Applied Energy 222 (2018) 872–884

Contents lists available at ScienceDirect

Applied Energy

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

The benefits of nuclear flexibility in power system operations with renewable energy

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HIGHLIGHTS

- Nuclear power plants are subject to different operational constraints than other power plants.
- We provide a mathematical representation of these distinct constraints on nuclear flexibility.
- Benefits of nuclear flexibility are significant in a power system with high shares of renewables.
- Benefits include lower power system operating costs and increased revenue for nuclear plants.

ARTICLE INFO

Keywords:
Nuclear energy
Flexible operations
Renewable energy integration
Unit commitment
Economic dispatch
Mixed integer linear programming

ABSTRACT

Nuclear power plants are commonly operated in a "baseload" mode at maximum rated capacity whenever online. However, nuclear power plants are technically capable of flexible operation, including changing power output over time (ramping or load following) and providing frequency regulation and operating reserves. At the same time, flexibility is becoming more valuable as many regions transition to low-carbon power systems with higher shares of variable renewable energy sources such as wind or solar power. We present a novel mixed integer linear programming formulation to more accurately represent the distinct technical operating constraints of nuclear power stations, including impacts of xenon transients in the reactor core and changing core reactivity over the fuel irradiation cycle. This novel representation of nuclear flexibility is integrated into a unit commitment and economic dispatch model for the power system. In a case study using representative utility data from the Southwest United States, we investigate the potential impacts of flexible nuclear operations in a power system with significant solar and wind energy penetration. We find that flexible nuclear operation lowers power system operating costs, increases reactor owner revenues, and substantially reduces curtailment of renewables.

1. Introduction

Due to traditional operational practice, economic efficiency, or regulatory requirements, nuclear power plants are commonly operated in a "baseload" mode, producing their maximum rated capacity whenever online. However, nuclear plants are technically capable of more flexible operation, changing their power output over time (i.e. ramping or load following) and contributing to power system reliability needs, including frequency regulation and operating reserves. Flexible operation can help manage daily and seasonal variability in demand or renewable energy output or respond dynamically to hourly market prices or system operator dispatch. Nuclear operators in several countries, e.g. France, Germany, Belgium, and the Slovak Republic, have developed considerable experience with flexible operation of existing reactor designs [1–6]. Nuclear operators in Ontario, Canada and the northwestern United States also manually adjust power output on a seasonal basis to accommodate changes in hydroelectric power generation [7]. In addition, all modern nuclear reactor designs under construction or licensing in the United States, Canada, and Europe are designed for flexible operation [7–10].

Power systems with increasing penetrations of variable renewable energy sources (i.e. wind and solar power) require greater system

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https://doi.org/10.1016/j.apenergy.2018.03.002
Received 12 October 2017; Received in revised form 23 February 2018; Accepted 3 March 2018
0306-2619/

Nomenclature

Indices

t	index of time, hour, $t \in [1, \ldots, 24]$
d	no. of days into nuclear fuel cycle
j	index for nuclear units

Variables

$p_{t,j}$	power output at time t, nuclear unit j [MW/h]
$St_{t,j}/Up_{t,j}/Rd_{t,j}$	binary state variables for stable output, ramp up, and ramp down, respectively, for nuclear unit j, time t [0/1]
$nsrn_{t,j}/sr_{t,j}/rgu_{t,j}$	upward reserve (non-spin/spin up/regulation up) from nuclear unit j, time t [MW]
$dr_{t,j}/rgd_{t,j}$	downward reserve (spin down/regulation down) from nuclear unit j, time t [MW]

Constants

RD_j/RU_j	nuclear unit ramping down/up limit [MW/h]
$PMINSTABLE_{d,j}$	minimum hours that nuclear unit j needs to stay at a stable power output, day d
$TOTRESPERCENT_j$	percent of capacity allowed for reserve provision, nuclear unit j [percent]
MSR_j	maximum sustained ramp, nuclear unit j [MW/minute]
$PMAX_j$	maximum power output, nuclear unit j [MW]
$PMIN_{d,j}$	minimum nuclear stable power output during day d, nuclear unit j [MW]
δ	auxiliary parameter (very small number (e.g. $1e10^{-4}$)) used to force $St_t = 1$ when there is no ramping activity
$NSRRESPTIME$	required non-spinning reserve response time [minutes]
$SRRESPTIME$	required spinning reserve response time [minutes]
$REGRESPTIME$	required regulation response time [minutes]

flexibility, including operating reserves and ramping capability to ensure that the supply-demand balance is maintained at all times [11–17]. At the same time, if power systems are to decarbonize, traditional sources of operating flexibility, such as natural gas or coal-fired power stations, must be replaced by low-carbon resources, including energy storage, demand response, hydropower, and/or flexible low-carbon thermal generators [15,18,19]. From a market perspective, production-based subsidies for renewable energy, such as production tax credits, feed-in tariffs, and feed-in premiums, can also distort market prices by increasing the prevalence of negative prices that reduce the profitability of inflexible generators [20–22].

In power systems with significant shares of variable renewable energy and/or where nuclear power supplies a substantial portion of the net load (i.e. the load less available variable renewable energy supply), the flexible capabilities of nuclear power stations can therefore be important to maximize revenues for reactor owners as well as ensure system reliability, reduce system costs, integrate renewable energy, and help meet greenhouse gas emissions reduction goals. To date, however, the electric power systems modeling literature typically represents nuclear units as inflexible "must-run" resources [17,18]. This is true even in studies that specifically explore operational flexibilities of low-carbon technologies [23]. Other studies apply the same constraints used for conventional thermal units to represent nuclear units (e.g. standard ramp limits, minimum output levels) [15,19,24–26]. In [27], seasonal changes in aggregate output of multiple nuclear units are exogenously specified, but without allowing for endogenous optimization of nuclear flexibility. These traditional representations do not accurately capture the flexible capabilities of nuclear power plants or the peculiar operational constraints arising from nuclear reactor dynamics and fuel irradiation cycles, including impacts of xenon transients and changing core reactivity over the irradiation cycle. Although it has been recognized in previous literature that flexibility in nuclear power plants has potential value, the focus has been on providing this flexibility through directing the fixed electricity generation from the nuclear plant towards other purposes, such as production of hydrogen through electrolysis [28], water desalination [29], or to energy storage as an alternative to electricity delivery to the power grid [29–31].

In this paper, we move beyond the previous literature by analyzing the potential benefits of flexible operation of nuclear power plants, including adjusting electricity production (ramping) and supplying frequency regulation and operating reserves in response to market prices and system reliability requirements. Specifically, we explore the potential benefits of flexible nuclear operations in power systems with relatively high shares of variable renewable energy sources (i.e. the role of nuclear flexibility in renewable energy integration). The main contributions of the paper are twofold. First, we provide a brief explanation of the distinct constraints on flexible operation of nuclear power plants arising from the physical and technical characteristics of nuclear reactors and present a novel mixed-integer linear programming (MILP) formulation to represent these constraints in models for power system operations. Second, in a case study using representative data from the U.S. Southwest, we analyze the potential benefits of flexible nuclear operations in a system with high shares of both nuclear and renewable energy. We find that flexible nuclear power operations are a "win-win-win" lowering total power system operating costs, increasing revenues for nuclear plant owners, and significantly reducing curtailment of renewable energy.

The rest of the paper has the following structure: Section 2 discusses the distinct technical constraints on flexible nuclear operations and presents a novel mathematical formulation to represent these constraints in a tractable manner in power systems optimization models. Section 3 briefly describes the unit commitment (UC), economic dispatch (ED), and market simulation model used in this paper. Section 4 presents a case study and results illustrating the benefits of flexible nuclear operation. Section 5 concludes by summarizing the main findings and discussing future work.

2. Constraints on flexible operation of nuclear power plants

Several designs for nuclear power plants are in common use throughout the world today, including pressurized water reactors (PWR), boiling water reactors (BWR), and Canadian Deuterium Uranium (CANDU) reactors. All three of these common reactor types are capable of flexible operation, utilizing different methods to either modulate reactor power output directly or control input to the steam turbine generators [1–5,7,9]. In this paper, we focus on light-water reactor designs (PWR and BWR) used in the United States, Western Europe, Japan, and elsewhere. This section briefly summarizes each of the key constraints on flexible nuclear operation arising from the physical and technical characteristics of light-water nuclear reactor designs and presents a mathematical formulation suitable for representing these reactor-related constraints in MILP power system optimization models. These reactor-related constraints are distinct from the constraints common to thermal generators arising from the characteristics of the steam generating system, and they deserve special attention in order to more accurately model the flexibility of nuclear power plants.