Achieving emission reduction goals: Long-term power system expansion under short-term operational uncertainty

Authors here

Abstract—**Recent work employs two-stage robust optimization to deal with uncertain demand and generation parameters in the generation and transmission expansion planning problem. We build on this work by considering multi-year investment horizon with an objective of reducing greenhouse gas emissions. In addition, we consider multiple hours in power system operations to capture the flexibility requirements for utilizing variable renewable energy sources such as wind and solar power. To improve the solution time of the existing exact methods for this problem, we employ Benders decomposition and solve a mixed-integer quadratic problem to avoid expensive big-M-linearizations. The results for a realistic case study for the Nordic and Baltic countries show the effectiveness of our solution method. Also, the results indicate that investments in new transmission lines, wind power and flexible generation capacity are required for reducing greenhouse gas emissions in this area.**

Index Terms—**Emission reduction, generation and transmission expansion, robust optimization, stochastic programming, Benders decomposition**

I. Introduction

Most nations have ratified the Paris agreement that aims at capping the increase in the global average temperature by lowering greenhouse gas (GHG) emissions, for example [1]. To this end, there are nation-level policies that set speficic goals for GHG emission reductions through measures such as increasing energy efficiency and the share of renewable energy of total energy consumption [2]. Due to the limited availability of dispatchable renewable energy sources (RES) such as hydro power and biomass, investments in non-dispatchable, variable RES (VRES) such as wind and solar power are required. However, integrating large investments in VRES to existing power systems is likely to require significant investments in transmission capacity as well as to flexible generation technologies (e.g. combined cycle gas turbines, CCGT) and storage to guarantee the power system adequacy and security [3].

Consequently, in this paper, we consider the Generation and Transmission Expansion Planning (G&TEP) problem with the objective of reducing GHG emissions under uncertain demand and VRES generation, for example. More specifically, we employ a tri-level model representing two stages in which the first stage and level consider a multi-year investment horizon for generation and transmission expansion. At the second stage, the second level uses robust optimization (RO) to choose a worst-case demand for the third level that uses stochastic programming to minimize the cost of detailed, multi-hour power system operation under a set of operating conditions (scenarios) for uncertain parameters such as VRES output and generation costs. This combination of RO and stochastic programming in two stages is called stochastic adaptive robust optimization (SARO) [4]. This framework allows us to study what transmission line, VRES, and other generation investments are required to meet long-term GHG emission reduction goals while meeting short-term operational constraints on demand, transmission, generator ramping and availability with random and worst-case realizations of the related parameters. We apply the framework to a realistic case study covering the Nordic and Baltic countries.

Similar tri-level framework is employed for the G&TEP problem in [5], [6], [4] but without the multi-year and multi-hour time dimensions and a goal for GHG emission reduction. [7], [8] consider multiple years but they do not focus on GHG emission reduction, do not model storage or hydro power, and use different solution techniques. Also, the G&TEP problem has been studied extensively in single- ([9], [10], [11], [12]) and bi-level settings ([13], [14], [15]) but these do not employ RO for uncertainty modeling.

Likewise, approaches for GHG emission reduction in the energy system have been studied extensively. [16], [17], [18], and [19] explore the long-term plan toward a fully renewable power system in Germany, Australia, California, and Japan respectively. They all find that significant amount of vRES generation needs to be complemented with dispatchable RES generation as well as storage technologies. However, their methodologies are limited in that they consider fixed cases for generation and transmission expansion and omit details such as transmission network, certain generation types, or ramping in short-term power system operations. In fact, [20] solve for an expansion plan with constraints on GHG emissions and the share of RES generation and show that ignoring operational constraints leads to large errors in estimating GHG emissions.

Typically, the G&TEP problem is solved from the perspective of a central planner such as the transmissions system operator (TSO). Although transmission investments are often made by such a central planner, the generation investments are usually made by independent market participants [4]. However, the central planner may use incentive policies to encourage investment into certain generation units [21], [22]. Nevertheless, [23], [24], [25] consider multiple companies investing in generation but this leads to problems with multiple equilibria which require custom solution algorithms, possibly with computationally expensive linearization schemes and no optimality guarantees.

Even with the simplifying assumption of a central planner, the tri-level SARO problems for G&TEP are computationally challenging. [5] combine the best features of earlier exact solution algorithms to develop a more effective solution method based on the column-and-constraint (CC) algorithm in which solving the first level and the second as well as third level problems alternate until their costs match. These alternating problems are called the master problem and subproblem, respectively. In the context of G&TEP, the master problem is a mixed-integer linear program (MILP) and the subproblem is a mixed-integer non-linear problem (MINLP) that can be reformulated as a computationally expensive MILP using big-M-based linearization. To this end, [26] develop an approximate block coordinate descent method to avoid the expensive linearization of the subproblem and thereby accelerate its solution. Other inexact solution methods involve metaheuristics such as genetic algorithms [27] and particle swarm optimization [28]. However, in this paper, we note that the subproblem is an MIQP, which can be solved faster than the linearized MILP using modern solvers such as Gurobi. Moreover, we profile the CC algorithm and note that the master problem is a computational bottleneck as its size increases at every CC iteration. Consequently, we employ Benders decomposition ([29]) to break up the large MILP master problem into a small MILP and a large linear program (LP), which are faster to solve for large problem instances and lend themselves to parallelization.

Given this context, the contributions of this paper are:

1) To consider multi-year and multi-hour time scales in a SARO problem for G&TEP.
2) To consider detailed power system operations including hydro power and a constraint for emissions in a realistic case study for Nordic and Baltic countries.
3) To improve the solution time of earlier exact methods by applying Benders decomposition to the master problem and by solving the subproblem as an MIQP.

The remaining of this paper is organized as follows. Section II presents the mathematical formulation of our SARO problem. Section IV presents a realistic case study and its results. Finally, Section V provides conclucions.

II. Problem description

At the first level of our tri-level SARO G&TEP problem, we consider a central planner that makes a generation and transmission expansion plan in a long-term horizon consisting of time steps t that we be interpret as years. While doing this, the central planner considers the 2nd level that chooses worst-case demand so as to maximize the power system operation costs. Also, the central planner considers the 3rd level in which a market operator minimizes the operation costs in multiple operating conditions o for each each 1st level time step t given the worst-case demand determined by the 2nd level. In order to capture the demand and VRE generation profile, we model power system operations within each upper-level time step t using a number of lower-level time steps τ that we interpret as hours. In addition to attaining minimum cost operations, the driver for the expansion plan is an upper bound for emissions in each 1st level time step.

A combination of RO and stochastic programming is used for modeling uncertainty when making the expansion plan. Following [4], we use RO at the 2nd level to identify the worst-case realization for demand. On the other hand, stochastic programming is used at the 3rd level to model the variability of VRES generation, transmission capacities and generation costs among others.

A. Notation

Indices

n	node
u	generation unit
ℓ	transmission line
o	operating condition
t	time step in the master problem
τ	time step in the subproblem
ν	iteration in the column-and-constraint algorithm

Sets

Ψ^G	existing generation units
Ψ^L	existing transmission lines
$\Psi^{L,AC}$	existing alternating current (AC) transmission lines
$\Psi^{G,H}$	existing hydro units
Ψ^{G+}	candidate generation units
Ψ^{L+}	candidate transmission lines
$\Phi^{L1/L2/L3}$	1st/2nd/3rd level decision variables
Ω^M	master problem decision variables
Ω^S	subproblem decision variables
Ω	uncertainty set
Ξ	feasibility set
$r(\ell)/s(\ell)$	receiving/sending-end node of line ℓ
T^0	first subproblem time step within each master problem time step
T^{-1}	last subproblem time step within each master problem time step
T^{ramp}	subproblem time steps in which the ramp constraints are considered

Parameters

P	scaling factor to make investment and operation costs comparable
W_o	weight of operating condition o
D	demand growth factor
$\tilde{D}_{o,\tau,n}$	nominal demand at node n in condition o in period τ (MWh)
$\hat{D}_{o,\tau,n}$	demand increase at node n in condition o in period τ (MWh)
E_t	CO_2 emission target in period t (tonne)
R	discount factor
$C^x_{t,u}$	investment cost per 1 MW of candidate unit u in period t (€)
$C^y_{t,\ell}$	investment cost of building candidate transmission line ℓ in period t (€)

C_u^g generation cost of unit u (€/MWh)
$A_{o,\tau,u}$ availability of unit u in condition o in period τ (%)
$G_u^{inv,max}$ maximum invested capacity in candidate unit u (MW)
$G_{o,\tau,u}^{max}$ maximum generation of unit u in condition o in period τ (MWh)
$G_{o,\tau,u}^{ramp,max}$ maximum ramp up of unit u in condition o in period τ (MWh)
$G_{o,\tau,u}^{ramp,min}$ maximum ramp down of unit u in condition o in period τ (MWh)
$G_u^{emission}$ CO_2 emission rate of unit u (tonne/MWh)
$S_{o,\tau,u}^0$ initial storage level of hydro unit u in condition o in period τ (MWh)
$S_{o,\tau,u}^{max}$ maximum final storage level of hydro unit u in condition o in period τ (MWh)
$S_{o,\tau,u}^{min}$ minimum final storage level of hydro unit u in condition o in period τ (MWh)
$I_{o,\tau,u}$ inflow to hydro unit u in condition o in period τ (MWh)
$F_{o,\tau,\ell}^{max}$ maximum flow on line ℓ in condition o in period τ (MWh)
$F_{o,\tau,\ell}^{min}$ minimum flow on line ℓ in condition o in period τ (MWh)
B_ℓ susceptance of line ℓ (1/Ω)
Λ^w demand uncertainty budget
$\Lambda^{min/max}$ minimum/maximum price in the exchange (€/MWh)

Binary variables

$\hat{y}_{t,\ell}$ equals 1 if the investment in candidate transmission line ℓ is made in period t
$y_{t,\ell}$ equals 1 if candidate transmission line ℓ is available in period t
w_n equals 1 if demand is increased from the nominal level at node n

Continuous variables

$\hat{x}_{t,u}$ new capacity of candidate generation unit u built in period t (MW)
$x_{t,u}$ total built capacity of candidate generation unit u in period t (MW)
$d_{o,\tau,n}$ uncertain demand at node n in condition o in period τ (MWh)
$z_{o,\tau,n}$ auxiliary variables for linearizing $\lambda_{o,\tau,n}d_{\tau,n}$ (€)
$\lambda_{o,\tau,n}$ price in condition o at node n in period τ (€/MWh)
$\tilde{\lambda}_{o,\tau,n}$ auxiliary variables for linearizing $\lambda_{o,\tau,n}d_{\tau,n}$ (€)
$f_{o,\tau,\ell}$ transmission flow in line ℓ in condition o in period τ (MWh)
$\delta_{o,\tau,n}$ voltage angle at node n in condition o in period τ (rad)
$g_{o,\tau,u}$ generation at unit u in condition o in period τ (MWh)
$s_{o,\tau,u}$ storage at hydro unit u in condition o in period τ (MWh)
$\bar{\beta}_{o,\tau,u}$ dual variable for maximum generation of unit u in condition o in period τ (€/MWh)
$\bar{\beta}_{o,\tau,u}^{ramp}$ dual variable for maximum ramp up of unit u in condition o in period τ (€/MWh)
$\underline{\beta}_{o,\tau,u}$ dual variable for minimum generation of unit u in condition o in period τ (€/MWh)
$\underline{\beta}_{o,\tau,u}^{ramp}$ dual variable for maximum ramp down of unit u in condition o in period τ (€/MWh)
$\beta_t^{emission}$ dual variable for maximum CO_2 emission in period t (€/MWh)
$\phi_{o,\tau,u}^0$ dual variable for initial storage level of hydro unit u in condition o in period τ (€/MWh)
$\underline{\phi}_{o,\tau,u}$ dual variable for minimum storage of hydro unit u in condition o in period τ (€/MWh)
$\phi_{o,\tau,u}$ dual variable for storage level of hydro unit u in condition o in period τ (€/MWh)
$\bar{\phi}_{o,\tau,u}^{-1}$ dual variable for maximum final storage level of hydro unit u in condition o in period τ (€/MWh)
$\underline{\phi}_{o,\tau,u}^{-1}$ dual variable for minimum final storage level of hydro unit u in condition o in period τ (€/MWh)
$\mu_{o,\tau,\ell}$ dual variable for flow in AC line ℓ in condition o in period τ (€/MWh)
$\bar{\mu}_{o,\tau,\ell}$ dual variable for maximum flow in line ℓ in condition o in period τ (€/MWh)
$\underline{\mu}_{o,\tau,\ell}$ dual variable for minimum flow in line ℓ in condition o in period τ (€/rad)
$\bar{\mu}_{o,\tau,n}^{va}$ dual variable for maximum voltage angle at node n in condition o in period τ (€/rad)
$\underline{\mu}_{o,\tau,n}^{va}$ dual variable for minimum voltage angle at node n in condition o in period τ (€/rad)
$\mu_{o,\tau}^{ref}$ dual variable for reference node voltage angle in condition o in period τ (€/MWh)
θ auxiliary variable for the column-and-constraint master problem objective function (€)

B. Model formulation

In the following, Ω denotes the uncertainty set from which the worst-case demand is selected and Ξ denotes the feasibility set for the operation decisions once the 1st and 2nd level decisions have been made. The mathematical formulation for our SARO G&TEP problem is

$$\min_{\Phi^{L1}} P\sum_t R^{-t}\left[\sum_{u\in\Psi^{G+}} C_{t,u}^x \hat{x}_{t,u} + \sum_{\ell\in\Psi^{L+}} C_{t,\ell}^y \hat{y}_{t,\ell}\right] + \max_{\Phi^{L2}\in\Omega}\ \min_{\Phi^{L3}\in\Xi} \sum_o W_o \sum_\tau R^{-t(\tau)} \sum_u C_u^g g_{o,\tau,u} \quad (1)$$

subject to

$$x_{t,u} = \sum_{t'=1}^{t} \hat{x}_{t',u} \quad \forall t, u \in \Psi^{G+} \quad (2)$$

$$y_{t,\ell} = \sum_{t'=1}^{t} \hat{y}_{t',\ell} \quad \forall t, \ell \in \Psi^{L+} \tag{3}$$

$$x_{t,u} \leq G_u^{inv,max} \quad \forall t, u \in \Psi^{G+} \tag{4}$$

where $\Phi^{L1} = \{\hat{x}_{t,u}, x_{t,u}, \forall u \in \Psi^{G+}; \hat{y}_{t,\ell}, y_{t,\ell}, \forall \ell \in \Psi^{L+}\}, \forall t$, $\Phi^{L2} = \{d_{o,\tau,n}, \forall o, \tau; w_n\}, \forall n$, and $\Phi^{L3} = \{g_{o,\tau,u}, \forall u; s_{o,\tau,u}, \forall u \in \Psi^{G,H}; f_{o,\tau,\ell}, \forall \ell; \delta_{o,\tau,n}, \forall n\}, \forall o, \tau$.

In the objective function (1), the first minimization problem represents the generation and transmission expansion costs (1st level) and the maximization problem represents the selection of the worst-case demand (2nd level) for the second minimization problem of attaining the least cost power system operations (3rd level). The parameter P is used to make the expansion and operation costs comparable. The constraints (2) and (3) define the capacities of candidate units and transmission lines that are available at each 1st level time step t, respectively. The constraints (4) define maximum investments in the new generation units.

Following [5] and [4], the uncertainty set Ω is given by

$$\{d_{o,\tau,n} = D^{-t(\tau)}(\tilde{D}_{o,\tau,n} + w_n \hat{D}_{o,\tau,n}) \qquad \forall o, \tau, n \tag{5}$$

$$\sum_n w_n \leq \Lambda^w\}. \tag{6}$$

Eq. (5) defines that demand is equal to the sum of nominal demand ($\tilde{D}_{o,\tau,n}$) and a possible demand increase ($\hat{D}_{o,\tau,n}$) multiplied by demand growth factor (D) that compounds at each 1st level time step t. The demand increase is selected using binary variables w_n in an attempt to maximize the operation costs. Eq. (6) sets an uncertainty budget on the number of demand increases the model can activate.

For formulating the power system operations in Eqs. (7)-(20), we define $n(u)$ as the node in which unit u is located. Also, the notation $\tau \in t$ indicates the 3rd level time steps τ within a 1st level time step t, and an inverse mapping $t(\tau)$ gives the 1st level time step t that the 3rd level time step τ is belongs to. The definition of the two different time scales and the related sets are shown in Figure 1. Consequently, given the optimal values $x^*_{t,u}, \forall t, u \in \Psi^{G+}$, $y^*_{t,\ell}, \forall t, \ell \in \Psi^{L+}$, and $d^*_{o,\tau,n}, \forall o, \tau, n$, the feasibility set $\Xi(g_{o,\tau,u}, s_{o,\tau,u}, f_{o,\tau,\ell}, \delta_{o,\tau,n})$ is

$$\{\sum_{u|n(u)=n} g_{o,\tau,u} - \sum_{\ell|s(\ell)=n} f_{o,\tau,\ell} + \sum_{\ell|r(\ell)=n} f_{o,\tau,\ell} = d^*_{o,\tau,n} \quad \forall o, \tau, n \tag{7}$$

$$0 \leq g_{o,\tau,u} \leq A_{o,\tau,u} G^{max}_{o,\tau,u} \quad \forall o, \tau, u \in \Psi^G_n \tag{8}$$

$$0 \leq g_{o,\tau,u} \leq A_{o,\tau,u} x^*_{t(\tau),u} \quad \forall o, \tau, u \in \Psi^{G+}_n \tag{9}$$

$$G^{ramp,min}_{o,\tau,u} \leq g_{o,\tau+1,u} - g_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^{ramp}, u \tag{10}$$

$$g_{o,\tau+1,u} - g_{o,\tau,u} \leq G^{ramp,max}_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^{ramp}, u \tag{11}$$

$$s_{o,\tau,u} \geq 0 \quad \forall o, \tau, u \in \Psi^{G,H} \tag{12}$$

$$s_{o,\tau,u} = S^0_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^0, u \in \Psi^{G,H} \tag{13}$$

$$s_{o,\tau+1,u} = s_{o,\tau,u} - g_{o,\tau,u} + I_{o,\tau,u} \; \forall o, \tau \in \mathrm{T}^{ramp}, u \in \Psi^{G,H} \tag{14}$$

$$S^{min}_{o,\tau,u} \leq s_{o,\tau,u} \leq S^{max}_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^{-1}, u \in \Psi^{G,H} \tag{15}$$

$$f_{o,\tau,\ell} = B_\ell(\delta_{o,\tau,s(\ell)} - \delta_{o,\tau,r(\ell)}) \quad \forall o, \tau, \ell \in \Psi^L \tag{16}$$

$$F^{min}_{o,\tau,\ell} \leq f_{o,\tau,\ell} \leq F^{max}_{o,\tau,\ell} \quad \forall o, \tau, \ell \in \Psi^L \tag{17}$$

$$F^{min}_{o,\tau,\ell} y^*_{t(\tau),\ell} \leq f_{o,\tau,\ell} \leq F^{max}_{o,\tau,\ell} y^*_{t(\tau),\ell} \quad \forall o, \tau, \ell \in \Psi^{L+} \tag{18}$$

$$-\pi \leq \delta_{o,\tau,n} \leq \pi \quad \forall o, \tau, n \tag{19}$$

$$\delta_{o,\tau,0} = 0 \quad \forall o, \tau\} \tag{20}$$

$$\sum_o \sum_{\tau \in t} \sum_u W_o G^{emission}_{o,\tau,u} g_{o,\tau,u} \leq E_t \quad \forall t \tag{21}$$

Eq. (7) requires that (possibly worst-case) demand equals generation and exchange at each node. Eqs. (8) and (9) impose that the generation of each unit is non-negative but less than or equal to the product of the unit's availability ($A_{o,\tau,u}$) and maximum capacity of an existing unit ($G^{max}_{o,\tau,u}$) or the built capacity of a candidate unit $x^*_{t(\tau),u}$, respectively. Moreover, generation is limited by ramping constraints (10) and (11).

Following [30], we assume that each hydro power unit has one reservoir that can act as a storage. Eq. (12) imposes that storage levels are non-negative. Eq. (13) sets the initial storage level at the first 3rd level time step τ within each 1st level time step t. Eq. (14) defines the storage level at the following time step $\tau + 1$ as the current storage plus the difference of hydro power generation ($g_{o,\tau,u}, u \in \Psi^{G,H}$) and inflows ($I_{o,\tau,u}$) at τ. To avoid possible storage depletion, Eq. (15) requires that the storage level at the last 3rd level time step τ within each 1st level time step t is within desired levels $S^{min}_{o,\tau,u}$ and $S^{max}_{o,\tau,u}$.

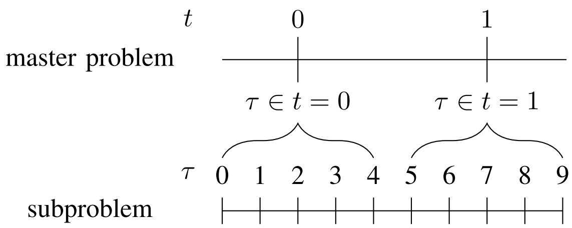
The transmission network is represented by active current (AC) and direct current (DC) circuits in Eqs. (16)-(20). For AC lines, the transmission flow is determined by Eq. (16). However, flows in existing and candidate transmission lines must be within the capacities of the lines as given by Eqs. (17) and (18), respectively. Related to the AC circuit, the voltage angles at each node and a reference voltage angle are given by Eqs. (19) and (20), respectively.

Finally, Eq. (21) determines the upper bound for GHG emissions at each 1st level time step t. The framework allows adding other criteria such as a lower bound found renewable power generation.

In the above formulation, we have assumed that all candidate transmission lines are DC lines. This is because we focus on emission reduction and VRES integration using cross-border transmission, which is typically implemented via high-voltage DC (HVDC) lines to minimize heat and other losses. In addition, this assumption reduces solution times because AC candidate lines would lead to constraints with a product of a binary and a continuous variable, which we would need to linearize.

III. Solution

Following [5], the problem (1)-(4) is solved using column-and-constraint (CC) algorithm in which solving the first minimization problem of (1) and solving the max-min problem of (1) alternates. These two problems are called CC master problem and CC subproblem, respectively. The alternation terminates when the total costs computed from the two problems match. The formulations for CC master problem and subproblem are given in the following subsections (Eqs. (22)-(39) and Eqs. (40)-(45), respectively) and solution algorithm is described in detail in Algorithm 1.



$$T^0 = \{0, 5\}, \quad T^{-1} = \{4, 9\}$$
$$T^{ramp} = \{0, 1, 2, 3, 5, 6, 7, 8\}$$
$$t(\tau) = \left\lfloor \frac{\tau}{5} \right\rfloor$$

Fig. 1. T^0, T^{ramp}, T^{-1}, $t(\tau)$, and $\tau \in t$ in an example problem with five subproblem timesteps within each of the two master problem time steps

Input: Transmission and generation parameters, CO_2 emission targets
Output: Transmission and generation expansion plan
$\epsilon \leftarrow 10^{-6}$
$LB \leftarrow -\infty$
$UB \leftarrow \infty$
$\nu \leftarrow 0$
$d_{o,\tau,n,\nu} \leftarrow \tilde{D}_{o,\tau,n} \quad \forall o, \tau, n$
while $(UB - LB)/UB \leq \epsilon$ **do**
    `// Solve the CC master problem`
    Obtain $x^*_{t,u}, \hat{x}^*_{t,u}, \forall t, u \in \Psi^{G+}; y^*_{t,\ell}, \hat{y}^*_{t,\ell}, \forall t, \ell \in \Psi^{L+}$ by solving CC master problem in Eqs. (22)-(39) using $d_{o,\tau,n,\nu'}, \forall o, \tau, n, \nu' \leq \nu$. LB is updated to the objective value of the master problem.

    `// Solve the CC subproblem`
    Obtain $w_n \, \forall n$ by solving CC subproblem in Eqs. (40)-(45) using the current $x^*_{t,u}, \forall t, u \in \Psi^{G+}; y^*_{t,\ell}, \forall t, \ell \in \Psi^{L+}$. UB is updated to the objective value of the subproblem + $P \sum_t R^{-t} \big(\sum_{u \in \Psi^{G+}} C^x_{t,u} \hat{x}^*_{t,u} + \sum_{\ell \in \Psi^{L+}} C^y_{t,\ell} \hat{y}^*_{t,\ell} \big)$

    $\nu \leftarrow \nu + 1$
    $d_{o,\tau,n,\nu} \leftarrow \tilde{D}_{o,\tau,n} + w_n \hat{D}_{o,\tau,n} \quad \forall o, \tau, n$
end

Algorithm 1: Algorithm for solving the problem (1)-(4)

A. CC master problem

At iteration ν, we have $\Omega^M = \{g_{o,\tau,u,\nu'}, \forall u; s_{o,\tau,u,\nu'}, \forall u \in \Psi^{G,H}; f_{o,\tau,\ell,\nu'}, \forall \ell; \delta_{o,\tau,n,\nu'}, \forall n\}, \forall o, \tau, \nu' \leq \nu$. Given $d^*_{\tau,n,\nu'}, \forall \tau, n, \nu' \leq \nu$ as input data obtained from all the previous solutions of the subproblem, the master problem at iteration ν is

$$\min_{\Phi^{L1}, \Omega^M, \theta} P \sum_t R^{-t} \left[\sum_{u \in \Psi^{G+}} C^x_{t,u} \hat{x}_{t,u} + \sum_{\ell \in \Psi^{L+}} C^y_{t,\ell} \hat{y}_{t,\ell} \right] + \theta \tag{22}$$

subject to

$$\text{Eqs. } (2) - (4) \tag{23}$$

$$\theta \geq \sum_o W_o \sum_\tau R^{-t(\tau)} \sum_u C^g_u g_{o,\tau,u,\nu'} \quad \forall \nu' \leq \nu \tag{24}$$

$$\sum_{u|n(u)=n} g_{o,\tau,u,\nu'} - \sum_{\ell|s(\ell)=n} f_{o,\tau,\ell,\nu'} + \sum_{\ell|r(\ell)=n} f_{o,\tau,\ell,\nu'} = d^*_{\tau,n,\nu'} \quad \forall o, \tau, n, \nu' \leq \nu \tag{25}$$

$$0 \leq g_{o,\tau,u,\nu'} \leq A_{o,\tau,u} G^{max}_{o,\tau,u} \quad \forall o, \tau, u \in \Psi^G_n, \nu' \leq \nu \tag{26}$$

$$0 \leq g_{o,\tau,u,\nu'} \leq A_{o,\tau,u} x_{t(\tau),u} \quad \forall o, \tau, u \in \Psi^{G+}_n, \nu' \leq \nu \tag{27}$$

$$G^{ramp,min}_{o,\tau,u} \leq g_{o,\tau+1,u,\nu'} - g_{o,\tau,u,\nu'} \quad \forall o, \tau \in \mathrm{T}^{ramp}, u, \nu' \leq \nu \tag{28}$$

$$g_{o,\tau+1,u,\nu'} - g_{o,\tau,u,\nu'} \leq G^{ramp,max}_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^{ramp}, u, \nu' \leq \nu \tag{29}$$

$$\sum_o \sum_{\tau \in t} \sum_u W_o G^{emission}_{o,\tau,u} g_{o,\tau,u,\nu'} \leq E_t \quad \forall t, \nu' \leq \nu \tag{30}$$

$$s_{o,\tau,u,\nu'} \geq 0 \quad \forall o, \tau, u \in \Psi^{G,H}, \nu' \leq \nu \tag{31}$$

$$s_{o,\tau,u,\nu'} = S^0_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^0, u \in \Psi^{G,H}, \nu' \leq \nu \tag{32}$$

$$s_{o,\tau+1,u,\nu'} = s_{o,\tau,u,\nu'} - g_{o,\tau,u,\nu'} + I_{o,\tau,u} \; \forall o, \tau \in \mathrm{T}^{ramp}, u \in \Psi^{G,H}, \nu' \leq \nu \tag{33}$$

$$S^{min}_{o,\tau,u} \leq s_{o,\tau,u,\nu'} \leq S^{max}_{o,\tau,u} \quad \forall o, \tau \in \mathrm{T}^{-1}, u \in \Psi^{G,H}, \nu' \leq \nu \tag{34}$$

$$f_{o,\tau,\ell,\nu'} = B_\ell (\delta_{o,\tau,s(\ell),\nu'} - \delta_{o,\tau,r(\ell),\nu'}) \quad \forall o, \tau, \ell \in \Psi^L, \nu' \leq \nu \tag{35}$$

$$F^{min}_{o,\tau,\ell} \leq f_{o,\tau,\ell,\nu'} \leq F^{max}_{o,\tau,\ell} \quad \forall o, \tau, \ell \in \Psi^L, \nu' \leq \nu \tag{36}$$

$$F^{min}_{o,\tau,\ell} y_{t(\tau),\ell} \leq f_{o,\tau,\ell,\nu'} \leq F^{max}_{o,\tau,\ell} y_{t(\tau),\ell} \forall o, \tau, \ell \in \Psi^{L+}, \nu' \leq \nu \tag{37}$$

$$-\pi \leq \delta_{o,\tau,n,\nu'} \leq \pi \quad \forall o, \tau, n, \nu' \leq \nu \tag{38}$$

$$\delta_{o,\tau,0,\nu'} = 0 \quad \forall o, \tau, \nu' \leq \nu \tag{39}$$

B. CC subproblem

For the subproblem, we set

$$\begin{aligned} \Omega^S = & \{\bar{\beta}_{o,\tau,u}, \underline{\beta}_{o,\tau,u}, \bar{\beta}^{ramp}_{o,\tau,u}, \underline{\beta}^{ramp}_{o,\tau,u}\}, \forall o, \tau, u \, \cup \\ & \beta^{emission}_t, \forall t \, \cup \\ & \{\phi^0_{o,\tau,u}, \forall \tau \in \mathrm{T}^0; \phi_{o,\tau,u}, \forall \tau \in \mathrm{T}^{ramp}; \\ & \bar{\phi}^{-1}_{o,\tau,u}, \underline{\phi}^{-1}_{o,\tau,u} \forall \tau \in \mathrm{T}^{-1}; \underline{\phi}_{o,\tau,u} \forall \tau\}, \forall o, u \in \Psi^{G,H} \cup \\ & \{\mu_{o,\tau,\ell}, \bar{\mu}_{o,\tau,\ell}, \underline{\mu}_{o,\tau,\ell}\} \forall o, \tau, \ell \, \cup \\ & \{\lambda_{o,\tau,n}, \bar{\mu}^{va}_{o,\tau,n}, \underline{\mu}^{va}_{o,\tau,n}\}, \forall o, \tau, n \, \cup \\ & \mu^{ref}_{o,\tau}, \forall o, \tau. \end{aligned}$$

With $x^*_{t,u}, \forall t, u \in \Psi^{G+}$ and $y^*_{t,\ell}, \forall t, \ell \in \Psi^{L+}$ as input data obtained from the previous solution of the master problem, the subproblem is

$$\begin{aligned} \underset{\Phi^{L2}, \Omega^S}{\text{maximize}} \sum_o \Bigg(& \sum_\tau \Big[\sum_n \lambda_{o,\tau,n} d_{o,\tau,n} - \\ & \sum_{u \in \Psi^G} \bar{\beta}_{o,\tau,u} A_{o,\tau,u} G^{max}_{o,\tau,u} - \\ & \sum_{u \in \Psi^{G+}} \bar{\beta}_{o,\tau,u} A_{o,\tau,u} x^*_{t(\tau),u} - \\ & \sum_{\ell \in \Psi^L} \Big(\bar{\mu}_{o,\tau,\ell} F^{max}_{o,\tau,\ell} - \underline{\mu}_{o,\tau,\ell} F^{min}_{o,\tau,\ell} \Big) - \end{aligned}$$

$$\sum_{\ell\in\Psi^{L+}}\left(\bar{\mu}_{o,\tau,\ell}F^{max}_{o,\tau,\ell}-\underline{\mu}_{o,\tau,\ell}F^{min}_{o,\tau,\ell}\right)y^{*}_{t(\tau),\ell}-$$
$$\sum_{n}\pi(\bar{\mu}^{va}_{o,\tau,n}+\underline{\mu}^{va}_{o,\tau,n})\Big]+$$
$$\sum_{u\in\Psi^{G,H}}\Big[\sum_{\tau\in\mathrm{T}^{0}}\phi^{0}_{o,\tau,u}S^{0}_{o,\tau,u}+$$
$$\sum_{\tau\in\mathrm{T}^{ramp}}\phi_{o,\tau,u}I_{o,\tau,u}+$$
$$\sum_{\tau\in\mathrm{T}^{-1}}\left(\underline{\phi}^{-1}_{o,\tau,u}S^{min}_{o,\tau,u}-\bar{\phi}^{-1}_{o,\tau,u}S^{max}_{o,\tau,u}\right)\Big]+$$
$$\sum_{\tau\in\mathrm{T}^{ramp}}\sum_{u}\left(\underline{\beta}^{ramp}_{o,\tau,u}G^{ramp,min}_{o,\tau,u}-\bar{\beta}^{ramp}_{o,\tau,u}G^{ramp,max}_{o,\tau,u}\right)\Bigg)-$$
$$\sum_{t}\beta^{emission}_{t}E_{t} \tag{40}$$

subject to

$$\lambda_{o,\tau,n(u)}-\bar{\beta}_{o,\tau,u}+\underline{\beta}_{o,\tau,u}+\mathbb{1}_{\tau\in\mathrm{T}^{ramp}\wedge u\in\Psi^{G,H}}\phi_{o,t,u}-$$
$$\mathbb{1}_{\tau\notin\mathrm{T}^{0}}\bar{\beta}^{ramp}_{o,\tau-1,u}+\mathbb{1}_{\tau\notin\mathrm{T}^{-1}}\bar{\beta}^{ramp}_{o,\tau,u}+\mathbb{1}_{\tau\notin\mathrm{T}^{0}}\underline{\beta}^{ramp}_{o,\tau-1,u}-$$
$$\mathbb{1}_{\tau\notin\mathrm{T}^{-1}}\underline{\beta}^{ramp}_{o,\tau,u}-W_{o}G^{emission}_{u}\beta^{emission}_{t(\tau)}=R^{-t(\tau)}C^{g}_{u}W_{o}\ \forall o,\tau,u \tag{41}$$

$$\mathbb{1}_{\tau\in\mathrm{T}^{0}}\phi^{0}_{o,\tau,u}+\underline{\beta}^{s}_{o,\tau,u}-\mathbb{1}_{\tau\notin\mathrm{T}^{-1}}\phi_{o,\tau,u}+\mathbb{1}_{\tau\notin\mathrm{T}^{0}}\phi_{o,\tau-1,u}+$$
$$\mathbb{1}_{\tau\in\mathrm{T}^{-1}}(\underline{\phi}_{o,\tau,u}-\bar{\phi}_{o,\tau,u})=0\quad\forall o,\tau,u\in\Psi^{G,H} \tag{42}$$

$$-\lambda_{o,\tau,s(\ell)}+\lambda_{o,\tau,r(\ell)}+\mathbb{1}_{\ell\in\Psi^{L,AC}}\mu_{o,\tau,\ell}-$$
$$\bar{\mu}_{o,\tau,\ell}+\underline{\mu}_{o,\tau,\ell}=0\quad\forall o,\tau,\ell \tag{43}$$

$$-\sum_{\ell\in\Psi^{L,AC}\ |s(\ell)=n}B_{\ell}\mu_{o,\tau,\ell}+\sum_{\ell\in\Psi^{L,AC}\ |r(\ell)=n}B_{\ell}\mu_{o,\tau,\ell}-$$
$$\bar{\mu}^{va}_{o,\tau,n}+\underline{\mu}^{va}_{o,\tau,n}+\mathbb{1}_{n=0}\mu^{ref}_{o,\tau}=0\quad\forall o,\tau,n \tag{44}$$

$$\text{Eqs. }(5)-(6), \tag{45}$$

where $\mathbb{1}_{cond}$ equals 1 if $cond$ is true and otherwise 0.

The subproblem can be solved directly as a MIQP using solvers such as Gurobi. Alternatively, the subproblem can be re-formulated as an MILP by linearizing the product of a continuous and a binary variable in $\lambda_{o,\tau,n}d_{o,\tau,n}=\lambda_{o,\tau,n}D^{-t(\tau)}(\tilde{D}_{o,\tau,n}+w_n\hat{D}_{o,\tau,n})$ in the objective function (40) exactly with $\lambda_{o,\tau,n}d_{o,\tau,n}=D^{-t(\tau)}(z_{o,\tau,n}\hat{D}_{o,\tau,n}+\lambda_{o,\tau,n}\tilde{D}_{o,\tau,n})$ and by adding the following constraints to the subproblem

$$z_{o,\tau,n}=\lambda_{o,\tau,n}-\tilde{\lambda}_{o,\tau,n}\quad\forall o,\tau,n \tag{46}$$
$$\Lambda^{min}w_{n}\leq z_{o,\tau,n}\leq\Lambda^{max}w_{n}\quad\forall o,\tau,n \tag{47}$$
$$\Lambda^{min}(1-w_{n})\leq\tilde{\lambda}_{o,\tau,n}\leq\Lambda^{max}(1-w_{n})\quad\forall o,\tau,n, \tag{48}$$

where parameters Λ^{min} and Λ^{max} can be set to exchange-specific values such as -500 €/MWh and 3000 €/MWh, respectively.

IV. Case study: modified Nordic and Baltic network

We study what investments are required to decrease the initial CO_2 emissions of the Nordic and Baltic electricity system to a target level under uncertain generation and transmission parameters and worst-case realization of demand. More specifically, we use the Nordic and Baltic network and its generation, load, and transmission line data from [31] as a base.

We augment this base system by having 10 time steps in the CC master problem (t) for making investments. For each master problem time step, we consider 24 time steps in the CC subproblem (τ). Consequently, the subproblem has 240 time steps in total. To consider increasing electricity demand, we assume that load values increase by a factor of $D=1.01$ at each master problem time step [32].

In addition, we define 3 operation conditions o for each subproblem time step. We apply the hierarchical clustering method of [33] on hourly load and wind power data of 2014 to obtain 3 representative days. The hourly load, wind, and solar power data on these 3 representative days are used as the operating conditions for each set of 24 subproblem time steps. This allows us to capture the short-term variability of load and renewables. Hydro power data such as initial storage levels ($S^{0}_{o,\tau,u}$) and inflows ($I_{o,\tau,u}$) have weekly granularity so, for each operating condition, we take the weekly value corresponding to each representative day. However, for generation ($G^{max}_{o,\tau,u}$) and transmission capacities ($F^{max}_{o,\tau,\ell}$ and $F^{min}_{o,\tau,\ell}$), the operation conditions are defined by sampling uniform noise from $\mathrm{U}(-50\text{ MW},50\text{ MW})$. The weights of the operation conditions (W_o) are equal to the weights of the representative days as defined in [33].

Gas, CCGT, oil, biomass, wind and solar power can be built at each (non-dummy) node. Each candidate unit has a maximum capacity ($G^{inv,max}_{u}$) of 10000 MW except for biomass units which we limit to 1000 MW due to limited fuel supply. In addition, neighboring (non-dummy) node pairs can be connected with a candidate DC transmission line with 1000 MW of capacity to both directions. The investment cost parameters are shown in Table I.

The initial CO_2 emission bound $E_0=90000$ tonne is obtained from the CO_2 emissions corresponding to the first master problem time step when solving the problem with no investments. This initial emission bound is realistic given that the average daily CO_2 emissions of both power and heat production were approximately $E_0=140000$ tonne in this area in 2014 [34]. We assume that the CO_2 emissions are required to decrease by approximately 10% at every master problem time step to a final emission bound of $E_9=35000$ tonne.

The uncertainty budget in the subproblem (Λ^{w}) is 2 meaning that the model can change load in maximum of 2 nodes. Each change the model makes increases load in a node for all operating conditions and subproblem time steps by $\hat{D}_{\tau,n}=100$ MWh.

We solve this case study using the Algorithm 1. The results are show in Table II.

Figure 2 shows the evolution of CO_2 emissions to the final desired level during the planning horizon and Figure 3 shows the corresponding CO_2 emission prices. Figures 4 and 5 show the generation and transmission investments, respectively, for achieving the final emission level. Already at $t=0$, the model builds transmission lines from Finland to Norway and

Parameter	Value
P	$\frac{1}{365}$
R	1.03
$C^x_{t,u}$ Gas (€/MW)	$0.8 \cdot 10^6$
$C^x_{t,u}$ CCGT (€/MW)	$1.0 \cdot 10^6$
$C^x_{t,u}$ Oil (€/MW)	$0.8 \cdot 10^6$
$C^x_{t,u}$ Biomass (€/MW)	$3.9 \cdot 10^6$
$C^x_{t,u}$ Wind (€/MW)	$1.6 \cdot 10^6$
$C^x_{t,u}$ Solar (€/MW)	$1.8 \cdot 10^6$
$C^y_{t,\ell}$ (€)	$1.0 \cdot 10^9$

TABLE I
INVESTMENT COST PARAMETERS IN THE CASE STUDY

Master problem	Subproblem	Objective value (€)	Solution time (s)
Benders	MIQP	95915334.5162	856.0
MILP	MIQP	95915334.5162	1656.18

TABLE II

Sweden and a total of 1600 MW of CCGT units in Latvia and Lithuania as well as 1100 MW of wind power in Finland. As a consequence, CO_2 emissions from $t = 0$ to $t = 4$ are below the bounds until demand increases to a high enough level at $t = 5$. To reduce CO_2 emissions to the final level, the model invests in approximately 700 MW of biomass units in Estonia and Finland. These transmission and generation investments allow replacing coal- and oil shale-fired generation with less-polluting wind power as well as gas and biomass-fired generation.

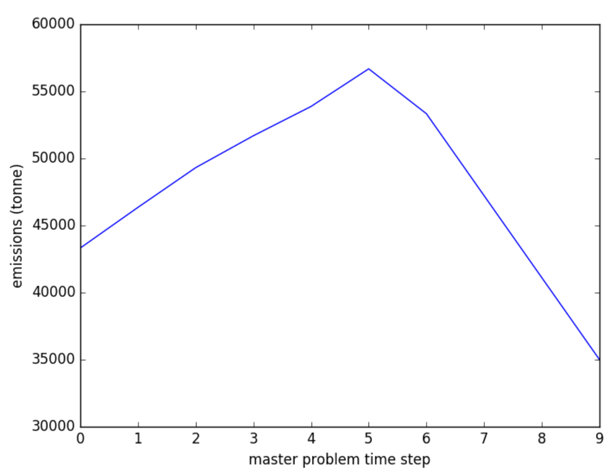


Fig. 2. CO_2 emissions during the planning horizon

V. CONCLUSIONS

foobar

REFERENCES

[1] United Nations, “Paris agreement,” 2015. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[2] European Commission, “EU climate action,” 2019. [Online]. Available: https://ec.europa.eu/clima/citizens/eu_en

[3] W. Zappa, M. Junginger, and M. van den Broek, “Is a 100% renewable European power system feasible by 2050?” *Applied Energy*, vol. 233-234, pp. 1027 – 1050, 2019.

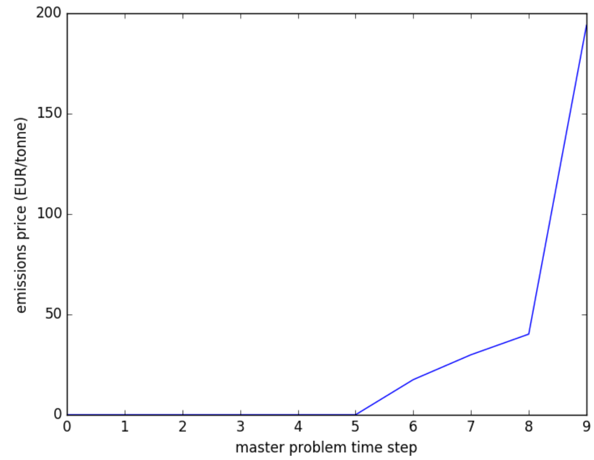


Fig. 3. CO_2 emission prices during the planning horizon

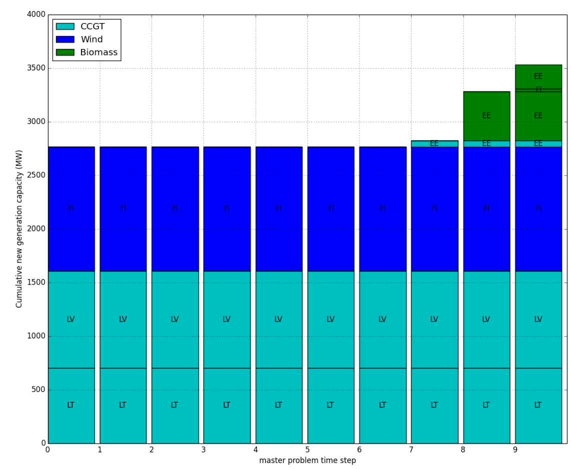


Fig. 4. Generation investments during the planning horizon. The country codes indicate the node where each generation unit is built

[4] L. Baringo and A. Baringo, “A stochastic adaptive robust optimization approach for the generation and transmission expansion planning,” *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 792–802, 2018.

[5] R. Mínguez and R. García-Bertrand, “Robust transmission network expansion planning in energy systems: Improving computational performance,” *European Journal of Operational Research*, vol. 248, no. 1, pp. 21 – 32, 2016.

[6] A. Moreira, D. Pozo, A. Street, and E. Sauma, “Reliable renewable generation and transmission expansion planning: Co-optimizing system’s resources for meeting renewable targets,” *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3246–3257, 2017.

[7] J. Li, Z. Li, F. Liu, H. Ye, X. Zhang, S. Mei, and N. Chang, “Robust coordinated transmission and generation expansion planning considering ramping requirements and construction periods,” *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 268–280, 2018.

[8] C. Roldán, A. S. de la Nieta, R. García-Bertrand, and R. Mínguez, “Robust dynamic transmission and renewable generation expansion planning: Walking towards sustainable systems,” *International Journal of Electrical Power Energy Systems*, vol. 96, pp. 52 – 63, 2018.

[9] J. Alvarez Lopez, K. Ponnambalam, and V. H. Quintana, “Generation and transmission expansion under risk using stochastic programming,” *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1369–1378, 2007.

[10] R. Domínguez, A. J. Conejo, and M. Carrión, “Toward fully renewable

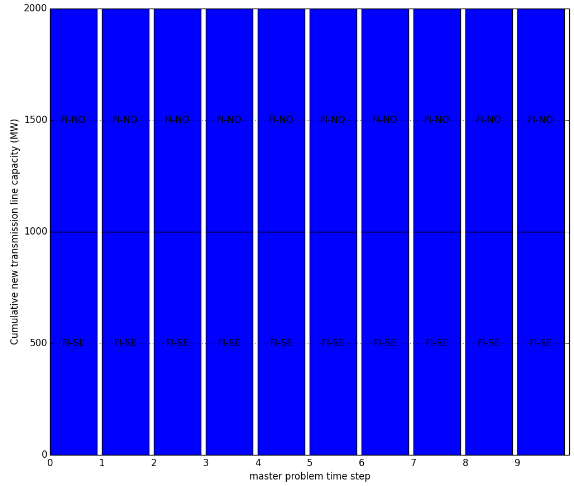


Fig. 5. Transmission investments during the planning horizon. The country codes indicate the start and end node of each line

electric energy systems," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 316–326, 2015.

[11] F. D. Munoz and J.-P. Watson, "A scalable solution framework for stochastic transmission and generation planning problems," *Computational Management Science*, vol. 12, no. 4, pp. 491–518, 2015.

[12] X. Chen, J. Lv, M. B. McElroy, X. Han, C. P. Nielsen, and J. Wen, "Power system capacity expansion under higher penetration of renewables considering flexibility constraints and low carbon policies," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6240–6253, 2018.

[13] N. Zhang, Z. Hu, C. Springer, Y. Li, and B. Shen, "A bi-level integrated generation-transmission planning model incorporating the impacts of demand response by operation simulation," *Energy Conversion and Management*, vol. 123, pp. 84 – 94, 2016.

[14] P. Pisciella, M. Bertocchi, and M. T. Vespucci, "A leader-followers model of power transmission capacity expansion in a market driven environment," *Computational Management Science*, vol. 13, no. 1, pp. 87–118, 2016.

[15] L. Maurovich-Horvat, T. K. Boomsma, and A. S. Siddiqui, "Transmission and wind investment in a deregulated electricity industry," *IEEE Transactions on Power Systems*, vol. 30, no. 3, pp. 1633–1643, 2015.

[16] K. Hansen, B. V. Mathiesen, and I. R. Skov, "Full energy system transition towards 100% renewable energy in Germany in 2050," *Renewable and Sustainable Energy Reviews*, vol. 102, pp. 1 – 13, 2019.

[17] A. Blakers, B. Lu, and M. Stocks, "100% renewable electricity in Australia," *Energy*, vol. 133, pp. 471 – 482, 2017.

[18] P. Colbertaldo, S. B. Agustin, S. Campanari, and J. Brouwer, "Impact of hydrogen energy storage on California electric power system: Towards 100% renewable electricity," *International Journal of Hydrogen Energy*, vol. 44, no. 19, pp. 9558 – 9576, 2019.

[19] M. Esteban, J. Portugal-Pereira, B. C. Mclellan, J. Bricker, H. Farzaneh, N. Djalilova, K. N. Ishihara, H. Takagi, and V. Roeber, "100% renewable energy system in Japan: Smoothening and ancillary services," *Applied Energy*, vol. 224, pp. 698 – 707, 2018.

[20] B. S. Palmintier and M. D. Webster, "Impact of operational flexibility on electricity generation planning with renewable and carbon targets," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 672–684, 2016.

[21] Y. Zhou, L. Wang, and J. D. McCalley, "Designing effective and efficient incentive policies for renewable energy in generation expansion planning," *Applied Energy*, vol. 88, no. 6, pp. 2201 – 2209, 2011.

[22] I. Das, K. Bhattacharya, and C. Cañizares, "Optimal incentive design for targeted penetration of renewable energy sources," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1213–1225, 2014.

[23] S. Jin and S. M. Ryan, "A tri-level model of centralized transmission and decentralized generation expansion planning for an electricity market—part i," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 132–141, 2014.

[24] J. H. Roh, M. Shahidehpour, and L. Wu, "Market-based generation and transmission planning with uncertainties," *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1587–1598, 2009.

[25] D. Pozo, E. E. Sauma, and J. Contreras, "A three-level static MILP model for generation and transmission expansion planning," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 202–210, 2013.

[26] R. Mínguez, R. García-Bertrand, J. M. Arroyo, and N. Alguacil, "On the solution of large-scale robust transmission network expansion planning under uncertain demand and generation capacity," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1242–1251, 2018.

[27] F. Barati, H. Seifi, M. S. Sepasian, A. Nateghi, M. Shafie-khah, and J. P. S. Catalão, "Multi-period integrated framework of generation, transmission, and natural gas grid expansion planning for large-scale systems," *IEEE Transactions on Power Systems*, vol. 30, no. 5, pp. 2527–2537, 2015.

[28] R. Hemmati, R.-A. Hooshmand, and A. Khodabakhshian, "Coordinated generation and transmission expansion planning in deregulated electricity market considering wind farms," *Renewable Energy*, vol. 85, pp. 620 – 630, 2016.

[29] A. J. Conejo, E. Castillo, R. Minguez, and R. Garcia-Bertrand, *Decomposition Techniques in Mathematical Programming. Engineering and Science Applications*. Springer-Verlag Berlin Heidelberg, 2006.

[30] S. Debia, D. Benatia, and P.-O. Pineau, "Evaluating an interconnection project: Do strategic interactions matter?." *Energy Journal*, vol. 39, no. 6, pp. 99 – 120, 2018.

[31] V. Virasjoki, A. S. Siddiqui, B. Zakeri, and A. Salo, "Market power with combined heat and power production in the Nordic energy system," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5263–5275, 2018.

[32] European Environment Agency, "Overview of electricity production and use in Europe," 2015. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-1/assessment

[33] P. Nahmmacher, E. Schmid, L. Hirth, and B. Knopf, "Carpe diem: A novel approach to select representative days for long-term power system modeling," *Energy*, vol. 112, pp. 430 – 442, 2016.

[34] European Environment Agency, "EEA greenhouse gas - data viewer," 2019. [Online]. Available: https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer