Application of Carbon Intensity in Generation Expansion Planning: A Comparative Study

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***Abstract*—Generation expansion planning (GEP), which integrates various environmental constraints under low-carbon economy, is a challenging problem due to its complexity. In this paper, different carbon intensity indexes are introduced to simplify the GEP problem. Marginal carbon intensity (MCI) and footprint carbon intensity (FCI) are mathematically formulated, and their corresponding GEP methods are provided. Based on a modified IEEE RTS 24-bus system, a comparative analysis of these methods in terms of carbon abatement and electricity purchasing cost is presented. Furthermore, the correlations between the methods are given to illustrate the simulation results. Finally, the general characteristics of each method are concluded.**

***Index terms*—carbon intensity, carbon price, generation expansion planning, locational marginal price, low-carbon economy.**

I. INTRODUCTION

Generation expansion planning (GEP) is the problem of determining location, capacity, technology and the time of building new power plants while satisfying load demand and reliability in the future. A comprehensive review of GEP problem from different aspects and views is given in [1]. Under low-carbon economy, its main objective function is to minimize either the cost or the environmental impact, or some weighted function of two [2]. Carbon emission has been considered in GEP problem from different aspects. In [3], [4], emission is considered as a constraint. In [5], [6], emission is defined as cost and included in objective function. The impacts of some incentive systems, such as feed-in tariffs, quota obligation, emission trade and carbon tax, are considered in the GEP model [7]. Integrated the impacts of various low-carbon factors, the GEP is a large-scale mixed integer nonlinear programming problem. Although the GEP modeling approach can be reasonably simplified [5], the GEP problem is still a challenging one due to its complexity. Therefore, reasonable and efficient indexes are needed to simplify the GEP problem.

Combining system-wide carbon emission with power flow and optimal power flow (OPF), some new concepts such as carbon emission flow, nodal carbon intensity, and locational carbon footprint, are proposed to help measure carbon emission in power system [8]–[11]. FCI is used to measure the carbon footprint at each node and address the emission obligation allocation in demand side of power system [9]. MCI, which is introduced in [10], is used as an optimal investment rule to improve the efficiency of RPS policies [11]. In [12], the locational marginal price (LMP) and MCI are combined as a new metric to measure the impact of the Demand Response Resource curtailments.

The traditional carbon control policies, like RPS policy, focus on the total quantity of renewable energy in power system. But the impacts of location selection and expansion capacity decision in GEP process are not fully considered. Through measuring the impacts of GEP at different conditions, the carbon intensity indexes (MCI and FCI) can be used to identify the locations which are suitable for generation expansion and decide the expansion capacity. Therefore, the use of MCI and FCI can effectively simplify the GEP problem. In order to further explore the carbon abatement effect and economic performance of them, it is necessary to make a comprehensive comparative analysis.

This paper is organized as follows. Section II provides the formulations of LMP, MCI and FCI. Section III integrates these indexes into the GEP problem, and illustrates the theoretical characteristics of each method. A comparative analysis of each method and the corresponding simulation results based on the IEEE RTS 24-bus system are presented in Section IV. Section V summarizes the limitations of each method and provides a possible direction for future research.

II. THREE INDEXES FOR GEP PROBLEM

A. Locational Marginal Price

Locational marginal pricing, which is widely used in electricity markets, such as the New England, PJM, ERCOT, is defined as the minimum cost of a unit increment of load at a particular node considering the constrains of generators and transmission [13]. Security-constrained economic dispatch (SCED) is used as a market clearing tool, and the LMPs are obtained in this framework. A general linearized SCED problem can be formulated as

$$\min_{\mathbf{P}_G} \boldsymbol{\lambda}_{\mathbf{G}}^{\mathbf{T}} \mathbf{P}_{\mathbf{G}} \tag{1}$$

$$s.t. \mathbf{e}^{\mathbf{T}}\mathbf{P}_{\mathbf{G}} - \mathbf{e}^{\mathbf{T}}\mathbf{P}_{\mathbf{D}} - loss = 0 \leftrightarrow \lambda \tag{2}$$

$$\mathbf{T}(\mathbf{P}_{\mathbf{G}} - \mathbf{P}_{\mathbf{D}}) \leq \mathbf{F} \leftrightarrow \boldsymbol{\mu} \tag{3}$$

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$$\underline{\mathbf{P_G}} \leq \mathbf{P_G} \leq \overline{\mathbf{P_G}} \leftrightarrow \breve{\boldsymbol{\tau}}, \widehat{\boldsymbol{\tau}} \quad (4)$$

where $\boldsymbol{\lambda}_\mathbf{G}$ is the vector of generators' offer prices, $\mathbf{e}$ is the vector of ones, $\mathbf{P_G}$ is the vector of generations, $\mathbf{P_D}$ is the vector of loads, $loss$ is system-wide power loss, $\mathbf{T}$ is the transmission distribution matrix, $\overline{\mathbf{F}}$ is the vector of transmission limits of lines, $\underline{\mathbf{P_G}}$ and $\overline{\mathbf{P_G}}$ are the vectors of generators' output lower limits and output upper limits, λ is the multiplier corresponding to the balance constraint, $\boldsymbol{\mu}$ is the vector of multipliers corresponding to the transmission constraints, and $\breve{\boldsymbol{\tau}}$, $\widehat{\boldsymbol{\tau}}$ are the vectors of multipliers corresponding to output limits of generators.

LMP at each node is calculated based on the shadow prices out of LP solution of the SCED problem. Each LMP can be split into three components:

- the energy component which is the same for any node and equals to the shadow price of system balance,
- the loss component which is the marginal cost of additional losses caused by serving the increment of load at the node,
- the congestion component which equals zero for any node when there are no binding transmission constraints.

Energy and loss components together can be defined as delivering energy component, representing the marginal cost of delivering the increment from the reference bus. For simplicity, the transmission losses are ignored. Therefore, the $\mathbf{LMP}$ in a lossless power network takes the form $\mathbf{LMP} = \lambda\mathbf{e} + \mathbf{T^T}\boldsymbol{\mu}$. Since we apply the LMP as an index for planning, the LMP mentioned in later sections equals to the locational clearing price where each generator offers its marginal cost, which means we do not consider gaming behaviors of market participants.

B. Marginal Carbon Intensity

Marginal carbon intensity, which is introduced in [11], reflects the impact of locational carbon footprint. The MCI at node n is defined as the change in system-wide carbon emission in response to an infinitesimal change of electricity demand at the node, and can be denoted by $MCI_n = \partial C/\partial P_{Dn}$, where C is the system-wide carbon emission and P_{Dn} is the demand at node n.

Under low-carbon economy, the vector of offer prices can be denoted by $\boldsymbol{\lambda}_\mathbf{G} = \mathbf{c} + \lambda_C\boldsymbol{\sigma}$ where $\mathbf{c}$ is the vector of non-carbon components, λ_C is the carbon price and $\boldsymbol{\sigma}$ is the vector of generators' carbon emission rate. Here, we assume that the offer prices or biddings of the generators are their marginal production costs. Any infinitesimal increment of load at a particular node will be delivered by the marginal generators. Therefore, the LMP at node n is the linear combination of the offer prices of the marginal generators, denoted by $LMP_n = \boldsymbol{\alpha}_\mathbf{n}^\mathbf{T}\boldsymbol{\lambda}_\mathbf{G} = \boldsymbol{\alpha}_\mathbf{n}^\mathbf{T}(\mathbf{c}+\lambda_C\boldsymbol{\sigma})$ where $\boldsymbol{\alpha_n}$ is the corresponding vector of coefficients (Only the coefficients of the marginal generators are non-zero) and $\mathbf{e}^T\boldsymbol{\alpha}_\mathbf{n}$=1 . The MCI at the node takes the form $MCI_n = \boldsymbol{\alpha}_\mathbf{n}^\mathbf{T}\boldsymbol{\sigma}$, thus the vector of MCIs can be represented in the following form:

$$\mathbf{MCI} = \frac{\partial \mathbf{LMP}}{\partial \lambda_C} = \frac{\partial \boldsymbol{\lambda}}{\partial \lambda_C} + \mathbf{T^T}\frac{\partial \boldsymbol{\mu}}{\partial \lambda_C}. \quad (5)$$

The MCI in an unconstrained and lossless power system equals to the carbon emission rate of the marginal generator. In a transmission-constrained power system with various types of energy, the transmission congestion may exist, and there will be multiple marginal generators with different carbon emission rates. In this situation, the MCI at each node, which is the linear combination of the carbon emission rates of all the marginal generators, may be higher than the highest carbon emission rate of generators or negative.

C. Footprint Carbon Intensity

Carbon emission flow in networks and the corresponding calculating method are introduced in [8]. By adding "carbon label" to the corresponding power flow, carbon flow is defined as a virtual network flow attached to power flow passing through power network. Based on the carbon flow tracing method [9] and the power flow tracing method [14], carbon flow and the corresponding power flow passing through branches and nodes considering power losses can be traced.

The equation of carbon flow tracing takes the form $\mathbf{CF_N^{gross}}$= $(\mathbf{A_u^{gross}})^{-1}\mathbf{CF_G}$ where $\mathbf{CF_N^{gross}}$ is the vector of gross nodal through-carbon-flows, $\mathbf{CF_G}$ is the vector of nodal carbon injections, and $\mathbf{A_u^{gross}}$ is the gross upstream distribution matrix [14]. The element (i, j) of $\mathbf{A_u^{gross}}$ is defined as

$$[\mathbf{A_u^{gross}}]_{ij} = \begin{cases} 1 & i = j \\ -\frac{|P_{ji}|}{P_{Nj}} & j \in \Gamma_-(i) \\ 0 & else \end{cases} \quad (6)$$

where P_{ji} is the gross power flow outgoing from node j in branch ij, which equals to the sum of the actual power flow injecting node i in branch ij and the power loss in branch ij. P_{Nj} is the through-power-flow of node j. $\Gamma_-(i)$ is the set of nodes, which belong to the injecting branches of node i.

The vector of FCIs can thus be denoted by $\mathbf{FCI} = \mathbf{CF_N^{gross}}/\mathbf{P_N}$ where $\mathbf{P_N}$ is the vector of nodal through-power-flows. Therefore, the FCI at a particular node can be defined as the carbon footprint per unit of the nodal through-power-flow, and is measured in tonnes CO_2/MWh. It has two components: the energy component and the loss component. The former, which reflects the energy mix of the nodal through-power-flow, is the linear combination of the carbon emission rates of all generators. And the coefficients are all positive and sum to one. The latter represents the additional carbon emission corresponding to power losses for delivering per unit of the nodal through-power-flow. Consequently, FCI is insensitive to transmission congestion, and its value is more stable than MCI in most situations.

III. Theoretical Comparative Analysis

Compared to life cycle assessment which focuses on carbon emission in different periods, MCI and FCI emphasize the spatial movement of carbon emission in network and give a new definition to the carbon emission in power system.

In a lossless power network, MCI can be split into a fixed component and a congestion component. The differences in MCI at each node, which are caused by the congestion components, reflect the different impacts of locational emission reducing. Adding renewable generators at the node with high MCI can reduce system-wide carbon emission. This improves the energy mix and alleviates the carbon congestion (When the carbon price is high enough, the output of low emission generators may be limited by the transmission lines, which is defined as carbon congestion). However, FCI is insensitive

TABLE I. ENERGY MIX AND CARBON EMISSION RATE

Energy of Generation	Proportion of System Capacity (%)	Carbon Emission Rate (tonnes CO_2/MWh)
coal	41.05%	0.9
gas	19.56%	0.3
oil	14.39%	0.6
nuclear, hrdro	25.00%	0

to carbon congestion, and the differences in FCI at each node reflect the energy mix of the nodal through-carbon-flows. Expanding renewable generators at the node with high FCI can replace the existing high emission generators, thereby achieving carbon abatement.

Therefore, MCI and FCI, as reasonable and efficient carbon intensity indexes, can be integrated into the GEP problem. For simplicity, considering each of them as the only criterion to determine the location selection of renewable generators in GEP, the generators will be built at the node with the highest MCI or FCI in each step. And the corresponding GEP location selection methods are referred to as the MCI or the FCI based methods. So MCI and FCI based methods can be considered as low-carbon oriented location selection methods.

In addition, the differences in LMP at each node are caused by the transmission congestion, making LMP an effective economic signal. Building renewable generators at the node with high LMP can probably alleviate transmission congestion when the peak load and high renewable generation (whose output is variable) coincides, and improve the efficiency of electricity market. Therefore, the LMP based method is also an option which focuses on reducing electricity purchasing cost. The method is economically oriented, and can be presented as a comparison for the two low-carbon oriented methods.

In sum, MCI, FCI and LMP based methods all have their own theoretical characteristics. The correlations between them change with the change of carbon price and GEP capacity. Therefore, it is necessary to make a comparative analysis of them at different carbon prices and GEP capacities.

IV. SIMULATION RESULTS AND DISCUSSIONS

The simulation results based on the IEEE RTS 24-bus system [15] are presented in this section. Considering the PJM power market as the prototype [16], the energy mix and the carbon emission rate data of the system are shown in Table I. The system is modified so that there are various types of energy and a sufficient level of congestion for illustrating the impacts of locational renewable generation expansion. The modified system comprises 38 lines, 32 generators and 17 loads, and has a total generation capacity of 3405MW and electricity demand of 2800MW. For simplicity, assume that the generators with the same energy and capacity have the same offer price, the offer prices of generators are constant, and the expanding renewable generators are wind turbines whose capacity and offer price are 1MW and \$1/MWh respectively. For illustration purpose, the simulation is carried at a point with sufficient wind resources.

A. Carbon Abatement and Electricity Purchasing Cost

The total electricity purchasing cost and the emission abatement are chosen as the evaluation indexes for the effect of MCI, FCI and LMP based methods at different carbon prices. As is shown in Fig. 1, the carbon abatement of the methods changes with the change of GEP capacity and carbon price. The comparison result of different methods on carbon abatement is listed in Table II.

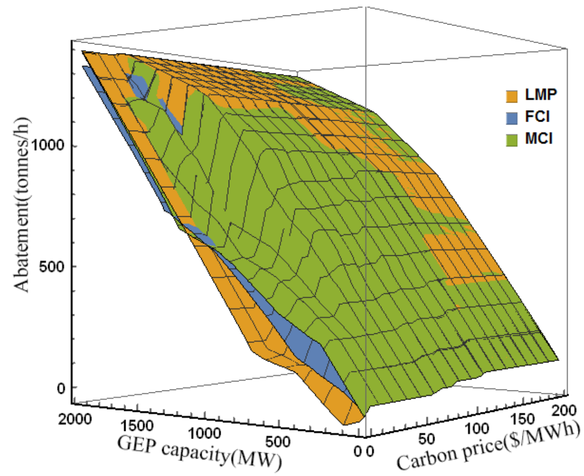

Fig. 1. Carbon abatement at different carbon prices and GEP capacities.

TABLE II. COMPARE OF METHODS ON CARBON ABATEMENT

Capacity of GEP(MW)	Low Carbon Price (\$0-67/MWh)	Medium Carbon Price (\$67-133/MWh)	High Carbon Price (\$133-200/MWh)
0-667(1st expansion period)	LMP<FCI<MCI	LMP<FCI<MCI	FCI<MCI,LMP
667-1333(2nd expansion period)	LMP<FCI<MCI	LMP<FCI<MCI	FCI<MCI,LMP
1333-2000(3rd expansion period)	FCI<MCI,LMP	FCI<MCI,LMP	FCI<MCI,LMP

When the carbon price and the GEP capacity are no more than \$133/MWh and 1333MW respectively, the MCI based method achieves the best carbon abatement. And the FCI based method makes a better performance than the LMP based method. That is because those transmission congestions (next to the high emission generators) result in high LMPs but negative MCIs at some load nodes. In this way, the LMP based method results in carbon emission increase. In other situations (The carbon price is more than \$133/MWh or the GEP capacity is more than 1333MW), the carbon abatement of MCI and LMP based methods are basically the same, and better than the FCI based method.

As is shown in Fig. 2, the total electricity purchasing cost is also affected by the same indexes as the carbon abatement does. It can be seen that the LMP based method is the best choice for minimizing the cost. This is because the method is economically oriented. When the carbon price and the GEP capacity are less than \$67/MWh and 667MW respectively, the FCI based method works better than the MCI method at the cost. In other situations (The carbon price is more than \$67/MWh or the GEP capacity is more than 667MW), the MCI based method works better than the FCI based method in most situations due to the economic attributes of MCI.

B. GEP Location Selections of the Three Methods at Selected Carbon Prices

The GEP location selections obtained by MCI, FCI and LMP based methods are variant at different carbon prices.

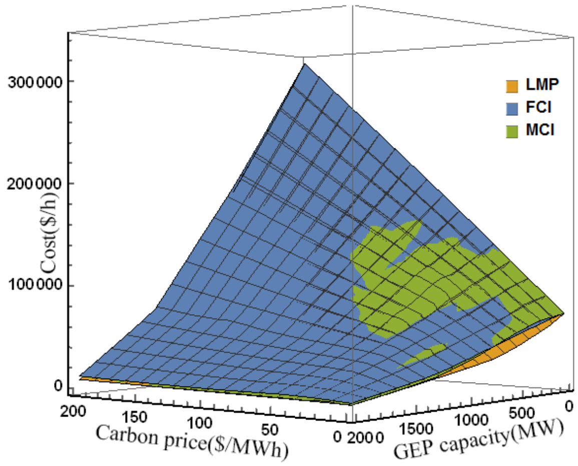

Fig. 2. Total cost at different carbon prices and GEP capacities.

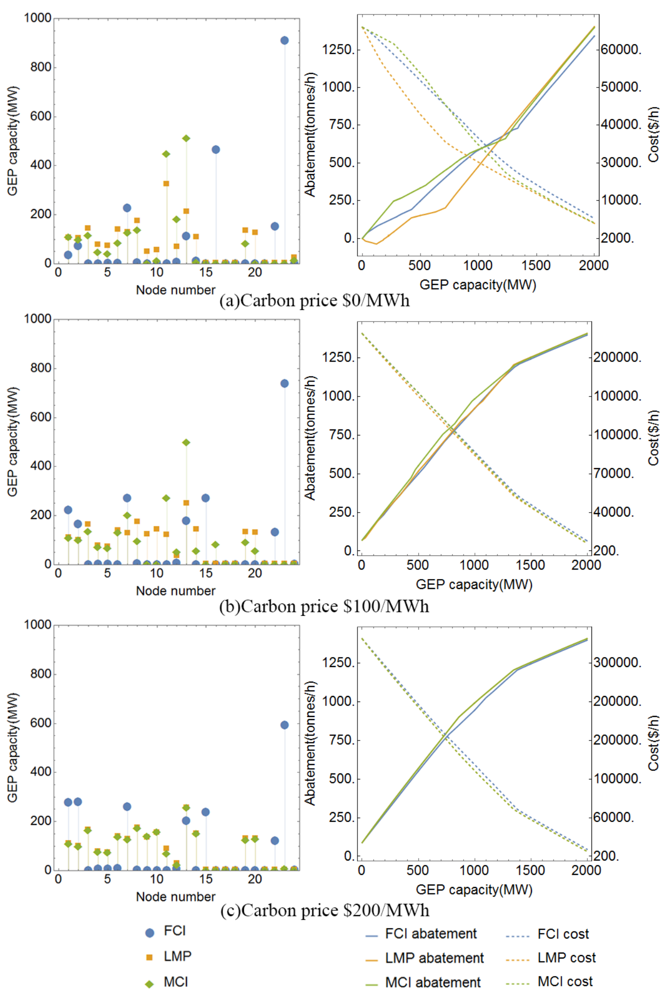

Fig. 3. Location selections and the corresponding performances at selected carbon prices.

The results at selected carbon prices ($0/MWh, $100/MWh, $200/MWh) are shown in Fig. 3.

When the carbon price is $0/MWh (Fig. 3(a)), the MCI based method has a better carbon abatement in the first and the second expansion periods (0-1333MW), and then comes close to the LMP method in the third expansion period (1333-2000MW). Whereas the FCI based method keeps its stability but falls behind the MCI based method in most time. For the FCI based method, too many (more than 900, which is fairly extreme) wind turbines are added at node 23, while the output of these wind turbines are limited. Therefore, the corresponding final carbon abatement is lower than the other methods. In addition, the MCI based method is worse than the FCI based method in the first period but better in the second and third at electricity purchasing cost.

When the carbon price is $100/MWh (Fig. 3(b)), the carbon abatement curves of FCI and LMP based methods are almost overlapped, and below the MCI curve. However, the cost curves of the three methods are nearly overlap.

At $200/MWh (Fig. 3(c)), MCI and LMP based methods have the same abatement and cost performance, and are better than the FCI based method. In this situation, the methods are low-carbon and economically oriented.

The results of MCI and LMP based methods are more evenly distributed than the FCI based method, though the extreme conditions of GEP location selection obtained by the FCI based method will be alleviated with the increase of carbon price. Therefore, MCI and LMP based methods are more applicable in GEP than the FCI based method, since they do not build too many wind turbines at a few nodes.

C. Correlations Between the GEP Location Selections

The correlations between the location selections of MCI, FCI and LMP based methods at selected GEP capacities and carbon prices are shown in Fig. 4 and Fig. 5. Although there are fluctuations in the correlation curves, the basic trends and characteristics can still be seen clearly.

The correlation between MCI and LMP based methods rises with the increase of carbon price or GEP capacity. It will get close to 1 especially when the carbon price is more than $133/MWh(Fig. 4). In this situation, the carbon component has become the major part of most generators' offer prices. Therefore, there exists the node with both the highest MCI and LMP in each step, which results that the GEP location selection obtained by the MCI based method are basically the same with the LMP based method.

The correlation between MCI and FCI based methods and the correlation between LMP and FCI based methods keep fluctuating around 0. The former, although positive in the first expansion period (There are nodes with high emission generators having both the highest MCI and FCI, like node 13), will drop to 0 with the increase of the GEP capacity as is shown in Fig. 5 (a) (b). In general, the FCI based method are distinct from MCI and LMP based methods. The GEP location selection distributions obtained by MCI, FCI and LMP based methods, which are shown in Fig. 3, can also evidence the phenomenon.

In sum, MCI, FCI and LMP based GEP methods all have their own theoretical bases and characteristics. On one hand, MCI and FCI are carbon intensity indexes, and their corresponding GEP methods are low-carbon oriented. While the LMP is a nodal price index, and its corresponding GEP method is economically oriented. On the other hand, MCI and

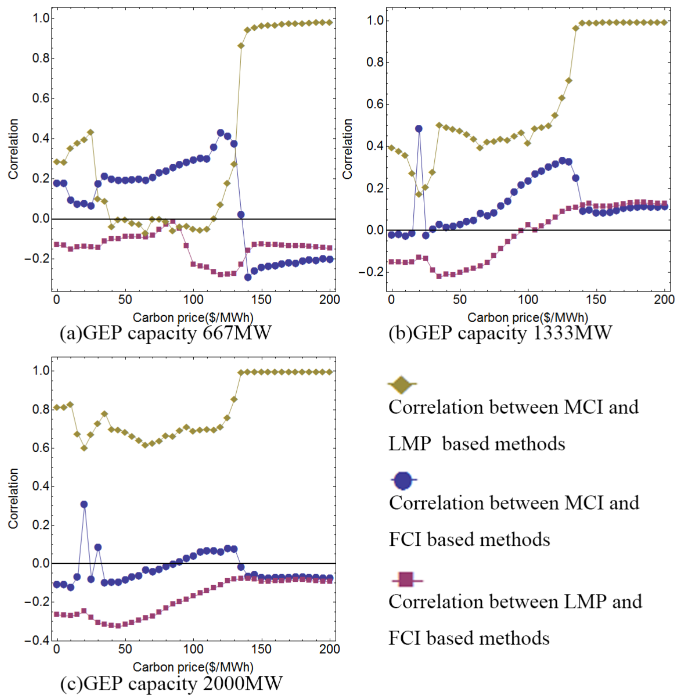

Fig. 4. Correlation curves of MCI, FCI and LMP based methods with the change of carbon price at selected GEP capacities.

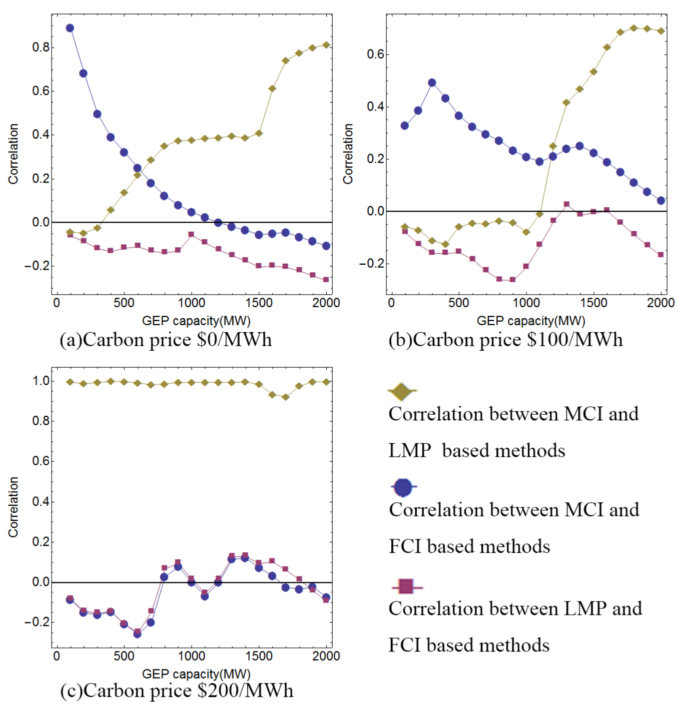

Fig. 5. Correlation curves of MCI, FCI and LMP based methods with the change of GEP capacity at selected carbon prices.

LMP are indexes of marginal utility, which are determined by optimal power flow. While FCI is an average index of carbon intensity, obtained by carbon flow tracing. Although MCI, FCI and LMP based methods finally have almost the same performance on carbon abatement and electricity purchasing cost, they will make differences during the GEP process.

V. Conclusion

Reasonable and efficient indexes are needed in order to reduce the complexity of GEP problem under low-carbon economy. The MCI based method is sort of greedy algorithm which is short-sighted, and does not guarantee the overall optimum. Whereas the FCI based method is an insensitive method, which may result in oddly distributed location selection. The economically oriented LMP based method, however, cannot identify the locations with low-carbon potential when the carbon price is not high enough. Methods based on single index all have their own flaws, so the integration of these indexes in GEP should be explored in the future.

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