A Minimal Budget Approach Algorithm for Integration of Clean Energy to Electricity Systems

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Abstract- ***In order to reduce green house emission, some clean energy policies have been approved or are being designed to stimulate clean energy development in electricity systems of some countries. The implementation of these clean energy policies needs a huge investment of money because this will reform the backbones of the energy infrastructure in these countries. Thus, it is important to find out how to minimize the investment meanwhile meet the growing power demand and satisfy the clean energy policies. This issue plays an important role in the development of a country in the aspects of economics, environment and energy. In this paper, we focus on the above issue and propose a Minimal Budget Approach (MBA) algorithm, which can help decison makers to find out how to realize the clean energy policies, meet increasing power demand and keep the budget as small as possible.***

Keywords: Electricity systems, Clean energy, RPS, Reduced green house emissions, Optimization models

I. INTRODUCTION

In the process of stimulating development of more clean energy in current fossil-major power systems, it is crucial for decision makers to consider and promote the realizability of related energy regulation or policies from the economic point of view. For example, the budget development to accomplish the goals of these policies is one of the substantial factors for decision makers to determine. In this paper, we propose a MBA (Minimal Budget Approach) algorithm that can help decision makers determine how to keep the investment volume in their proposed buget plan as small as possible and also make sure that (i) the burgeoning power demand is met and (ii) the clean power market share satisfies the requirement of related clean energy policies. In this work, we use wind energy in the five midwest states (North Dakota, South Dakota, Nebraska, Minnesota, Iowa) of America (with rich wind energy) as an example to show that our MBA algorithm can realize the above requirements with the minimal clean-energy budget plan.

As one of the major forms of renewable energy, wind energy has some built-in advantages. One of them is that it is environment friendly and another is that it cannot be depleted. By the end of 2008, the worldwide wind-powered generator capacity was 121.2 GW (gigawatt), which is about 1.5% of the worldwide electricity consumption. From 2005 to 2008, the capapcity doubled. Some countries have obtained high levels of wind power penetration in their power systems. For example, there is 19% of stationary electricity production in Denmark, 11% in Spain, and 7% in Germany in 2008. In May 2009, there are eighty countries that are using wind power on a commercial basis. [2] However, wind energy also has some disadvantages that prevent it from being integrated into current energy infrastructure at large-scale. The biggest one is that it fluctuates. It is difficut to accurately predict the wind class of a future day. Another problem of wind energy is that it is usually located in remote areas, which are far away from the high-power-demand regions with high population density. Moreover, we also need to consider the related clean energy policies such as RPS [1] (in U.S.A.), which has been approved by Washington D.C. and 30 states. RPS requires that the clean power fraction should reach a specified value by a specified future year. In order to find solutions for the above problems and satisfy related requirements, we need to stimulate wind power development, satisfy growing power demand, manage power transmission, and maintain the real-time balance of power demand and supply.

In this paper, we implement our MBA algorithm on the basis of a multi-function energy investment modeling tool proposed in [8]. The tool is designed with optimization techniques such as linear programming and mixed integer linear programming, which usually are used to find how to achieve the best outcome (e.g. minimal cost or maximum profit) within some given constraints represented as linear equations or inequations. The modeling tool allows strategy-level long-term energy investment plan modeling for renewable and conventional energy infrastructure reform. It can also be used to analyze the the complicated issues in domains of energy, power system, investment management, and energy policy. Among the five Midwest states of America (ND, SD, NE, MN, IA), ND (North Dakota) is ranked as No. 1 state with the highest potential wind energy in America. SD (South Dakota) is ranked as No. 4; NE (Nebraska) is ranked as No. 6; MN (Minnesota) is ranked as No. 9; IA (Iowa) is ranked as No. 10. [5] We developed a new power trading modeling tool [8]. In this paper, we present our MBA algorithm, show how to find the minimal budget plan, and present the quantitative results on the minimal budget plan using the algorithm.

II. RELATED WORK

Several related works about energy planning have been done in this domain. One of them is WinDS (Wind Deployment Systems Model) [3] developed by SEAC (Strategic Energy Analysis Center) of NREL (National Renewable Energy Lab). WinDS is a multiregional and multitime-period linear programming model embedded with the Geographic Information System (GIS). This model focuses on the market issues, transmission access and cost, and the fluctuation of wind power. In this model, the optimization objective is to minimize system-wide costs and also meet the demands of reserve, loads, and CO_2 emission by designing new generation and transmission systems from 2000 to 2050 over 25 two-year periods [3].

Another related model is the All-Modular Industry Growth Assessment (AMIGA) model [6] - a comprehensive economic model of energy markets. But, the AMIGA model does not consider developing renewable energy and its related transmission investment requirements. A comprehensive energy planning model (developed by Brookhaven National Laboratory) is MARKAL (MARKet ALlocation) [7] is a dynamic optimization model with the integration of energy, environmental, and economic factors. However, this model may not be able to solve large size optimization model with high speed because it can run only on a PC Windows platform. Another economic and energy model NEMS (National Energy Modeling System) for U.S. energy markets is designed by Department of Energy. This model makes predictions on the consumption, production, import, conversion and pricing of energy.

III. CONTRIBUTIONS

None of the above works focus on the issues of how to find a solution for the current power system reform by stimulating clean energy in order to satisfy clean energy policy requirements. In these works, the basic power flow principles are also ignored such as Kirchoff's current law, which needs to be maintained in any power systems in real time. Compared with these related works, our contributions mainly include : (1) propose a MBA algorithm to find optimal budget plans for clean power system development; (2) develop a new power trading model and integrate it into the modeling tool designed by us in [8]. The model can provide basis for the year-level planning models to do the minimal budget planning; (3) deploy high performance computing platforms such as supercomputers, to be able to easily handle large-scale energy budget planning problems with different geographic resolutions (county/state/nation/global level) and timing resolutions (hour/month/year level). Thus, our MBA algorithm can be used to handle large-scale energy planning problems with different requirements for timing and space resolutions.

IV. THE MBA ALGORITHM

A. *The conceptual model of the MBA algorithm*

A budget is a saving and spending plan that is used to show all scheduled expenses and revenues of buying or selling some products in terms of money. The purpose of a budget is to provide a schedule about the revenues and expenditures to implement a plan or strategy. In the domain of energy planning, the per-unit energy (MWh: megawatts-hour) is treated as a commercial product, which is sold by power generation system operators and bought by retailers in wholesale deregulation power markets. Then, the retailers sell the commercial product to end-consumers in retail deregulation power markets.

In this paper, we mainly focus on the strategy-level budget planning for conventional/clean power generation systems and their associated transmission system capacity expansion in order to (1) meet the growing power demand of a region; and (2) satisfy the clean energy policy RPS requirements. Thus, a region that can supply surplus power is treated as a power seller; a region that needs power is treated as a power buyer. In our example of five U.S. states, each state is treated as a region, which needs to meet its local power demand by generating power locally or buying power from other regions that can provide surplus power after meeting its local power demand.

From the above analysis, we observe that a region can be a power seller at a time point and a power buyer at another time point. As the power demand is growing in a region, its local power generation system capacity needs to be expanded. Moreover, if one region may need to buy surplus power from another region, the transmission system capacity also needs to be expanded in order to accommodate the transmission of the per-unit energy (MWh) product between the power buyer and power seller. When we make a decision about the power generation capacity expansion, we also need to consider if the expansion needs to be in fossil power systems or clean power systems to satisfy the RPS policy of the planned regions while keeping the budget under control. In this paper, we consider two major investment costs: (1) the total investment cost of fossil/clean power generation system capacity expansions; (2) the total investment cost of necessary transmission system capacity expansions. These two kinds of cost play a significant role in the power system development because generation and transmission systems usually result in high costs. Both of the costs need to be considered such that the total investment budget is minimized while the increasing power demand of all planned regions are met and the RPS policies are satisfied. The budget that satisfies the above requirements is defined as an optimal budget for the planned regions.

To address the above issues, the following MBA (Minimal Budget Approach) conceptual model (**MBA-Conceptual**) is proposed:

$$
\begin{array}{ll}
\textbf{min} & Gen\_Cost + Tran\_Cost \\
\textbf{s.t.} & \\
& meet\ power\ demand\ of\ each\ region \\
& satisfy\ RPS\ requirements\ of\ each\ region \\
& \textbf{decision variables:} \\
& wind/fossil\ power\ generation\ capacity \\
& \quad expansion \\
& energy\ storage\ capacity\ expansion \\
& transmission\ capacity\ expansion
\end{array}
$$

Here, the Gen_Cost is the investment cost of power generation system (fossil or clean energy) capacity expansion of planned regions. The $Tran\_Cost$ is the investment cost of transmission system capacity expansion of planned regions. The decision variables also include energy storage capacity expansion because we assume that the clean energy storage systems can store the surplus wind power in order to reduce the variations caused by wind energy fluctuations. The clean energy storage systems can be of any kind of system proposed in [9], such as pumped storage, flywheels. In our model, we use heat tank [10] as an example storage system that can perform transformation between electricity energy and thermal energy. The surplus wind power is transformed into thermal energy and then released later to satisfy the peak demand. [10]

B. The principles of the MBA algorithm

From the conceptual model presented in the section IV-A, we observe that we need to minimize the investment budget of generation systems and transmission systems over the whole planning period in the planned regions. Because the generation and transmission systems needs to be planned at year level, we design a year level model (YLM), in which we minimize the investment cost of generation and transmission capacity expansion, and the related operation costs for the capacity expansions. In YLM, we also need to satisfy the constraints of the power demand and RPS policy requirements of each planned region. The conceptual YLM is described below:

$$
\begin{array}{ll}
\textbf{min} & Inv\_Cost_{iy} + Tran\_Cost_{iy} + Op\_cost_{iy} + CO\_cost_{iy} \\
\textbf{s.t.} & \\
& meet\ power\ demand\ of\ ith\ region\ in\ year\ y \\
& satisfy\ RPS\ requirements\ of\ ith\ region\ in\ year\ y \\
& \textbf{decision variables:} \\
& wind/fossil\ power\ generation\ capacity \\
& \quad expansion\ in\ year\ y \\
& energy\ storage\ capacity\ expansion\ of\ ith \\
& \quad region\ in\ year\ y \\
& transmission\ capacity\ expansion\ of\ ith \\
& \quad region\ in\ year\ y
\end{array}
$$

Here, the Inv_Cost_{iy}, $Tran\_Cost_{iy}$ and Op_cost_{iy} represent the investment cost of generation and transmission capacity expansion, and operation costs of region i in year y respectively. CO_cost_{iy} is the cost of CO_2 emission from fossil power systems in the planned reigon i. The constraints are built to meet power demand and satisfy the RPS requirements. It is a linear programming model and needs to be solved for each planned region for every year during the panning period.

The above YLM mainly focuses on the year-level budget planning for the capacity expansion in power systems. Besides this, we also need to meet hourly power demand and make power balance hour by hour for each planned region during the whole planning period. Thus, we design a hour level model (HLM), in which we minimize the CO_2 emission from fossil power systems and satisfy power balance at hour level of each region during the planning period. The modeling results from the HLM are accumulated to generate yearly results, which are used by the YLM to make decisions for mininal budget planning. The conceptual HLM is described below:

$$
\begin{array}{ll}
\textbf{min} & CO\_Cost_{it} + PC_{it} \\
\textbf{s.t.} & \\
& meet\ power\ demand\ of\ ith\ region\ at\ hour\ t \\
& \textbf{decision variables:} \\
& wind/fossil\ power\ supply\ of\ ith\ region\ at\ hour\ t
\end{array}
$$

Here, the $CO_2\_Cost_{it}$ is the cost of CO_2 emission from fossil power systems in region i at hour t. PC_{it} is the production cost of wind/fossil power supply. The hourly results of fossil and clean power supply from HLM are accumlated together to form the yearly results of total fossil and clean power supply in region i for year y. The ratio of $(clean\ power\ supply)/(total\ power\ supply)$ is used to compare with the specified clean power percentage required by the RPS policy of region i in year y. If the comparison shows that the ratio is equal to or greater than the target percentage, the YLM is not needed to solve and the modeling flow goes to the next year. Otherwise, the YLM needs to be solved to do capacity expansion of clean power generation systems and its related transmission systems in order to satisfy the RPS requirements. Then, the corresponding HLM is solved again to check whether the hour level power balance can be maintained in the new expaneded systems. Moreover, the new ratio of $(clean\ power\ supply)/(total\ power\ supply)$ also needs to be computed to do the comparison with target clean power percentage of RPS. In this way, our solution from the YLM and the HLM can make sure that the RPS policy is satified at year level and the new capacity expansion can maintain the power balance and is operable at the hour level.

In the YLM and HLM, we have minimized the cost of generation meanwhile satisfying the constraints of hourly power balance and the clean power requirements of RPS. We also need to consider the cost of transmission system capacity expansion because the neighbouring regions are allowed to trade clean power between each other. As the power demand is growing year by year, the generation system capacity also needs to be increased to provide enough power. Because of the fluctuations of clean energy such as wind energy, it is possible for a region to generate surplus power from wind energy at certain hours in a day. These surplus power can be stored in energy storage systems and traded to other regions that need to buy more clean power to meet their local power demand. The clean power trading needs to be supported by power transmission capacity expansion. Because the cost of transmission capacity expansion between different regions may be different and a region may be a power seller at some hours and then become a power buyer at other hours, therefore, it is necessary to analyze the relationship between power trading and the related transmission system capacity expansion to minimize the total cost of transmission system capacity expansion. In order to do this, we propose a power trading model (PTM) described below:

$$\begin{aligned}
&\textbf{min} \quad Trade\_Cost_{it} \\
&\textbf{s.t.} \\
&\qquad meet\ power\ demand\ of\ buyer\ i\ at\ hour\ t \\
&\qquad sold\ power\ upperbounded\ by\ power\ available \\
&\qquad\quad for\ sale\ of\ seller\ j\ at\ hour\ t \\
&\qquad power\ flow\ among\ regions\ satisfy\ their \\
&\qquad transmission\ line\ capacity\ constraints \\
&\qquad \textbf{decision variables:} \\
&\qquad power\ traded\ between\ buyer\ i\ and\ seller\ j\ at \\
&\qquad\quad hour\ t
\end{aligned}$$

Here, the $Trade\_Cost_{it}$ is the product of the traded power quantity and the power price asked by the seller. The first constraint means that each buyer only buys the quantity that it really needs to meet its local power demand. The second constraint means that each power seller cannot sell more surplus power than what is available for sale. Usually, as a special product, most of electricity power is traded by long-term bilateral contract, option contract, and future/forward contract in a wholesale power market organized and managed by ISO (independt system operator). For example, in ERCOT (Electric Reliability Council of Texas), 95% power is traded through bilateral wholesale forward contracts and only 5% of total generated power is transacted in spot market. This spot-market trading percentage can rarely be more than 10%. [12] [13] In this paper, we focus on the strategy-level budget planning for power system development rather than modeling real-time ISO-based power markets. We assume that the real-time supply-demand power pricing and related financial issues have been settled by an ISO before the physical power flows are scheduled. On the basis of this, the HLM provides hourly modeling results and the PTM is to minimize the total cost of the power trading among the regions at hour level. The YLM make decisions on the basis of the accumulated hourly results.

With the above YLM, HLM and PTM models, we observe that we minimize the cost from generation part and transmission part of each region at hour level and year level. We have decomposed the conceptual model **MBA-Conceptual** proposed in Section IV-A into three different models with different functions, which are summarized in Table I.

TABLE I
THE SUMMARY OF FUNCTIONS OF HLM, YLM AND PTM

Model	**Functions**
HLM	(i) maintain power balance of region i at hour t (ii) minimize CO_2 emission and production cost of region i at hour t
YLM	(i) minimize cost from generation and transmission capacity expansion of region i in year y (ii) satisfy the clean power requirements from RPS of region i in year y
PTM	(i) minimize the cost of power trading between power buyer and seller at hour t

The MBA algorithm is to run the above three models in each region at hour level and year level over the whole planning period. If all models yield optimal solutions at each time point, the final buget designed on the basis of the accumulated results of the three models is optimal because we realize the power balance, satisfy RPS requirements of each region and also minimize the cost of generation/transmission system capacity expansion of each region. The flowchart of the MBA algorithm is described in Figure 1.

V. THE MATHEMATICAL FORMULATION OF THE MBA ALGORITHM

In this section, we present the mathematical formulations of the HLM, YLM and PTM models. The formulations of the HLM and YLM have been built and presented in our previous work [8]. We briefly describe them here for a convenient reference. The PTM model is a new model, which is developed for the MBA algorithm. The definitions of terms used in HLM and YLM can be found in [8]. We only include the definitions of the new terms used in PTM model.

A. *The description of the HLM*

$$\textbf{min } CO_{it} + PC_{it} \tag{1a}$$

$$\textbf{s.t.}$$

$$PS^{fp}_{it} + PS^{wp}_{it} + PS^{wh}_{it} + PB_{it} = PD_{it} \tag{1b}$$

$$PS^{wh}_{it} \leq \eta^{h}_{it} \times SP^{wh}_{i(t-1)} \times R^{wh}_{it} \tag{1c}$$

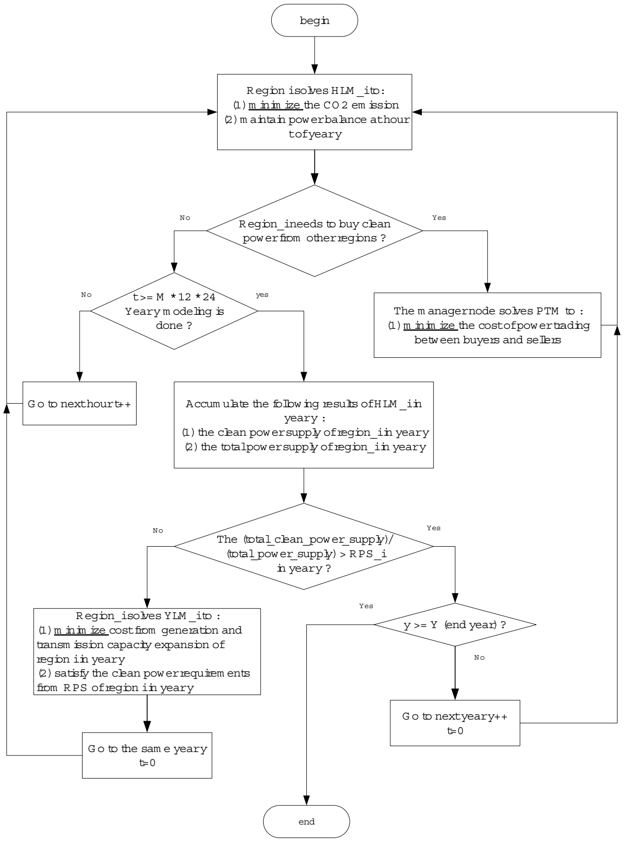

Fig. 1. the flowchart of MBA algorithm

$$PB_{it} \leq BB_{it} \times PN_{it} \tag{1d}$$

$$PS_{it}^{fp} \leq EC_{it}^{fp} \times CF_{it}^{fp} \tag{1e}$$

$$PS_{it}^{wp} \leq min\{EC_{it}^{wp}, TWP_{it}^{A}\} \times TF_{it} \times CF_{it}^{wp} \tag{1f}$$

$$PS_{it}^{wp} + PS_{it}^{wh} \leq (EC_{it}^{wp} + EC_{it}^{wh}) \times TF_{it} \tag{1g}$$

where :

$$SP_{it}^{wh} = PO_{it}^{wp} - PS_{it}^{wp} \tag{1h}$$

$$PO_{it}^{wp} = min\{EC_{it}^{wp}, TWP_{it}^{A}\} \tag{1i}$$

$$CO_{it} = CO_{it}^{fp} \times PS_{it}^{fp} \tag{1j}$$

$$PC_{it} = PS_{it}^{fp} \times PC_{it}^{fp} + PS_{it}^{wp} \times PC_{it}^{wp} + PS_{it}^{wh} \times PC_{it}^{wh} \tag{1k}$$

The objective in Eq. (1a) is to minimize the cost of CO_2 emission and the production cost. The constraint in Eq. (1b) is to meet power demand of the period t in region i. The constraint in Eq. (1c) is to set the upperbound of power supply from storage systems. The constraint in Eq. (1d) describes the upperbound of power supply bought from other regions. The PN_{it} is the power that can be provided from other regions to the region i in period t. In the constraint in Eq. (1f), the power supply from wind energy is upperbounded by the minimal value of the existing wind power plant capacity and the total wind power available in period t of region i. The equation in Eq. (1h) shows that the stored power is the power supply that cannot be transmitted because of transmission line capacity limitations. The equation in Eq. (1i) shows that the output power generated by the wind turbines is equal to the minimal value of existing wind power capacity and the total wind power available of the region i in the period of t. The equation in Eq. (1j) is the cost of CO_2 emission. The equation in Eq. (1j) is the cost of power production from fossil/renewable/storage systems.

B. *The description of the YLM*

$$\min\ OC_{iy} + TC_{iy} + IC_{iy} + CO_{iy} \tag{2a}$$

s.t.

$$PS_{iy}^{fp} + PS_{iy}^{wp} + PS_{iy}^{wh} + PB_{ijy} = PD_{iy} \tag{2b}$$

$$PS_{iy}^{fp} \leq (EC_{iy}^{fp} + CE_{iy}^{fp}) \times CF_{iy}^{fp} \tag{2c}$$

$$PS_{iy}^{wp} \leq (EC_{iy}^{wp} + CE_{iy}^{wp}) \times TF_{iy} \times CF_{iy}^{wp} \tag{2d}$$

$$PS_{iy}^{wh} \leq \eta^{h} \times (EC_{iy}^{wh} + CE_{iy}^{wh}) \times R_{iy}^{wh} \tag{2e}$$

$$CE_{iy}^{wp} \leq (TWP^{A} - EC_{iy}^{wp}) \tag{2f}$$

$$(PS_{iy}^{wp} + PS_{iy}^{wh}) \geq RPS_{iy} \times (PS_{iy}^{fp} + PS_{iy}^{wp} + PS_{iy}^{wh}) \tag{2g}$$

$$(EC_{iy}^{wh} + CE_{iy}^{wh}) \leq (EC_{iy}^{wp} + CE_{iy}^{wp}) \times (1 - TF_{iy}) \tag{2h}$$

$$PS_{iy}^{wp} + PS_{iy}^{wh} \leq (EC_{iy}^{wp} + CE_{iy}^{wp} + EC_{iy}^{wh} + CE_{iy}^{wh}) \times TF_{iy} \tag{2i}$$

where :

$$OC = (OC_{iy}^{fp} \times (EC_{iy}^{fp} + CE_{iy}^{fp})) + (OC_{iy}^{wp} \times (EC_{iy}^{wp} + CE_{iy}^{wp})) + (OC_{iy}^{wh} \times (EC_{iy}^{wh} + CE_{iy}^{wh})) \tag{2j}$$

$$TC = TC_{iy}^{w} \times (CE_{iy}^{wp} + CE_{iy}^{wh}) \times TF_{iy} + TC_{iy}^{fp} \times CE_{iy}^{fp} \tag{2k}$$

$$IC = \frac{(IC_{iy}^{fp} \times CE_{iy}^{fp})}{DR_{iy}^{f}} + \frac{(IC_{iy}^{wp} \times CE_{iy}^{wp})}{DR_{iy}^{w}} + \frac{(IC_{iy}^{wh} \times CE_{iy}^{wh})}{DR_{iy}^{w}} \tag{2l}$$

$$CO_{iy} = CO_{iy}^{fp} \times PS_{iy}^{fp} \tag{2m}$$

The constraint in Eq. (2b) is to guarantee the balance of power demand and supply. The constraints in Eq. (2c, 2d and 2e) set up the upperbounds of the fossil/wind/storage power supply. The constraint in Eq. (2f) means that the total existing/expanded wind capacity should not be more than the total wind power available in the year y. The constraint in Eq.

(2g) expresses the RPS requirements of the region i in the year. The constraint in Eq. (2h) means that the energy storage system capacity expansion is upperbounded by the product of its associated wind power capacity expansion and the transmission line capacity. The constraint in Eq. (2i) means that the power supply from wind plants and storage systems is upperbounded by the total existing and expanded capacity of wind power plants and storage systems and their associated transmission line capacity. The equations in Eqs. (2j, 2k and 2l) express the cost of operation, transmission and investment about related capacity expansion for fossil/wind/storage systems.

C. *The PTM model*

In the case that some regions need to buy or sell some power, we need to do power flow study in order to find the numerical values of the power generation at each bus, the power flow of each transmission line connected the regions and the voltage angle of each bus.

In the PTM model, each region is abstracted as a bus with generation and load. The power flow is transferred from one bus to another bus according to Kirchhoff's Current Law (KCL). In KCL, each of the current injections generated by a generator bus should be equal to the sum of the currents flowing out of the bus and flowing into the transmission lines that connects the bus to other buses, or to the ground in the whole power grid system [11]. The electrical energy is transferred from power supply to power load through the transmission network. We need to determine how to schedule the power flow such that the loads are met and KCL is obeyed meanwhile minimizing the total generation cost of the whole power system. This is referred to as economic optimization power flow (OPF) problem [11]. If the objective functions of the OPF problem are non-linear, we use linear approximation to the objective function because each objective function is a function only one variable (power generation). In this way, we can solve power flow scheduling problem by linear programming optimal power flow (LPOPF). The constraints include (1) DC injection power flow equation, which depends on the admittances of branches connected to each bus and obey Kirchhoff's current law; (2) branch power flow equation, which depends on the power transmission-network topology and susceptance of each branch in the network. More detailed reasoning processes at engineering-level can be found in [11]. The conceptual power trading model is as follows:

min *Generation_cost*
s.t.
DC power flow equation
Branch power flow equation
decision variables:
power generation at each bus
power flow at each branch
voltage angle at each bus

The mathematical formulation of the power-trading model is given below:

$$\textbf{min } GC_{it} \tag{3a}$$

s.t.

$$\overline{PG} - \overline{PD} = AD \times \overline{\theta} \tag{3b}$$

$$\overline{PB} = (SM \times NT) \times \overline{\theta} \tag{3c}$$

$$0 \leq \overline{PG} \leq \overline{PGM} \tag{3d}$$

$$-\overline{PBM} \leq \overline{PB} \leq \overline{PBM} \tag{3e}$$

$$-\overline{\pi} \leq \overline{\theta} \leq \overline{\pi} \tag{3f}$$

where

$$i \textit{ is an element of } G \textit{ (set of buses)} \tag{3g}$$

$$b \textit{ is an element of } B \textit{ (set of branches)} \tag{3h}$$

$$\overline{PG} \textit{ is the vector of } PG_{it} \tag{3i}$$

$$\overline{PB} \textit{ is the vector of } PB_{bt} \tag{3j}$$

$$\overline{PGM} \textit{ is the vector of } PGM_{it} \tag{3k}$$

$$\overline{PBM} \textit{ is the vector of } PBM_{bt} \tag{3l}$$

$$\overline{\theta} \textit{ is the vector of } \theta_{it} \tag{3m}$$

$$\overline{\pi} \textit{ is the vector of } \pi \tag{3n}$$

$$\textbf{decision variables} \tag{3o}$$

$$\overline{PG}, \overline{PB}, \overline{\theta} \tag{3p}$$

Here, in Eq. (3), $GC_t = \sum_{j \in G} PR_j \times PG_{jt}$, where PR_j is the power generation cost of generator bus j [\$/MWh]. The constraint (3b) expresses Kirchhoff's current law, in which the difference between power generation of bus j at time t (PG_{jt}) and the power load at bus j at time t (PD_{jt}) is equal to the product of admittance matrix of the power grid network (AD) and nodal phase angle (θ_{jt}) at each generator bus j at time t. The constraint (3b) guarantees that the Kirchhoff's current law (KCL) is obeyed at bus j. The constraint (3c) expresses the branch power flow equation. The power flow on branch b at time t is the product of the branch susceptance matrix (SM), the bus-branch matrix (NT) of the grid system and the bus j phase angle θ at time t. The constraint (3d) sets up the upperbound and lowerbound for each branch power flow PB at branch b at time t. The constraint (3e) sets up the upperbound and lowerbound for power generation of bus j at time t (PG_{jt}). The constraint (3f) sets up upperbound and lowerbound for each bus phase angel. The conceptual power trading model (PTM) can be described by a single-line diagram example in Figure 2, in which there are 5 buses and each of them has generation and load. The buses are connected by transmission lines (also called branch). The arrow of each branch represents a power flow direction. If the real power flow on branch j is the same as the arrow direction, the power flow value of PB_{bt} is positive. Otherwise, it is negative. If some buses need to buy more power to meet its local power demand, the LPOPF model (3) will reschedule the power flows in the whole power grid system such that the KCL and other constraints are all satisfied meanwhile minimizing the total

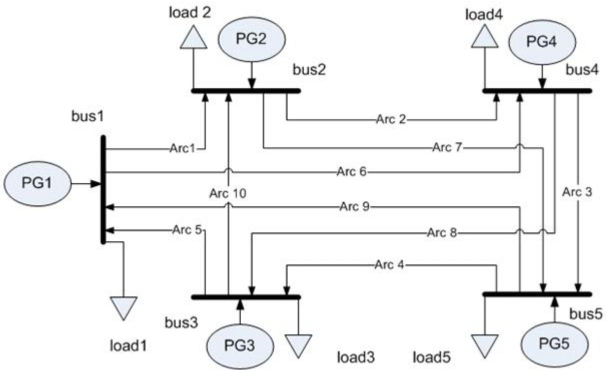

Fig. 2. A single-line diagram for the power trading model

TABLE II
THE INSTALLED FOSSIL/WIND AND POTENTIAL WIND POWER CAPACITY

state	**installed fossil power capacity** [MW]	**installed wind power capacity** [MW]	**potential wind power [MW]**
ND	5091	767	138400
SD	2933	288	117200
NE	7023	153	99100
MN	12890	1805	75000
IA	12287	3053	62900

generation cost at time t.

VI. EXPERIMENTAL RESULTS

The data resources of the parameters for the models in this paper are the official online documents [14], [15], [16], [17], [18], [19], [20], and [22]. The CO_2 emission cost is set to be $30\$/ton$. The energy transformation efficiency (η) is set to be 0.7. The the average growth rate of power demand (from 1998 to 2008) is used as the future power demand growth rate for each state. The existing installed wind power capacity [21] and the potential wind power of each state are summarized in Table II. The RPS policy requirement data [23] are shown in Table III. It is assumed that the currently existing wind energy storage system is 0. Tables IV, V, VI, VII, and VIII depict the experimental results on the investment planning budget of fossil/wind generation and transmission capacity expansion and the associated storage system capacity expansion during the planning period from 2010 to 2049 for the five states. The results show that the regions with higher potential for wind energy and lower power demand need much less investment than the regions with relatively lower potential for wind energy and higher power demand. For example, the investment budget of MN (total 31.98 billion \$) is 16.66 times higher than that of SD (total 1.92 billion \$) because the potential wind energy of MN is only 64% of SD but the MN's predicted average power demand is 3.42 times higher than SD.

VII. CONCLUSION AND FURTHER WORK

In this paper, we present the MBA (Minimal Budget Approach) algorithm implemented by three models for integration of clean energy to electricity systems. In the HLM model, we minimize the CO_2 emission cost and production cost of

TABLE III
THE RPS POLICY

state	**clean power fraction**	**use in our model**
ND	10% by 2015	after 2015, the goal is 30% by 2049
SD	10% by 2015	after 2015, the goal is 30% by 2049
NE	not available	the goal is 30% by 2049
MN	25% by 2025	after 2025, the goal is 30% 2049
IA	105 MW	the goal is 30% by 2049

TABLE IV
THE INVESTMENT BUDGET OF ND

Year	**FPCE [MW]**	**FPCR [M\$/MW]**	**INVT [B\$]**	**WPCE [MW]**	**WPCR [M\$/MW]**	**INVT [B\$]**
2010-2020	0	1.3	0	832	1.7	1.41
2021-2030	0	1.3	0	1040	1.7	1.77
2031-2040	0	1.3	0	936	1.7	1.59
2041-2049	0	1.3	0	0	1.7	0
total	0		0	2808		4.77
Year	**TCWP [MW]**	**TCR [M\$/MW]**	**INVT [B\$]**	**STCE [MW]**	**STCR [M\$/MW]**	**INVT [B\$]**
2010-2020	312	0.3	0.09	416	1.2	0.5
2021-2030	390	0.3	0.21	520	1.2	0.62
2031-2040	351	0.3	0.32	468	1.2	0.56
2041-2049	0	0.3	0	0	1.2	0
total	1053		0.62	1404		1.68

FPCE: fossil power generation capacity expansion
FPCR: present value of FPCE cost rate [M\$/MW] : million \$/mega-watts
INVT: investment budget [B\$] : billion \$
WPCE: wind power generation capacity expansion
WPCR: present value WPCE cost rate
TCWP: transmission capacity expansion associated with wind power
TCR: present value of TCWP cost rate
STCE: surplus clean power storage system capacity expansion
STCR: present value of STCE cost rate

TABLE V
THE INVESTMENT BUDGET OF SD

Year	**FPCE [MW]**	**FPCR [M\$/MW]**	**INVT [B\$]**	**WPCE [MW]**	**WPCR [M\$/MW]**	**INVT [B\$]**
2010-2020	0	1.3	0	728	1.7	1.24
2021-2030	0	1.3	0	208	1.7	0.35
2031-2040	0	1.3	0	0	1.7	0
2041-2049	0	1.3	0	0	1.7	0
total	0		0	936		1.59
Year	**TCWP [MW]**	**TCR [M\$/MW]**	**INVT [B\$]**	**STCE [MW]**	**STCR [M\$/MW]**	**INVT [B\$]**
2010-2020	273	0.3	0.08	364	0.5	0.18
2021-2030	78	0.3	0.02	104	0.5	0.05
2031-2040	0	0.3	0	0	0.5	0
2041-2049	0	0.3	0	0	0.5	0
total	351		0.1	468		0.23

TABLE VI

THE INVESTMENT BUDGET OF NE

Year	**FPCE [MW]**	**FPCR [M$/MW]**	**INVT [B$]**	**WPCE [MW]**	**WPCR [M$/MW]**	**INVT [B$]**
2010-2020	0	1.3	0	832	1.7	1.41
2021-2030	0	1.3	0	1144	1.7	1.95
2031-2040	249.6	1.3	0.33	1786.3	1.7	3.04
2041-2049	873.6	1.3	1.14	2263.4	1.7	3.85
total	1123.2		1.47	6025.7		10.25
Year	**TCWP [MW]**	**TCR [M$/MW]**	**INVT [B$]**	**STCE [MW]**	**STCR [M$/MW]**	**INVT [B$]**
2010-2020	561.6	0.3	0.17	416	0.5	0.21
2021-2030	772.2	0.3	0.23	572	0.5	0.29
2031-2040	1205.8	0.3	0.36	893.15	0.5	0.45
2041-2049	1527.8	0.3	0.46	1131.7	0.5	0.57
total	4067.4		1.22	3012.9		1.52

TABLE VII

THE INVESTMENT BUDGET OF MN

Year	**FPCE [MW]**	**FPCR [M$/MW]**	**INVT [B$]**	**WPCE [MW]**	**WPCR [M$/MW]**	**INVT [B$]**
2010-2020	2342.9	1.3	3.05	3858.5	1.7 1.7	6.56
2021-2030	2553.5	1.3	0.72	3855.3	1.7	6.55
2031-2040	386.1	1.3	0.5	2306.2	1.7	3.92
2041-2049	860	1.3	1.12	2591.1	1.7	4.41
total	6142.5		5.39	12611		21.44
Year	**TCWP [MW]**	**TCR [M$/MW]**	**INVT [B$]**	**STCE [MW]**	**STCR [M$/MW]**	**INVT [B$]**
2010-2020	2025.7	0.3	0.61	1929.25	0.5	0.97
2021-2030	2024	0.3	0.61	1927.6	0.5	0.96
2031-2040	1210.8	0.3	0.36	1153.1	0.5	0.58
2041-2049	1360.4	0.3	0.41	1295.6	0.5	0.65
total	6620.9		1.99	6305.5		3.16

TABLE VIII

THE INVESTMENT BUDGET OF IA

Year	**FPCE [MW]**	**FPCR [M$/MW]**	**INVT [B$]**	**WPCE [MW]**	**WPCR [M$/MW]**	**INVT [B$]**
2010-2020	0	1.3	0	728	1.7	1.24
2021-2030	0	1.3	0	1976	1.7	3.36
2031-2040	803.31	1.3	1.04	2883.3	1.7	4.9
2041-2049	1733.2	1.3	2.25	2605.2	1.7	4.43
total	2536.5		3.29	8192.5		13.93
Year	**TCWP [MW]**	**TCR [M$/MW]**	**INVT [B$]**	**STCE [MW]**	**STCR [M$/MW]**	**INVT [B$]**
2010-2020	273	0.3	0.08	364	0.5 0.5	0.18
2021-2030	741	0.3	0.22	988	0.5	0.49
2031-2040	1081.2	0.3	0.32	1441.7	0.5	0.72
2041-2049	1352	0.3	0.41	1802.6	0.5	0.9
total	3447.2		1.03	4596.3		2.29

fossil/wind/storage generation systems. In the PTM model, we minimize the generation cost caused by trading surplus clean power from sellers to buyers in the whole planned regions. In the YLM model, we minimize the investment cost of generation/transmission/storage system capacity expansions and their associated operation cost. The decisions about the final (year-level) investment planning budget are decided based on the results from the HLM and PTM models. The planning purpose is to realize the goals required by clean power policies and the growing power demand of each region. The whole planning environment is implemented on supercomputer systems, which support further expansions for large-scale nation level energy planning problems with finer space and timing resolutions.

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