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A multi-period, multi-regional generation expansion planning model incorporating unit commitment constraints

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HIGHLIGHTS

- A short-term structured investment planning model has been developed.
- Unit commitment problem is incorporated into the long-term planning horizon.
- Inherent intermittency of renewables is modelled in a comprehensive way.
- The impact of CO_2 emission pricing in long-term investment decisions is quantified.
- The evolution of system's marginal price is evaluated for all the planning horizon.

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ABSTRACT

This work presents a generic mixed integer linear programming (MILP) model that integrates the unit commitment problem (UCP), i.e., daily energy planning with the long-term generation expansion planning (GEP) framework. Typical daily constraints at an hourly level such as start-up and shut-down related decisions (start-up type, minimum up and down time, synchronization, soak and desynchronization time constraints), ramping limits, system reserve requirements are combined with representative yearly constraints such as power capacity additions, power generation bounds of each unit, peak reserve requirements, and energy policy issues (renewables penetration limits, CO_2 emissions cap and pricing). For modelling purposes, a representative day (24 h) of each month over a number of years has been employed in order to determine the optimal capacity additions, electricity market clearing prices, and daily operational planning of the studied power system. The model has been tested on an illustrative case study of the Greek power system. Our approach aims to provide useful insight into strategic and challenging decisions to be determined by investors and/or policy makers at a national and/or regional level by providing the optimal energy roadmap under real operating and design constraints.

1. Introduction

It is widely recognized that our contemporary world is characterized by high instability and rapid changes in many aspects of our daily lives. With regard to energy systems, there exists high uncertainty for the projection of their trends and evolution, as many parameters can influence them to a significant extent. These parameters include market dynamics (e.g., sharp cost reductions in the investment cost of renewable energy technologies, shale gas boom in the United States), political decisions (e.g., nuclear phase-out in several countries), financial decisions (e.g. credit risk) or even geopolitical tensions affecting fuel price evolution (e.g., oil price) [1].

As a consequence, there is a need to implement a comprehensive, analytical and detailed energy planning in order to provide a roadmap towards an affordable, sustainable and secure energy future. In this context, a modelling framework is necessary to optimally determine the energy technologies to be utilized in the power sector and/or in other energy sectors according to specific projections and policy targets. Several modelling approaches of energy systems have been developed including top-down macroeconomic energy models, bottom-up energy systems models covering several end-use sectors and sector-specific energy/power systems planning models. Each methodological framework has its own advantages and disadvantages based on technology details, temporal resolution and interaction among energy (one and/or other sectors) and economy [2].

Focusing on the power generation sector, for decades, traditional long-term generation expansion planning (GEP) models are

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Nomenclature

Acronyms

EU	European Union
GEP	generation expansion planning
MILP	mixed integer linear programming
NGCC	natural gas combined cycle
NGGT	Natural Gas Gas Turbine (or Natural Gas Open Cycle)
p.u.	per unit
RET	renewable energy technologies
SMP	System Marginal Price
UCP	unit commitment problem

Sets

$a \in A$	set of start-up types {hot, warm, cold}
$bl \in BL$	set of blocks of the energy offer function of each hydrothermal unit (or energy bids for load representatives)
$i \in I^{EX}$	set of existing units
$i \in I^{HT}$	set of hydrothermal units
$i \in I^{NEW}$	set of new candidate units
$i \in I^{RES}$	set of renewable units (including hydro units)
$i \in I^{RES-}$	set of renewable units (not including hydro units)
$i \in I^{S}$	set of units $i \in I$ that are (or can be) installed in sector $s \in S$
$i \in I^{TH}$	set of thermal units
$i \in I^{z}$	set of units $i \in I$ that are (or can be) installed in zone $z \in Z$
$i \in I$	set of all units
$m \in M$	set of months
$nc \in NC^{s}$	set of neighbouring countries $nc \in NC$ interconnected with sector $s \in S$
$nc \in NC^{z}$	set of neighbouring countries $nc \in NC$ interconnected with zone $z \in Z$
$nc \in NC$	set of interconnections (neighbouring countries)
$s \in S^{s'}$	set of sectors $s \in S$ interconnected with sector $s' \neq s \in S$
$(s, s') \in S$	set of sectors
$(t, t') \in T$	set of hours
$(y, y') \in Y$	set of years
$z \in Z$	set of zones

Parameters

$AV_{i,z,m,t}$	availability factor of each unit $i \in I^{RES}$ in zone $z \in Z$, month $m \in M$, and hour $t \in T$ (p.u.)
$CEXPB_{nc,bl,y,m,t}$	price of block $bl \in BL$ of the load bid curve of each interconnection $nc \in NC$ (exports), in year $y \in Y$, month $m \in M$, and hour $t \in T$ (€/MW h)
$CFL_{s,s',y}$	maximum corridor flow from sector $s \in S$ to sector $s' \neq s \in S$ in year $y \in Y$ (MW)
$CIMPB_{nc,bl,y,m,t}$	marginal cost (price) of block $bl \in BL$ of the imported energy offer function from interconnection $nc \in NC$, in year $y \in Y$, month $m \in M$, and hour $t \in T$ (€/MW h)
$CIM_{nc,y}$	power capacity of interconnection $nc \in NC$ in each year $y \in Y$ (MW)
$CO2\_CAP_{y}$	maximum allowable CO_2 emissions produced in year $y \in Y$ (t CO_2)
$CO2\_EF_{i,bl}$	CO_2 emission factor of each unit $i \in I^{TH}$, in power capacity block $bl \in BL$ (t CO_2/MW h)
$CPB_{i,bl,y,m,t}$	marginal cost (price) of block $bl \in BL$ of the energy offer function of each unit $i \in I^{HT}$, in year $y \in Y$, month $m \in M$, and hour $t \in T$ (€/MW h)
$CR1_{i,y,m,t}$	price of the primary energy offer of each unit $i \in I^{HT}$, in year $y \in Y$, month $m \in M$, and hour $t \in T$ (€/MW)
$CR2_{i,y,m,t}$	price of the secondary range energy offer of each unit $i \in I^{HT}$, in year $y \in Y$, month $m \in M$, and hour $t \in T$ (€/MW)
CRF_{i}	capital recovery factor of each unit $i \in I^{NEW}$ (p.u.)
CSD_{i}	shut-down cost of each thermal unit $i \in I^{TH}$ (€)
DUR_{m}	duration of each month (in days)
$Dem_{s,y,m,t}$	power load of sector $s \in S$, in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$EFORIM_{nc,y}$	unavailability factor of each interconnection $nc \in NC$ in each year $y \in Y$ (p.u.)
$EFOR_{i,y}$	unavailability factor of each unit $i \in I^{TH}$ in each year $y \in Y$ (p.u.)
$Exblock_{nc,bl,y,m,t}$	quantity of each power capacity block $bl \in BL$ of the load bid curve of each interconnection $nc \in NC$ (exports), in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
FOM_{i}	fixed operational and maintenance cost of each unit $i \in I^{RES-}$ (€/MW)
$FastR2Req^{down}_{y,m,t}$	system requirements in fast secondary-down reserve in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$FastR2Req^{up}_{y,m,t}$	system requirements in fast secondary-up reserve in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$IC_{i,y}$	installed capacity of unit $i \in I^{EX}$ in year $y \in Y$ (MW)
$INL_{z,y,m,t}$	injection losses coefficient in zone $z \in Z$, year $y \in Y$ month $m \in M$, and hour $t \in T$ (p.u.)
$INVC_{i,y}$	investment cost of unit $i \in I^{NEW}$ in year $y \in Y$ (€/MW)
$Imblock_{nc,bl,y,m,t}$	quantity of each power capacity block $bl \in BL$ of the energy offer function of each interconnection $nc \in NC$ (imports), in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
MAX_RES_{y}	maximum RES penetration in year $y \in Y$ (p.u.)
$PBL_{i,bl,y,m,t}$	quantity of each power capacity block $bl \in BL$ of the energy offer function of unit $i \in I^{HT}$ in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$PFX_{i,y,m,t}$	fixed (non-priced) component of the energy offer function of each unit $i \in I$ in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$PMAX^{dp}_{i}$	maximum power output (dispatchable phase) of each unit $i \in I^{HT}$ (MW)
$PMAX^{sc}_{i}$	maximum power output (when providing secondary reserve) of each unit $i \in I^{HT}$ (MW)
$PMIN^{dp}_{i}$	minimum power output (dispatchable phase) of each unit $i \in I^{HT}$ (MW)
$PMIN^{sc}_{i}$	minimum power output (when providing secondary reserve) of each unit $i \in I^{HT}$ (MW)
PSK_{i}	power output of each thermal unit $i \in I^{TH}$ when operating in soak phase (MW)
$R1Req_{y,m,t}$	system requirements in primary-up reserve in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$R1_{i}$	maximum contribution of unit $i \in I^{HT}$ in primary reserve (MW)
$R2Req^{down}_{y,m,t}$	system requirements in secondary-down reserve in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$R2Req^{up}_{y,m,t}$	system requirements in secondary-up reserve in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$R2_{i}$	maximum contribution of unit $i \in I^{HT}$ in secondary reserve (MW)
$R3Req_{y,m,t}$	system requirements in tertiary reserve in year $y \in Y$, month $m \in M$, and hour $t \in T$ (MW)
$R3^{nsp}_{i}$	maximum contribution of unit $i \in I^{HT}$ in non-spinning tertiary reserve (MW)
$R3^{sp}_{i}$	maximum contribution of unit $i \in I^{HT}$ in spinning tertiary reserve (MW)
REN_{y}	RES penetration target in the power mix in year $y \in Y$ (p.u.)
$RES\_CAP_{i,z,y}$	maximum allowable capacity of each unit $i \in I^{RES-}$ in zone $z \in Z$, year $y \in Y$ (MW)