A long-term investment planning model for mixed energy infrastructure integrated with renewable energy

Jinxu Ding and Arun Somani
Department of Electrical and Computer Engineering
Iowa State University
Ames, IA 50011
Email: {jxding,arun}@iastate.edu

Abstract—**The current energy infrastructure heavily depends on fossil energy, which will be mostly depleted beyond 21st century. Another built-in disadvantage of fossil energy is the pollutant and green house gas emission. It is time to reform the environment-degrading energy infrastructure into a sustainable and resilient energy infrastructure such that it is more environmental friendly. Compared with fossil energy, it is expensive to transport renewable energy for a long distance. Another problem of renewable energy is fluctuation and it is not so stable as fossil energy. To solve the two bottleneck energy investment planning problems (transmission and fluctuation) of renewable energy development, we propose a long-term investment planning model that can help analysts, investors and policy makers find out how to take full use of current and emerging technologies to support the development of renewable energy so that our energy infrastructure can be refomed to be cleaner in a long-term periond, e.g. 40 years.**

In this model, we propose and implement a parallel planning method for power systems. In this method, a large region that needs to be planned is partitioned into multiple subregions. Each subregion is modeled as two optimization models. One is an hour-level model with the goal to minimize the power price volatility caused by imbalance of power demand and supply and the CO_2 emission at hour level. Another is a year-level model with the goal to minimize the investment cost of transmission, operation, and fossil/clean power capapcity expansion at year-level. The year-level model also needs to satisfy the RPS [1] (Renewable Portfolio Standard, which has been approved by 27 states and D.C.) requirements because it is a year-level policy. We use an energy storage system to store surplus clean power e.g. wind power and this helps solve the fluctuation problem of wind energy. The stored energy is allowed to be traded among neighbouring subregions. All models are linear or mixed integer linear programming models and need to satisfy the constraints about fossil/clean power capacity expansion and available clean energy. We use Midwest area and wind energy as an example and implement the parallel modeling method in a cluster system, which supports parallel computing. According to our best knowledge, this is the first parallel long-term energy investment planning model for exploring the relationships between public policy (RPS), renewable energy and fossil energy. It can be used to solve large-scale planning problems on supercomputers.

Keywords: Renewable energy investment planning, Reduced CO_2 emissions, RPS, High-perfermance computing, Operation research

I. INTRODUCTION

Since the energy crisises happened in 1970's, many countries have realized that their energy security will depend on some countries or regions that have rich fossil energy sources if they do not reform their energy infrastructures. Thus, renewable energy becomes one of important alternative sources because they cannot be depleted. Moreover, the CO_2 emitted by fossil energy leads to greenhouse effects that make the Earth's surface and lower atmosphere warmer. This may cause species extinctions, more extreme weather events and negative impacts on agricultural product yields. These are the important motivations of RPS also called renewable electricity standard (RES). RPS is a regulation that requires the energy production from the renewable energy sources, such as wind, solar, biomass, and geothermal to be increased. RPS also requires that the electricity supply companies produce a specified fraction of their electricity from renewable energy sources. [1]

Because RPS is implemented by private markets, it is important to design an investment planning method such that (i) the markets can help implement RPS and provide an environment in which the renewable energy can be developed and related services can be delivered more cost-efficiently; (ii) the renewable energy can compete with fossil energy sources more fairly and transparently. The similar schemes have been proposed in other countries, such as Italy, Belgium and Britain. In U.S.A, RPS has been adopted in 27 states and the District of Columbia. But, RPS is not a federal policy and each state has different detailed regualtions. In U.S.A, more than 42 percent of the electricity sales comes from the 27 states [2].

But, the renewable energy sources are usually located in remotes areas that are far away from power load regions such as big cities with large populations. There are vary little existing power load or generation in these remote areas. For example, Figure 1 shows that wind energy sources are mainly located in Midwest, where the developers will not build wind power plants if there are no transmission lines that can

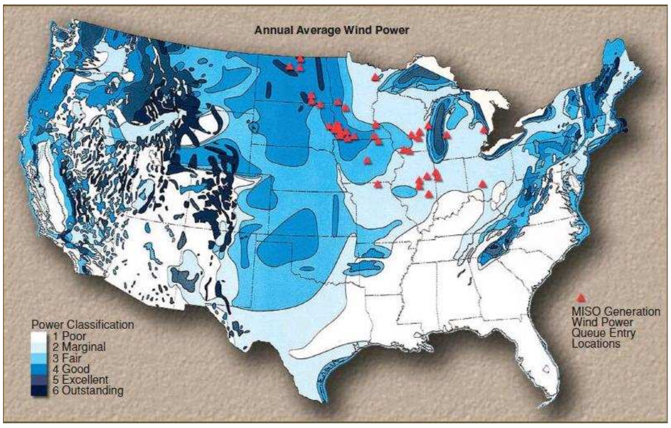

Fig. 1. Wind power map of U.S.A from NREL (National Renewable Energy Lab) [3]

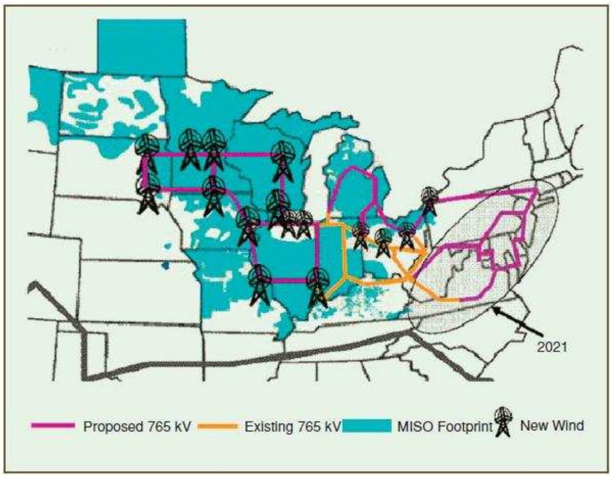

Fig. 2. Wind energy resources in the Midwest ISO footprint. [4]

deliver power to the major load regions. Moreover, because the wind energy is not so stable as fossil energy, it is always fluctuating and may produce surplus power when supply is greater than demand, or is not able to produce enough power to satisfy the power demand according to the schedules in the day-ahead markets. This can lead to unexpected changes of voltage and frequency in the power grids and even result in some damages on the power equipment. Thus, it is important and necessary to investigate how to address the two above issues (transmission planning and fluctuation) such that our current energy infrastructure can be more sustainable (reduced CO_2 emissions) and reliable (reduced negative impacts of fluctuating wind energy) when more wind energy is integrated into the infrastructure. In this paper, we use an energy storage system to store the surplus power generated from wind energy and release it when it is needed. This can reduce the negative impacts caused by the fluctuation of wind energy. Some north European countries have implemented this kinds of energy storage systems e.g. heat tank [8]. It can transform electricity to thermal energy and store it in heat tanks for up to one week. The thermal energy can be released as electricity energy by heat engines later [9]. We also present an investment planning method in which we use Midwest area as an example and minimize the investment cost of renewable and fossil energy, CO_2 emissions and satisfy the RPS of each state in this area.

II. Literature and Model Review

A. *Literature review*

In [4], the authors indicated that wind power has just begun to develop and grow very fast in U.S.A in recent years. The power grid operators have just begun to learn how to integrate wind power into current power transmission systems and how to handel the fluctuation output of wind power plants. After the transmission parts and generation parts are seperated, it is a challenege to do the transmission planning for the remote rich-wind-energy areas. Transmission planning also plays an important role in addressing the issue of RPS. Some states or organizations have implemented some plans or made some policies to encourage development of renewable energy in remote areas. Texas developes a concept called competitive renewable energy zones (CREZs) [5], in which ERCOT (Electric Reliability Council of Texas) can assess the potential wind energy resources in Texas and analyze how to develop transmission upgrades such that more wind power in remote areas can be integrated into existing power grid. Colorado also has a similar policy [4]. The Midwest ISO (MISO) is investigating the possibility of carrying up to 40 GW from a variety of potential wind energy sites to load regions in the Mid-Atlantic states. This can be shown in Figure 2.

Figure 2 shows that the footprint of the Midwest ISO covers all or part of 15 Midwest states and Manitoba in Canada, whose total area is 920,000 square miles. If only 40 GW wind energy is developed to deliver power by 2027, this expansion plan can greatly reduce the output from baseload coal and nuclear generation, which play an important role in the Widwest ISO area. This can help realize RPS in this area and also make it possible for the excess capacity to provide power for the areas outside of Midwest IOS area. This is very promising for high-power demand area such as New England area, which is heavily populated and its land is so expensive that the cost of building wind power plants is very high. But, one of the major bottleneck problems is to build additional 765-kV power lines to carry power from Midwest to east-coast area. Figure 2 presents the existing 765-kV powerlines and new 765-kV power lines that need to be built as a system so that each part of the system is connected to other parts. The authors of [4] argue that the profits generated from the wind expansion plan can help offset the cost of the wind energy development.

The paper [4] shows that it is possible and cost-effective to develop the potential wind energy in Midwest ISO area through existing market mechanisms. In the initial phase, the transmission costs are allocated to individual states. Then, in the new-built transmission system under a new tariff or tariff provisions by FERC, the costs would be allocated among the users. But, these ideas or proposals are still not completely implemented, and very few new transmission lines have been built under these proposals. Moreover, the paper [4] does not present the detailed wind expansion planning that is supported by quantitative results. It only provides some possible strategies that may help develop wind energy in remote areas and carry the wind power from these areas to high-demand areas.

In the paper [6], the authors partitions Rock mountain area (the states of MT, ID, WY, CO and UT) into 18 load regions and present some problems that need to be considered. For example, how to distribute the financial load for transmission lines among generators and users. These load regions have similar characteristics of load and generation, and there is limited existing transmission lines between adjacent load regions. The study focuses on finding solutions that can reduce total cost and stimulate construction of upgrades. The ABB MarketSimulator (COUGER) production cost model is used as the major tool. The input data to the tool includes the data about generation (size, cost, capability and so on), transmission (network data, constraints and so on) and load (distribution, hourly variation and so on). The model can also do the market modeling and market simulation with scenarios about clearing prices, revenues/Rents, capacity factors and flows/congestion. The conclusions of the paper include (1) it is important to calculate power output and capacity factors with the latest wind turbine technology and power curves (adjusted for elevation) and this may have significant impacts on the capacity factors; (2) the locations and capacities of potential wind energy are mainly stimulated and determined by transmission planning expansion in the near future.

The model in [6] has some limitations: (1) there is not an explicit standard or systematic approach used to choose the mix of wind and fossil energy modeled for each scenario; (2) the model does not present the quantitative results of the long-term investment planning for the wind energy developement in Rocky mountain area.

In report [10], the authors presented that the impacts of fluctuation of wind energy on the utility operations depended on the penetration levels and the time length of wind variations. In the report, we can see that the higher penetration level of wind energy in the total energy portfolio and the longer planning time, the more important and necessary it is to use more regulating capacity to handle the wind fluctuations. Although we have realized that transmission is an important issue and storage facilities are helpful for mixed energy infrastructure, it is still not clear how to solve the transmission problem and how to use storage facilities to reduce the impacts of wind energy fluctuation on the operation of power systems meanwhile improving the penetration level of the renewable energy to realize the RPS goals.

B. *Model review*

In this section, we review two optimization models that are developed to analyze how to integrate wind energy to our current energy infrastructure.

The first model is WinDS (Wind Deployment Systems Model) [11], which is developed by SEAC (Strategic Energy Analysis Center) of NREL (National Renewable Eenergy Lab). It is a multiregional and multitime-period linear programming model embedded with the Geographic Information System (GIS). It focuses on the market issues about transmission access and cost, and the fluctuation of wind power. In this model, the objective function is to minimize system-wide costs and also satisfy the constraints of loads, reserve, and green house gas emission by building and operating new generation and transmission systems from 2000 to 2050 over 25 two-year periods [11].

In the WinDS model [11], the linear programming model minimizes the present value of generation and transmission capacity cost and operating cost and also the cost of ancillary services and storage. The linear programming model has more than 100,000 constraints and 300,000 variables, which needs 5-10 hours to run for each of 26 two-year periods from 2000 to 2050 and 5-10 days for the whole period. A major disadvantage of the WinDS model is that the higher spatial resolution means the longer run-time. If the spatial resolution is down to the county level, the number of variables and constraints in WinDS model could be overwhelming because there are more than 3,000 counties in the USA. This may lead to a much longer run-time to solve the linear programming model in WinDS. The resolution problem has been realized by officials of (DOE) Department of Energy.

The second model is NEMS [13] (National Energy Modeling System). It is an energy and economic model of U.S. energy markets developed by Energy Information Administration at Department of Energy. NEMS can be used to forecast the production, consumption, import, and pricing of energy and it depends on the assumptions for economic variables, which include world energy market interactions, resource availability and technological choice. The output from NEMS are fossil fuel prices, production, gas/electric industry output, refinery output, and end-user fuel consumption. In NEMS model, there are only 13 regions, no new transmission lines, and no cost or limits on use of transmission within regions. The NEMS model does not address the issues about renewable energy fluctuation and transmission capacity expansion.

There are also other energy planning models. For example, the All-Modular Industry Growth Assessment (AMIGA) model [14] is a comprehensive economic model of energy markets. But, the AMIGA model does not consider developing renewable energy and its related transmission investment requirements. Another comprehensive energy planning model (developed by Brookhaven National Laboratory) is MARKAL (MARKet ALlocation), which is a dynamic optimization model with the integration of enrgy, environmental, and economic factors. But, it may not be able to solve large size optimization model with high speed because it can run only on a PC Windows [15] platform.

III. The Contribution of Our Parallel Investment Planning Methodology

Except the WinDS and NEMS models, none of the above works have presented a long-term investment plan in an area of America, which can provide decision makers with some advices about how to develop renewable energy such that the RPS of some states in the area can be realized.

In this paper, we use Midwest area as a case to show that our parallel modeling methodology can support modeling large-scale energy planning problem with the finer spatial resolution. With this methodology, we present a long-term investment plan for Midwest area, which has rich wind energy sources. Our contributions mainly include:

- We propose an investment planning methodology that focuses on the realtionship between renewable energy and fossil energy in the case that RPS [1] has become a real clean energy stimulation standard and future target in 27 states and D.C. in USA.
- Our methodology can help analysts, policy makers and financial institutes to understand the relationships beteween transmission line expansion, storage technology advancement and renewable energy developement. The quantitative results of the investment plan can help decision makers figure out how to reform our current energy infrastructure such that it is more sustainable and reliable in a long-term period.
- In order to improve the computation performance, we design a parallel computing algorithm to implement the above methodology. Compared with the WinDS and NEMS models that use sequential computing to solve their optimization problems, our algorithm is more suitable for large-scale and high spatial resolution optimization problems about energy investment planning. It can be implemented in any kinds of supercomputer system to model nation or global level energy investment planning problems.
- This is the first study work in the area of using a combination knowledgy of operation research and parallel computing algorithm for long-term investment planning of clean energy. The algorithm can be used for long-term investment planning for any other kinds of renewable energy sources.

This paper is organized as follows: In Section IV, we present the conceptal description about the planning problem that we want to solve. In Section V, the terms that are used to set up the models are presented. In Section VI, we present the conceptial and mathematical models of our investment planning methodology. In Section VII, we show the computation results of our models and analysis on them. In Section VIII, we present the conclusion and further work.

IV. Problem Description and Proposed Solutions

Our study work on this methodology focuses on (1) how to use the parallel computing method to improve the performance of solving large scale energy planning problems; (2) how to do investment on renewable energy development in order to satisfy some public policies about stimulating clean power in power markets, such as RPS; (3) analysis on the impacts of wind energy development on fossil energy development.

We use the region of seven states (ND,SD,NE,MN,IA) of Midwest as a case to show how our planning method work for the above key points. We use wind energy as an example of renewable energy, which is rich in Midwest area.

The long-term investment planning can be expressed as follows. Given a region that has the following information: (1) existing renewable and fossil power capacities; (2) the potential wind energy sources; (3) the existing fossil/wind power capacity; (4) the RPS [1] of each state in the area, find out an investment plan such that

1) The growing power demand is met in the region.
2) The RPS of each state of the region is realized according to their own schedule.
3) The investment costs (including tranmission line expansion, capacity expansion) and operation costs are minimized in the region.
4) The impact of fluctuation of wind energy is minimized in the region.

Our proposed solutions for the problem above include:

(1) In our paralllel planning method, a large planned region is partitioned into multiple small subregions, which

have some fossil power plants and wind energy sources. Each subregion is modelled as a year-level model (a linear programming model) and an hour-level model (a mixed integer linear programming model). The parallel method is implemented in a cluster computer system that is composed of some computing nodes. Each computing node is responsible for solving the two models of a distinct subregion. The computation results of all these subregion models are sent to a computing node that makes a global decision on the base of these received subregion results. The global decision is to allow clean-power trading between neighbouring subregions in order to reduce the total CO_2 emission of the whole region.

(2) As the power demand is growing in a subregion, our method encourages the development of wind energy at first and then fossil energy by imposing penalties on the CO_2 emissions from the fossil power plants.

(3) Because of the wind energy fluctuation and transmission line capacity limitations, the surplus wind power that cannot be transmitted online is stored in an energy storage system (heat tank [7]) that can transform electricity energy to thermal energy. A well-insulated heat tank can store the thermal energy for up to one week [7]. In the case that the power demand grows, the stored energy will be released by heat engines [9], which can transform thermal energy to electricity energy. The stored energy can be traded between neighbouring subregions so that the green house gas emission can be reduced in the whole region.

V. NOMENCLATURE

(A) Sets and Indices :

S	the set of load subregions in Midwest areas
i	a load subregion $i \in S$
j	a load subregion $j \in S$
Y	the set of years from 2010 to 2049
y	the current year, $y \in Y$
z	a future year, $z \in Y$
T	the set of hours in a day from 1 to 24
t	$t \in T$ for hour-level model, $t \in Y$ for year-level model
k	a future hour, $k \in T$

(B) Constants

EC_i^{wp}	the existing wind power plant capacity of load region i [MW]
EC_i^{fp}	the existing fossil power plant capacity of load region i [MW]

(C) Objective function variables :

PV_{it}	the total price volatility caused by the difference between power supply and power demand in S of load region i in period t
CO_{it}	the total CO_2 emission cost of load region i in period t [$]
OC_{it}	the total operation and management cost of wind and fossil power plant of load region i in period t [$]
TC_{it}	the total cost of transmission lines built up for transmitting wind power from power plants to its closest existing power grids of load region i in in period t [$]
IC_{it}	the total investment cost of wind and fossil power plant capacity expansion of load region i in in period t [$]

(D) Decision variables :

PS_{it}^{fp}	the power supply from fossil power plants of load region i in period t [MW]
PS_{it}^{wp}	the power supply from wind power plants of load region i in period t [MW]
PS_{it}^{wh}	the power supply from the heating storage of wind power plants of load region i in period t [MW]
PB_{it}	the power bought from the stored surplus wind power of other regions in period t
CE_{it}^{wp}	the capacity expansion of wind power plants of load region i in period t [MW]
CE_{it}^{fp}	the capacity expansion of fossil power plants of load region i in period t [MW]
CE_{it}^{wh}	the capacity expansion of heating storage of wind power plants of load region i in period t [MW]
BB_{it}	the binary variable that indicates whether the load region i needs to buy power from other regions
R^{wh}	the percentage of stored power released from storage systems of wind power plants

(E) Parameters about the cost of operation and investment:

OC_{iy}^{wp}	the operation and management cost rate of a wind power plant of load region i in year y [$/MW]
OC_{iy}^{fp}	the operation and management cost rate of a fossil power plant of load region i in year y [$/MW]
OC_{iy}^{h}	the operation and management cost rate of heating storage of load region i in year y [$/MW]
IC_{iy}^{wp}	the investment cost of wind power plants of load region i in year y [$/MW]
IC_{iy}^{fp}	the investment cost of fossil power plants of load region i in year y [$/MW]
IC_{iy}^{h}	the investment cost of heating storage of load region i in year y [$/MW]

(F) Parameters about the cost of transmission:

TC^{w}_{iy} the cost of transmission lines corresponding to wind power capacity expansion of load region i in year y [\$/MW]

TC^{fp}_{iy} the cost of transmission lines corresponding to fossil power capacity expansion of load region i in year y [\$/MW]

(G) Other parameters :

EC^{wp}_{iy} the existing wind power plant capacity of load region i in year y [MW]

SP^{wh}_{it} the surplus power stored in the heating storage of wind power plants of load region i in period t [MW]

PO^{wp}_{it} the output power generated by the wind turbines in wind power plants is the minimal value among existing wind power plant capacity and total available wind power of load region i in period t [MW]

PN_{it} the power that can be bought from the neighbouring subregions of i in the period t [MW]

η^{h}_{it} the transformation effciency rate of heating storage of load region i in period t

TWP^{A}_{it} the total potential wind power of load region i in period t [MW]

RPS_{it} the percentage of clean power in the total power supply of load region i in period t

PD_{it} the power demand of load region i in period t [MWh]

TF_{iy} the transmission factor of region i in year y It expresses the limitation of transmission systems on the wind power that can be transmitted online.

DR^{w}_{it} the discount rate of funding invested on wind energy development of load region i in period t

DR^{f}_{it} the discount rate of funding invested on fossil energy development of load region i in period t

CO^{fp}_{it} the cost of CO_2 emission of fossil power plants of region i in period t [\$/MW]

VI. THE PARALLEL INVESTMENT PLANNING METHODOLOGY

In our parallel computing method, we use the Midwest area (the five states of ND,SD,NE,MN,IA) as an example to show that our method can solve the long-term energy planning problem more efficiently. First, the whole region is partitioned into five load subregions and each of them is a distinct state. Each load subregion is modelled by two mathematical programming models. One model is an hour-level model, which is a mixed integer linear programming model; another is a year-level model, which is a linear programming model. The computation task of the two models for each subregion is assigned to a computing node in a computer cluster system.

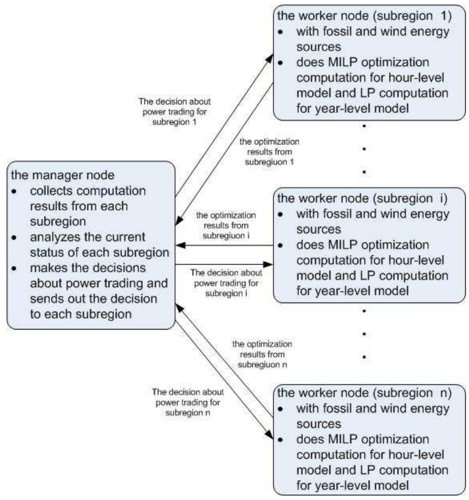

Fig. 3. The modeling framework diagram

The system is composed of some computing nodes, which can communicate with each other by MPI (message passing interface). So, the five subregions use five computing nodes, which are called worker nodes. In order to support the information exchange (e.g. trading stored clean energy among these subregions), we allocate another manager node, which is responsible for collecting optimization results from each worker node. The manager node makes some decisions about stored energy trading among some subregions on the base of analyzing the collected results. After that, it sends out the decisions to related worker nodes such that they know how to trade their stored energy with each other.

In each worker node, the hour-level model is to minimize the power price volatility (caused by demand and supply imbalance) and CO_2 emission hour by hour. Meanwhile, it also needs to meet the local power demand with the power generated by fossil/wind power plants or the power bought from neighbouring load subregions with some stored energy. The hour-level model guarrantees the power demand and supply balance at hour level. The year-level model is to miminize the cost of investment for fossil/wind power plant capacity expansion and wind energy storage system capacity expansion, the cost of related operation and management of power plants and the cost of transmission capacity expansion. These investment and capacity expansion can only be done at year-level. Another goal of the year-level model is to guarranttee that the RPS requirement is satisfied in each subregion because RPS [1] [2] is a year-level policy. The modeling framework is shown in Figure 3 and the modeling flowchart of year-level and hour-level models are shown in Figure 4. In Figure 4, $(pswp + pswh)$ is the total wind power supply and $(pswp + pswh + psfp)$ is the total power supply including fossil power of subregion i in year y. RPS is the required fraction value of wind power out of the total power supply of subregion i in year y.

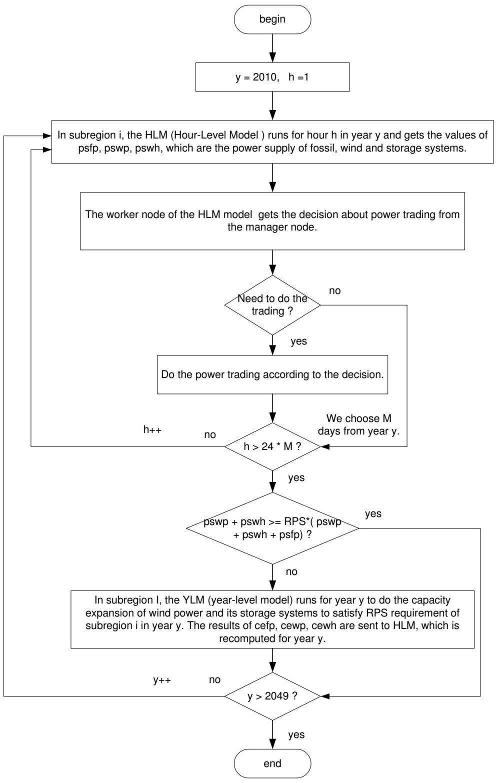

Fig. 4. The modeling flowchart

A. *Mathematical formulation of the year-level model*

The year-level model is a linear programming model, in which we minimize the investment costs, transmission costs, operation cost, CO_2 emission cost and capacity expansion cost and also satisfy the RPS requirements of the subregion. The optimization problem of each load subregion can be expressed as an hour-level model, which is a mixed integer linear programming model, and a year-level model, which is a linear programming model.

The conceptual year-level model of subregion i is as follows:

$$
\begin{aligned}
\textbf{min} \quad & CO + OC + TC + IC \\
\textbf{s.t.} \quad & \\
& meet\ power\ demand\ each\ year \\
& satisfy\ RPS\ requirements\ each\ year \\
& \textbf{decision variables:} \\
& wind/fossil\ power\ capacity\ expansion \\
& energy\ storage\ capacity\ expansion \\
& transmission\ capacity\ expansion
\end{aligned}
$$

Here, CO is the CO_2 emission cost; OC is the cost of operation and management of fossil/wind power plant capacity expansion; TC is the cost of related transmission line expansion; IC is the cost of investment for fossil/wind power plant capacity expansion. The mathematical formulation of the year-level model is as follows:

$$\textbf{min}\ OC_{iy} + TC_{iy} + IC_{iy} + CO_{iy} \tag{1a}$$

s.t.

$$PS_{iy}^{fp} + PS_{iy}^{wp} + PS_{iy}^{wh} + PB_{ijy} = PD_{iy} \tag{1b}$$

$$PS_{iy}^{fp} \leq EC_{iy}^{fp} + CE_{iy}^{fp} \tag{1c}$$

$$PS_{iy}^{wp} \leq (EC_{iy}^{wp} + CE_{iy}^{wp}) \times TF_{iy} \tag{1d}$$

$$PS_{iy}^{wh} \leq \eta^{h} \times (EC_{iy}^{wh} + CE_{iy}^{wh}) \tag{1e}$$

$$CE_{iy}^{wp} \leq (TWP^{A} - EC_{iy}^{wp}) \tag{1f}$$

$$(PS_{iy}^{wp} + PS_{iy}^{wh}) \geq RPS_{iy} \times (PS_{iy}^{fp} + PS_{iy}^{wp} + PS_{iy}^{wh}) \tag{1g}$$

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

$$PS_{iy}^{wp} + PS_{iy}^{wh} \leq (EC_{iy}^{wp} + CE_{iy}^{wp} + EC_{iy}^{wh} + CE_{iy}^{wh}) \times TF_{iy} \tag{1i}$$

$where:$

$$
\begin{aligned}
OC = {} & (OC_{iy}^{fp} \times (EC_{iy}^{fp} + CE_{iy}^{fp})) \\
& + (OC_{iy}^{wp} \times (EC_{iy}^{wp} + CE_{iy}^{wp})) \\
& + (OC_{iy}^{wh} \times (EC_{iy}^{wh} + CE_{iy}^{wh}))
\end{aligned} \tag{1j}
$$

$$
\begin{aligned}
TC = {} & TC_{iy}^{w} \times (CE_{iy}^{wp} + CE_{iy}^{wh}) \times TF_{iy} \\
& + TC_{iy}^{fp} \times CE_{iy}^{fp}
\end{aligned} \tag{1k}
$$

$$
IC = \frac{(IC_{iy}^{fp} \times CE_{iy}^{fp})}{DR_{iy}^{f}} + \frac{(IC_{iy}^{wp} \times CE_{iy}^{wp})}{DR_{iy}^{w}} + \frac{(IC_{iy}^{wh} \times CE_{iy}^{wh})}{DR_{iy}^{w}} \tag{1l}
$$

$$CO_{iy} = CO_{iy}^{fp} \times PS_{iy}^{fp} \tag{1m}$$

The constraint (1b) is to guarrantee the balance of power demand and supply. The constraints of (1c, 1d and 1e) set up the upperbounds of the fossil/wind/storage power supply. The constraint (1f) means that the total existing/expanded wind capacity should not be more than the total wind power available in the year. The constraint (1g) expresses the RPS requirements of the region i in the year. The constraint of (1h) 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 (1i) means that the power supply from wind plant and storage system is upperbounded by the total existing and expanded capacity of wind power plant and storage systems and their associated transmission line capacity. The equations of (1j, 1k and 1l) express the cost of operation, transmission and investment about related capacity expansion for fossil/wind/storage systems. All equations and inequations of the model 1a should hold for $\forall i, j \in S, y \in Y$.

B. Mathematical formulation for the hour-level model

The hour-level model of sub-region i :

min $PV_{it} + CO_{it}$

s.t.

$meet\ power\ demand\ each\ hour$

decision variables:

$wind/fossil\ power\ supply$

$wind\ power\ trading\ among\ subregions$

Here, PV_{it} is the price volatility determined by the relationship between power supply and demand of subregion i in period t. CO_{it} is the CO_2 emission cost of subregion i in period t.

The mathematical formulation of the hour-level model is as follows:

$$\min PV_{it} + CO_{it} \tag{2a}$$

$$\text{s.t.}$$

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

$$PS_{it}^{wh} \leq \eta_{it}^{h} \times SP_{i(t-1)}^{wh} \times R_{it}^{wh} \tag{2c}$$

$$PB_{it} \leq BB_{it} \times PN_{it} \tag{2d}$$

$$PS_{it}^{fp} \leq EC_{it}^{fp} \tag{2e}$$

$$PS_{it}^{wp} \leq min\{EC_{it}^{wp}, TWP_{it}^{A}\} \times TF_{it} \tag{2f}$$

$$PS_{it}^{wp} + PS_{it}^{wh} \leq (EC_{it}^{wp} + EC_{it}^{wh}) \times TF_{it} \tag{2g}$$

$$\textbf{where}:$$

$$PV_{it} = 1 - \frac{PS_{it}^{fp} + PS_{it}^{wp} + PS_{it}^{wh}}{PD_{it}} \tag{2h}$$

$$SP_{it}^{wh} = PO_{it}^{wp} - PS_{it}^{wp} \tag{2i}$$

$$PO_{it}^{wp} = min\{EC_{it}^{wp}, TWP_{it}^{A}\} \tag{2j}$$

$$CO_{it} = CO_{it}^{fp} \times PS_{it}^{fp} \tag{2k}$$

The constraint of (2b) is to meet power demand of the period t in subregion i. All equations and inequations of the hour-level model (2a) should hold for $\forall i \in S, t \in T$. The constraint of (2c) is to set the upperbound of power supply from storage systems. The constraint of (2d) describes the upperbound of power supply bought from other subregions. The PN_{it} is the power that can be provided from other subregions to the subregin i in period t. In the constraint of (2f), 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 subregion i. The equation of (2h) expresses the definition of price volatility. If the total power supply from fossil/wind plant or its storage systems is equal to the power demand, we have $PV_{it} = 0$, which means that there is no price volatility caused by power demand-supply imbalance. The equation of (2i) shows that the stored power is the power supply that cannot be transmitted because of transmission line capacity limitations. The equation of (2j) shows that the output power generated by the wind turbines is upperbounded by the minimal value of existing wind power capacity and the total wind power available of the subregion i in the period of t. The equations and inequations of (2b - 2k) should hold for $\forall i \in S, t \in T$.

C. Computing the year/hour-level model

Each worker node is responsible for doing computation for the hour-level and year-level models. Then, each worker node sends its year-level optimiation results and CO_2 emission results to the manager node, which is responsible for realizing the global optimization goals, e.g. reducing CO_2 emission in the whole region. If the sum of the CO_2 emission from each sub-region is greater than the standard of the global region, which is an upperbound set by an international treaty for environment protection, the manager node will choose the sub-region that has the highest CO_2 emission compared with other subregions and let it do the local optimization again with the new local CO_2 emission upperbound in order to satisfy the global CO_2 emission requirements. In this way, we realize the global goals and local goals at the same time.

VII. The Implementation Results

This parallel modeling methodology is implemented on a MPI [16] cluster system. We use six nodes to do the parallel computing. Five nodes are worker nodes and one node is the manager node, who is responsible for coordinating among worker nodes. Our hour-level model (mixed integer linear programming) has $138,242 (40 \times 24 \times 24 \times 6)$ variables and $161,280 (40 \times 24 \times 24 \times 7)$ constraints totally for the 40 years, 24 typical days each year and 24 hours each day. Our year-level model (linear programming) has $240 = 40 \times 6$ variables and $320 (40 \times 8)$ constraints totally for the 40 years. For each worker node, we decompose the hour-level model into smaller models and use an open source solver lp_solve5.5 [24] to solve the smaller models with 6 variables and 7 constraints hour-by-hour for 40 years. We also do the similiar decomposition for year-level model. It takes 120 seconds to solve all hour-level and year-level models with Intel Xeon [19] 3.06 GHz CPU on all worker nodes. All five worker nodes do the computation at the same time.

A. Parameters

The data of the parameters for this model is collected from the offical documents of [17], [18], [20], [21], [12] and [22]. The CO_2 emission cost is set to be $30\$/ton$. The energy transformation efficency is set to be 0.7, which means that there is 30% loss in the process of transformation in the energy storage systems. We use the average value of the power demand increasement rate from 1998 to 2008 as the future power demand increasement rate of each state. The

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

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

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 II
THE RPS POLICY

existing installed wind power capacity [23] and the potential wind power of each state are summarized in Table I. The RPS policy data [2] are summarized in Table II. It is assumed that the currently existing wind energy storage system is 0. Our model's time horizon is from 2010 to 2049.

B. *The experimental results*

The results of capacity expansion for the fossil, wind and its associated energy-storage systems and transmission systems of each state are summarized in Table III, IV, V, VI and VII. The terms of these tables include **AI-FPC**: Accumulated Installed Fossil Power Capacity; **AI-WPC**: Accumulated Installed Wind Power Capacity; **AI-SSC**: Accumulated Installed Storage System Capacity; **AI-TC**: Accumulated Installed Transmission Capacity; **WPF**: Wind Power Fraction out of the total power supply. The results in the tables of (III-VII) show that we can realize RPS goals in the five states by developing wind power systems. It is necessary to develop associated energy storage systems to solve fluctuation problems of wind energy and the related transmission systems should also be developed. It is not necessary to expand wind power capacity in some years. For example, in IA, it is not necessary to develop more new wind power capapcity and its associated storage capacity from 2010 to 2015. The **WPF** (the fraction value of wind power out of total power supply) can still satisfy the RPS reqirement by 2049. In NE, we do not need to develop more fossil power capacity in the next 40 years as long as we can develop more wind power and its associated storage and transmission system capacity. We also find that each state can satisfy their local power demand and RPS requirements without trading power with other subregions.

year	AI-FPC [MW]	AI-WPC [MW]	AI-SSC [MW]	AI-TC [MW]	WPF
2010	5289	767	0	191	10.9%
2015	5289	1007	120	281	11.2%
2020	5449	1625	400	506	21.2%
2025	5929	3091	960	1823	29.1%
2030	5929	3091	960	1823	27.8%
2035	5929	3091	960	1823	22.5%
2040	6329	5342	1560	2176	31.2%
2045	6489	6611	1880	2176	31.6%
2049	6649	6771	1960	2182	31%

TABLE III
THE SUMMARY OF EXPERIMENTAL RESULTS OF ND

year	AI-FPC [MW]	AI-WPC [MW]	AI-SSC [MW]	AI-TC [MW]	WPF
2010	2962	288	0	144	9.6%
2015	2962	448	80	264	11.9%
2020	2962	608	160	384	19.4%
2025	2962	1088	400	744	29.2%
2030	2962	1088	400	744	27.4%
2035	2962	1088	400	744	23.9%
2040	2962	1488	600	1044	29.6%
2045	2962	1648	680	1164	30.3%
2049	3042	1728	720	1224	30.6%

TABLE IV
THE SUMMARY OF EXPERIMENTAL RESULTS OF SD

year	AI-FPC [MW]	AI-WPC [MW]	AI-SSC [MW]	AI-TC [MW]	WPF
2010	7551	153	0	114	2.9%
2015	7551	233	40	204	4.7%
2020	7551	393	120	384	7.8%
2025	7551	633	240	654	11.1%
2030	7551	953	400	1014	15.3%
2035	7551	1273	560	1374	19%
2040	7551	1753	800	1914	22.8%
2045	7551	2333	1040	2454	26.6%
2049	7551	2633	1240	2904	30.1%

TABLE V
THE SUMMARY OF EXPERIMENTAL RESULTS OF NE

year	AI-FPC [MW]	AI-WPC [MW]	AI-SSC [MW]	AI-TC [MW]	WPF
2010	13905	1805	0	722	8%
2015	13905	1965	80	818	9%
2020	13905	3165	680	1538	16.7%
2025	14305	4685	1440	2450	25.2%
2030	14785	5885	2040	3170	30.2%
2035	15185	6365	2280	3458	30.3%
2040	15185	6845	2520	3746	30.1%
2045	15985	7405	2800	4082	30.1%
2049	16305	7965	3080	4418	30.3%

TABLE VI
THE SUMMARY OF EXPERIMENTAL RESULTS OF MN

year	AI-FPC [MW]	AI-WPC [MW]	AI-SSC [MW]	AI-TC [MW]	WPF
2010	14211	3053	0	457	6.6%
2015	14211	3053	0	457	6.9%
2020	14211	3213	80	493	7.5%
2025	14531	4253	600	727	11.2%
2030	15651	5773	1360	1069	14.9%
2035	17011	7533	2240	1465	18.7%
2040	18771	9693	3320	1951	22.7%
2045	20851	12173	4560	2509	26.6%
2049	22931	14573	5760	3049	30%

TABLE VII
THE SUMMARY OF EXPERIMENTAL RESULTS OF IA

VIII. THE CONLUSION AND FURTHER WORK

In this paper, we present a parallel modelling methodology that can solve the large-scale long-term investment planning problems for fossil and renewable energy infrastructure reformation such that (1) we can reduce green house gas emission in the new mixed energy infrastructure; (2) we can stimulate the development of renewable energy and increase market shares of clean power in power market to satisfy RPS requirements in some states of USA; (3) we can understand the realtionships between transmission capacity expansion and fossil/renewable power capacity expansion; (4) we can solve the imbalance problems caused by the fluctuation of renewable energy, which is one of bottleneck problems that prevent renewable energy from being integrated into current energy infrastructures in large scales. The solutions about the above four points can transform our current energy infrastructure to be more sustainable (we stimulate clean power), more resilient (we use energy storage to solve fluctuation problems of renewable energy).

In our parallel modeling methodology, we partition the whole region with renewable and fossil energy sources and power load into multiple subregions. The parallel method is implemented with six computing nodes in a MPI [16] cluster system. Each computing node is responsible for computing the hour-level and year-level optimization models of investment planning in each subregion. In the hour-level model, we minimize the price volatility caused by power demand-supply imbalance and CO_2 emission. In the year-level model, we minimize the investment cost of fossil/renewable power plant and transmission capacity expansion and operation $\&$ management and also minimize CO_2 emission. Meanwhile, we use energy storage systems to store the surplus power generated by wind and minimize the power demand and supply imbalance caused by the fluctuation of renewable energy.

In sum, we use Midwest area and wind energy planning as an example to show that our parallel modeling methodology is not only of theoretical value but also of practical value because it is very flexible for further enhancement to handel larger size energy planning problems expecially the problems about the renewable energy development at regional, national or even global levels. In our further work, we will explore more parallelism from our current method so that we can improve it to solve larger-scale energy planning problems with finer spatial resolution at these different levels.

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REFERENCES

[1] Renewables portfolio standard http://www.awea.org/policy/rpsbrief.html
[2] States with Renewable Portfolio Standards http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm
[3] Wind power map of the United States http://rredc.nrel.gov/wind/pubs/atlas/maps/chap2/2-01m.html
[4] R. Piwko, R. DeMello, R. Gramlich, W. Lasher, D. Osborn, C. Dombek, and K. Porter, "What comes first ?", IEEE Power and Energy Magazine, Nov/Dec. 2007.
[5] David Hurlbut, "Competitive Renewable Energy Zones in Texas", National Governors Association Center for Best Practices Clean Energy States Grant Program Workshop , NREL, November 18, 2008.
[6] R. Hamilton, R. Lehr, D. Olsen, J. Nielsen, T. Acker, M. Milligan, H. Geller, "Integrating Wind into Transmission Planning: The Rocky Mountain Area Transmission Study (RMATS)", the Global WindPower Conference Chicago, Illinois, March 29-31, 2004.
[7] Thermal energy storage, http://www.nrel.gov/csp/troughnet/thermal_energy_storage.html
[8] www.dongenergy.com
[9] http://aether.lbl.gov/www/classes/p10/heat-engine.html
[10] Utility Wind Interest Group, "Integrating an ever-changing resource", the Technical Information Program located ar NREL and published by EPRI (Electric Power Research Institute), July 1992.
[11] Background of WinDS Model http://www.nrel.gov/analysis/winds/background.html
[12] Documentation of WinDS Base Case Data, http://www.nrel.gov/analysis/winds/pdfs/winds_data.pdf
[13] NEMS, http://www.eia.doe.gov/oiaf/aeo/overview/
[14] AMIGA, http://amiga.dis.anl.gov/Tutorial1.pdf
[15] Microsoft, http://www.microsoft.com/windows/default.aspx
[16] MPI, http://www.mcs.anl.gov/research/projects/mpi/
[17] Electricity Data, http://www.eia.doe.gov/cneaf/electricity
[18] 20% wind energy by 2030 http://www.nrel.gov/docs/fy08osti/41869.pdf
[19] Intel processor http://www.intel.com/p/en_US/products/server/processor
[20] Annual report on U.S. wind power installation, cost, and performance trends: 2007 http://www.nrel.gov/docs/fy08osti/43025.pdf
[21] Modular Trough Power Plant Cycle and Systems Analysis http://www.nrel.gov/docs/fy02osti/31240.pdf
[22] Form EIA-826 Database http://www.eia.doe.gov/cneaf/electricity/page/eia826.html
[23] U.S. Wind Energy Projects, http://www.awea.org/projects/
[24] lp_solve5.5 solver, http://lpsolve.sourceforge.net/5.5/