

Transmission and Wind Power Investment

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Abstract—This paper jointly considers wind power investment and transmission reinforcement. The proposed model is a mathematical program with equilibrium constraints (MPEC) that seeks to identify the optimal wind projects to be developed and the required network reinforcements. Under the transmission/system operator perspective, this MPEC seeks to minimize consumer payments and is constrained by investment conditions and the equilibria of the market under different operating conditions. An array of subsidies is considered to promote independent wind power investment. An example and two case studies illustrate the characteristics of the proposed model.

Index Terms—Electricity market, mathematical program with equilibrium constraints (MPEC), transmission investment, wind power investment.

NOTATION

THE main notation used throughout this paper is stated below, while other symbols are defined as needed.

Constants:

B_k	Susceptance of line k .
c_{ib}	Price offered by the b th production block of the i th generation unit.
c_{\max}^{line}	Budget for investment in transmission lines.
c_{\max}^{wind}	Budget for investment in wind power.
c_k^{line}	Investment cost of line k .
$\tilde{c}_k^{\text{line}}$	Annualized investment cost of line k .
c_n^{wind}	Investment cost of wind power at bus n .
$\tilde{c}_n^{\text{wind}}$	Annualized investment cost of wind power at bus n .
$d_{j,t\omega}$	Power consumed by the j th demand in scenario ω and demand block t .
f_k^{\max}	Transmission capacity of line k .
g_{ib}^{\max}	Upper limit of the b th production block of the i th generation unit.
$k_{n,t\omega}$	Wind intensity at bus n in demand block t and scenario ω .

N_t^h	Number of hours in demand block t .
$o(k)$	Sending-end bus of line k .
$r(k)$	Receiving-end bus of line k .
$\tilde{s}_n^{\text{wind}}$	Annualized subsidy for wind power investment at bus n .
$\gamma_{t\omega}$	Weight of scenario ω in demand block t .
ρ_n^l	Power up to the l th block of wind capacity that can be installed at bus n (being block 1 equal to 0).

Variables:

$f_{k,t\omega}$	Power flow through line k in demand block t and scenario ω .
$g_{ib,t\omega}$	Power produced by the b th production block of the i th generation unit in demand block t and scenario ω .
$P_{n,t\omega}^{\text{wind}}$	Wind power produced at bus n in demand block t and scenario ω .
w_n^l	Binary variable that is equal to 1 if the l th wind power block determines the wind power installed at bus n and 0 otherwise.
x_k^{line}	Binary variable that is equal to 1 if prospective line k is built and 0 otherwise.
X_n^{wind}	Wind power built at bus n .
$\delta_{n,t\omega}$	Voltage angle at bus n in demand block t and scenario ω .

Indices and Sets:

Ψ_n^D	Set of indices of the demands located at bus n .
Ψ_n^G	Set of indices of the generation units located at bus n .
Ψ_n^L	Set of indices of wind power blocks at bus n .
Ψ_t^{ω}	Set of indices of scenarios pertaining to the t th demand block.
Ω_i	Set of indices of the blocks of the i th generation unit.
Ω^G	Set of indices of generation units.
Ω^K	Set of indices of all transmission lines (existing and prospective).
Ω^{K+}	Set of indices of prospective transmission lines.
Ω^N	Set of indices of buses.
Ω^T	Set of indices of demand blocks.

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I. INTRODUCTION

A. Motivation and Approach

Since wind power investment is generally tightly conditioned by transmission investment, we jointly consider these two related problems, henceforth denoted as wind power plus transmission investment problem.

The objective is to identify the most attractive wind power projects and the required transmission reinforcements that result in minimum consumer payment and investment costs for given transmission and wind power investment budgets.

In most electricity markets, transmission expansion is decided by a publicly controlled entity, called the transmission system operator (TSO) or the regional transmission operator (RTO) with the target of facilitating the energy trading. This is the case in most European markets and, particularly, in the market of the Iberian Peninsula that motivates this work.

In most markets with a significant wind power penetration (e.g., Germany or Spain), wind investment has been and is either subsidized or heavily subsidized. If wind investment is subsidized with public funds, a public entity has the duty of identifying and promoting the building of wind power plants in the most appropriate locations taking into account potential network bottlenecks. Such public entity, the planner, seeks to identify a harmonious development of both wind production plants and transmission facilities. The planner, in its role as TSO, actually builds the transmission facilities and actively promotes wind investment in the most suitable sites. This is actually the situation of the TSO of the Spanish part of the electricity market of the Iberian Peninsula.

Needless to say, the planner recognizes that the electricity business revolves around an electricity market and, thus, such market environment is properly represented in the decision-making model of the planner. The planner objective is therefore to identify optimal investments in transmission facilities and in wind production plants while maximizing a measure of social welfare, e.g., the minus total consumer payment, and subject to investment constraints, investment budgets, and the clearing of the market under many and diverse operating conditions within the planning horizon. The clearing of the market for any given operating condition is represented as an optimization problem that identifies the operating decisions that maximize social welfare. Thus, the planner problem is constrained by a collection of optimization problems, one per market operating condition.

We select the objective function of the planner to be the total consumer payment because wind investment tends to lower market prices, and using such objective function, we efficaciously capture this effect. Since investment costs are also relevant for the planner, we add the investment costs to the objective function to be minimized.

The aim of this paper is minimizing the consumer payment. However, we need to incorporate within the modeling framework the investment costs in wind power and transmission lines. Since wind power producers are considered to offer at zero price, if investment costs are not added to the objective function, the optimal solution would consist in building all possible wind power plants, which is not a realistic solution.

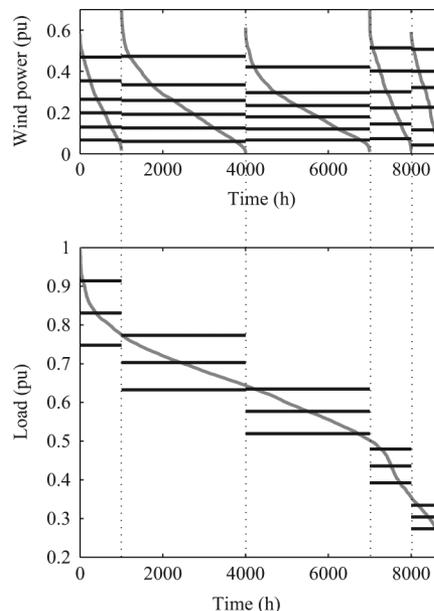


Fig. 1. Load and wind-duration curves.

The optimal solution of the planner decision-making problem results in transmission investment decisions to be actually carried out and wind investment proposals to be promoted among independent profit-oriented wind investors. Once the wind plants are built, wind power investment costs are recovered by the subsidies and by selling the wind power generation in the pool [1].

Once the most socially attractive wind projects have been identified, independent investors may undertake them. The effect of subsidies in making attractive such wind power projects is comprehensively analyzed using the proposed model.

As it is customary in capacity expansion models, we adopt a static approach that focuses on a future target year [2], [3]. Within this target year, the load at each node is described by a piecewise constant load-duration curve composed of a number of demand blocks. Load uncertainty is described considering different load levels per demand block, as indicated in the lower plot of Fig. 1. Wind production uncertainty is also represented by considering different wind power intensities per demand block, as indicated in the upper plot of Fig. 1.

The proposed description of the load and the wind-production uncertainty results in a number of demand blocks and a number of scenarios per demand block that should be large enough to accurately represent all possible combination of demand and wind production for the target year and throughout the nodes of the considered electric energy system.

Modeling the load and the wind production through load and wind-duration curves, respectively, constitutes an appropriate approach for an investment problem such as the one proposed in this paper. However, this modeling may not allow accurately representing the working of storage units or operation constraints such as minimum up and down times of conventional units. Nevertheless, to a certain extent, the working of pumped-storage units can be represented within a load-duration curve framework [4], [5].

The proposed investment model is formulated as a stochastic MPEC that seeks to identify the optimal wind investment level per node (at selected nodes) and the optimal transmission reinforcements (at selected corridors) and that is constrained by investment limits and conditions, and by the equilibrium of the market per scenario. This stochastic MPEC can be recast as a mixed-integer linear programming (MILP) problem, solvable using available branch-and-cut solvers.

B. Literature Review and Contributions

Not many works reported in the technical literature jointly consider generation plus transmission investment. Some examples are [6]–[9]. In [6], the investment problem is tackled modeling as random events the demands, the availability of the power units, and the transmission capacity factors of the lines. Reference [7] proposes an iterative procedure to coordinate generation and transmission expansion, using incentives for investors to recover their investment costs. In [8], the interaction among producers, transmission companies, and the ISO is simulated in a competitive market in which a capacity payment mechanism is considered to promote agents' investments. In this reference, the Monte Carlo method is applied to simulate random outages of generation units and transmission lines. Finally, [9] uses a four-level optimization model to determine the optimal transmission expansion anticipating the generation expansion plans. It should be noted that the above references approach the investment problem considering conventional generation sources and provide models which cannot be directly applied to the renewable investment problem due to the uncertain character of these power sources.

The wind investment problem considering a fixed transmission network has been tackled in [1] and [10]–[13]. Reference [1] provides a model to obtain the optimal wind investment of a wind power producer participating in a pool-based electricity market. Reference [10] provides a methodology to establish the optimal allocation of wind capacity, maximizing the wind power penetration and preserving the network security. Other references such as [11] and [12] solve the optimal wind power investment problem in distribution networks with the aim of minimizing energy losses. Reference [13] provides a technique to optimally design incentives to promote wind power investment.

Regarding the transmission investment problem in a market environment, it is worth mentioning [14], [15]. Reference [14] proposes a MILP problem to solve the transmission investment problem, while a bilevel model is provided in [15].

To jointly tackle the wind power plus transmission investment problem, a bilevel model is considered in this paper. A detailed background of bilevel models can be found in [16].

Within the framework above, the contributions of this paper are fourfold:

- 1) to provide a stochastic MPEC to solve the wind power plus transmission investment problem within a market environment;
- 2) to reformulate the MPEC problem in item 1) as a MILP problem;
- 3) to analyze and qualify the effect of subsidies on wind power investment;
- 4) to provide and discuss in detail results from an illustrative example and two case studies.

C. Paper Organization

The rest of this paper is organized as follows. Section II describes the proposed bilevel model, its transformation into an MPEC, and its equivalent MILP problem. Sections III and IV discuss and give results for an illustrative example and two case studies, respectively. In Section V some relevant concluding remarks are provided. Finally, the Appendix provides the exact linearization process carried out.

II. MODEL FORMULATION

A. Bilevel Model

The investment problem in both wind power and transmission capacity can be formulated using a bilevel model [16]. This bilevel problem comprises an upper-level problem and a collection of lower-level problems. The upper-level problem represents the investment decisions with the target of minimizing both the consumer payment and the investment costs. The lower-level problems represent the market clearing under different load and wind power production conditions. The problem formulation is provided as follows:

Minimize $_{\Delta^{UL} \cup \Delta^{LL}, \forall t, \omega}$

$$\sum_{t \in \Omega^T} N_t^h \sum_{\omega \in \Psi_t^\omega} \gamma_{t\omega} \left[\sum_{n \in \Omega^N} \lambda_{n,t\omega} \sum_{j \in \Psi_n^D} d_{j,t\omega} \right] + \sum_{n \in \Omega^N} (\tilde{c}_n^{\text{wind}} - \hat{s}_n^{\text{wind}}) X_n^{\text{wind}} + \sum_{k \in \Omega^{K+}} \tilde{c}_k^{\text{line}} x_k^{\text{line}} \quad (1a)$$

subject to

$$X_n^{\text{wind}} = \sum_{l \in \Psi_n^L} u_n^l \rho_n^l, \quad \forall n \quad (1b)$$

$$\sum_{l \in \Psi_n^L} u_n^l = 1, \quad \forall n; u_n^l = \{0, 1\}, \quad \forall n, \forall l \quad (1c)$$

$$x_k^{\text{line}} = \{0, 1\}, \quad \forall k \in \Omega^{K+} \quad (1d)$$

$$\sum_{n \in \Omega^N} c_n^{\text{wind}} X_n^{\text{wind}} \leq c_{\max}^{\text{wind}} \quad (1e)$$

$$\sum_{k \in \Omega^{K+}} c_k^{\text{line}} x_k^{\text{line}} \leq c_{\max}^{\text{line}} \quad (1f)$$

where $\lambda_{n,t\omega} \in \arg\{$

Minimize $_{\Delta^{LL}, \forall t, \omega}$

$$\sum_{i \in \Omega^G} \sum_{b \in \Omega_i} c_{ib} g_{ib,t\omega} \quad (2a)$$

subject to

$$\sum_{i \in \Psi_n^G} \sum_{b \in \Omega_i} g_{ib,t\omega} - \sum_{k|o(k)=n} f_{k,t\omega} + \sum_{k|r(k)=n} f_{k,t\omega} + P_{n,t\omega}^{\text{wind}} = \sum_{j \in \Psi_n^D} d_{j,t\omega} : \lambda_{n,t\omega}; \quad \forall n \quad (2b)$$

$$0 \leq P_{n,t\omega}^{\text{wind}} \leq k_{n,t\omega} X_n^{\text{wind}} : \eta_{n,t\omega}^{\max}; \quad \forall n \quad (2c)$$

$$f_{k,t\omega} = B_k (\delta_{o(k),t\omega} - \delta_{r(k),t\omega}) : \phi_{k,t\omega}; \quad \forall k \setminus k \in \Omega^{K+} \quad (2d)$$

$$f_{k,t\omega} = x_k^{\text{line}} B_k (\delta_{o(k),t\omega} - \delta_{r(k),t\omega}) : \phi_{k,t\omega}^+; \quad \forall k \in \Omega^{K+} \quad (2e)$$

$$-f_k^{\max} \leq f_{k,t\omega} \leq f_k^{\max} : \phi_{k,t\omega}^{\min}, \phi_{k,t\omega}^{\max}, \forall k \quad (2f)$$

$$0 \leq g_{ib,t\omega} \leq g_{ib}^{\max} : \varphi_{ib,t\omega}^{\max}, \forall i, \forall b \quad (2g)$$

$$-\pi \leq \delta_{n,t\omega} \leq \pi : \xi_{n,t\omega}^{\min}, \xi_{n,t\omega}^{\max}, \forall n \setminus n : \text{ref.} \quad (2h)$$

$$\delta_{n,t\omega} = 0 : \chi_{n,t\omega}; n : \text{ref.} \quad (2i)$$

$$\left. \begin{array}{l} \delta_{n,t\omega} = 0 \\ \forall t, \forall \omega \end{array} \right\}$$

where $\Delta^{\text{UL}} = \{X_n^{\text{wind}}, \forall n; u_n^l, \forall n, l; x_k^{\text{line}}, \forall k \in \Omega^{K+}\}$, and $\Delta^{\text{LL}} = \{P_{n,t\omega}^{\text{wind}}, \delta_{n,t\omega}, \forall n; g_{ib,t\omega}, \forall i, b; f_{k,t\omega}, \forall k; \lambda_{n,t\omega}, \forall n; \phi_{k,t\omega}, \forall k \setminus k \in \Omega^{K+}; \phi_{k,t\omega}^+, \forall k \in \Omega^{K+}; \phi_{k,t\omega}^{\min}, \phi_{k,t\omega}^{\max}, \forall k; \varphi_{ib,t\omega}^{\max}, \forall i, b; \xi_{n,t\omega}^{\min}, \xi_{n,t\omega}^{\max}, \forall n \setminus n : \text{ref.}; \chi_{n,t\omega}, n : \text{ref.}\}$, $\forall t, \omega$.

Note that the dual variable associated to each constraint of the lower-level problems (2) is provided following a colon.

The objective function (1a) of the upper-level problem (1) represents the total consumer payment (first term) plus the investment costs in both wind power capacity (second term) and transmission lines (third term). The amount that each consumer has to pay is computed as its power consumption in each demand block and scenario multiplied by the corresponding market clearing price. We assume that the price that any consumer has to pay, $\lambda_{n,t\omega}$, is the locational marginal price (LMP) of the bus at which the consumer is located. LMPs for each demand block and scenario are computed as the dual variable associated to the balance constraints (2b) in the corresponding lower-level problem (2). Factor $N_t^h \gamma_{t\omega}$ allows making comparable the annual consumer payment and the annualized investment costs. A subsidy (s_n^{wind}) is considered to promote wind power investment. Note that we consider that subsidies are fixed percentages of the investment costs. A different subsidy scheme, as the one reported in [13], can be easily incorporated in the proposed model.

Constraints (1b) and (1c) state that wind power is only available in discrete blocks. Constraints (1c) impose that only one wind power block is binding and determines the wind power to be installed at each bus of the system. For example, if wind power is available in 50-MW blocks, constants ρ_n^l are $\rho_n^1 = 0$, $\rho_n^2 = 50$, $\rho_n^3 = 100$, $\rho_n^4 = 150$, etc. If the optimal wind power to be installed is 100 MW, then variables u_n^l are $u_n^3 = 1$ and $u_n^l = 0, \forall l \neq 3$. Constraints (1d) define the binary variables x_k^{line} which indicate if the prospective line k is built ($x_k^{\text{line}} = 1$) or not ($x_k^{\text{line}} = 0$). Finally, constraints (1e) and (1f) impose caps on investment in wind power capacity and transmission lines, respectively.

The objective function (2a) of each of the lower-level problems (2) constraining the upper-level problem represents the maximization of the social welfare. Since we consider that power producers offer at marginal costs and loads are constant in each demand block and scenario, maximizing the social welfare is equivalent to minimizing the production cost. Additionally, note that wind producers offer at zero price.

Constraints (2b) enforce the power balance at each bus of the system. Constraints (2c) limit the wind power generation to the wind power availability at each bus for each demand block and scenario. Note that wind production is curtailed if needed to satisfy network capacity limits. This is embedded within the proposed model through equations (2c). Constraints (2d) and (2e) define the power flow through existing and prospective lines, respectively, using a lossless dc model. These power flows are limited to the line transmission capacities by constraints (2f). Con-

straints (2g) limit the power production of each generation block to its size. Finally, constraints (2h) and (2i) enforce angle bounds and fix the voltage angle at the reference bus, respectively.

The transmission and wind power investment model (1)–(2) can be extended to consider other generation technologies. To do so, constraints (2c) should be modified to represent the characteristics of the generation sources under study, while the objective function (2a) should incorporate the offering costs of the new plants to be built in the system, other than wind plants, since wind producers are considered to offer at zero price.

B. MPEC Problem

The upper-level problem (1) and the collection of lower-level problems (2) provided in the previous subsection need to be solved jointly. Thus, it is necessary to transform the bilevel problem (1)–(2) into a single-level problem, i.e., an MPEC. Note that for fixed values of the optimization variables Δ^{UL} of the upper-level problem, the lower-level problems (2) are continuous and linear (and thus convex). Therefore, there are two options to obtain the MPEC:

- 1) KKT formulation: to replace each lower-level problem by its Karush-Kuhn-Tucker (KKT) conditions.
- 2) Primal-dual formulation: to replace each lower-level problem by its primal constraints, its dual constraints and the strong duality theorem (SDT) equality.

Both options are equally valid. However, using the KKT conditions involves solving a large number of complementarity constraints, one for each inequality constraint of problem (2). These complementarity constraints are nonlinear and make the problem generally intractable if a large number of demand blocks and scenarios is considered. Thus, the primal-dual formulation is considered below:

$$\text{Minimize}_{\Delta^{\text{UL}} \cup \Delta^{\text{LL}}, \forall t, \omega} \quad (1a) \quad (3a)$$

subject to

$$\text{Constraints (1b)-(1f)} \quad (3b)$$

$$\left\{ \text{Constraints (2b)-(2i)} \right. \quad (3c)$$

$$c_{ib} - \lambda_{n(i),t\omega} + \varphi_{ib,t\omega}^{\max} \leq 0; \forall i, \forall b \quad (3d)$$

$$-\lambda_{n,t\omega} + \eta_{n,t\omega}^{\max} \leq 0; \forall n \quad (3e)$$

$$\lambda_{o(k),t\omega} - \lambda_{r(k),t\omega} - \phi_{k,t\omega} + \phi_{k,t\omega}^{\max} - \phi_{k,t\omega}^{\min} = 0; \forall k \setminus \Omega^{K+} \quad (3f)$$

$$\lambda_{o(k),t\omega} - \lambda_{r(k),t\omega} - \phi_{k,t\omega}^+ + \phi_{k,t\omega}^{\max} - \phi_{k,t\omega}^{\min} = 0; \forall k \in \Omega^{K+} \quad (3g)$$

$$- \sum_{k \setminus k \in \Omega^{K+} | o(k)=n} B_k \phi_{k,t\omega} + \sum_{k \setminus k \in \Omega^{K+} | r(k)=n} B_k \phi_{k,t\omega} - \sum_{k \in \Omega^{K+} | o(k)=n} B_k x_k^{\text{line}} \phi_{k,t\omega}^+ + \sum_{k \in \Omega^{K+} | r(k)=n} B_k x_k^{\text{line}} \phi_{k,t\omega}^+ + \xi_{n,t\omega}^{\max} - \xi_{n,t\omega}^{\min} = 0; \forall n \setminus n : \text{ref.} \quad (3h)$$

$$- \sum_{k \setminus k \in \Omega^{K+} | o(k)=n} B_k \phi_{k,t\omega} + \sum_{k \setminus k \in \Omega^{K+} | r(k)=n} B_k \phi_{k,t\omega} - \sum_{k \in \Omega^{K+} | o(k)=n} B_k x_k^{\text{line}} \phi_{k,t\omega}^+ + \sum_{k \in \Omega^{K+} | r(k)=n} B_k x_k^{\text{line}} \phi_{k,t\omega}^+ - \chi_{n,t\omega} = 0; n : \text{ref.} \quad (3i)$$

$$\eta_{n,tw}^{\max} \geq 0; \forall n \quad (3j)$$

$$\phi_{k,tw}^{\min}, \phi_{k,tw}^{\max} \geq 0; \forall k \quad (3k)$$

$$\varphi_{ib,tw}^{\max} \geq 0; \forall i, \forall b \quad (3l)$$

$$\xi_{n,tw}^{\min}, \xi_{n,tw}^{\max} \geq 0; \forall n \setminus n : \text{ref.} \quad (3m)$$

$$\begin{aligned} \sum_{i \in \Omega^G} \sum_{b \in \Omega_i} c_{ib} g_{ib,tw} &= \sum_{n \in \Omega^N} \lambda_{n,tw} \left[\sum_{j \in \Psi_n^D} d_{j,tw} \right] \\ &- \sum_{n \in \Omega^N} \eta_{n,tw}^{\max} k_{n,tw} X_n^{\text{wind}} - \sum_{k \in \Omega^K} (\phi_{k,tw}^{\max} + \phi_{k,tw}^{\min}) f_k^{\max} \\ &- \sum_{i \in \Omega^G} \sum_{b \in \Omega_i} \varphi_{ib,tw}^{\max} g_{ib}^{\max} - \sum_{n \in \Omega^N \setminus n:\text{ref.}} (\xi_{n,tw}^{\max} + \xi_{n,tw}^{\min}) \pi \quad (3n) \end{aligned}$$

} $\forall t, \forall \omega.$

Note that primal constraints (3c), dual constraints (3d)–(3m), and the SDT equality (3n) are included as constraints of the upper-level problem (1) rendering an MPEC model for the wind power plus transmission investment problem.

C. MILP Problem

Problem (3) provided in the previous subsection includes nonlinearities in constraints (2e), (3h), (3i), and (3n). These nonlinear constraints can be transformed into exact linear ones using the technique provided in the Appendix.

Finally, the wind power plus transmission investment problem can be formulated as the following MILP problem:

$$\text{Minimize}_{\Delta^{\text{UL}} \cup \Delta^{\text{LL}}, \forall t, \forall \omega} \quad (1a)$$

subject to

Constraints (1b)–(1f)

{ Constraints (2b)–(2d) and (2f)–(2i) } (4c)

Constraints (3d)–(3g) and (3j)–(3m) (4d)

$$-x_k^{\text{line}} f_k^{\max} \leq f_{k,tw} \leq x_k^{\text{line}} f_k^{\max}; \forall k \in \Omega^{K+} \quad (4e)$$

$$\begin{aligned} &- (1 - x_k^{\text{line}}) M \leq \frac{f_{k,tw}}{B_k} - (\delta_{o(k),tw} - \delta_{r(k),tw}) \\ &\leq (1 - x_k^{\text{line}}) M; \forall k \in \Omega^{K+} \quad (4f) \end{aligned}$$

$$- \sum_{k \setminus k \in \Omega^{K+} | o(k)=n} B_k \phi_{k,tw} + \sum_{k \setminus k \in \Omega^{K+} | r(k)=n} B_k \phi_{k,tw}$$

$$- \sum_{k \in \Omega^{K+} | o(k)=n} B_k (\phi_{k,tw}^+ - \bar{\phi}_{k,tw}^+)$$

$$+ \sum_{k \in \Omega^{K+} | r(k)=n} B_k (\phi_{k,tw}^+ - \bar{\phi}_{k,tw}^+) + \xi_{n,tw}^{\max}$$

$$- \xi_{n,tw}^{\min} = 0; \forall n \setminus n : \text{ref.} \quad (4g)$$

$$- \sum_{k \setminus k \in \Omega^{K+} | o(k)=n} B_k \phi_{k,tw} + \sum_{k \setminus k \in \Omega^{K+} | r(k)=n} B_k \phi_{k,tw}$$

$$- \sum_{k \in \Omega^{K+} | o(k)=n} B_k (\phi_{k,tw}^+ - \bar{\phi}_{k,tw}^+)$$

$$+ \sum_{k \in \Omega^{K+} | r(k)=n} B_k (\phi_{k,tw}^+ - \bar{\phi}_{k,tw}^+) - \chi_{n,tw} = 0; n : \text{ref.} \quad (4h)$$

$$-x_k^{\text{line}} \Gamma^{\max} \leq \phi_{k,tw}^+ - \bar{\phi}_{k,tw}^+ \leq x_k^{\text{line}} \Gamma^{\max}; \forall k \in \Omega^{K+} \quad (4i)$$

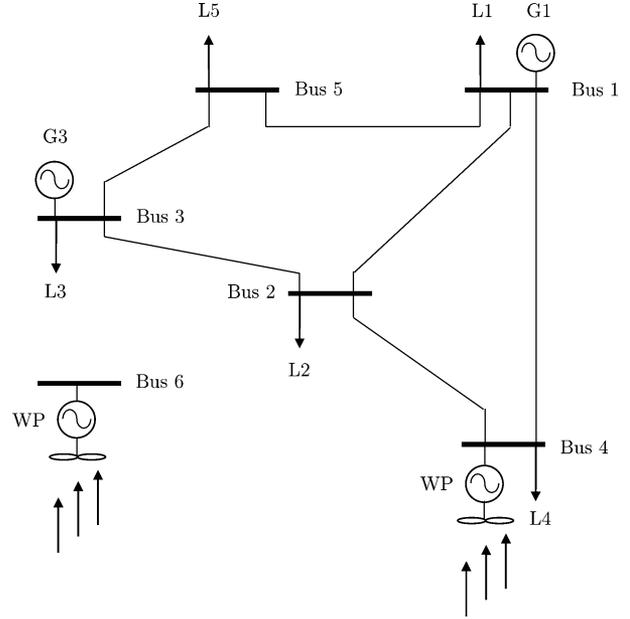


Fig. 2. Garver's six-bus test system.

$$- (1 - x_k^{\text{line}}) \Gamma^{\max} \leq \bar{\phi}_{k,tw}^+ \leq (1 - x_k^{\text{line}}) \Gamma^{\max}; \forall k \in \Omega^{K+} \quad (4j)$$

$$\sum_{i \in \Omega^G} \sum_{b \in \Omega_i} c_{ib} g_{ib,tw} = \sum_{n \in \Omega^N} \lambda_{n,tw} \left[\sum_{j \in \Psi_n^D} d_{j,tw} \right]$$

$$- \sum_{n \in \Omega^N} k_{n,tw} \sum_{l \in \Omega_n^L} z_{n,tw}^l - \sum_{k \in \Omega^K} (\phi_{k,tw}^{\max} + \phi_{k,tw}^{\min}) f_k^{\max}$$

$$- \sum_{i \in \Omega^G} \sum_{b \in \Omega_i} \varphi_{ib,tw}^{\max} g_{ib}^{\max} - \sum_{n \in \Omega^N \setminus n:\text{ref.}} (\xi_{n,tw}^{\max} + \xi_{n,tw}^{\min}) \pi \quad (4k)$$

Constraints (5) (4l)

} $\forall t, \forall \omega$

where $\eta_{n,tw}^{\max}$, $\bar{\eta}_{n,tw}^{\max}$, Γ^{\max} , and M are sufficiently large constants and $\bar{\phi}_{k,tw}^+$ and $\bar{\chi}_{n,tw}$ are auxiliary continuous variables used to derive linear expressions.

III. ILLUSTRATIVE EXAMPLE

A. Data

The proposed model is illustrated using the Garver's six-bus test system [17], depicted in Fig. 2. This electric energy system comprises six buses, two generation units, five demands, and six transmission lines. Note that bus 6 is not initially connected to the system.

Table I provides the generation unit and demand data. The second and third columns give, for each generation unit, the blocks of power offered to the market and their corresponding offering prices, respectively. These offers are considered fixed throughout the planning horizon. The fourth column provides the peak load at each bus of the system.

Wind power is available in 50-MW blocks at buses 4 and 6 up to 1000 MW at each bus. The annualized wind power investment cost is 10% of the total investment cost, which is equal to \$1 million per MW. Wind power producers offer at zero price.

TABLE I
GENERATING UNIT AND LOAD DATA FOR GARVER'S SIX-BUS TEST SYSTEM

Bus	Generation Units		Loads
	Offer size (MW)	Offer price (\$/MWh)	Peak (MW)
1	100, 100, 100, 100	54, 68, 82, 95	110
2			132
3	100, 100, 100, 100	64, 85, 99, 110	88
4			132
5			88

TABLE II
DEMAND AND WIND SCENARIOS PER DEMAND BLOCK

Scenario #	Demand block #	Number of hours	Demand levels	Wind intensities
1–18	1	1000	0.914	0.469
			0.831	0.354
			0.748	0.264
				0.199
				0.130
19–36	2	3000	0.773	0.473
			0.703	0.335
			0.633	0.259
				0.192
				0.125
37–54	3	3000	0.635	0.421
			0.577	0.297
			0.519	0.234
				0.179
				0.120
55–72	4	1000	0.480	0.514
			0.436	0.402
			0.392	0.301
				0.223
				0.144
73–90	5	760	0.334	0.507
			0.304	0.400
			0.274	0.321
				0.225
				0.116
			0.042	

The data defining the existing and prospective lines is based on that provided in [15] and [17]. The line building cost is considered equal to \$700 000/km, with the annualized investment cost equal to 10% of the total cost. The considered prospective lines are 2–4, 2–6, 3–6, and 4–6.

Finally, Fig. 1 depicts the load and wind-duration curves defining the demand blocks and scenarios. Fig. 1 is based on historical data of the electricity market of the Iberian Peninsula [18], [19]. We consider five demand blocks to adjust the load-duration curve (lower plot of Fig. 1). For each demand block, three demand levels and six wind intensities (as represented in the upper plot of Fig. 1) are considered to describe the load and the wind uncertainty. This results in 18 scenarios per demand block and a total of 90 load and wind scenarios throughout the target year. The load and wind conditions for each scenario are provided in Table II. In each scenario, the demand levels and wind power intensities multiply the peak load and the installed

TABLE III
RESULTS FOR THE SIX-BUS SYSTEM AND DIFFERENT VALUES OF THE WIND POWER SUBSIDY

Subsidy (%)	Lines built	X_4^{wind} (MW)	X_6^{wind} (MW)	Objective (M\$)	CPU (s)
0	-	-	-	235.43	124.69
10	-	-	-	235.43	138.63
15	2–6;3–6	850	450	264.10	149.81
25	2–6;3–6	850	600	219.11	136.92
35	2–6;3–6	1000	600	204.46	136.46
45	2–6;3–6	1000	750	187.71	113.34

wind power capacity, respectively, obtaining the actual demand and the maximum wind power production for each scenario. For the sake of simplicity, all scenarios within a demand block are considered to have the same weight (1/18). Although the model can accommodate different wind and load patterns at different locations, due to lack of data, we consider the same wind and load pattern at all buses, i.e., the correlation between wind and load is the same throughout the system. Additionally, we consider that the wind power intensity at bus 6 is 10% higher than at bus 4 (wind intensities at bus 6 are the values of the fifth column of Table II times a factor equal to 1.1). However, note that if wind power data at different locations were available and used in the model, more realistic results could be obtained.

B. Results

Results for this illustrative example and the case study (Section IV) are obtained using CPLEX 11.2.1 [20] under GAMS [21] on a Linux-based server with four processors clocking at 2.9 GHz and 250 GB of RAM.

First, we discuss how different values of the wind power investment subsidy (\bar{s}_n^{wind}) modify the optimal investment decisions. Results are provided in Table III. The first column indicates the percentage of the wind power cost that is covered by the subsidy. The second column provides the prospective lines to be built. The third and fourth columns give the optimal wind power capacity to be installed at buses 4 and 6, respectively. Finally, the fifth and sixth columns provide the optimal value of the objective function (4a) and the required CPU time, respectively.

Note that for a wind power investment subsidy lower than or equal to 10% of the wind power investment cost, it is optimal building neither additional transmission lines nor wind power capacity. Observe also that if no wind power is installed in the system, there is enough transmission capacity.

As the value of the investment subsidy increases, it becomes attractive building wind plants at buses 4 and 6. Observe that wind intensity is 10% higher at bus 6 than at bus 4 and that bus 6 is not initially connected to the system. The optimal investment decisions consist in installing lower wind capacity at bus 6 than at bus 4, since bus 4 is better connected to the loads of the system and contributes to decrease the consumer payment without building any additional lines. Additionally, note that a load is located at bus 4, which can be satisfied directly using the wind power generation of this bus.

Next, we analyze how increasing the load levels modifies the investment decisions. We consider that the subsidy is fixed and equal to 10% of the wind power investment cost. We also limit the investment budget in wind power to \$1500 million.

TABLE IV
RESULTS FOR THE SIX-BUS SYSTEM AND DIFFERENT LOAD LEVELS

Load increase (%)	Lines to be built	X_4^{wind} (MW)	X_6^{wind} (MW)	Objective (M\$)	CPU (min)
0	-	-	-	235.43	14.69
5	2-6($\times 2$);3-6	600	750	249.32	14.19
10	2-6($\times 2$);3-6	850	600	264.09	14.21
20	2-6($\times 2$);3-6	800	600	294.24	17.70
30	2-6($\times 2$);3-6	750	750	324.03	11.20
40	2-6($\times 2$);3-6	900	600	359.00	8.25
50	2-6($\times 2$);3-6	800	600	394.71	9.87

Regarding transmission investment, the prospective lines that we consider in this case are: 2-4, 2-6 ($\times 2$), 3-6, and 4-6 ($\times 2$). The investment budget in transmission lines is limited to \$200 million.

Results are provided in Table IV. The first column indicates the percentage of load increase with respect to the base case. The second column provides the lines to be built. The third and fourth columns give the optimal wind power capacity to be installed at buses 4 and 6, respectively. Finally, the fifth and sixth columns provide the optimal value of the objective function (4a) and the required CPU time, respectively.

Note that it is not optimal to build any wind power capacity for the considered wind power investment subsidy and the original value of the load. However, as the load in the system increases, market prices increase and consequently, the consumer payment increases. Since wind power generation is offered at zero price, it contributes to decrease the market prices. Thus, for load increases higher than 5%, wind power investment becomes attractive.

It is worth mentioning that transmission investment costs are comparatively much lower than wind power investment costs (e.g., transmission investment cost is 10.86% of the wind power investment cost for the case of 20% load increase), and thus, the optimal transmission investment decisions adapt to the wind power investment ones.

IV. CASE STUDIES

To further analyze the proposed MPEC model, results for the IEEE Reliability Test System (RTS) [22] and the IEEE 118-bus Test System [23] are discussed in this section.

A. IEEE RTS Case Study

The IEEE RTS comprises 24 buses, 32 generating units, and 38 transmission lines. The data defining this system is based on that provided in [22]. To obtain more realistic results, peak loads and generation levels are considered twice the values provided in [22].

Wind power capacity can be built in 100-MW blocks at buses 4 and 7, with the maximum wind power capacity that can be installed at each bus equal to 1200 MW. Wind power investment costs are equal to those provided in the illustrative example (Section III). Note that the wind power offer price is considered to be zero. The peak load at these buses is considered 50% lower than the values provided in [22]. Furthermore, the capacity of transmission lines 2-4 and 4-9 is limited to 50 MW

TABLE V
PROSPECTIVE LINE DATA FOR THE IEEE RTS

From bus	To bus	Reactance (p.u.)	Capacity (MW)	Investment cost (M\$)
2	7	0.120	175	10.667
3	4	0.120	175	12.000
4	5	0.120	175	10.667
5	7	0.140	175	11.333
7	8	0.165	175	11.100

TABLE VI
RESULTS FOR THE IEEE RTS

Subsidy (%)	Lines built	X_4^{wind} (MW)	X_7^{wind} (MW)	Objective (M\$)
0	4-5	-	-	2375.48
25	4-5	-	200	2372.61
45	-	100	200	2368.48
55	4-5	800	200	2364.53

(being the original value equal to 175 MW); and line 7-8 is not considered. This means that bus 7 is initially isolated. These assumptions represent the situation in some electric energy systems with wind power generation far away from the load centers.

The data of the candidate transmission lines is provided in Table V. The annualized investment costs of transmission lines are equal to 10% of the total costs provided in Table V.

Investment budgets are considered unlimited in this case study.

The load and wind conditions are represented using the load and wind-duration curves provided in Fig. 1 and Table II. The load and wind patterns are assumed to be the same at all buses of the system, and wind intensity at bus 7 is considered to be 20% higher than at bus 4.

Table VI provides the optimal investment decisions for different values of the wind power subsidy. The first column indicates the percentage of the wind power cost covered by the subsidy. The second column provides the prospective lines to be built. The third and fourth columns give the optimal wind power capacity to be installed at buses 4 and 7, respectively. Finally, the fifth column provides the optimal value of the objective function (4a).

The average CPU time required to solve each of the cases in Table VI is 14.37 min.

Note that for subsidies lower than 25% of the wind power investment cost, it is not optimal to build wind power capacity. For values between 25 and 40%, it is optimal to build wind power capacity only at bus 7, which has the highest wind intensity. However, subsidies higher than 55% of the wind power investment cost make optimal to build a higher wind power capacity at bus 4 than at bus 7 because the wind power generation at bus 7 is only consumed by the load at this bus, since it is isolated and building transmission lines connecting this bus to the system does not reduce the objective function (4a).

Regarding transmission investment, note that since the initial transmission capacity is rather limited, it is optimal to build some of the prospective lines for almost all cases. Building a transmission line between buses 4 and 5 reduces the consumer payment and the objective function (4a).

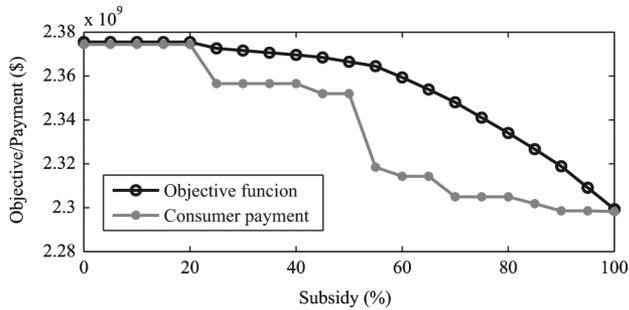


Fig. 3. Optimal value of the objective function and the consumer payment for different subsidy values for the IEEE RTS.

TABLE VII
PROSPECTIVE LINE DATA FOR THE IEEE 118-BUS TEST SYSTEM

From bus	To bus	Reactance (p.u.)	Capacity (MW)	Investment cost (M\$)
6	7	0.0208	400	10.670
2	12	0.0616	400	14.800
3	12	0.16	400	15.200
7	12	0.034	400	13.580
11	13	0.0731	400	12.200

The value of the objective function (4a) is composed of three terms: the consumer payment, the wind power investment cost, and the transmission investment cost. Fig. 3 depicts the optimal value of the objective function (4a) and the consumer payment for different subsidy values. Note that the value of the objective function decreases as the subsidy for wind power increases. However, there are several subsidy values that provide the same total consumer payment because the corresponding investment decisions are the same. Thus, under the perspective of decreasing the total consumer payment, two possible optimal values of subsidy are 25% or 55% of the total investment cost, which are the minimum values of subsidy that provide approximately the same consumer payment in a particular subsidy interval. Since wind investment is usually subsidized with public funds, it is required to design and implement a subsidy mechanism that maximizes the overall social welfare but also minimizes the amount of resources used to encourage wind power investment.

B. IEEE 118-Bus Test System Case Study

The IEEE 118-bus Test System [23] comprises 186 transmission lines, 54 generating units, and 99 loads. The data defining this system is based on that provided in [23].

Wind power capacity can be built at buses 7, 12, and 13 in 100-MW blocks, up to 1000 MW at each bus. Load and wind is represented using the load and wind-duration curves depicted in Fig. 1. Wind intensity at buses 7 and 12 is assumed to be 10% and 20% higher than at bus 13, respectively. Transmission capacity of lines connected to these buses is limited to 50 MW. Wind investment costs are equal to those provided in the illustrative example (Section III) and wind power producers offer at zero price.

Finally, Table VII provides the data of prospective lines.

Investment budgets in wind power capacity and transmission lines are not limited in this case study.

Results of solving problem (4) for different subsidy values are provided in Fig. 4, which depicts the total wind power capacity to be built in the system as a function of the wind power subsidy.

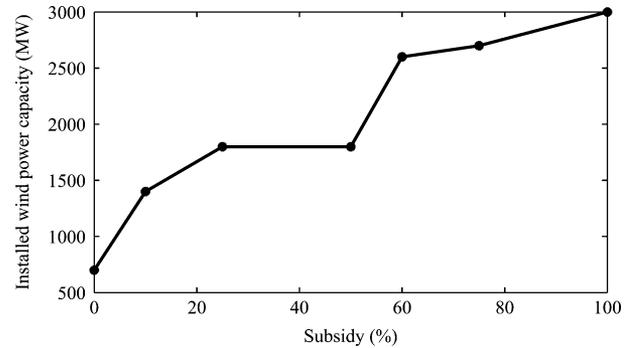


Fig. 4. Optimal value of the installed wind power capacity for different subsidy values for the IEEE 118-bus Test System.

As the percentage of wind power investment cost that is covered by the subsidies increases, the investment in wind power facilities becomes more attractive. Wind power is installed preferably at bus 12, where the wind intensity is the highest. However, subsidies higher or equal than 10% of the investment cost makes also optimal building wind power plants at buses 7 and 13. High values of the wind power subsidy result in building almost all the available wind power capacity. However, in these cases there is a high wind spillage in some scenarios (in those related to low demands and high wind power production).

Regarding the transmission lines, results differ for each value of subsidy. However, lines 2–12 and 3–12 are built for all the subsidy values. This is due to the fact that bus 12 has the highest wind power production which is delivered to the adjacent buses.

As an example, the optimal solution for a subsidy of 25% of the investment cost consists in installing 600, 1000, and 200 MW of wind power capacity at buses 7, 12, and 13, respectively, and building transmission lines 2–12, 3–13, and 7–12. The objective function (4a) in this case is \$4564.3 million.

The mean computation time required to obtain the optimal solution for each value of the subsidy is 12.25 h. This computational burden is appropriate for planning studies. However, if more prospective transmission lines are considered or a more precise description of load and wind conditions is required, the computation time significantly increases. However, the decomposable structure of problem (4) allows applying a decomposition approach to obtain the optimal solution [24].

V. CONCLUSIONS

Optimal wind power investment decisions are highly conditioned by transmission reinforcements, and thus, both investment undertakings need to be jointly addressed by a coordinating planner. Within a market environment, the proposed model allows both jointly considering these two capacity expansion endeavors and analyzing the complex relationship among them, including the effect of subsidies to promote wind power investment.

Considering the results of the reported case studies and taking into account the considered simplifying assumptions in the developed model, the following concluding remarks are in order:

- 1) Although investment cost in transmission facilities is comparatively much lower than investment cost in wind power capacity, transmission investment decisions highly condition wind power capacity investment alternatives.

- 2) Comparatively small subsidies involving a percentage of the investment cost may play a significant role in promoting wind power capacity investments.
- 3) Since both transmission and wind power capacity investments are made within a market environment, a stochastic MPEC approach is most appropriate.
- 4) The proposed stochastic MPEC model can be easily converted into a tractable MILP problem that can be efficiently solved using currently available branch-and-cut solvers. The resulting MILP problem has a decomposable structure and can be solved using a decomposition approach if needed.
- 5) The proposed model identifies the network reinforcements to be carried out by the TSO, and also identifies the most attractive wind power projects to be eventually developed by profit-oriented private investors.

APPENDIX
LINEARIZATION

Problem (3) includes two types of nonlinearities:

- 1) the nonlinearities in constraints (2e), (3h), and (3n);
- 2) the term $\eta_{n,tw}^{\max} k_{n,tw} X_n^{\text{wind}}$ in constraints (3n).

The nonlinearities in item 1) can be linearized using the linearization procedure proposed in [15]. These constraints are replaced by the equivalent linear constraints (4e)–(4j).

On the other hand, term $\eta_{n,tw}^{\max} k_{n,tw} X_n^{\text{wind}}$ can be written as

$$\eta_{n,tw}^{\max} k_{n,tw} X_n^{\text{wind}} = k_{n,tw} \eta_{n,tw}^{\max} \times \sum_{l \in \Omega_n^l} u_n^l \rho_n^l = k_{n,tw} \sum_{l \in \Omega_n^l} z_{n,tw}^l$$

where $z_{n,tw}^l = \eta_{n,tw}^{\max} u_n^l \rho_n^l$.

Each of the terms $z_{n,tw}^l$ can be replaced by the following set of exact mixed-integer linear expressions:

$$z_{n,tw}^l = \eta_{n,tw}^{\max} u_n^l \rho_n^l - s_{n,tw}^l \tag{5a}$$

$$u_n^l \eta_{n,tw}^{\max} \rho_n^l \leq z_{n,tw}^l \leq u_n^l \bar{\eta}_{n,tw}^{\max} \rho_n^l \tag{5b}$$

$$(1 - u_n^l) \eta_{n,tw}^{\max} \rho_n^l \leq s_{n,tw}^l \leq (1 - u_n^l) \bar{\eta}_{n,tw}^{\max} \rho_n^l \tag{5c}$$

$$u_n^l \in \{0, 1\} \tag{5d}$$

where $\eta_{n,tw}^{\max}$ and $\bar{\eta}_{n,tw}^{\max}$ are lower and upper bounds for variable $\eta_{n,tw}^{\max}$, respectively, and $s_{n,tw}^l$ is an auxiliary continuous variable used to linearize.

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