Operational Planning for Integrated Energy System with Carbon Flow and Trading Scheme Towards Emission Reduction

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Abstract—The operational planning for Integrated Energy System (IES) with different energy carriers provides a new perspective of synergies towards a low-carbon society. Existing carbon trading scheme promotes this process via finical incentives. However, as customers are the underlying driver of emission. Planning with accurate carbon tracing and demand response would improve the effectiveness of decarbonization. Meanwhile, customers would be encouraged to participate with extra environmental profits rather than passive price takers, under the double taxation principle. Therefore, a forward cycle can be established to reduce carbon emission. This paper proposes an operation planning model for IES to study the influence of demand response to emission mitigation and system dispatch in both energy market and carbon trading market. The proposed model is tested on an IES system involving a modified IEEE 24-bus electricity network and a modified 20-bus natural gas network. Based on the simulation result, the proposed model is effective to achieve emission mitigation.

Keywords—: integrated energy system, low-carbon economy, emission trading market, carbon emission flow, demand response

I. Nomenclature

A. Indices and Sets

t	Index of time periods for planning
Ω_{BESS}, Ω_{DG}	Set of BESS and distributed generators
$\Omega_G^{Gas-fired}$	Set of gas-fired generators
$\Omega^{Storage}$	Set of gas storage facilities
Ω_D^{Ele}, Ω_D^{Gas}	Set of demand buses in electricity network and gas network, respectively
$\Omega_D^{Ele,Gas}$	Set of integrated buses in IES
Ω_G^{Ele}, Ω_S^{Gas}	Set of power generators and gas supplies in electricity and gas network, respectively
Ω_i^{Ele}, Ω_i^{Gas}	Set of power generators and gas supplies connected to bus i in IES
Ω_N^{Ele}, Ω_N^{Gas}	Set of electricity network and gas network, respectively
$\Omega_i^{(\cdot)^+}$	Set of branches with inflow power into bus i

B. Parameters

A	Price elasticity constant
$a_{Gi}^{(\cdot)}$, $b_{Gi}^{(\cdot)}$, $c_{Gi}^{(\cdot)}$	First, second, third order cost coefficients of electricity generators
a_{Si}, b_{Si}, c_{Si}	First, second, third order cost coefficients of gas supplies
$a_{(\cdot),ij}^{Comp}$	Horsepower coefficients of gas compressor
B_{ij}	Admittance between bus i and j
L_{ij}	Constant associated with compressor suction temperature and compressor efficiency
$T^{(\cdot)}$	Daily operational horizon, with index of time t
Z_{ij}	Constant associated with heat ratio and gas compressibility
Δt	Time interval
β_i^{BESS}	Cost coefficient of the BESS i lifetime degradation
$\delta^{(\cdot)}$	The unit price of renewable generators
ε_j	Price elasticity at demand bus j
$\eta^{(\cdot)}$	Energy conversion ratio
κ_{ij}	Pipeline constant between bus i and j

λ^{Carbon}	Carbon price in carbon trading market
$\psi_{(\cdot)}$	Energy amount of BESS at various time period
$\psi_i^{BESS\_rate}$	Energy capacity of BESS i
$\varpi_{(\cdot)}$	Energy amount of gas storage at various time period
$Ramp_{Gi}^{Up}$, $Ramp_{Gi}^{Down}$	Ramp-up and ramp-down limits for generator i
$\overline{(\cdot)}$, $\underline{(\cdot)}$	Upper and lower bounds

C. Variables

E	Carbon emission amount
f	Energy flow
$H_{ij,t}$	Horsepower consumption between bus i and j time t, respectively
$P_D^{'}$, P_D	Demand of power before and after demand response, respectively
P_G, g_S	Output of generators and gas sources, respectively
P^{BESS}, $g^{Storage}$	Power and gas output from BESS and gas storage, respectively
$P^{pv/wind}$, P^{DG}	Power output from PV/wind generation and renewable generators, respectively
g_D, $\hbar_D$	Gas demand and thermal demand, respectively
SOC	State of charge for BESS
$x^{(\cdot)}$	Installation number of renewable generators at demand side.
λ^{Ele}, λ^{Gas}	Energy price in electricity market and gas market, respectively
$\pi_{i,t}, \pi_{j,t}$	Pressure at bus i and j time t, respectively
$\psi_{i,t}^{BESS}$, $\psi_{i,t+1}^{BESS}$	Energy amount of BESS i time t and $t+1$, respectively
$\varpi_{i,t}$, $\varpi_{i,t+1}$	Energy amount of gas storage i at time t and $t+1$, respectively

D. Functions

$C^{(\cdot)}$	Cost correlated function
$R^{(\cdot)}$	Revenue correlated function
$S^{(\cdot)}$	Consumer surplus correlated function
$U^{(\cdot)}$	Utility function

II. INTRODUCTION

Integrated Energy System (IES) is considered to be the most mainstream energy form during the process of synergies, it can enable multiple energy carriers with different characteristics participating in the energy supply chain. The different characteristics consist of various aspects including economy, delivery, storage, etc., which provides more flexible options in operational planning. For instance, compared to electricity power, natural gas has shown obvious better performance in energy storage and carbon emission during the combustion process. However, based on the mature network and market principle, electricity power has advantages in economic aspect. Under the definition of low-carbon society, IES has potential in emission mitigation covering from the whole energy supply chain from primary energy sources to end-use customers. Therefore, how to plan the operation of IES toward emission reduction attracts more and more attention. Ref. [1] and [2] investigate the coordinated operation of coupled electricity and gas systems. Moreover, a game-theory model is employed in Ref. [3] to study the cooperation between electricity and gas systems. However, those studies only focus on the advantage of gas in carbon emission, the impacts of carbon policy to planning is not included.

As for the carbon policies, carbon trading scheme is considered as one of the most effective and fair methods by using financial incentives to encourage emission mitigation. According to [4], the total European Union emission has decreased by 5.9% from combustion installation between 2017 and 2018. the main reason is caused by the phasing out coal use in power plants. Meanwhile, the total emission reduction made approximately EUR 14.1 billion of revenue from auctions. There are much research works coordinating the system planning with relevant carbon policies. A restriction on carbon emission is modeled as inequality constraint, aiming to optimize the entire system with a given emission cap in Ref. [5]. Ref. [6] and [7] propose a model with multiple objectives functions, one of them is to minimize the total carbon emission amount. Moreover, the impact of carbon price on power system has been studied in Ref**.** [8] and [9]. However, most of the existing emission control mainly focuses on the "observed" emission, i.e. fossil fuel combustion at power generation, and utility companies would simply fully (or almost fully) pass-through carbon cost to end-use customers. Since end-use customers are the main underlying drivers of emission, it is more reasonable to clearly rearrange the responsibility of emission. A carbon emission tracing model called "carbon emission flow (CEF)" has been defined in Ref. [10], it provides a more accurate perspective to calculate emission from demand side. Ref. [11] comprehensively introduces the CEF and reveals the relationship between this "virtual" emission and power flow in electricity system. Furthermore, a two-level multi-energy system planning model under electricity market and carbon trading market is studied in Ref. [12]. However, above mentioned studies fail to involve demand response. Because active customers would be encouraged to participate with extra environmental profits rather than passive price takers. It can establish a forward cycle to more effectively reduce carbon emission.

This paper proposes a coordinated operation planning model for IES to study the influence of demand response to emission mitigation and system dispatch in both energy market and carbon trading market. Moreover, optimal installed renewable generators including PV, wind are also considered.

III. CARBON FLOW MODEL IN IES

Based on the Ref. [10] and [11], a concept of “carbon emission flow (CEF)” has been introduced to reveal the relationship between energy flow and accompanying carbon emission. In this paper, we utilize this methodology to trace the carbon emission in IES. Mathematically, the CEF model can be expressed as:

$$e_{i,t}^{Ele}=\frac{\sum_{k\in\Omega_i^{Ele}}P_{Gk,t}\cdot e_{Gk}+\sum_{j\in\Omega_i^{p+}}\left|f_{ij,t}^{Ele}\right|\cdot\rho_{ij,t}^{Ele}}{\sum_{k\in\Omega_i^{Ele}}P_{Gk,t}+\sum_{j\in\Omega_i^{p+}}\left|f_{ij,t}^{Ele}\right|} \tag{1}$$

$$\rho_{ij,t}^{Ele}=\begin{cases}e_{i,t}^{Ele}, & if\ f_{ij,t}^{Ele}\geq 0\\ e_{j,t}^{Ele}, & if\ f_{ij,t}^{Ele}\leq 0\end{cases} \tag{2}$$

$$e_{i,t}^{Gas}=\frac{\sum_{n\in\Omega_i^{Gas}}g_{Sn,t}\cdot e_{Sn}+\sum_{j\in\Omega_i^{g^+}}\left|f_{ij,t}^{Gas}\right|\cdot\rho_{ij,t}^{Gas}}{\sum_{n\in\Omega_i^{Gas}}g_{Sn,t}+\sum_{j\in\Omega_i^{g^+}}\left|f_{ij,t}^{Gas}\right|} \tag{3}$$

$$\rho_{ij,t}^{Gas}=\begin{cases}e_{i,t}^{Gas}, & if\ f_{ij,t}^{Gas}\geq 0\\ e_{j,t}^{Gas}, & if\ f_{ij,t}^{Gas}< 0\end{cases} \tag{4}$$

$$E_{i,t}^{Ele}=P_{i,t}\cdot e_{i,t}\cdot\Delta t,\quad \forall t\in 1:T^{Ele},\forall i\in\Omega_N^{Ele} \tag{5}$$

$$E_{i,t}^{Gas}=g_{i,t}\cdot e_{i,t}\cdot\Delta t,\quad \forall t\in 1:T^{Gas},\forall i\in\Omega_N^{Gas} \tag{6}$$

where $e_{i,t}^{(\cdot)}$ denotes nodal carbon intensity at bus i time t; $\rho_{ij,t}^{(\cdot)}$ denotes branch carbon intensity between bus i to j at time t; $E_{i,t}^{(\cdot)}$ denotes the carbon emission amount at bus i time t. Detailed introduction of nodal and branch carbon intensity and relevant definition can be found in Ref. [11].

IV. Price-Based Demand Response Model

There are many research works focusing on the demand response subproblem. As there is different timescale between electricity and gas market, and gas price is only fluctuated with the massive changing amount. In this paper, we mainly focus on the changing electricity demand with price, an exponential function with price elasticity introduced in Ref. [13] is employed to illustrate the relationship between changing demand and price. Mathematically, it can be expressed as:

$$P_{Di,t}=A\cdot P_{Di,t}^{'\ \varepsilon_i} \tag{7}$$

where $P_{Di,t}^{'}$, $P_{Di,t}$ denotes the demand amount at demand bus i at time t before demand response and after demand response, respectively; A denotes the price elasticity constant; ε_j is the price elasticity at demand bus i. Note that there are many other methods can be used to describe this relationship.

V. Proposed Operation Model

A. Principle

Firstly, the *double taxation principle* is applied to the proposed model to clearly identify the responsibility of carbon emission from both the supply side and demand side.

Secondly, the cap-and-trade principle of carbon trading scheme is used in the proposed model.

Finally, a zero sum gains-data envelopment analysis (ZSG-DEA) model introduced in Ref. [14] is utilized to allocate the carbon emission allowance at the demand side. Furthermore, developed multiple indicators for the ZSG-DEA has been rearranged in Ref. [15] aiming particularly on the energy sector. In the ZSG-DEA model, *equity*, *efficiency*, *feasibility*, and *sustainability* principles are employed.

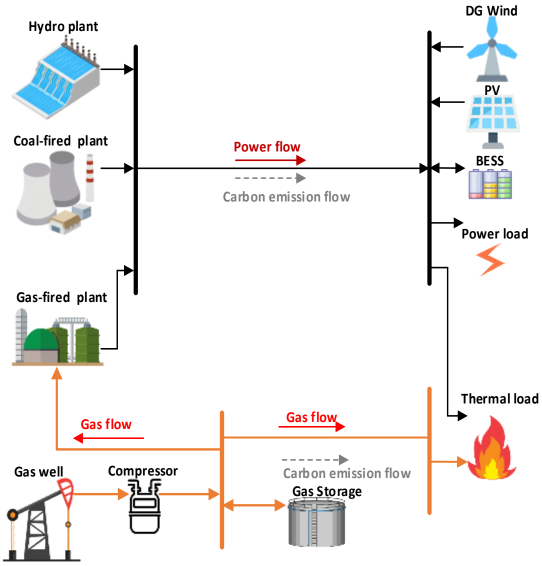

Fig. 1. A paradigm of integrated energy system with renewable generation

B. Mathematical Formulation

The following assumptions are considered in the proposed model:

- All distributed generations, battery energy storage system (BESS) at customer side is considered as a combined component with renewable distributed generations. Moreover, we only consider gas-fired plant and thermal load as the integrated components of electricity and gas systems. The typical integration of two networks is illustrated in Fig. 1.

The overall proposed framework is modeled as a two-stage optimization problem. At the first stage, the objective is formulated to maximize the overall social welfare in the integrated energy market and potential environmental welfare from the perspective of the supply side, for a period of operation planning collated to the time-interval of allocated emission (e.g. One season). Mathematically, it can be expressed as below:

$$\max\ S^{Ele}+S^{Ele}+S^{Env}=\min-(S^{Ele}+S^{Ele}+S^{Env}) \tag{8}$$

$s.t.$

$$\begin{aligned}S^{Ele}=&\sum\sum_{t=1}^{T^{Ele}}[\sum_{\substack{j\in\Omega_D^{Ele}\\ m\in\Omega_D^{Ele,Gas}}}U^{Ele}(P_{Dj,t},P_{Dm,t})\\&-\sum_{i\in\Omega_G^{Ele}}C^{Ele}(P_{Gi,t})-\sum_{i\in\Omega_G^{Gas-fired}}C^{Gas-fired}(P_{Gi,t}^{Gas})]\end{aligned} \tag{9}$$

$$\begin{aligned}S^{Gas}=&\sum\sum_{t=1}^{T^{Gas}}[\sum_{\substack{j\in\Omega_D^{Gas}\\ m\in\Omega_D^{Ele,Gas}}}U^{Gas}(g_{Dj,t},g_{Dm,t})\\&-\sum_{i\in\Omega_S^{Gas}}C^{Gas}(g_{Si,t})]\end{aligned} \tag{10}$$

$$C^{Ele}(P_{Gi,t}) = a_{Gi} \cdot P_{Gi,t}^2 + b_{Gi} \cdot P_{Gi,t} + c_{Gi} \tag{11}$$

$$C^{Gas}(g_{Si,t}) = a_{Si} \cdot g_{Si,t}^2 + b_{Si} \cdot g_{Si,t} + c_{Si} \tag{12}$$

$$\begin{aligned} C^{Gas-fired}(P_{Gi,t}^{Gas}) &= a_{Gi,t}^{Gas-fired} \cdot P_{Gi,t}^{Gas^2} \\ &+ b_{Gi,t}^{Gas-fired} \cdot P_{Gi,t}^{Gas} + c_{Gi,t}^{Gas-fired} \end{aligned} \tag{13}$$

$$S^{Env} = \sum_{i \in \Omega_G^{Ele}} \lambda_i^{Carbon} \cdot (E_{Gi}^{Cap} - \sum \sum_{t=1}^{T^{Ele}} E_{Gi,t}) \tag{14}$$

$$\begin{aligned} & P_{Dj,t} + P_{Dm,t} = P_{Dj,t}^{'} + P_{Dm,t}^{'} - \Delta P_{Dj,t} - \Delta P_{Dm,t} - P_{i,t}^{DG}, \\ & \forall t \in 1:T^{Ele}, \forall j \in \Omega_D^{Ele}, \forall m \in \Omega_D^{Ele,Gas}, \forall i \in \Omega_{DG} \end{aligned} \tag{15}$$

$$P_{Dm,t} = P_{Dm,t}^{power} + P_{Dm,t}^{power,heat}, \quad \forall t \in 1:T^{Ele}, \forall m \in \Omega_D^{Ele,Gas} \tag{16}$$

$$P_{i,t}^{DG} = P_{i,t}^{Wind} + P_{i,t}^{PV} + P_{i,t}^{BESS}, \quad \forall t \in 1:T^{Ele}, \forall i \in \Omega_{DG} \tag{17}$$

$$\underline{P}_{Gi} \le P_{Gi,t} \le \overline{P}_{Gi}, \ \forall t \in 1:T^{Ele}, \ \forall t \in \Omega_G^{Ele} \tag{18}$$

$$\begin{cases} P_{Gi,t} - P_{Gi,t-1} \le Ramp_{Gi}^{Up}, & if \ \ P_{Gi,t} \ge P_{Gi,t-1} \\ P_{Gi,t-1} - P_{Gi,t} \le Ramp_{Gi}^{Down}, & if \ \ P_{Gi,t-1} \ge P_{Gi,t} \end{cases} \tag{19}$$

$$P_{i,t}^{DG} + P_{Gi,t} - \sum f_{ij,t}^{Ele} - P_{Di,t} = 0, \ \forall t \in 1:T^{Ele}, \forall i,j \in \Omega_N^{Ele} \tag{20}$$

$$f_{ij,t}^{Ele} - B_{ij} \cdot (\theta_{i,t} - \theta_{j,t}) = 0, \ \ \forall t \in 1:T^{Ele}, \ \forall i,j \in \Omega_N^{Ele} \tag{21}$$

$$\underline{P}_{\ell ine} \le f_{ij,t}^{Ele} \le \overline{P}_{\ell ine}, \quad \forall t \in 1:T^{Ele}, \forall i,j \in \Omega_N^{Ele} \tag{22}$$

$$\psi_{i,t+1} = \psi_{i,t} - P_{i,t}^{BESS} \cdot \Delta t, \ \ \forall t \in 1:T^{Ele}, \ \forall i \in \Omega_{BESS} \tag{23}$$

$$SOC_{i,t} = \frac{\psi_{i,t}^{BESS}}{\psi_i^{BESS\_rate}} \tag{24}$$

$$\underline{SOC}_i \le SOC_{i,t} \le \overline{SOC}_i \tag{25}$$

$$-\overline{P}_i^{BESS,Chr} \le P_{i,t}^{BESS} \le \overline{P}_i^{BESS,Dis} \tag{26}$$

$$\overline{P}_i^{BESS,Chr} \ge 0; \ \overline{P}_{i,t}^{BESS,Dis} \ge 0 \tag{27}$$

$$\psi_{i,0} = \psi_{i,Initial}; \ \ \psi_{i,T^{Ele}} \ge \psi_{i,End} \tag{28}$$

$$\begin{aligned} & f_{ij,t}^{Gas} = sgn(\pi_{i,t}, \pi_{j,t}) \cdot \kappa_{ij} \cdot \sqrt{\left| \pi_{i,t}^2 - \pi_{j,t}^2 \right|}, \\ & sgn(\pi_{i,t}, \pi_{j,t}) = \begin{cases} 1 & \pi_{i,t} \ge \pi_{j,t} \\ -1 & \pi_{i,t} < \pi_{j,t} \end{cases} \end{aligned} \tag{29}$$

$$H_{ij,t} = L_{ij} \cdot f_{ij,t}^{Gas,Comp} \cdot [(\frac{\pi_{i,t}}{\pi_{j,t}})^{Z_{ij}} - 1] \tag{30}$$

$$g_{i,t}^{Comp} = a_{3,ij}^{Comp} + a_{2,ij}^{Comp} \cdot H_{ij,t} + a_{1,ij}^{Comp} \cdot H_{ij,t}^2 \tag{31}$$

$$\begin{aligned} & g_{Si,t} + g_{i,t}^{Storage} = g_{i,t}^{Comp} + \sum f_{ij,t}^{Gas} + g_{Di,t} + g_{Gi,t}^{Gas-fired}, \\ & \forall t = 1:T^{Gas}, \forall i,j \in \Omega_N^{Gas} \end{aligned} \tag{32}$$

$$\begin{aligned} & \hbar_{Dm,t} = \eta^{Gas,heat} \cdot g_{Dm,t} + \eta_m^{Power,heat} \cdot P_{Dm,t}^{Power,heat}, \\ & \forall t = 1:T^{Gas}, \forall m \in \Omega_D^{Ele,Gas} \end{aligned} \tag{33}$$

$$\begin{aligned} & P_{Gi,t}^{Gas} = \eta_i^{Gas-fired} \cdot g_{Gi,t}^{Gas-fired}, \\ & \forall t = 1:T^{Ele/Gas}, \forall i \in \Omega_G^{Gas-fired} \end{aligned} \tag{34}$$

$$\underline{g}_{Si,t} \le g_{Si,t} \le \overline{g}_{Si,t}, \ \ \forall t = 1:T^{Gas}, \forall i \in \Omega_S^{Gas} \tag{35}$$

$$\underline{\pi}_{i,t} \le \pi_{i,t} \le \overline{\pi}_{i,t}, \quad \forall t = 1:T^{Gas}, \forall i \in \Omega_N^{Gas} \tag{36}$$

$$\varpi_{i,t+1} = \varpi_{i,t} - g_{i,t}^{Storage} \cdot \Delta t, \quad \forall t = 1:T^{Gas}, \ i \in \Omega^{Storage} \tag{37}$$

$$\underline{\varpi}_i \le \varpi_{i,t} \le \overline{\varpi}_i \tag{38}$$

$$\varpi_0 = \sum \varpi_{i,Initial}; \ \ \sum \varpi_{i,T^{Gas}} \ge \varpi_{End} \tag{39}$$

Eq. (5)-(6)

Constraints (9)-(10) describe the detailed social welfare in the integrated energy market in terms of electricity and gas market, respectively. Constraints (11)-(13) define the supply cost. Constraints (14) represents the potential environmental welfare. Constraints (15)-(17) guarantee the power balance in electricity network. Constraints (18)-(19) impose the fossil generators bounds and up/down limitation. Constraints (20)-(22) denote nodal power balance and power flow related constraints including bounds of transmission feeders. Constrains (23)-(28) are the BESS related constraints in terms of energy balance, state of charging, charging and discharging limitation. Constrains (29) is the Weymouth equation for pipeline gas flow, where $sgn(\cdot)$ is the function equals to 1 when $\pi_{i,t} \ge \pi_{j,t}$, and -1 otherwise. Constraints (30)-(31) are compressor related constraints. Constraints (32) denotes nodal gas balance in gas network. Constrains (33)-(34) impose the energy conversion between thermal and gas, gas and electricity, respectively. Constrains (35) denotes the bounds of gas supply. Constrains (36) is the pressure relevant constraints. Constrains (37)-(39) describe the constraints of gas storage. Eq. (5)-(6) are carbon emission related constraints. Moreover, it should be noted that a piecewise function in Ref. [15] is applied to describe the behavior of customers in energy purchase and energy consumption.

Based on the energy price and nodal carbon intensity, at the second stage, the formulated objective function aims to maximize the total consumer surplus in energy market and potential environmental profits in carbon trading market for the same time-interval as stage one. Mathematically, it can be expressed below as:

$$\max \ \underbrace{(U_D^{Ele} - C_D^{Ele}) + (U_D^{Gas} - C_D^{Gas})}_{Consumer\ surplus\ in\ integrated\ energy\ market} + R^{DG} - C^{DG} + R_D^{Env} \tag{40}$$

s.t.

$$U_D^{Ele} - C_D^{Ele} = \sum \sum_{t=1}^{T^{Ele}} \sum_{\substack{j \in \Omega_D^{Ele} \\ m \in \Omega_D^{Ele,Gas}}} \begin{Bmatrix} U^{Ele}(P_{Dj,t}^{'} - \Delta P_{Dj,t}, P_{Dm,t}^{'} - \Delta P_{Dm,t},) \\ -[\lambda_{j,t}^{Ele} \cdot (P_{Dj,t}^{'} - \Delta P_{Dj,t}) \\ +\lambda_{m,t}^{Ele} \cdot (P_{Dm,t}^{'} - \Delta P_{Dm,t})] \cdot \Delta t \end{Bmatrix} \tag{41}$$

$$U_D^{Gas} - C_D^{Gas} = \sum\sum_{t=1}^{T^{Gas}} \sum_{\substack{j\in\Omega_D^{Gas} \\ m\in\Omega_D^{Ele,Gas}}} \left\{ \begin{matrix} U^{Gas}(g_{Dj,t}, g_{Dm,t}) \\ -[\lambda_{j,t}^{Gas}\cdot g_{Dj,t} + \lambda_{m,t}^{Gas}\cdot g_{_{Dm,t}}]\cdot\Delta t \end{matrix} \right\} \tag{42}$$

$$R^{DG} = \sum_{t=1}^{T^{Ele}} \sum_{i\in\Omega^{Ele}} P_{i,t}^{DG}\cdot\lambda_{i,t}^{Ele}\cdot\Delta t \tag{43}$$

$$C^{DG} = \sum_{i\in\Omega_{DG}^{PV}} C^{PV} + \sum_{i\in\Omega_{DG}^{Wind}} C^{Wind} + \sum_{t}^{T^{Ele}} \sum_{i\in\Omega^{BESS}} C_{i,t}^{BESS} \tag{44}$$

$$\begin{aligned} R_D^{Env} = [& \sum_{j\in\Omega_D^{Ele}} \lambda_j^{Carbon}\cdot(\sum\sum_{t=1}^{T^{Ele}} E_{Dj,t} - E_{Dj}^{Cap}) \\ & + \sum_{m\in\Omega_D^{Ele,Gas}} \lambda_m^{Carbon}\cdot(\sum\sum_{t=1}^{T^{Ele}} E_{Dm,t} - E_{Dm}^{Cap\_mix})] \end{aligned} \tag{45}$$

$$C^{PV/Wind} = C_R^{PV/Wind}\cdot x_i^{PV/Wind}\cdot\delta^{PV/Wind} \tag{46}$$

$$\begin{aligned} P_{i,t}^{pv/wind} = x_i^{pv/wind}\cdot P_t^{pv\_single/wind\_single}, \\ \forall t\in 1:T^{Ele}, \forall i\in\Omega_{DG} \end{aligned} \tag{47}$$

$$\begin{aligned} 0\le P_t^{pv\_single/wind\_single} \le \overline{P}_t^{pv\_single/wind\_single}, \\ \forall t\in 1:T^{Ele}, \forall i\in\Omega_{DG} \end{aligned} \tag{48}$$

$$C_{i,t}^{BESS} = \beta_i^{BESS}\cdot\left|P_{i,t}^{BESS}\right|\cdot\Delta t + \beta_i^{BESS}\cdot\psi_{i,t}^{BESS}\cdot\phi^L\cdot\Delta t \tag{49}$$

$$\Delta P_{Dj,t} \le \Delta\overline{P}_{Dj,t}, \forall j\in\Omega_D^{Ele};\ \ \Delta P_{Dm,t} \le \Delta\overline{P}_{Dm,t}, \forall m\in\Omega_D^{Ele,Gas} \tag{50}$$

Eq. (5)-(6)

Constraint (41)-(45) describes the items in Eq. (40) in detail; herein, the item in bracket is defined as consumer surplus in the integrated energy market; constraints (43) imposes the revenue from replaced electricity produced via renewable generation; constraints (44) denotes the operation cost of renewable generation; constrains (45) denotes the potential environmental profits in carbon trading market. Constraints (46)-(48) represent the renewable generation related constraints including investment cost, power output, and output bounds. Constraints (49) employs the life cycle function of BESS to describe its operation cost. Constrains (50) imposes the demand response amount of each consumer. Finally, Eq. (5)-(6) are carbon emission related constraints.

Noted that the *Power Transfer Distribution Factor (PTDF)* [16] is employed to calculate power flow. Furthermore, energy price for each demand bus can be obtained via calculating the first order derivative *of Karush-Kuhn-Tucker* (*KKT*) condition at stage one, it can be considered as a shadow price [17].

VI. Result

The proposed model is tested on an IES involving a modified IEEE-24 bus power system and a modified 20-bus natural gas system. As shown in Fig. 2, there are 11 generators (6 thermal generators, 4 gas-fired generators, and 1 hydro plant), 21 load buses and 31 transmission feeders in the modified electricity network. Further, the natural gas network consists of 6 gas suppliers, 10 gas load buses, 20 gas pipelines, and 2 compressor stations. Both energy demand data and energy prices are from the State of the energy market report for 2018 by the Australia Energy Market Regulator on the website [18]. Moreover, the carbon price relevant subproblem is based on the environmental strategy report provided by CSIRO in Ref. [19].

The proposed planning model is verified using the following cases:

Case 1: Conventional energy scheduling with price-based demand response without carbon trading policy.

Case 2: Proposed two-stage planning model with price-based demand response and optimizing renewable generation installation at the customer side.

The *sequential quadratic programming* (*SQP*) is applied to solve the two-stage nonlinear optimization problem on Matlab® by a PC with an Intel Core (TM) i7-8700 CPU @3.20GHz with 16.00 GB RAM.

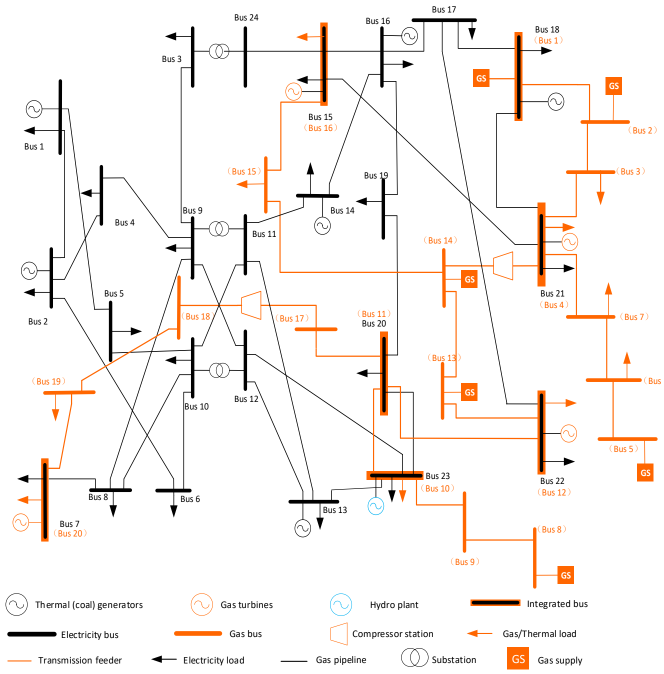

Fig. 2. Tested IES with modified electricity and gas network

Total carbon emission comparison for different types of buses (generation/supply bus, load bus, integrated bus) in two cases are given in Table I, we round all data to the whole number in the entire paper. Note that all carbon emission is considered from the demand perspective, in order to avoid double counting of emission amount. Moreover, emission from gas-fired generation is added into electricity network, so that under this view, emission occurred in gas network is from thermal load. It is observed that case 2 has an advantage in emission reduction. Further, from the individual network perspective, all types of buses in electricity network decrease the emission amount. Herein, the highest mitigation occurred in the integrated buses, which reaches almost 58% of previous value in case 1. Compare to case 1, there is also effective emission reduction in generation buses and load buses, the decreased value is nearly about 41% and 42 %, respectively. This might because of the installation of renewable generations at the demand side. Detailed power mixes would be discussed later. As for the gas network, there is almost no emission amount change in supply buses and integrated buses. However, it might due to the shortage of electricity supply to thermal load, there is an approximately 31% emission increase in integrated bus.

TABLE I. CARON EMISSION OCCURRED COMPARISON

Case	Generation/Supply buses[a] (kton)		Load bus (kton)		Integrated bus (kton)		Total (kton)
	Ele[b]	*Gas*	*Ele*	*Gas*	*Ele*	*Gas*	
Case 1	371	169	645	78	416	232	1911
Case 2	215	169	372	78	173	305	1348

a. The emission from generation bus is considered from the demand perspective

b. Ele represents the electricity network in IES and Gas represents the gas network in IES

Detailed power mixes in different cases are shown in Fig. 3. It can be seen there is a significant decrease of power output produced by coal generators in total power consumption from case 1 to case 2, the value is around 26%. Meanwhile, the proportion of power from the hydro plant has the biggest increase, the value changes from 4% to 13%. As aforementioned, the usage of power from gas-fired generators increase about 6% of power proportion. Distributed generators totally hold 11% percent in total power output, herein, 5% is from PV, 6% is from wind generators.

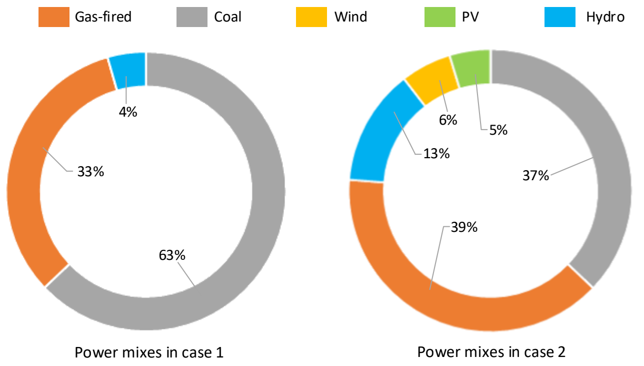

Fig. 3. Detailed Power mixes in cases for electricity network in IES

The power demand changing between case 1 and case 2 is shown in Fig. 4. Compared to case 1, the demand curve becomes smoother in case 2. Moreover, there is about 40% demand reduction by active participation of customers. Except the increasing power out from clean energy, demand response is also the reason why so much emission decreased in case 2

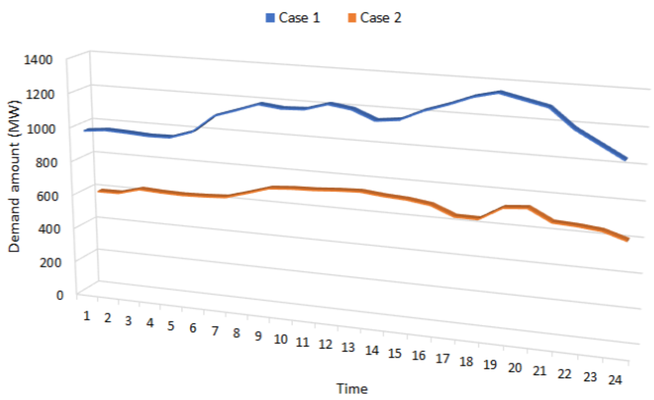

Fig. 4. Total power demand changing comparison in one typical day

VII. CONCLUSION

This paper proposes an operation planning model for IES to study the influence of demand response to emission mitigation and system dispatch in both energy market and carbon trading market. Case studies show that the proposed model can achieve emission mitigation effectively. This model can a guide for energy source companies and energy, carbon market operators.

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