Applied Energy 170 (2016) 1–21

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An optimization framework for the integrated planning of generation and transmission expansion in interconnected power systems

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HIGHLIGHTS

- A novel optimization framework for the design and planning of interconnected power systems is proposed.
- The framework integrates generation and transmission capacity expansion planning.
- Reserve and emission constraints are included.
- Business as usual and CO_2 mitigation policy scenarios are evaluated.
- Reconfiguration of existing power generation technologies is the most cost-effective option for CO_2 emissions mitigation.

ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form 14 January 2016
Accepted 2 February 2016
Available online 1 March 2016

Keywords:
Optimization framework
Integrated design and planning
Generation and transmission expansion
Interconnected power systems
Reserve and emission constraints

ABSTRACT

Energy, and particularly electricity, has played and will continue to play a very important role in the development of human society. Electricity, which is the most flexible and manageable energy form, is currently used in a variety of activities and applications. For instance, electricity is used for heating, cooling, lighting, and for operating electronic appliances and electric vehicles. Nowadays, given the rapid development and commercialization of technologies and devices that rely on electricity, electricity demand is increasing faster than overall primary energy supply. Consequently, the design and planning of power systems is becoming a progressively more important issue in order to provide affordable, reliable and sustainable energy in timely fashion, not only in developed countries but particularly in developing economies where electricity demand is increasing even faster.

Power systems are networks of electrical devices, such as power plants, transformers, and transmission lines, used to produce, transmit, and supply electricity. The design and planning of such systems require the selection of generation technologies, along with the capacity, location, and timing of generation and transmission capacity expansions to meet electricity demand over a long-term horizon. This manuscript presents a comprehensive optimization framework for the design and planning of interconnected power systems, including the integration of generation and transmission capacity expansion planning. The proposed framework also considers renewable energies, carbon capture and sequestration (CCS) technologies, demand-side management (DSM), as well as reserve and CO_2 emission constraints. The novelty of this framework relies on an integrated assessment of the aforementioned features, which can reveal possible interactions and synergies within the power system. Moreover, the capabilities of the proposed framework are demonstrated using a suite of case studies inspired by a real-world power system, including "business as usual" and "CO_2 mitigation policy" scenarios. These case studies illustrated the adaptability and effectiveness of the framework at dealing with typical situations that can arise in designing and planning power systems.

1. Introduction

Energy demand, including electricity demand, is directly linked to factors such as economic development, population growth, and urbanization. This linkage entails a critical challenge to use the Earth's energy resources in a sustainable fashion, enhancing quality of life, and facilitating human development. Historically, different energy resources such as traditional biomass, fossil fuels, and

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http://dx.doi.org/10.1016/j.apenergy.2016.02.014

Nomenclature

Indices

- b load blocks
- c circuits
- f primary energy resources
- i power plants
- r, r' regions
- t, t' time periods (i.e. years)

Sets

- *co* set of coal power plants
- *err* set of existing transmission connections between regions
- *fo* set of fossil power plants
- *lfi* set that defines the linkage between fuels and power plants
- *lri* set that defines the linkage between power plants and regions
- *lrr* set that defines the transmission connections between regions
- *ni* set of potential (new) power plants
- *pi* set of already planned power plants
- *ref* region used as reference for voltage angles (defined arbitrarily)
- *re* set of renewable power plants

Scalars

- *BasePow* base power i.e. 100 MWA
- *CapRate* CO_2 capture fraction, i.e. 0.95 for a 95% CO_2 capture level
- *MaxPo* maximum active or real power flow for original transmission lines
- *MaxRep* maximum active or real power flow for repowered transmission lines
- *ResMarg* non-spinning reserve margin
- *SpinRes* spinning reserve margin
- t_{CCS} lead time for retrofitting with CCS
- t_{DSM} lead time for the implementation of DSM strategies
- t_{ne} lead time for the installation of new circuits
- *TranLoss* transmission losses
- t_{rep} lead time for repowering
- γ discount rate
- $\overline{\theta}$ maximum absolute value of voltage angles

Parameters

- $AvaiFac(i,t)$ availability factor for power plant i during period t
- $BlockDur(b)$ duration of load block b
- $Cap(i)$ capacity of power plant i
- $CapexCap(i,t)$ capital expenditures for CCS retrofitting
- $CapexDSM(r,t)$ capital expenditures for the implementation of DSM strategies
- $CapFac(i,t)$ capacity factor for power plant i during period t
- $CostNewc(r,r',t)$ capital cost for adding new circuits
- $CostRep(r,r',t)$ capital cost for repowering existing transmission lines
- $CostTSM(i,t)$ cost for transport, sequestration, and monitoring per unit of CO_2
- $CO2Emi(i)$ emission factor, without CCS retrofitting, for power plants
- $ECO2(i)$ energy consumption – required for CO_2 capture, dehydration, and compression – per unit of CO_2
- $ElecDem(r,b,t)$ electricity demand in region r for load block b during period t
- $FixCost(i,t)$ FIXED operating cost for power plant i during time period t
- $FuelAvai(f,t)$ availability of fuel f during period t
- $HeatRate(i)$ heat rate for power plant i
- $InvCost(i,t)$ capital investment for power plant i during period t
- $MaxEmi(t)$ CO_2 emission limit for time period t
- $MaxLin(r,r')$ maximum number of circuits allowed to be installed between regions r and r'
- $OpexCap(i,t)$ extra operating cost – for CO_2 capture, dehydration, and compression – per unit of energy generated by coal power plant i during time period t
- $PeakPower(t)$ peak-load power demand for period t
- $RawCost(i,t)$ unit cost of primary energy resource i during time period t
- $React(r,r')$ per unit value of reactance of original transmission lines
- $ReaRep(r,r')$ per unit value of reactance of repowered transmission lines
- $Startup(i,t)$ startup period for already planned power plants
- $tp(i)$ lead time for the construction of power plant i
- $TranLin(r,r')$ number of existing transmission lines in the branch between regions r and r'
- $UnitCost(t)$ unit transmission cost during time period t
- $VarCost(i,t)$ unit variable cost for power plant i during period t
- $\phi(b,r)$ factor by which electricity demand at each load block and region is modified as a consequence of the implementation of the corresponding DMS strategy

Positive continuous variables

- $Capex(t)$ total capital expenditures during time period t
- $ElecFlow(r,r',b,t)$ electricity transmission between regions r and r' during block b during time period t
- $ElecNew(r,r',c,b,t)$ electricity flow between regions through new circuits
- $ElecRep(r,r',b,t)$ electricity flow between regions through existing or repowering candidate circuits
- $Electricity(i,b,t)$ dispatched electricity from power plant i in load block b during periods t
- $Emission(t)$ total CO_2 emissions during time period t
- $EnCap(i,b,t)$ total energy required for CO_2 capture, dehydration, and compression
- $FuelCost(t)$ total fuel cost during time period t
- $Opex(t)$ total operating costs during time period t
- $OpexFix(t)$ total fixed operating expenditures during time period t
- $OpexVar(t)$ total variable operating cost during time period t
- $Power(i,t)$ power allocation for power plant i during time period t
- $SpinnRes(i,b,t)$ allocation of spinning reserve for power plant i in load block b during time period t
- *TotCost* net present value of total cost t
- $TranCapex(t)$ capital expenditures in expansion of transmission capacity during time period t
- $TranCost(t)$ total transmission costs during time period t

Free continuous variables

- $\theta_{r,b,t}$ voltage angles (i.e. in radians)

Binary variables

- $Build(i,t)$ equal to 1 if power plant i is built during period t; 0 otherwise
- $CCS(i,t)$ equal to 1 if coal power plant i is retrofitted with CCS technology in time period t; 0 otherwise
- $Circuit(c,r,r',t)$ equal to 1 if circuit c is installed between regions r and r' during time period t; 0 otherwise