G Model
ELECTR 6241 No. of Pages 10

ARTICLE IN PRESS

The Electricity Journal xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

The Electricity Journal

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

Modeling the integrated expansion of the Canadian and US power sectors

Eduardo Ibanez[a,*], Owen Zinaman[b]

[a] GE Energy Consulting, Schenectady, NY, USA
[b] National Renewable Energy Laboratory, Golden, CO, USA

ARTICLE INFO

Article history:
Received 6 November 2015
Accepted 27 December 2015
Available online xxx

ABSTRACT

This paper presents the development effort that created a robust representation of the combined capacity expansion of the U.S. and Canadian electric sectors within the NREL ReEDS model. The abbreviated scenario analysis effort was designed to understand drivers behind various Canadian–U.S. power sector futures out to 2036. We model the impact of natural gas prices, increased Canadian hydropower deployment, and increased renewable energy (RE) penetrations. The sample results analyzed in this paper show the highly dynamic nature of the modeling tool as it performs a simultaneous optimization of the two countries' generation portfolios. The interactions between the two countries go beyond energy generation and also include firm capacity contracts and renewable energy certificates (RECs). The reference scenario results show a significant increase in wind generation in both the United States and Canada with a gradual retirement of coal and nuclear energy. The evolution of net energy and firm capacity exchange was very dynamic through the span of the analysis period and drives significant investment in transmission capacity across the border, almost doubling the existing capacity of transmission lines. The exchange of energy was driven by regional stories. ISO-NE and NYISO import energy throughout the analysis period. However, in the Western Interconnection we observed increasing imports to Canada from the United States, whereas the exchanges with MISO switched directions.

Published by Elsevier Inc.

1. Introduction

The United States and Canada share an important electricity relationship, physically interconnected at over 35 points at the high-voltage level from New England to the Pacific Northwest (CEA, 2010). This integration of electricity resources allows for greater coordination, higher levels of reliability, and significant opportunity for expanding access to affordable, low-carbon energy.

In this paper, we document a development effort to update an endogenous treatment of the integrated U.S.–Canada electricity sectors in the NREL Regional Energy Deployment System (ReEDS) model. This effort is thoroughly documented in Martinez et al. (2013) and Zinaman et al. (2015). We also present results from an abbreviated scenario analysis, using this endogenous treatment, which demonstrates the new capability and yields initial insights into the influence of various drivers on power sector deployment. None of the scenarios presented are intended to be a forecast or prediction. The sample results analyzed in this report are intended to demonstrate the newly established capability and illustrate the highly dynamic nature of the modeling tool as it performs a simultaneous optimization of the two countries' generation portfolios.

The remainder of the paper is organized as follows: Section 2 introduces the ReEDS model, Section 3 present the data sources used to build the model, Section 3 presents the list of scenarios modeled in this study, Section 5 summarizes results and Section 6 concludes.

2. The regional energy deployment system (ReEDS) model

Modeling future renewable energy scenarios requires tools that can accommodate the diversity of the various renewable energy technologies and applications, the location-dependent quality of many of these resources, and the inherent variability and uncertainty of wind and solar generation. Although no modeling tool can meet all needs simultaneously, ReEDS is the analytical backbone of many NREL studies that involve capacity expansion, including the U.S. Department of Energy (DOE) *20% Wind Energy by 2030* study (DOE, 2008), DOE *SunShot Vision Study* (DOE, 2012), the

* Corresponding author.
E-mail addresses: eduardo.ibanez1@ge.com (E. Ibanez), owen.zinaman@nrel.gov (O. Zinaman).

http://dx.doi.org/10.1016/j.tej.2015.12.003
1040-6190/Published by Elsevier Inc.

Please cite this article in press as: E. Ibanez, O. Zinaman, Modeling the integrated expansion of the Canadian and US power sectors, Electr. J. (2016), http://dx.doi.org/10.1016/j.tej.2015.12.003

Renewable Electricity Futures Study (NREL, 2012), DOE *Wind Vision Study* (DOE, 2015) and others (Logan et al., 2013, and Mai et al., 2014). For detailed documentation of an earlier version of the model, see Short et al. (2011).

ReEDS is a generation and transmission capacity expansion model of the electricity system of the contiguous United States and, through. ReEDS is unique among nationwide and long-term capacity expansion models for its highly discretized regional structure and statistical treatment of the impact of variability of wind and solar resources on capacity planning and dispatch.

More specifically, ReEDS is a linear program that minimizes overall electric system costs subject to a large number of constraints. The major constraints include meeting electricity demand within specific regions, regional resource supply limitations, planning and operating reserve requirements, state and federal policy demands, and transmission constraints. To satisfy these constraints, the ReEDS optimization routine chooses from a broad portfolio of conventional generation, renewable generation, storage, and demand-side technologies (see Table 1), including the deployment location of these technologies. Additionally, because of its detailed regional and temporal representation, ReEDS can estimate the costs of transmission expansion and operational integration and has a simplified representation of transmission power flow.

The capacity expansion and dispatch decision making of ReEDS considers the net present value cost of adding new generation capacity and operating it (considering transmission and operational integration) over an assumed financial lifetime (20 years). This cost-minimization routine was applied for each 2-year investment period from 2010 until 2050. As a cost-optimization model, ReEDS does not attempt to capture non-economic (e.g., behavioral, social, institutional) considerations in its investment and dispatch decision-making routine. These noneconomic factors can be significant, particularly regionally, and further work is necessary to quantify their impacts.

ReEDS represents the contiguous United States using 403 wind and concentrating solar power (CSP) resource regions (356 in the United States and 47 in Canada). These resource supply regions are grouped into four levels of larger regional groupings: balancing areas (BAs), reserve-sharing groups, North American Electric Reliability Council (NERC) regions (NERC, 2010) [6], and interconnects. This level of geographic detail, depicted in Fig. 1, enables the model to account for geospatial differences in resource quality, transmission needs, electrical (grid-related) boundaries, political and jurisdictional boundaries, and demographic distributions. In ReEDS, BAs are the regional areas within which demand requirements must be satisfied. Although existing BA authority boundaries were considered in the design of the BAs, the BA boundaries are often not aligned with the boundaries of real BA authorities to accommodate other aforementioned boundaries (e.g., political boundaries). There are 154 BAs in ReEDS, with 134 in the United States and 20 in Canada.

Table 1
Generation, storage, and demand technologies considered in reeds.

Category	Technologies
Conventional Generation	Pulverized coal
	Natural gas combined cycle[a]
	Natural gas combustion turbine
	Nuclear
	Integrated gasification combined cycle[a]
Renewable Generation	Onshore wind
	Offshore wind
	CSP with and without thermal storage[b]
	Utility-scale and distributed rooftop PV[c]
	Dedicated and co-fired biomass
	Geothermal
	Hydropower
	Ocean
Storage	Pumped storage hydropower
	Compressed air energy storage
	Batteries
Demand-Side Technologies	Thermal energy storage in buildings
	Interruptible load
	Utility-controlled PEV charging[d]

[a] Carbon capture and storage version of these technologies are also implemented in ReEDS.
[b] CSP is concentrated solar power.
[c] PV is photovoltaics.
[d] PEV is plug-in electric vehicle.

ReEDS dispatches generation within 17 time slices (four time slices for each season representing morning, afternoon, evening, and nighttime, with an additional summer-peak time slice). This level of temporal detail—though not as sophisticated as that of an hourly chronological dispatch model—enables ReEDS to consider seasonal and diurnal changes in demand and resource availability. Fig. 2 compares a typical load duration curve and the discretized version based on the 17 time slices. Moreover, because significant demand and resource variations can occur within each time slice, ReEDS uses statistical calculations to estimate the capacity value, forecast error reserves, and curtailment of wind and solar resources; these calculations also consider the correlations of output profiles between projects of the same type in different locations, between projects that rely on different resource types, and between different regional demand profiles.

The statistical calculations in ReEDS are used in multiple reserve and load balancing constraints in the model. At the longest timescales, ReEDS enforces a planning reserve requirement that ensures there is sufficient generating capacity to exceed the annual forecasted peak demand hour by the requisite reserve margin, which ranges from 12.5% to 17.2%. At shorter hourly to sub-hourly timescales relevant to daily electric system operations, ReEDS requires sufficient supply- and demand-side technologies to satisfy operating reserve requirements. The operating reserves considered in ReEDS included wind and solar forecast error reserves, contingency reserves, and frequency regulation. Because contingency reserves and frequency regulation requirements were assumed to be established as a fraction of demand (6% for contingency and 1.5% for frequency regulation), they were independent of the amount of variable generation. In contrast, forecast error reserve requirements were estimated based on hourly persistence forecasts for wind and solar PV, and therefore increased as variable generation increased. ReEDS does not directly capture the wear-and-tear costs associated with operating the conventional thermal power plant fleet in a more flexible fashion. Additional research on these costs and their implications for renewable energy integration is warranted.

In ReEDS, planning and operating reserves were assumed to be maintained independently in reserve sharing groups for all years of the study period, representing greater cooperation over larger areas than exists in the current grid. Existing regional transmission organizations and independent system operators (such as Midwest ISO, New England ISO, PJM, or California ISO) were used in the construction of some of the reserve sharing groups; where there was no existing regional transmission organization or independent system operator, a future reserve-sharing region was assumed. Some of these reserve-sharing groups were larger than those that currently operate under the assumption that additional market integration and transmission expansion over the next 40 years would expand current reserve-sharing regions.

For transmission, existing transmission infrastructure was assumed to continue to be operable throughout the study period, and existing line capacity was assumed to be usable by both conventional and renewable generation sources. The regional

Please cite this article in press as: E. Ibanez, O. Zinaman, Modeling the integrated expansion of the Canadian and US power sectors, Electr. J. (2016), http://dx.doi.org/10.1016/j.tej.2015.12.003