function of the conventional units is the key reason for this increase, since when the generating power exceeds nominal value the produced emission rate will increase per each unit of power. However, it is highly dependent on some factors, including network topology and operation goals. The effect of these factors is indicated obviously in the case study, and discussion sections in detail. Therefore the main contribution of this paper is to provide the fact that PEVs cannot reduce GHGs emission in all load management cases and networks.

Economically, employing PEVs can impose incremental costs because of the extra power required to charge the vehicles. It can also necessitate new power plants being installed if the peak load is highly increased, and that would be very costly. In this paper, it is shown that integration of RESs (mainly wind and solar) will lead to production cost and emission reduction that is predictable. Finally, the results demonstrate that implementation of PEVs cannot reduce emission and production cost unless they can be utilised, along with the RESs. In fact, two important specifications of the smart grid are mentioned in standards [17, 18], that is, RESs and PEVs are surveyed simultaneously in this paper in detail. In order to obtain precise and more realistic results, a new model of wind farm (WF) is used for economic dispatch (ED). Owing to the non-linearity of this ED problem caused by the proposed WF cost function, the particle swarm optimisation (PSO) algorithm [19] is applied to the combined economic emission dispatch (CEED) optimisation. The PSO is selected because of the high ability in finding the best result, more computational efficiency (uses fewer function evaluations) compared to the other methods such as the genetic algorithm (GA), and less computational effort to reach accurate solutions [20]. The authors avoid explaining the concepts related to the PSO, since they are known and mentioned in many papers.

The rest of this paper is organised as follows: Section 2 describes the CEED problem formulation, introduces the WF cost function and makes an appropriate model of the PEV. In Section 3, numerical examples and simulation results are presented. Section 4 contains a discussion on obtained results and sensitivity analysis of effective factors. Finally, the conclusion is given in Section 5.

2 Problem formulation

2.1 Combined economic emission dispatch

In this study, the objective function is set to be the minimisation of the generation cost and emission, as given in (1). For a specified power plant, both cost and emission can be expressed as a quadratic function, as described in (2) and (3), respectively; subject to (4) and (5) as physical and operating constraints [21, 22]

$$\mathrm{OF} = \omega_c \mathrm{TC} + \omega_e \mathrm{TE} \tag{1}$$

$$\mathrm{TC} = \sum_{i=1}^{N} a_i + b_i P_i(t) + c_i P_i^2(t) \tag{2}$$

$$\mathrm{TE} = \sum_{i=1}^{N} \left(A \times \left(\gamma_i P_i^2(t) + \beta_i P_i(t) + \alpha_i \right) + \xi_i \times \exp\left(P_i(t) \times \lambda_i\right) \right) \tag{3}$$

$$D(t) = \sum_{i=1}^{N} P_i(t) + P_{\mathrm{loss}}(t) \tag{4}$$

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$$P_{i_{\min}} \le P_i(t) \le P_{i_{\max}} \tag{5}$$

$P_{\text{loss}}(t)$ can be expressed in the quadratic form given below using the $\boldsymbol{B}$-matrix loss coefficient

$$P_{\text{loss}}(t) = \sum_{i=1}^{N} \sum_{j=1}^{N} P_i(t) B_{ij} P_j(t) + \sum_{i=1}^{N} B_{0i} P_i(t) + B_{00} \tag{6}$$

2.2 Wind farm cost function

In the literature, WF is modelled as a negative load regardless of any flawed estimation cost [23, 24], but it is not compatible with reality because of the uncertain nature of the wind speed and the WF output. Underestimation and overestimation of the available wind energy, which may happen as a result of WF's imperfect modelling, can impose additional costs on a private owner who participates in the electricity market. For this reason, it is necessary to model WF in a more detailed and accurate manner. In this study, a new WF cost function has been proposed in the ED formulation, which is composed of three sub-objective terms described in (7) [25].

$$\begin{aligned} C = {} & \sum_{i=1}^{N_{\text{WF}}} C_{w,i}(w_i) + \sum_{i=1}^{N_{\text{WF}}} C_{p,w,i}(W_{i,\text{av}} - w_i) \\ & + \sum_{i=1}^{N_{\text{WF}}} C_{r,w,i}(w_i - W_{i,av}) \end{aligned} \tag{7}$$

The first term is the cost that the system operator must pay to the WF owner against the generated power. This cost function is modelled linearly as indicated in (8)

$$C_{w,i}(w_i) = d_i w_i \tag{8}$$

In [25, 26], it has been shown that the total generation cost of a WF is around 57% of that for a thermal plant with similar generation capacity, which can be chosen accordingly as the cost coefficient in the optimal dispatch formulation.

The second and third terms in (7) are related to the uncertain nature of the WF power output given in (9) and (10). (9) is supposed to be a penalty cost function for not using all the available wind power and is assumed to be linearly proportional to the difference between $W_{i,\text{av}}$ and w_i. Indeed, the owner will be charged when the available wind power is more than the scheduled value which is calculated by (9). On the other hand, if the available power is less than the scheduled value then energy storage sources are responsible for supplying the difference, which will impose an additional cost on the system and is calculated by (10). If the WF is not owned by the system operator, the direct cost coefficient and the penalty cost may be equal to zero. The probability density function of the wind energy conversion system output power is indicated by $f_w(w)$ in (11) and obtained by the well-known two-parameter Weibull function. Detailed information about the formulation of the WF cost function is given in [25]. Estimation methods of Weibull shape and scale factors (k & c) using the available wind speed data can be found completely in [27]

$$\begin{aligned} C_{p,w,i}(W_{i,\text{av}} - w_i) = k_{p,i}(W_{i,\text{av}} - w_i) = k_{p,i} & \\ \times \int_{w_i}^{w_{r,i}} (w - w_i) f_w(w) \mathrm{d}w + k_{p,i} & \\ \times w_i \left\{ \exp\left(-\left(\frac{v_r}{c}\right)^k\right) - \exp\left(-\left(\frac{v_o}{c}\right)^k\right) \right\} & \end{aligned} \tag{9}$$

$$\begin{aligned} C_{r,w,i}(w_i - W_{i,\text{av}}) & = k_{r,i}(w_i - W_{i,\text{av}}) \\ & = k_{r,i} \times \int_0^{w_i} (w_i - w) f_w(w) \mathrm{d}w + k_{r,i} \\ & \times w_i \left\{ 1 - \exp\left(-\left(\frac{v_i}{c}\right)^k\right) + \exp\left(-\left(\frac{v_o}{c}\right)^k\right) \right\} \end{aligned} \tag{10}$$

$$f_w(w) = \frac{klv_i}{w_r c} \left(\frac{(1+\rho l) v_i}{c} \right)^{(k-1)} \times \exp\left(-\left(\frac{(1+\rho l) v_i}{c} \right)^k \right) \tag{11}$$

2.3 PEV modelling

V2G technology enables the network to establish a controllable and bi-directional power flow between a vehicle and the power grid. The vehicle's battery can be charged, discharged or operate as energy storage depending on the grid demand and revenue. The PEV owner can participate in the energy market by selling energy stored in the battery at high prices during peak-hours and buying during off-peak hours, when the energy price is cheap. The charge/discharge decision making could be done through a management system, such as home energy management in a residential station, or via more advanced program embedded inside the vehicles to determine the charge/discharge status under different conditions, whether connected to a residential electric vehicle supply equipment (EVSE) or to a public electric vehicle charging station [17]. For this purpose, a communication and information technology infrastructure, in addition to energy exchange infrastructure, is needed to monitor online pricing, grid's demand and owner's preferences between vehicles, market and operation section. The requirements to set up the mentioned substructures are given in related standards such as the National Institute of Standards and Technology (NIST) framework and the IEEE 2030 standard [17, 18]. In this paper, it is assumed that all communications between EVSE and the operation and control centre are established through customer energy service interface and Backhaul entity [17]. According to the above explanations, PEVs are modelled as loads or energy sources, depending on the operation mode. Thus, (4) will be modified as (12) and (13) to consider PEVs, wind, and solar energies

$$\begin{aligned} & \sum_{i=1}^{N} P_i(t) + P_{\text{solar}}(t) + \sum_{j=1}^{N_{\text{PEV}}(t)} \eta P_j^{\text{PEV}}(t) \left(\psi_{\text{pre}} - \psi_{\text{dep}} \right) \\ & + P_{\text{wind}}(t) = D(t) + P_{\text{loss}}(t) \quad \text{if PEVs are sources} \end{aligned} \tag{12}$$

$$\sum_{i=1}^{N} P_i(t) + P_{\text{solar}}(t) + P_{\text{wind}}(t) = D(t) + P_{\text{loss}}(t)$$

$$+ \sum_{j=1}^{N_{\text{PEV}}(t)} \eta P_j^{\text{PEV}}(t)\left(\psi_{\text{pre}} - \psi_{\text{dep}}\right) \quad \text{if PEVs are loads} \tag{13}$$

$$\sum_{j=1}^{T} N_{\text{PEV}}(t) = N_{\text{PEV}}^{\max} \tag{14}$$

The number of vehicles that take part in the load management program during a specific period (T), often 24 h, is limited to a specific number, shown by $N_{\text{PEV}}^{\max}$ in (14).

3 Case study

In this section, two test systems are simulated to investigate the effectiveness of the proposed model. To compare the amount of emissions produced by each of the transportation and electricity industries, a comprehensive well-to-wheel (WTW) analysis is selected, which examines GHGs generated by primary energy source through vehicle operation. This method is often divided into two parts, named as well-to-pump (WTP) and pump-to-wheel (PTW) sections. The WTP step generally studies the amount of emissions produced in the procedure of delivering the generated fuel to pumps, whereas the PTW step deals with the released GHGs by the vehicles (fuel combination). The WTP and PTW information needed for analysis and comparison are obtained from related valid references [15, 28].

The GHGs emitted by thermal power plants and conventional vehicles (CVs) are composed of several gases, such as CO_2, NO_x, SO_2, CH_4 and hydro fluorocarbon, but the amount of CO_2 is much more than other gases [28, 29] so they can be neglected without loss of accuracy. Thus, only the amount of released CO_2 is considered as the GHGs emission in this paper.

All the calculations and simulations are performed using MATLAB 2011a software and are executed on a 3.2 GHz, Core i5 processor with 4 GB RAM. The number of vehicles for this system has been calculated based on an approximate method proposed in [29]. Solar insolation and wind speed profile for 24 h are shown in Figs. 1*a* and *b*, respectively [30]. The WF parameters are given in Table 1. Other parameters' values used in this paper are as follows: charging–discharging frequency = 1 time per day; scheduling period = 24 h; the average distance traversed by each PEV in a year and its needed energy are assumed 12 000 miles and 8.22 kWh per day, respectively and finally, the average amount of emissions produced by each CV is supposed to be 445 grams/mile [29].

Table 1 Parameter of WF

w_r, MW	v_{in}, m/s	v_r, m/s	v_{out}, m/s	d, \$/MW	k_p, \$/MW	k_r, \$/MW
30	5	15	45	7	6	10

To show the effects of integrating PEVs and RESs on the electricity and transportation industries, six scenarios are considered in this paper as follows: (i) without PEVs and RESs; (ii) with PEVs considering load levelling; (iii) with PEVs considering V2G capability; (iv) with PEVs and WF; (v) with PEVs and solar parks; and (vi) with PEVs and RESs (solar and wind simultaneously).

3.1 Case study I: ten-unit test system

In this case, a ten-unit system with 50 000 PEVs is surveyed. The capacity of solar farm and WF are considered 40 and 30 MW, respectively. The parameters of the generators and the load data are provided in Appendix 1 [31]. The active power loss is not considered in this case study. According to the average CV's emission (445 grams/mile), it can be concluded that GHGs emission produced by a CV will be 5 340 000 g per year. Therefore the total emission reduction achieved from substituting 50 000 CVs with PEVs will be around 267 000 tons per year [20, 24].

3.1.1 Without plug-in electric vehicles (PEVs) and renewable energy sources (RESs): First, the PSO is applied to the system without considering PEVs and RESs for an interval of 24 h in order to find the optimal power

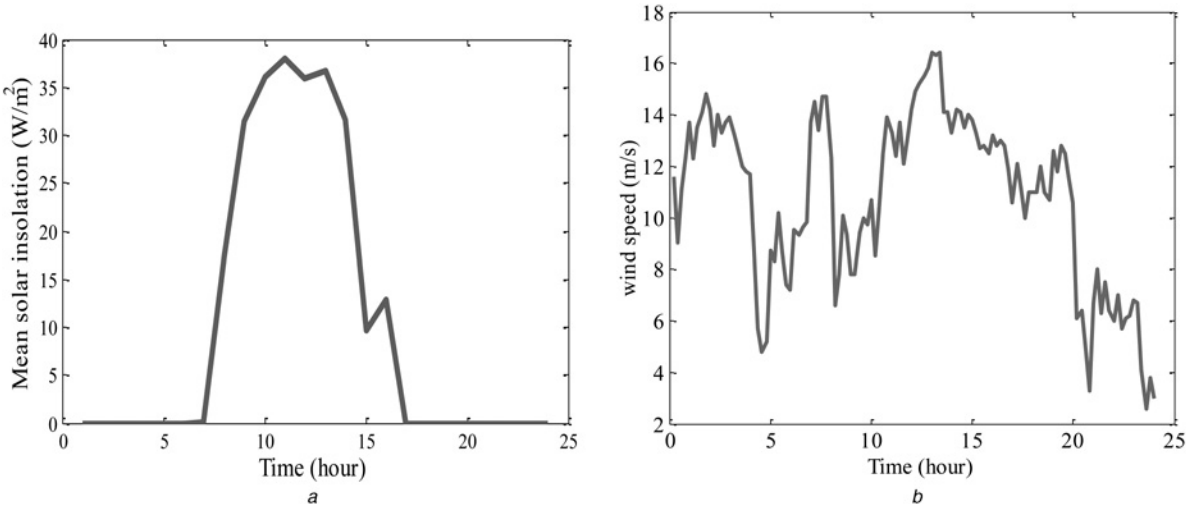

Fig. 1 *Solar insolation and wind speed profile for 24 h*

a Solar insolation data diagram
b Wind speed data diagram

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Table 2 Emission and cost of ten-unit system without considering PEVs and RESs

Time	Demand, MW	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	Emission (ton)	Fuel Cost ($)
1	700	203.07	150.43	118.99	119.57	32.93	20	25	10	10	10	410.01	19172.87
2	750	217	164.47	126.23	127.24	40.05	20	25	10	10	10	446.90	20041.54
3	850	250.78	199.7	130	130	64.52	20	25	10	10	10	524.70	21811.65
4	950	287.88	237.6	130	130	89.53	20	25	10	10	10	624.13	23589.05
5	1000	306.20	256.21	130	130	102.59	20	25	10	10	10	681.40	24482.38
6	1100	338.89	291.16	130	130	124.65	30.30	25	10	10	10	797.03	26318.43
7	1150	354.43	305.93	130	130	135.96	38.67	25	10	10	10	855.39	27257.99
8	1200	370.07	321.76	130	130	145.93	47.23	25	10	10	10	919.18	28196.35
9	1300	403.21	354.61	130	130	162	65.18	25	10	10	10	1063.31	30069.06
10	1400	444.75	398.25	130	130	162	80	25	10	10	10	1256.64	31867.13
11	1450	455	438	130	130	162	80	25	10	10	10	1376.90	32733.90
12	1500	455	455	130	130	162	80	25	43	10	10	1415.37	33894.61
13	1400	445.32	397.68	130	130	162	80	25	10	10	10	1256.81	31866.62
14	1300	403.41	354.89	130	130	162	64.70	25	10	10	10	1064.28	30066.16
15	1200	370.56	321.64	130	130	145.64	47.16	25	10	10	10	919.80	28194.51
16	1050	324.29	273.98	130	130	115.42	21.30	25	10	10	10	742.04	25383.79
17	1000	306.54	255.68	130	130	102.78	20.01	25	10	10	10	681.30	24482.68
18	1100	337.87	290.92	130	130	125.94	30.28	25	10	10	10	795.36	26323.46
19	1200	371.03	321.06	130	130	146.45	46.46	25	10	10	10	920.29	28193
20	1400	445.55	397.45	130	130	162	80	25	10	10	10	1256.87	31866.43
21	1300	402.65	355.13	130	130	162	65.22	25	10	10	10	1063.06	30069.81
22	1100	338.85	290.24	130	130	125.96	29.94	25	10	10	10	796.21	26320.89
23	900	270.13	217.75	130	130	77.12	20	25	10	10	10	571.85	22698.97
24	800	231.95	181.56	129.99	130	51.50	20	25	10	10	10	483.56	20924.53
											Total	20922.38	645825.79

dispatch according to the CEED objective function. The obtained results are shown in Table 2.

3.1.2 With PEVs considering load levelling: In this case, PEVs are charged through conventional units under the load-levelling scheme. The PEVs are only charged at off-peak hours (10 PM–10 AM) and will be imposed on the network as additional loads (50 000 × 8.22 kWh = 411 MWh). This extra 411 MWh demand caused by charging the vehicles can be divided between off-peak hours to be supplied, so the load profile of each hour during this interval will increase around 34.3 MW. There is certain discretion of how much the PEVs load can be managed for load management. PEVs can be scheduled by intelligent agents based on real-time price.

In this paper, it is assumed that all PEVs accept load management suggestions and will participate in the load-levelling program. The load profile is shown in Fig. 2 before and after the load-levelling plan implementation.

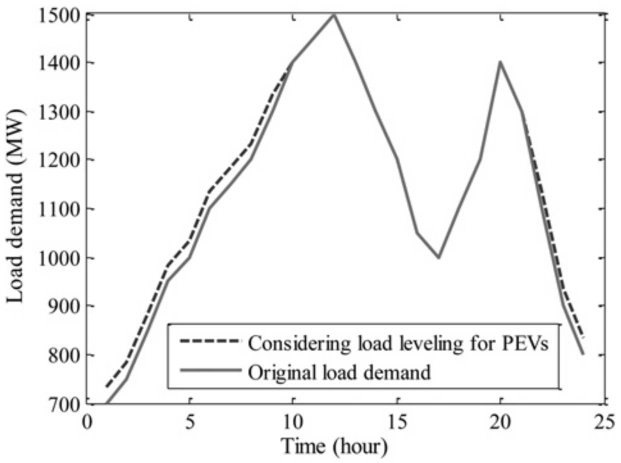

Fig. 2 *Effect of PEVs on the load profile*

The load data of the system is obtained from [31]. This type of load profile can be seen in many power networks such as the electric power grid of Iran [32] and Spain's electricity network [33] which is more frequent in the summer and spring days. Cost and emission are calculated based on the load demand of 50 000 PEVs and levelling the extra load. The results are shown in Table 3.

By comparing Tables 2 and 3, it can be inferred that the daily emission is increased by 763.32 tons (21685.7–20922.38 tons) in the load-levelling strategy. This extra emission (763.32 tons) generated by power plants is to supply the energy demand of 50 000 PEVs during 24 h. Thus, the added emission would be 278611.8 tons (763.32 ton × 365) per year compared to 267 000 tons emission reduction obtained from the transportation sector so the net emission will still be positive (278611.8–267000 = 1611.8 tons).

Moreover, degradation of the system efficiency because of the aging of the elements and rise of losses caused by the added load will result in an additional emission term that must be taken into account. Therefore, as it was shown, load levelling by PEVs will not only lead to significant GHGs emission reduction but also will increase it.

As it was mentioned earlier, the WTW analysis considers all emissions produced over the life cycle of a vehicle. In this case, the 267 000 tons emission produced in one year by CVs is representing the PTW release portion. In accordance to the values reported in [15], the amount of emission reduced in the transportation upstream section interpreted as WTP part will be 0.2 tons per year for a single vehicle. Since there are 50 000 vehicles in this case, 10 000 tons emission related to WTP will be eliminated. Therefore the total emission reduced by replacing CVs with PEVs will be 277 000 tons, whereas the increased emission generated by conventional units to supply the extra load caused by PEVs is 278611.8 tons. This means that using PEVs instead of CVs for the load-levelling purpose leads to more emissions, which is 1611.8 tons per year in this case. The reason for this increase refers to the

Table 3 Emission and cost of ten-unit system with PEVs considering load levelling

Time	Demand, MW	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	Emission, ton	Fuel cost, $
1	734.3	429.10	150.03	20.01	35.17	25	20	25	10	10	10	739.84	19644.81
2	784.3	226.42	175.784	129.89	129.97	47.235	20	25	10	10	10	472.03	20645.54
3	884.3	264.218	212.837	130	130	72.245	20	25	10	10	10	557.39	22417.37
4	984.3	299.002	251.39	130	130	98.907	20	25	10	10	10	661.96	24204.31
5	1034.3	318.595	268.744	130	130	111.95	20.01	25	10	10	10	723.33	25097.78
6	1134.3	350.418	301.232	130	130	132.52	35.13	25	10	10	10	838.37	26957.43
7	1184.3	365.591	315.418	130	130	143.4	44.89	25	10	10	10	897.52	27904.99
8	1234.3	380.446	330.843	130	130	154.52	53.49	25	10	10	10	962.59	28849.83
9	1334.3	416.972	367.737	130	130	162	72.59	25	10	10	10	1122.22	30699.04
10	1400	444.568	398.432	130	130	162	80	25	10	10	10	1256.59	31867.30
11	1450	455	438	130	130	162	80	25	10	10	10	1376.90	32733.90
12	1500	455	455	130	130	162	80	25	43	10	10	1415.37	33894.61
13	1400	445.265	397.735	130	130	162	80	25	10	10	10	1256.79	31866.67
14	1300	403.184	354.54	130	130	162	65.28	25	10	10	10	1063.11	30069.65
15	1200	370.194	321.896	130	130	146.17	46.74	25	10	10	10	919.84	28194.34
16	1050	324.473	274.856	130	130	114.72	20.95	25	10	10	10	743.44	25379.56
17	1000	306.42	256.015	130	130	102.56	20	25	10	10	10	681.49	24482.10
18	1100	338.867	290.955	130	130	125.75	29.43	25	10	10	10	797.35	26317.45
19	1200	370.429	322.046	130	130	146.69	45.83	25	10	10	10	920.98	28190.95
20	1400	444.962	398.038	130	130	162	80	25	10	10	10	1256.70	31866.95
21	1300	402.322	355.237	130	130	162	65.44	25	10	10	10	1062.54	30071.37
22	1134.3	351.649	301.742	130	130	132.05	33.86	25	10	10	10	841.53	26948.00
23	934.3	281.202	232.432	130	130	85.665	20	25	10	10	10	606.75	23310.52
24	834.3	245.335	193.225	130	130	60.74	20	25	10	10	10	511.06	21533.32
											Total	21685.70	653147.79

emission function. In fact, this issue is a very important key point of the problem but has been neglected in many conducted studies (some of which were mentioned in the introduction) investigating the effects of PEVs on the emission. Indeed, they have oversimplified the problem by considering the influence of PEVs as a linear proportional ratio. In this simplification, the amount of increased emission impose by PEVs will be obtained through the multiplication of the energy consumed by vehicles and a constant value which is equal to the produced emission by units per 1 (MWh or kWh) energy consumed by vehicles, regardless of the characteristics of the emission function.

The authors of this paper have made an attempt to prove that this simplification can influence emission and change the obtained results. As it can be seen, the obtained outcomes in this case confirm the authors' claim. This increase in the produced emission can be explained in the following manner, that when PEVs are charged, an additional load is imposed on the grid so that it makes units operate in a new operating point. Since the emission curve of the units is incremental and non-linear, the additional

Table 4 Emission and cost of ten-unit system with PEVs considering V2G capability

Time	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	Emission, ton	Fuel Cost, $
1	201.004	155.47	120.39	121.848	49.25	20	25	10	10	10	412.87725	19615.776
2	212.08	169.52	127.52	128.921	56.04	20	25	10	10	10	447.37756	20420.367
3	246.49	202.81	130	129.995	81.36	20	25	10	10	10	524.26415	22136.79
4	283.538	240.41	130	130	108.5	24.72	25	10	10	10	625.58029	24061.725
5	300.927	257.28	130	130	119.5	32.42	25	10	10	10	678.12735	25043.794
6	328.221	284.7	130	130	139.8	49.78	25	10	10	10	773.35617	26789.167
7	341.644	301.66	130	130	148.2	57.53	25	10	10	10	830.06322	27660.685
8	344.353	303.64	130	130	150.1	58.61	25	10	10	10	839.64481	27803.197
9	378.164	335.97	130	130	162	77.8	25	10	10	10	974.15418	29622.15
10	428.633	387.4	130	130	162	80	25	13.20	10	10	1191.819	31492.692
11	448.733	408.26	130	130	162	80	25	25.45	10	10	1286.0202	32511.281
12	448.234	407.36	130	130	162	80	25	24.30	10	10	1282.8779	32457.349
13	431.324	390.89	130	130	162	80	25	15.75	10	10	1205.3538	31665.068
14	384.558	341.68	130	130	162	80	25	10	10	10	998.84664	29879.325
15	349.359	306.19	130	130	153.1	61.32	25	10	10	10	855.53326	28055.229
16	314.198	271.46	130	130	129	41.8	25	10	10	10	723.5785	25918.861
17	304.058	261.18	130	130	122.1	35	25	10	10	10	689.3977	25275.079
18	328.048	286.35	130	130	137.8	49.08	25	10	10	10	774.45089	26756.817
19	347.077	305.06	130	130	153.3	60.21	25	10	10	10	849.39644	27977.589
20	416.544	375.73	130	130	162	80	25	10	10	10	1138.8533	31004.653
21	380.01	338.01	130	130	162	80	25	10	10	10	982.22172	29739.865
22	329.428	284.88	130	130	138	48.3	25	10	10	10	774.82802	26740.009
23	272.458	228.36	130	129.999	99.32	20.09	25	10	10	10	592.37123	23376.705
24	242.826	199.41	129.99	130	79.04	20	25	10	10	10	515.73688	21970.402
										Total	19966.731	647974.57

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Table 5 Emission and cost of ten-unit system with PEVs and RESs

Time	Demand, MW	V2G/G2 V, MW	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	Wind, MW	Emission, ton	Fuel Cost, $
1	700	−22.96	204.58	151.08	120.16	121.78	33.72	20	25	10	10	10	16.64	414.65	19282.07
2	750	−19.09	221.26	166.00	120.52	122.55	38.94	20	25	10	10	10	24.78	444.08	19939.14
3	850	−15.66	244.51	199.29	130	129.91	63.30	20	25	10	10	10	23.64	515.99	21675.62
4	950	−22.16	285.52	240.58	130	130	92.33	20	25	10	10	10	18.73	624.90	23659.49
5	1000	−25.15	313.34	269.45	129.85	130	104.83	20.57	25	10	10	10	2.09	712.41	24887.49
6	1100	−17.52	341.99	294.55	130	129.97	126.58	31.79	25	10	10	10	7.65	808.87	26501.79
7	1150	−14.08	351.83	306.05	130	130	137.66	40.67	25	10	10	10	12.78	851.20	27297.92
8	1200	28.32	350.13	299.90	129.99	130	131.29	37.08	25	10	10	10	20.82	834.71	26948.45
9	1300	31.07	374.92	336.72	130	130	148.62	55.85	25	10	10	10	6.36	957.79	28792.47
10	1400	23.77	418.26	367.09	130	129.99	161.49	67.56	25	10	10	10	10.79	1123.04	30582.40
11	1450	20.56	432.49	387.03	130	130	161.81	77.18	25	10	10	10	17.85	1200.75	31397.74
12	1500	73.1	431.37	382.07	129.99	130	162	77.99	25	10	10	10	22.54	1187.56	31314.87
13	1400	15.03	410.34	361.83	130	129.99	162	69.00	25	10	10	10	30	1094.33	30402.77
14	1300	16.76	375.41	332.80	130	130	151.27	51.14	25	10	10	10	26.03	953.38	28678.77
15	1200	15.08	357.30	305.26	130	130	133.65	38.36	25	10	10	10	25.64	858.71	27238.73
16	1050	−21.43	323.46	264.91	130	130	110.32	21.81	25	10	10	10	22.99	725.39	25118.82
17	1000	−37.33	321.31	257.26	129.97	130	104.66	20	25	10	10	10	19.13	709.37	24791.87
18	1100	−16.27	334.42	295.20	130	129.98	124.66	30.32	25	10	10	10	16.66	795.11	26316.33
19	1200	19.34	358.34	307.34	130	130	137.92	44.30	25	10	10	10	17.70	866.00	27517.92
20	1400	50.73	418.79	366.76	130	130	161.99	70.56	25	10	10	10	16.16	1124.30	30664.93
21	1300	24.98	393.85	346.47	130	130	161.46	58.23	25	10	10	10	0.01	1025.80	29599.54
22	1100	−15.59	342.39	291.07	130	130	128.57	34.98	25	10	10	10	3.58	804.66	26562.22
23	900	−35.22	282.02	232.78	130	130	82.47	20.01	25	10	10	10	2.93	607.77	23265.48
24	800	−56.28	255.55	199.71	129.99	130	66.02	20	25	10	10	10	0	531.17	21920.61
													Total	19771.93	634357.42

produced emission will not increase linearly. In fact, a small increase from the nominal operating point leads to a great rise in emission, which is the main point that has been neglected in many studies. This conclusion is mentioned shortly in the Electric Power Research Institute (EPRI) report [16] where it is shown that the shifted emission from the transportation industry to the electric industry by presence of PEVs can increase net emission in some power networks. It is important to note that the above conclusion is not comprehensive and depends on several determinant factors, which are analysed completely in Section 4.

3.1.3 With PEVs considering V2G capability: In this scenario, it is assumed that PEVs can charge/discharge smartly. The obtained results are given in Table 4. As it can be seen, PEVs are charged during off-peak hours and discharged during peak-hours in this state. This mode of integration will smooth the load profile and consequently will decrease the total production cost and emission by \$5173.22 and 1718.969 tons per day, respectively, compared with the previous scenario.

3.1.4 With PEVs and wind farms: In this scenario, the WF has been added to the network to generate the electricity along with the conventional units and PEVs with V2G capability function in a smart manner. The obtained results are 20197.48 tons and \$638933.23 for emission and cost, respectively. It can be observed that the emission and generation cost have been reduced because of utilising the clean and cheap wind energy.

3.1.5 With PEVs and solar park: The WF is replaced with a solar park in this scenario. The total production cost and emission will be \$641026 and 20255.7 tons. As it was shown in Fig. 1*a*, the solar energy is not available all day long (only available from 7 AM to 4 PM), whereas the WF can generate electricity 24 h in a normal day. For this reason, although the rated power of the solar park is greater than that of the WF, the total generated energy by the solar park is less than the WF and consequently the production cost and emission in this scenario will be higher than the wind scenario.

3.1.6 With PEVs and RESs (solar and wind simultaneously): Finally, the results of this scenario are shown in Table 5. According to Table 5, PEVs are charged from the grid during off-peak hours from 1–7, 16–18 and 22–24. On the other hand, PEVs are discharged into the grid during peak-hours from 8–15 and 19–21. Figs. 3*a* and *b* illustrate the comparison of the proposed scenarios with respect to the emission and cost, respectively. Based on these figures, the sixth scenario is preferable because of less GHGs emission and production costs resulting from supplying a part of the grid's demand by RESs and employing PEVs with V2G capability under a smart schedule of charging/discharging.

3.2 Case Study II: twenty-unit test system

In this case, a twenty-unit system is simulated to illustrate the effect of the network topology on the emission value. The active power loss has been also included in this simulation. The units' cost and emission coefficients, ***B*** matrix and the load data are given in Appendix 3 [34]. According to the mentioned method, the number of PEVs is estimated to be 120 000 for this case. The capacity of the solar park and the WF are considered as 100 and 61.5 MW, respectively. All the other assumptions in the case study I are also applicable to this system. In this case, the results of the three important scenarios are given and explained in details. For the three other scenarios (3, 4 and 5), only the final results are shown in Fig. 4.

3.2.1 Without PEVs and RESs: The CEED is applied to the test system and the obtained results are given in Table 7 in Appendix 2.

3.2.2 With PEVs considering load levelling: Similar to case study I, PEVs are employed during off-peak hours to smooth the load profile in this scenario. In this case, the off-peak hours are considered to be from 11PM-8AM so PEVs will impose an extra load of about 111.43 MW to the demand profile of these intervals. The obtained results are given in Table 8 in Appendix 2. As it can be seen, the

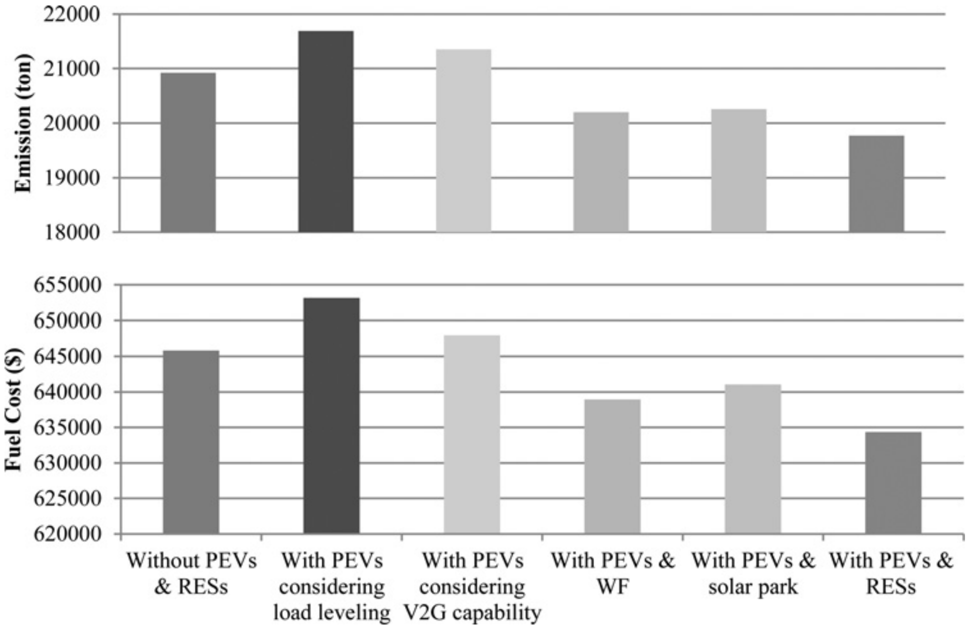

Fig. 3 *Comparison of the proposed scenarios for ten-unit system*

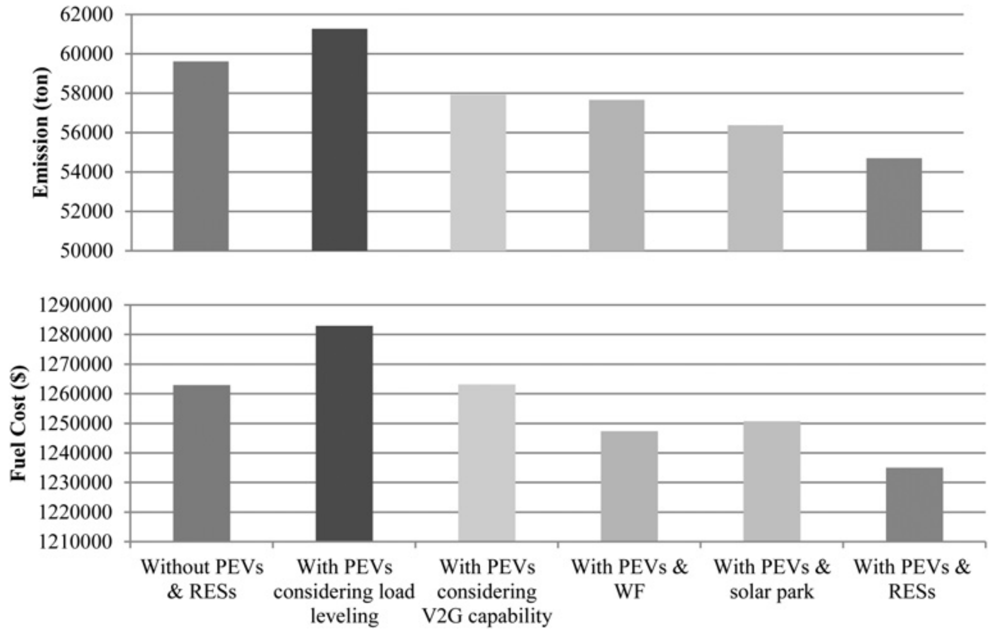

Fig. 4 *Comparison of the proposed scenarios for twenty-unit system*

emission will be 61264.802 tons in this state. The WTP and PTW share of the emission are 24 000 and 633 600 tons, respectively; so the total emission reduction by CV mitigation will be 657 600 tons whereas increased emission in this scenario is 603937.03 tons compared with the previous scenario. This means that, in this system, the load levelling scheme does not increase emission against case study I. Although the power loss is included in the calculations, it cannot affect the emission significantly. Therefore it can be concluded that contrary to the power losses, the network topology is a substantial and determinative factor on emission and cost.

3.2.3 With PEVs and RESs (solar and wind simultaneously): In this case, PEVs and RESs are employed in the simulation. The obtained results are given in Table 9 in Appendix 2. As it was expected, the emission and cost have been reduced significantly. The obtained results of six scenarios in the case study II are shown in Fig. 4 summarily.

4 Discussion

There are two effective parameters, weight factors and the network topology, on which the obtained results are highly dependent. Therefore this section will make comparisons and do some sensitivity analysis to investigate their effects separately.

4.1 Weight factors

To illustrate the influence of weight coefficients on the emission, a sensitivity analysis is performed by changing ω_c

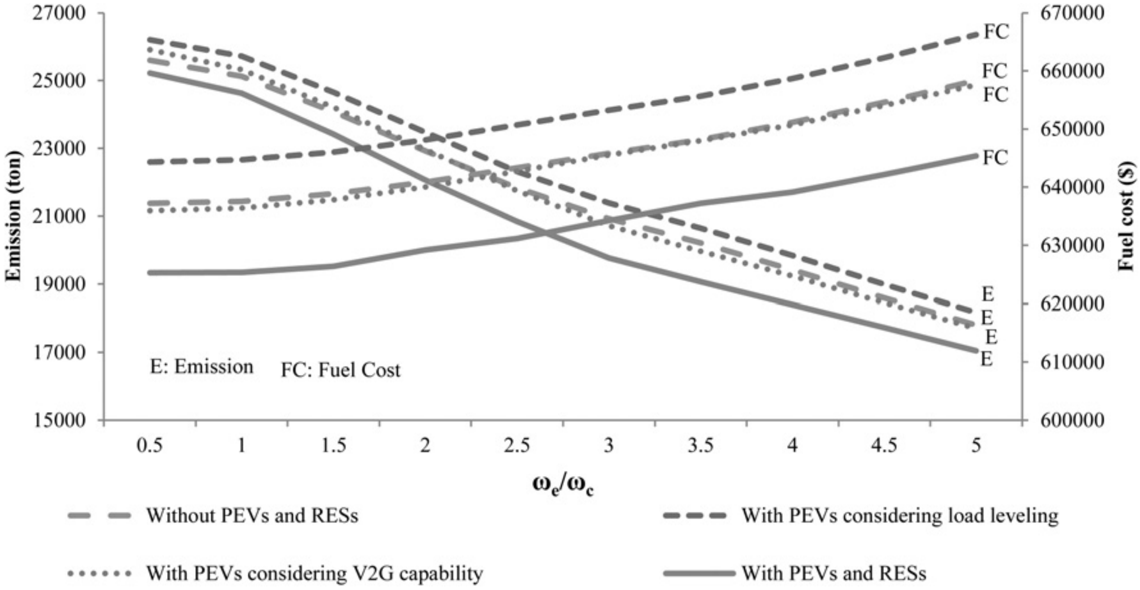

Fig. 5 *Sensitivity analysis for ten-unit system*

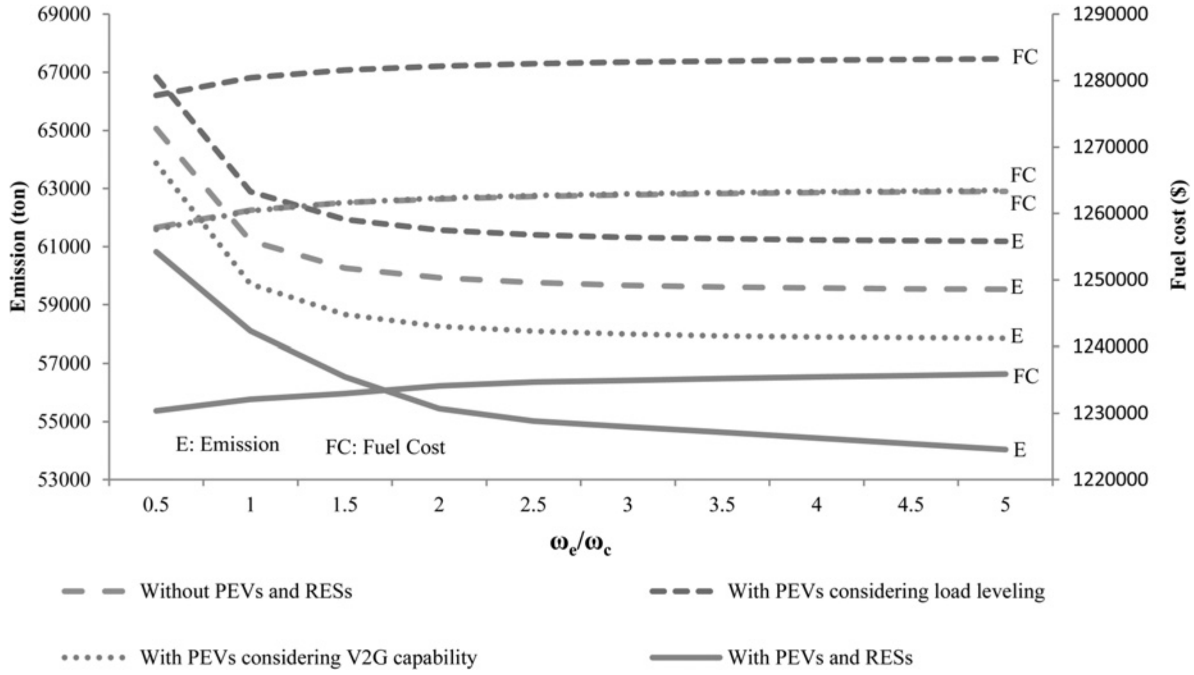

Fig. 6 *Sensitivity analysis for twenty-unit system*

and ω_e for four scenarios. The obtained results for a 24-hour period are given in Figs. 5 and 6.

From Fig. 5, as ω_e increases, the GHGs emission decreases. In the first three scenarios, when ω_e is less than 1.5, the emission produced by conventional units is more than the emission reduced by CVs elimination (277 000 tons) but when ω_e is greater than 1.5, the added emission will be less than 277 000 tons per year. This means that replacing CVs with PEVs will reduce the net emission of these states. Thus, it can be inferred that selecting proper weight factors could have a significant impact on the emission and therefore the efficacy of the scenario. In fact, the operator's economic and environmental aims as well as environmental regulatory laws can be effective on the emission.

4.2 Network topology

As the results of the 20-unit system show, the emission of the load-levelling scenario has not been increased compared to the base scenario. This fact proves that the emission changes are highly correlated with the network characteristics. Although the emission is declined in presence of PEVs in this case, this change is not considerable. Accordingly, the load-levelling scenario cannot guarantee a remarkable emission reduction because the emission will be only shifted from the transportation section to the electricity generation part. Indeed, it implies that replacing CVs with PEVs alone cannot reduce emission significantly and needs additional supports, such as integrating RESs or implementing modern emission absorption techniques for power plants.

On balance, it can be concluded that opposed to what is given in the literature, the emission reduction is not guaranteed in all cases and networks as mentioned shortly in [16]. Actually, it can be increased or decreased depending on many factors, such as the network topology, efficiency of power plants and aims of the operator. It should be noted that these conclusions are related to the load-levelling scenario as a common scheme used in many countries for the load management purposes, whereas the emission will be decreased in all of the last four modes of operation. Comparing two cases' results, it can be understood that the network topology and the efficiency of units are more effective on the emission than the power loss consideration. It should be also noted that the net emission is decreased in the second case, even though the power losses are considered.

5 Conclusions

In this paper, the influence of PEVs and RESs on the production cost and the emission of the electricity and the transportation industries is investigated comprehensively. Combined economic emission objective function is used for optimal power dispatch among network's units. Two test systems are simulated in six different scenarios to analyse the efficacy of each approach and find the best manner of integration of PEVs and RESs. This paper challenges the common belief that substituting CVs with PEVs can reduce net GHGs emitted by mentioned industries individually.

In fact, this paper tries to answer the following set of questions:

1. What are the impacts of PEVs and RESs penetration on the production cost and the emission?
2. Can PEVs alone reduce the net GHGs emitted by the transportation and the electricity sectors in all situations? If no, what are the effective factors and important considerations?

The obtained results indicate that PEVs are not always able to reduce the emission and it is dependent on several factors, such as the operator aim and the network characteristics. The acquired outcomes are briefly presented as follows:

- RESs integration reduces the emission and the cost of energy production significantly.
- PEVs may increase net GHGs emitted by the electricity and the transportation industries in the load-levelling

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scenario depending heavily on the weight coefficients in the objective function and the network topology.

- The extra load imposed by connecting PEVs on the grid without RESs will make conventional units generate more electricity and therefore produce more emission. This is a key point that is neglected in the literature.
- The sensitivity analysis shows that the net emission reduction will be positive starting from a certain ω_e/ω_c ratio and higher
- The results of two systems illustrate that the topology of the network influences the obtained outcomes. Accordingly, same conclusions cannot be attributed to all networks regardless of their conditions and characteristics.
- The 20-unit system results express that although the losses can be effective on emission, it does not have a critical role in our problem compared with the other mentioned influential factors.

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7 Appendix

See Tables 6, 7, 8, 9 and 10

7.1 *Appendix 1. ten-unit test system data*

The data of the ten-unit test system are given in Table 6. In this case, ξ_i and λ_i are assumed to be zero and $A = 1$.

Table 6 Data for 10-generating units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_{\max}$ (MW)	455	455	130	130	162	80	85	55	55	55
$P_{\min}$ (MW)	150	150	20	20	25	20	25	10	10	10
a (\$/h)	1000	970	700	680	450	370	480	660	665	670
b (\$/MWh)	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
c (\$/MWh^2)	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.0079	0.00413	0.00222	0.00173
α (ton/h)	10.33908	10.33908	30.0391	30.0391	32.00006	32.00006	33.00056	33.00056	35.00056	36.00012
β (ton/MWh)	−0.24444	−0.24444	−0.4069	−0.4069	−0.38132	−0.38132	−0.39023	−0.39023	−0.39524	−0.39864
γ (ton/MWh^2)	0.00312	0.00312	0.00509	0.00509	0.00344	0.00344	0.00465	0.00465	0.00465	0.0047

Table 7 Emission and cost of twenty-unit system without considering PEVs and RESs

Time	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	P11, MW
1	150.0000	87.9498	80.8114	92.4122	121.8352	99.9955	125.0000	110.6266	121.9184	113.7736	133.8228
2	150.0102	82.8489	75.2885	84.7388	112.6793	99.6523	119.1789	102.8128	112.4833	107.2698	127.0277
3	150.0005	83.6849	74.6064	81.3705	109.0987	98.7378	117.4717	100.7883	111.1164	103.8197	125.8168
4	150.0000	81.8596	73.8666	80.2720	107.3787	99.6671	115.8386	98.9448	110.2241	102.4492	125.9030
5	150.0000	82.2795	71.8036	83.5332	109.9557	100.0000	116.9848	100.5403	110.8734	104.2752	126.7620
6	150.0000	87.9716	78.9406	89.7408	117.2417	99.8572	122.7649	109.2361	118.3394	114.2273	131.4333
7	150.0347	96.0642	92.0359	111.4223	136.3641	99.9999	125.0000	128.5340	137.0179	130.7815	145.8315
8	156.9656	105.7819	102.3182	132.9780	151.3109	99.9999	125.0000	147.2237	154.6367	150.0000	162.6905
9	156.5933	106.0471	102.3057	133.6164	153.0523	99.9978	125.0000	148.0392	154.6713	149.9989	162.8482
10	158.7375	107.1677	103.4697	135.0848	153.7313	99.9999	124.9973	149.3160	156.1043	150.0000	162.9575
11	160.2167	107.6540	104.0199	137.6968	155.2218	99.9997	124.9942	150.0000	158.0363	149.9462	165.7633
12	156.9003	105.8152	101.9907	132.6183	151.1289	100.0000	124.9989	147.4741	153.7884	149.7936	161.5071
13	154.4335	104.8307	99.8731	130.5094	149.8335	100.0000	124.9999	145.1211	151.8893	149.6256	160.1264
14	156.0740	105.2019	100.8106	131.0320	150.8176	100.0000	124.9941	145.4679	153.2474	150.0000	161.0063
15	157.1928	105.6312	101.6492	134.1245	152.6313	99.9979	124.9957	148.5407	154.5428	149.9999	162.1075
16	158.4872	106.8603	104.2123	135.9215	155.2850	100.0000	125.0000	149.9916	155.5528	150.0000	163.1342
17	166.1304	110.6134	107.3130	146.1765	160.0000	99.9999	125.0000	149.9990	162.9673	150.0000	169.5201
18	176.3960	115.5460	113.2585	158.9644	160.0000	99.9998	124.9998	149.9999	174.0432	149.9978	179.6530
19	186.2420	120.4161	118.5551	170.9194	159.9994	100.0000	124.9997	150.0000	184.7696	150.0000	189.2159
20	180.3651	117.7436	115.3220	163.6730	160.0000	99.9993	125.0000	150.0000	178.5192	150.0000	183.2038
21	174.7889	115.1258	112.2708	157.0998	160.0000	99.9997	125.0000	149.9991	172.9878	150.0000	178.8391
22	165.0681	110.1615	106.6414	143.1873	159.9672	100.0000	125.0000	150.0000	161.7969	150.0000	168.3226
23	150.5825	102.8476	99.5561	126.1050	144.9938	99.9867	124.9984	139.8104	146.6426	143.0001	155.2667
24	150.0002	95.2651	88.7192	105.4180	131.5056	100.0000	124.9475	123.0418	131.4365	127.6115	142.5916
Time	P12, MW	P13, MW	P14, MW	P15, MW	P16, MW	P17, MW	P18, MW	P19, MW	P20, MW	Emission, ton	Fuel Cost, $
1	150.0005	122.8183	118.6299	25.0005	20.0000	30.0000	30.0076	40.0000	30.0000	1901.08	47563.98
2	150.0004	115.6027	109.5024	25.0001	20.0000	30.0011	30.0727	40.0000	30.0305	1800.62	45979.54
3	150.0058	114.2167	108.3504	25.0013	20.0033	30.0002	30.0002	40.0277	30.0000	1778.75	45582.13
4	150.0003	112.8480	109.8084	25.0002	20.0007	30.0000	30.0183	40.0003	30.0055	1767.87	45384.72
5	150.0675	115.0652	106.7921	25.0049	20.0000	30.0002	30.0144	40.0345	30.1432	1779.76	45579.51
6	150.0016	121.4536	118.2709	25.0000	20.0000	30.0002	30.0124	40.0000	30.0000	1873.78	47169.21
7	150.0000	138.5722	129.9988	25.0029	20.0000	30.0000	35.0222	40.0000	33.5935	2140.64	50567.76
8	163.8541	153.9764	130.0000	25.0000	20.0000	30.0000	43.2668	44.2971	41.8991	2579.29	54248.63
9	163.7816	154.9921	129.9435	25.0076	20.0001	30.0013	43.4138	44.4873	42.4177	2592.65	54351.16
10	165.8735	156.6618	130.0000	25.0006	20.0000	30.0000	44.5400	44.9732	42.6897	2636.78	54646.99
11	166.6206	157.4453	130.0000	25.0001	20.0001	30.0018	44.4224	45.8978	43.4625	2682.57	54942.40
12	163.3277	152.8900	129.9977	25.0000	20.0000	30.0000	43.4281	44.1581	41.3415	2564.74	54150.73
13	161.4889	152.2082	130.0000	25.0008	20.0000	30.0000	41.7273	43.6844	40.7096	2509.51	53754.34
14	162.5638	152.8472	129.9990	25.0000	20.0010	30.0010	42.1596	44.0426	40.8503	2537.57	53950.15
15	164.5590	154.5985	129.9999	25.0004	20.0000	30.0008	43.7233	44.6223	42.3022	2592.99	54349.83
16	165.7728	157.5916	129.9943	25.0000	20.0000	30.0000	44.7477	45.9148	42.8563	2650.66	54749.74
17	171.8813	159.9883	129.9994	25.0007	20.0003	30.0000	48.0678	48.1174	45.9209	2846.74	55927.05
18	181.7283	159.9983	129.9998	25.0000	20.0000	30.0000	54.1437	52.9192	50.5553	3163.27	57492.16
19	190.8487	159.9998	130.0000	25.0000	20.0000	30.0000	59.1180	57.0727	55.5431	3528.34	58965.77
20	185.0553	160.0000	129.9999	25.0000	20.0000	30.0007	56.1189	54.4569	52.9374	3300.22	58081.96
21	180.0047	160.0000	129.9977	25.0000	20.0000	30.0000	53.3712	52.2033	50.4515	3119.71	57296.81
22	171.0817	159.9900	129.9990	25.0007	20.0024	30.0007	47.6293	47.5074	45.2761	2812.36	55729.51
23	159.5204	146.2142	130.0000	25.0000	20.0000	30.0002	40.0507	42.5041	38.7305	2381.40	52758.63
24	150.0028	135.0325	129.5781	25.0035	20.0000	30.0000	32.5554	40.0000	32.3823	2068.88	49763.66
									Total	59610.18	1262986.4

Table 8 Emission and cost of twenty-unit system with PEVs considering load levelling

Time	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	P11, MW
1	150.0366	94.9056	88.5790	105.6024	130.6712	100.0000	125.0000	123.3841	132.8083	129.2968	143.0095
2	150.0057	90.8732	84.4212	96.8712	122.5481	100.0000	124.9926	113.7944	123.6729	118.5503	137.4457
3	150.0000	89.9622	82.7287	94.1352	119.3191	99.9999	124.9995	112.1940	122.8090	115.2399	135.5082
4	150.0000	87.7748	80.4014	94.1882	118.5159	100.0000	125.0000	111.5902	121.3945	114.8621	134.3076
5	150.0000	88.7271	83.1579	94.5342	119.2598	99.9994	124.6396	111.4890	122.8263	116.3523	136.3237
6	150.0014	93.7687	86.6617	104.2606	128.6863	99.9929	124.9900	122.8382	130.2758	125.0091	140.6192
7	150.0007	103.0754	99.3758	124.9817	145.3113	100.0000	125.0000	139.2842	148.3506	144.7939	155.4302
8	156.5879	105.4175	102.9165	133.2841	152.6994	99.9997	125.0000	147.0660	154.4138	149.9377	161.7226
9	155.9671	105.9711	102.2369	134.2565	153.0310	100.0000	125.0000	147.9293	153.9268	149.9121	162.0279
10	158.9945	107.5456	103.6735	137.1177	153.8656	100.0000	124.9990	148.8630	155.1078	149.9983	163.0127
11	160.6216	107.4668	103.8363	137.6558	155.6732	99.9990	125.0000	150.0000	157.4842	150.0000	165.3290
12	157.7316	105.5376	102.2459	132.9397	149.8162	100.0000	125.0000	146.4715	153.1276	149.9823	161.2430
13	154.7191	104.9912	101.5208	131.1030	149.3183	100.0000	124.9875	145.4300	151.1288	148.5585	159.6788
14	155.0483	105.9453	101.3283	131.8951	150.5488	100.0000	124.9962	146.0413	152.4083	149.2786	160.2712
15	156.2102	106.6058	102.4541	133.8313	152.3247	100.0000	125.0000	149.9850	154.2988	150.0000	161.9239
16	159.6004	107.1779	103.9927	135.9540	154.5790	99.9998	125.0000	149.8151	155.7894	150.0000	164.4971
17	166.2606	110.3430	107.5733	145.0191	160.0000	100.0000	125.0000	150.0000	163.6534	150.0000	169.8825
18	176.2466	115.6698	113.0591	158.7610	159.9989	99.9998	125.0000	150.0000	174.4101	150.0000	179.5749
19	186.0137	120.3802	118.4877	171.2933	159.9995	99.9998	125.0000	150.0000	184.8004	149.9995	189.1636
20	180.5805	117.6187	115.5749	163.4464	160.0000	100.0000	124.9995	150.0000	178.6575	150.0000	183.1219
21	175.3446	115.0905	112.3534	156.6929	159.9985	100.0000	124.9999	149.9992	173.1116	149.9999	178.7286
22	164.5968	109.6718	106.7726	143.5092	159.9581	100.0000	124.9997	149.9276	162.2175	150.0000	168.6788
23	161.0986	107.4781	103.9459	137.9556	156.5396	100.0000	125.0000	149.8828	157.2761	149.9987	164.2865
24	150.1339	101.1187	95.4459	120.8356	141.4605	99.9973	125.0000	136.2607	143.6885	141.1429	152.6853

Time	P12, MW	P13, MW	P14, MW	P15, MW	P16, MW	P17, MW	P18, MW	P19, MW	P20, MW	Emission, ton	Fuel Cost, $
1	150.0000	133.8744	129.8502	25.0009	20.0000	30.0001	32.7160	40.0000	31.7920	2071.3	49792.19
2	150.0000	125.4187	122.1035	25.0000	20.0001	30.0006	30.4055	40.0000	30.0634	1945.0	48190.42
3	150.0000	124.4830	119.6807	25.0000	20.0000	30.0002	30.0139	40.0113	30.0000	1916.8	47791.10
4	150.0001	122.5219	120.3472	25.0002	20.0000	30.0000	30.0904	40.0406	30.0000	1902.8	47593.02
5	150.0000	124.1065	119.4505	25.0000	20.0000	30.0004	30.1190	40.0000	30.0942	1916.9	47790.78
6	150.0000	132.6304	129.5144	25.0000	20.0000	30.0000	31.0009	40.0005	31.1909	2036.9	49393.99
7	158.3598	148.1478	129.9978	25.0000	20.0023	30.0001	39.3370	42.1588	38.6391	2383.8	52790.44
8	163.6162	154.0848	130.0000	25.0000	20.0041	30.0000	43.2171	44.6061	41.6157	2578.3	54252.13
9	164.8742	156.1977	129.9870	25.0033	20.0001	30.0000	43.1143	44.6258	42.1648	2592.6	54351.42
10	164.8482	155.8224	129.9800	25.0000	20.0005	30.0000	44.5780	45.5149	42.3681	2636.5	54648.25
11	166.9119	157.4925	129.9969	25.0000	20.0000	30.0013	45.1568	45.7927	42.9769	2682.7	54941.46
12	163.6180	154.2674	130.0000	25.0000	20.0000	30.0000	42.9315	44.6542	41.5980	2565.6	54148.21
13	162.1625	152.2301	130.0000	25.0000	20.0013	30.0000	41.8952	43.0074	40.3225	2509.2	53755.12
14	162.6170	153.8957	129.9993	25.0063	20.0015	30.0015	42.4373	43.2539	41.1375	2536.4	53954.40
15	163.8169	154.4090	130.0000	25.0000	20.0000	30.0001	43.1805	44.6500	42.5203	2591.5	54355.57
16	165.5272	156.6186	129.9995	25.0000	20.0000	30.0000	44.5826	45.7916	42.4047	2651.9	54745.28
17	171.5479	159.9870	129.9994	25.0000	20.0000	30.0001	48.3674	48.3128	45.7465	2846.9	55926.33
18	181.5455	160.0000	130.0000	25.0001	20.0004	30.0000	54.2565	52.6007	51.0789	3163.0	57493.01
19	190.4586	159.9999	129.9995	25.0000	20.0000	30.0000	59.5929	57.1228	55.3858	3528.0	58966.94
20	184.9098	159.9999	130.0000	25.0001	20.0000	30.0000	56.2590	54.4974	52.7293	3300.2	58082.11
21	179.7987	160.0000	129.9999	25.0000	20.0000	30.0007	53.3638	52.4052	50.2502	3119.9	57296.09
22	170.4073	160.0000	130.0000	25.0000	20.0030	30.0011	47.2331	48.0363	45.6205	2811.8	55731.47
23	166.4792	157.7678	130.0000	25.0000	20.0000	30.0001	45.8587	45.9991	43.2550	2686.5	54972.10
24	155.3285	143.7504	129.9751	25.0000	20.0000	30.0005	38.2028	40.1539	36.8627	2290.2	51990.93
									Total	61264.802	1282952.8

Table 9 Emission and cost of twenty-unit system with PEVs and RESs

Time	V2G, MW	P1, MW	P2, MW	P3, MW	P4, MW	P5, MW	P6, MW	P7, MW	P8, MW	P9, MW	P10, MW	P11, MW
1	−90.5345	150.0201	91.6743	83.3987	97.3253	125.5372	99.7701	125	116.2289	127.5292	120.0879	142.1913
2	−119.0540	150.0114	87.9019	78.3748	89.1913	120.8986	100.0000	125	109.5806	118.5431	111.7135	134.9701
3	−126.1838	150.0024	87.5224	77.2922	90.1436	116.7904	100.0000	125	105.7305	118.9059	111.6497	135.8495
4	−129.7488	150.0047	87.2078	76.1195	89.6739	119.3098	99.9154	124.73	107.7838	120.8286	112.8451	135.6783
5	−126.1838	150.0090	88.8846	81.8986	93.7650	120.6658	99.9888	125	112.4267	124.3784	117.3724	139.0302
6	−97.6644	150.0000	92.3663	84.3854	100.7277	125.6921	99.9532	125	116.4785	127.9500	119.9243	141.8519
7	−37.0605	150.0000	98.1310	91.6618	110.0409	134.9050	100.0000	125	128.4446	138.8418	132.1415	148.8966
8	28.8908	150.0162	100.9569	95.7198	118.3066	142.3218	99.9756	125	134.8904	142.7660	137.9507	155.0206
9	30.6733	150.0006	100.7867	95.1857	118.4545	139.8736	100.0000	125	135.1368	143.3649	139.0545	154.4310
10	36.0207	150.1783	99.7979	93.9561	117.6753	139.8530	99.9907	125	132.9052	142.2686	137.6174	152.8496
11	41.3681	150.0000	98.7435	95.1163	116.5440	138.4210	99.9992	125	131.6352	140.3380	138.4149	152.7583
12	27.1084	150.0238	98.8271	92.6505	113.6835	136.4270	100.0000	125	128.2065	137.6141	131.9218	149.9879
13	19.9785	150.0000	97.2045	90.3662	108.6300	133.3086	99.9982	125	125.6981	135.0731	131.7049	147.2949
14	23.5434	150.0015	97.5615	92.4117	111.9670	136.7834	99.9669	125	128.4473	138.2866	133.6056	149.3678
15	30.6733	150.0003	101.7353	95.9705	121.9703	141.0026	99.9757	125	136.2737	145.6762	138.9659	156.6085
16	37.8032	150.0116	102.5759	97.3708	122.4469	143.2796	100.0000	125	137.9513	146.7106	141.8732	154.0334
17	59.1928	157.2591	105.0350	100.3700	131.5980	150.5253	99.9887	125	143.4420	153.1690	148.3134	161.8545
18	87.7123	161.1017	108.2561	103.9289	137.2862	155.8797	99.9998	125	149.7315	158.2123	150.0000	166.6373
19	114.4493	166.9444	110.5947	107.0572	144.7029	159.9807	100.0000	125	149.9920	163.4215	150.0000	170.7064
20	98.4071	163.5977	108.9703	105.2332	140.6243	158.8396	100.0000	125	150.0000	159.8146	150.0000	167.0969
21	84.1473	164.1047	109.3159	104.9536	141.8466	159.4040	99.9967	125	149.9997	160.7738	149.9998	169.0197
22	55.6278	159.6944	106.0302	101.6919	133.0293	154.0591	100.0000	125	146.4966	155.7945	149.9960	163.2013
23	2.1538	153.3324	101.6162	96.4240	124.9990	143.7606	100.0000	125	137.0802	147.6655	141.0908	156.6259
24	−51.3202	150.0805	98.0217	91.1223	111.5097	135.8766	99.9559	125	129.4141	138.0456	131.0714	149.0290

Time	P12, MW	P13, MW	P14, MW	P15, MW	P16, MW	P17, MW	P18, MW	P19, MW	P20, MW	Wind, MW	Emission, ton	Fuel Cost, $
1	150.0000	129.4864	124.2735	25.0000	20.0000	30.0069	31.1985	40.0002	30.1338	36.5495	1981.86	48631.51
2	150.0013	122.9991	117.0802	25.0000	20.0002	30.0037	30.0000	40.0161	30	52.3396	1885.46	47293.51
3	150.0000	121.5313	116.2013	25.0026	20.0000	30.0000	30.1017	40	30.0545	48.9381	1874.75	47100.00
4	150.0065	120.6639	115.5658	25.0005	20.0000	30.0000	30.0000	40.0159	30.0287	38.8993	1879.17	47172.76
5	150.0000	126.9558	120.5862	25.0001	20.0005	30.0000	30.0000	40.0000	30	4.9396	1932.70	47980.09
6	150.0005	130.3009	125.9705	25.0000	20.0000	30.0048	30.6050	40.0001	30.0402	16.3295	1992.16	48780.78
7	151.4372	139.1225	129.9256	25.0058	20.0000	30.0000	35.9273	40.1005	33.8458	28.7384	2159.54	50718.94
8	156.7718	143.3122	130.0000	25.0014	20.0003	30.0000	38.0710	40.0000	37.4218	44.5809	2285.46	51910.08
9	158.2709	142.4261	130.0000	25.0000	20.0000	30.0011	38.5068	40.1530	36.0162	14.6527	2282.55	51870.11
10	156.0909	142.6116	129.9636	25.0009	20.0001	30.0000	37.7286	40.3652	37.7455	22.9149	2259.44	51673.35
11	153.9140	142.3323	129.9975	25.0005	20.0000	30.0000	36.9021	40.1535	35.9547	37.7836	2235.66	51471.85
12	152.9126	138.4283	129.9997	25.0000	20.0021	30.0000	35.7427	40.1205	35.1232	46.7815	2176.35	50880.38
13	150.0393	134.1487	129.9993	25.0000	20.0000	30.0008	34.4737	40.0279	33.8417	61.5000	2117.54	50292.00
14	152.4363	137.2899	129.8865	25.0009	20.0000	30.0019	35.3995	40.0146	35.1647	54.2371	2169.32	50822.91
15	157.4147	144.7074	130.0000	25.0001	20.0000	30.0028	39.2717	40.8202	37.2845	53.1016	2318.11	52189.52
16	158.7724	145.5981	129.9878	25.0001	20.0001	30.0000	38.7629	41.1472	37.4462	47.6673	2339.50	52401.60
17	163.7052	152.0449	129.9836	25.0007	20.0004	30.0000	43.0595	44.7257	40.9259	40.9363	2540.65	53937.01
18	168.8458	158.5437	129.9838	25.0000	20.0000	30.0000	45.5384	46.5512	42.9120	35.3388	2706.37	55072.61
19	173.0987	159.9985	130.0000	25.0001	20.0000	30.0000	48.4362	48.4488	46.1266	37.7621	2858.31	55975.89
20	170.1924	159.9668	129.9988	25.0000	20.0001	30.0020	47.1211	47.6457	44.0377	35.0058	2768.31	55462.79
21	171.0070	159.9999	129.9905	25.0000	20.0004	30.0003	47.8884	47.9143	44.6482	1.5973	2794.59	55611.45
22	165.6299	153.7817	130.0000	25.0000	20.0000	30.0000	44.5565	45.6748	42.3935	8.6069	2613.21	54453.36
23	159.0080	145.2311	129.9816	25.0000	20.0018	30.0019	40.6661	41.8884	37.7699	6.4962	2365.24	52571.93
24	152.9521	138.9631	130.0000	25.0059	20.0036	30.0011	36.2509	40.0034	34.3695	0.0000	2166.79	50780.83
										Total	54703.056	1235055.3

Table 10 Data for 20-generating units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_{\max}$ (MW)	600	200	200	200	160	100	125	150	200	150
$P_{\min}$ (MW)	150	50	50	50	50	20	25	50	50	30
a (\$/h)	1000	970	600	700	420	360	490	660	765	770
b (\$/MWh)	18.19	19.26	19.8	19.1	18.1	19.26	17.14	18.92	18.27	18.92
c (\$/MWh^2)	0.00068	0.00071	0.0065	0.005	0.00738	0.00612	0.0079	0.00813	0.00522	0.00573
α (ton/h)	300	520	510	510	220	222	220	220	290	285
β (ton/MWh)	−4.18	−3.34	−3.55	−3.55	−2.68	−2.66	−2.68	−2.68	−2.22	−2.22
γ (ton/MWh^2)	0.0296	0.0512	0.0496	0.0496	0.0151	0.0151	0.0151	0.0151	0.0145	0.0145
ξ (ton/h)	0.5035	0.02075	0.02075	0.5035	0.5035	0.5035	0.5035	0.5035	0.5035	0.5035
λ (1/MWh)	0.02075	0.05035	0.05035	0.02075	0.02075	0.02075	0.02075	0.02075	0.02075	0.02075

	Unit 11	Unit 12	Unit 13	Unit 14	Unit 15	Unit 16	Unit 17	Unit 18	Unit 19	Unit 20
$P_{\max}$ (MW)	300	500	160	130	185	80	85	120	120	100
$P_{\min}$ (MW)	100	150	40	20	25	20	30	30	40	30
a (\$/h)	800	970	900	700	450	370	480	680	700	850
b (\$/MWh)	16.69	16.76	17.36	18.7	18.7	14.26	19.14	18.92	18.47	19.79
c (\$/MWh^2)	0.0048	0.0031	0.0085	0.00511	0.00398	0.0712	0.0089	0.00713	0.00622	0.00773
α (ton/h)	295	295	310	310	360	360	360	50	80	80
β (ton/MWh)	−2.26	−2.26	−2.42	−2.42	−1.11	−1.11	−1.11	−1.89	−2.08	−2.08
γ (ton/MWh^2)	0.0138	0.0138	0.0132	0.0132	1.842	1.842	1.842	0.085	0.0121	0.0121
ξ (ton/h)	0.5035	0.5035	0.5035	0.5035	0.9936	0.9936	0.9936	0.9936	0.9142	0.9142
λ (1/MWh)	0.02075	0.02075	0.02075	0.02075	0.0406	0.0406	0.0406	0.0406	0.0454	0.0454

7.2 Appendix 2: simulation results of case study II

7.3 Appendix 3: twenty-unit test system data

The data of the 20-generating units are given in Table 10. The ***B*** matrix of the transmission losses is given in the following.

B_{i0} and B_{00} are assumed to be equal to zero and $A = 10^{-2}$. (see equation at the bottom of next page).

$$B_{ji} = 10^{-6}\begin{bmatrix} 8.7 & 0.43 & -4.61 & 0.36 & 0.32 & -0.66 & 0.96 & -1.6 & 0.8 & -0.1 & 3.6 & 0.64 & 0.79 & 2.1 & 1.7 & 0.8 & -3.2 & 0.7 & 0.48 & -0.7 \\ 0.43 & 8.3 & -0.97 & 0.22 & 0.75 & -0.28 & 5.04 & 1.7 & 0.54 & 7.2 & -0.28 & 0.98 & -0.46 & 1.3 & 0.8 & -0.2 & 0.52 & -1.7 & 0.8 & 0.2 \\ -4.61 & -0.97 & 9 & -2 & 0.63 & 3 & 1.7 & -4.3 & 3.1 & -2 & 0.7 & -0.77 & 0.93 & 4.6 & -0.3 & 4.2 & 0.38 & 0.7 & -2 & 3.6 \\ 0.36 & 0.22 & -2 & 5.3 & 0.47 & 2.62 & -1.96 & 2.1 & 0.67 & 1.8 & -0.45 & 0.92 & 2.4 & 7.6 & -0.2 & 0.7 & -1 & 0.86 & 1.6 & 0.87 \\ 0.32 & 0.75 & 0.63 & 0.47 & 8.6 & -0.8 & 0.37 & 0.72 & -0.9 & 0.69 & 1.8 & 4.3 & -2.8 & -0.7 & 2.3 & 3.6 & 0.8 & 0.2 & -3 & 0.5 \\ -0.66 & -0.28 & 3 & 2.62 & -0.8 & 11.8 & -4.9 & 0.3 & 3 & -3 & 0.4 & 0.78 & 6.4 & 2.6 & -0.2 & 2.1 & -0.4 & 2.3 & 1.6 & -2.1 \\ 0.96 & 5.04 & 1.7 & -1.96 & 0.37 & -4.9 & 8.24 & -0.9 & 5.9 & -0.6 & 8.5 & -0.83 & 7.2 & 4.8 & -0.9 & -0.1 & 1.3 & 0.76 & 1.9 & 1.3 \\ -1.6 & 1.7 & -4.3 & 2.1 & 0.72 & 0.3 & -0.9 & 1.2 & -0.96 & 0.56 & 1.6 & 0.8 & -0.4 & 0.23 & 0.75 & -0.56 & 0.8 & -0.3 & 5.3 & 0.8 \\ 0.8 & 0.54 & 3.1 & 0.67 & -0.9 & 3 & 5.9 & -0.96 & 0.93 & -0.3 & 6.5 & 2.3 & 2.6 & 0.58 & -0.1 & 0.23 & -0.3 & 1.5 & 0.74 & 0.7 \\ -0.1 & 7.2 & -2 & 1.8 & 0.69 & -3 & -0.6 & 0.56 & -0.3 & 0.99 & -6.6 & 3.9 & 2.3 & -0.3 & 2.8 & -0.8 & 0.38 & 1.9 & 0.47 & -0.26 \\ 3.6 & -0.28 & 0.7 & -0.45 & 1.8 & 0.4 & 8.5 & 1.6 & 6.5 & -6.6 & 10.7 & 5.3 & -0.6 & 0.7 & 1.9 & -2.6 & 0.93 & -0.6 & 3.8 & -1.5 \\ 0.64 & 0.98 & -0.77 & 0.92 & 4.3 & 0.78 & -0.83 & 0.8 & 2.3 & 3.9 & 5.3 & 8 & 0.9 & 2.1 & -0.7 & 5.7 & 5.4 & 1.5 & 0.7 & 0.1 \\ 0.79 & -0.46 & 0.93 & 2.4 & -2.8 & 6.4 & 7.2 & -0.4 & 2.6 & 2.3 & -0.6 & 0.9 & 11 & 0.87 & -1 & 3.6 & 0.46 & -0.9 & 0.6 & 1.5 \\ 2.1 & 1.3 & 4.6 & 7.6 & -0.7 & 2.6 & 4.8 & 0.23 & 0.58 & -0.3 & 0.7 & 2.1 & 0.87 & 3.8 & 0.5 & -0.7 & 1.9 & 2.3 & -0.97 & 0.9 \\ 1.7 & 0.8 & -0.3 & -0.2 & 2.3 & -0.2 & -0.9 & 0.75 & -0.1 & 2.8 & 1.9 & -0.7 & -1 & 0.5 & 11 & 1.9 & -0.8 & 2.6 & 2.3 & -0.1 \\ 0.8 & -0.2 & 4.2 & 0.7 & 3.6 & 2.1 & -0.1 & -0.56 & 0.23 & -0.8 & -2.6 & 5.7 & 3.6 & -0.7 & 1.9 & 10.8 & 2.5 & -1.8 & 0.9 & -2.6 \\ -3.2 & 0.52 & 0.38 & -1 & 0.8 & -0.4 & 1.3 & 0.8 & -0.3 & 0.38 & 0.93 & 5.4 & 0.46 & 1.9 & -0.8 & 2.5 & 8.7 & 4.2 & -0.3 & 0.68 \\ 0.7 & -1.7 & 0.7 & 0.86 & 0.2 & 2.3 & 0.76 & -0.3 & 1.5 & 1.9 & -0.6 & 1.5 & -0.9 & 2.3 & 2.6 & -1.8 & 4.2 & 2.2 & 0.16 & -0.3 \\ 0.48 & 0.8 & -2 & 1.6 & -3 & 1.6 & 1.9 & 5.3 & 0.74 & 0.47 & 3.8 & 0.7 & 0.6 & -0.97 & 2.3 & 0.9 & -0.3 & 0.16 & 7.6 & 0.69 \\ -0.7 & 0.2 & 3.6 & 0.87 & 0.5 & -2.1 & 1.3 & 0.8 & 0.7 & -0.26 & -1.5 & 0.1 & 1.5 & 0.9 & -0.1 & -2.6 & 0.68 & -0.3 & 0.69 & 7 \end{bmatrix}$$

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