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Innovative Applications of O.R.

Deterministic electric power infrastructure planning: Mixed-integer programming model and nested decomposition algorithm

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ABSTRACT

This paper addresses the long-term planning of electric power infrastructures considering high renewable penetration. To capture the intermittency of these sources, we propose a deterministic multi-scale Mixed-Integer Linear Programming (MILP) formulation that simultaneously considers annual generation investment decisions and hourly operational decisions. We adopt judicious approximations and aggregations to improve its tractability. Moreover, to overcome the computational challenges of treating hourly operational decisions within a monolithic multi-year planning horizon, we propose a decomposition algorithm based on Nested Benders Decomposition for multi-period MILP problems to allow the solution of larger instances. Our decomposition adapts previous nested Benders methods by handling integer and continuous state variables, although at the expense of losing its finite convergence property due to potential duality gap. We apply the proposed modeling framework to a case study in the Electric Reliability Council of Texas (ERCOT) region, and demonstrate massive computational savings from our decomposition.

1. Introduction

Energy systems planning models allow the evaluation of alternate scenarios for future growth, providing information to support the decision-making process and the selection of technologies in the power sector (e.g, EPRI, 2013; Short et al., 2011; U.S. Environmental Protection Agency Clean Air Markets Division, 2013). Generation and transmission expansion models can vary widely in scope (local versus regional) as well as in resolution of time and space. These models can be used to study the impact of new technology developments, resource cost trends, and policy shifts on the projected generation mix in order to meet future demand.

Although transmission expansion is not considered in this work, it is important to be aware of its impact on long-term planning decisions, and thus we discuss it here. Traditionally, generation and transmission expansion are modeled separately: the generation is planned first and the transmission network is designed to meet this supply (e.g., Alguacil, Motto, & Conejo, 2003; Bahiense, Oliveira, Pereira, & Granville, 2001; Bakirtzis, Biskas, & Chatziathanasiou, 2012; Latorre, Cruz, Areiza, & Villegas, 2003; Zhu & yuen Chow, 1997). Their simultaneous optimization is, however, a better way of capturing the trade-off between investing in local generation or transmission from remote supplies (Krishnan et al., 2016). We recognize the potential benefits of co-optimizing transmission and generation expansion and that this co-optimized problem is important, especially in the context of high insertion of renewables (Krishnan et al., 2016). However, since these decisions are typically made independently of one another (Munoz, Hobbs, & Kasina, 2012), we chose to pursue the generation expansion side only, as has been done by many authors.

There is growing interest to use planning models to study scenarios with increasing penetration of solar and wind generation (Macdonald et al., 2016). Historically, since power systems were dominated by *dispatchable* thermal resources, planning models could ignore short-term operating constraints and have longer time periods without impacting much the quality of the results. However, in a system deriving a large proportion of generation from intermittent resources, it is critical to include/consider hourly or subhourly operational decisions to assess the flexibility of the system (e.g., Albadi & El-Saadany, 2010; Lannoye, Flynn, & O'Malley, 2011; North American Electric Reliability Corporation, 2009). Only then it is possible to systematically/rigorously assess the trade-off

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Nomenclature

Indices and Sets

$r \in \mathcal{R}$	set of regions within the area considered
$i \in \mathcal{I}$	set of generator clusters
$i \in \mathcal{I}_r$	set of generator clusters in region r
$i \in \mathcal{I}_r^{\text{old}}$	set of existing generator clusters in region r at the beginning of the time horizon, $\mathcal{I}_r^{\text{old}} \subseteq \mathcal{I}_r$
$i \in \mathcal{I}_r^{\text{new}}$	set of potential generator clusters in region r, $\mathcal{I}_r^{\text{new}} \subseteq \mathcal{I}_r$
$i \in \mathcal{I}_r^{\text{TH}}$	set of thermal generator clusters in region r, $\mathcal{I}_r^{\text{TH}} \subseteq \mathcal{I}_r$
$i \in \mathcal{I}_r^{\text{RN}}$	set of renewable generator clusters in region r, $\mathcal{I}_r^{\text{RN}} \subseteq \mathcal{I}_r$
$i \in \mathcal{I}_r^{\text{Told}}$	set of existing thermal generator clusters in region r, $\mathcal{I}_r^{\text{Told}} \subseteq \mathcal{I}_r^{\text{TH}}$
$i \in \mathcal{I}_r^{\text{Tnew}}$	set of potential thermal generator clusters in region r, $\mathcal{I}_r^{\text{Tnew}} \subseteq \mathcal{I}_r^{\text{TH}}$
$i \in \mathcal{I}_r^{\text{Rold}}$	set of existing renewable generator clusters in region r, $\mathcal{I}_r^{\text{Rold}} \subseteq \mathcal{I}_r^{\text{RN}}$
$i \in \mathcal{I}_r^{\text{Rnew}}$	set of potential renewable generator clusters in region r, $\mathcal{I}_r^{\text{Rnew}} \subseteq \mathcal{I}_r^{\text{RN}}$
$j \in \mathcal{J}$	set of storage unit clusters
$t \in \mathcal{T}$	set of time periods (years) within the planning horizon
$d \in \mathcal{D}$	set of representative days in each year t
$s \in \mathcal{S}$	set of sub-periods of time per representative day d in year t
$k \in \mathcal{K}$	set of iterations in the Nested Decomposition algorithm

Deterministic Parameters

$L_{r,\,t,\,d,\,s}$	load demand in region r in sub-period s of representative day d of year t (MW)
$L_t^{\max}$	peak load in year t (MW)
W_d	weight of the representative day d
Hs	duration of sub-period s (h)
$Qg_{i,r}^{\text{np}}$	nameplate (nominal) capacity of a generator in cluster i in region r (MW)
$Ng_{i,r}^{\text{old}}$	number of existing generators in each cluster, $i \in \mathcal{I}_r^{\text{old}}$, per region r at the beginning of the time horizon
$Ng_i^{\max}$	maximum number of generators in the potential clusters $i \in \mathcal{I}_r^{\text{new}}$
$Q_{i,t}^{\text{inst,UB}}$	upper bound on yearly capacity installations based on generation technology (MW/year)
$R_t^{\min}$	system's minimum reserve margin for year t (fraction of the peak load)
ED_t	energy demand during year t (MW hour)
LT_i	expected lifetime of generation cluster i (years)
T_t^{remain}	remaining time until the end of the time horizon at year t (years)
$Ng_{i,r,t}^{\text{r}}$	number of generators in cluster i of region r that achieved their expected lifetime
Q_i^{v}	capacity value of generation cluster i (fraction of the nameplate capacity)
$Cf_{i,r,t,d,s}$	capacity factor of generation cluster $i \in \mathcal{I}_r^{\text{RN}}$ in region r at sub-period s, of representative day d of year t (fraction of the nameplate capacity)
$Pg_i^{\min}$	minimum operating output of a generator in cluster $i \in \mathcal{I}_r^{\text{TH}}$ (fraction of the nameplate capacity)
$Ru_i^{\max}$	maximum ramp-up rate for cluster $i \in \mathcal{I}_r^{\text{TH}}$ (fraction of nameplate capacity)
$Rd_i^{\max}$	maximum ramp-down rate for cluster $i \in \mathcal{I}_r^{\text{TH}}$ (fraction of nameplate capacity)
F_i^{start}	fuel usage at startup (MMbtu/MW)
$Frac_i^{\text{spin}}$	maximum fraction of nameplate capacity of each generator that can contribute to spinning reserves (fraction of nameplate capacity)
$Frac_i^{\text{Qstart}}$	maximum fraction of nameplate capacity of each generator that can contribute to quick-start reserves (fraction of nameplate capacity)
$Op^{\min}$	minimum total operating reserve (fraction of the load demand)
$Spin^{\min}$	minimum spinning operating reserve (fraction of the load demand)
$Qstart^{\min}$	minimum quick-start operating reserve (fraction of the load demand)
α^{RN}	fraction of the renewable generation output covered by quick-start reserve (fraction of total renewable power output)
$T_{r,r'}^{\text{loss}}$	transmission loss factor between region r and region $r' \neq r$ (%/miles)
$D_{r,r'}$	distance between region r and region $r' \neq r$ (miles)
$Ns_{j,r}$	number of existing storage units in each cluster j per region r at the beginning of the time horizon
$Charge_j^{\min}$	minimum operating charge for storage unit in cluster j (MW)
$Charge_j^{\max}$	maximum operating charge for storage unit in cluster j (MW)
$Discharge_j^{\min}$	minimum operating discharge for storage unit in cluster j (MW)
$Discharge_j^{\max}$	maximum operating discharge for storage unit in cluster j (MW)
$Storage_j^{\min}$	minimum storage capacity for storage unit in cluster j (MW hour)
$Storage_j^{\max}$	maximum storage capacity (i.e. nameplate capacity) for storage unit in cluster j (MW hour)
η_j^{charge}	charging efficiency of storage unit in cluster j (fraction)
$\eta_j^{\text{discharge}}$	discharging efficiency of storage unit in cluster j (fraction)
LT_j^{s}	lifetime of storage unit in cluster j (years)
Ir	nominal interest rate
If_t	discount factor for year t
$OCC_{i,t}$	overnight capital cost of generator cluster i in year t (\$/MW)
$ACC_{i,t}$	annualized capital cost of generator cluster i in year t (\$/MW)
$DIC_{i,t}$	discounted investment cost[1] of generator cluster i in year t (\$/MW)
$SIC_{j,t}$	investment cost of storage cluster j in year t (\$/MW)
CC_i^{m}	capital cost multiplier of generator cluster i (unitless)
LE_i	life extension cost for generator cluster i (fraction of the investment cost of corresponding new generator)

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[1] $DIC_{i,\,t}$ is used in the calculation for the life extension investment cost, which is in terms of a fraction LE_i of the capital cost. Therefore the investment cost for the existing cluster is approximated as being the same as for the potential clusters that have the same or similar generation technology.