Energy Strategy Reviews 22 (2018) 196–206

Contents lists available at ScienceDirect

Energy Strategy Reviews

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

Valuing infrastructure investments to reduce curtailment

T. Niet[a,b,*], B. Lyseng[a], J. English[a], V. Keller[a], K. Palmer-Wilson[a], B. Robertson[a], P. Wild[a], A. Rowe[a]

[a] Institute for Integrated Energy Systems, University of Victoria, PO Box 1700, STN CSC, Victoria, BC, V8W 2Y2, Canada
[b] School of Energy, British Columbia Institute of Technology, 3700 Willingdon Avenue, Burnaby, BC, V5G 3H2, Canada

ABSTRACT

Curtailment due to high penetrations of variable renewable (VR) capacity leads to increased costs borne by the electricity system. These curtailment costs can be implicitly included as integration costs in long term models but to date have not been included in short or medium term models in the literature. We implement curtailment cost tracking into a medium term version of the OSeMOSYS linear programming model and show how the inclusion of curtailment costs adds to the value proposition when considering infrastructure investments to reduce curtailment. Infrastructure investments such as storage and dispatchable load technologies are considered for a system with high wind penetration.

We find that including curtailment costs in the value of storage and dispatchable loads adds significantly to the value of that infrastructure to the system, depending on the curtailment cost and the penetration level of wind power. Ignoring curtailment costs potentially under-values investments to reduce curtailment. No other works compare the value of curtailment to investment in storage or dispatchable load technologies.

1. Introduction

High penetrations of variable renewable (VR) capacity, such as wind and solar, can lead to curtailment of the VR generator due to the limited ability of the electricity grid to receive this power [1]. Curtailment leads to increased costs that are either borne by the electricity system operator, if the contract with the VR generator is *must take*, or by the owner of the generator. These costs, which we term *curtailment costs*, include: contractual requirements for direct payment to the operator of the generator; loss of renewable energy credits (RECs); and increased life cycle cost of the VR energy because capital and fixed costs are amortized over a lower amount of generation. As an example, in Germany in 2015, wind generators were paid an average of €53/MWh to curtail their generation [2].

Previous studies such as Ueckerdt [3] and Hirth et al. [4] implicitly include curtailment costs within integration costs in long term models but the explicit inclusion of curtailment costs in a short and medium term optimization models is not present in the literature. With the increased penetration of VR generation, and the corresponding increase in VR curtailment, this can no longer be justified.

In this study, we use a curtailment-enabled model to value infrastructure investments that reduce curtailment. Two types of infrastructure investment are used to demonstrate the applicability of the method: storage and dispatchable loads. Other studies have evaluated how VR generation owners can benefit from reduced curtailment [5] or how curtailment schemes work in the marketplace [6,7]. We take a system-level view and consider the overall system value that specific infrastructure investments provide when curtailment costs are included in a one year system model. This allows us to value investments in storage or dispatchable load technologies when curtailment costs are included in the model.

2. Literature review

We first review the literature on integration of VR generation into power systems and find that, although integration costs are considered in some long term studies, short and medium term studies focus primarily on reducing curtailment and not on the cost that curtailing imposes on the system. Model frameworks that have been used to evaluate VR energy integration costs are then presented and we show how integration costs for long term models can implicitly include curtailment costs, but that shorter term studies do not include curtailment costs. Finally, a discussion of model time scales is provided.

2.1. Integration of VR generation in power systems

There is much research on integrating VR generation into power systems. Much of this work focusses on long term optimization of the generation mix rather than on short and medium term impacts of curtailment. These studies address the efficacy of demand side management and grid enhancements, such as storage, transmission expansion or increased flexibility, to increase the long term penetration of VR

---

[*] Corresponding author. School of Energy, British Columbia Institute of Technology, 3700 Willingdon Avenue, Burnaby, BC, V5G 3H2, Canada.
E-mail addresses: Taco_Niet@bcit.ca (T. Niet), bcl@uvic.ca (B. Lyseng), pwild@uvic.ca (P. Wild), arowe@uvic.ca (A. Rowe).

https://doi.org/10.1016/j.esr.2018.08.010
Received 27 June 2017; Received in revised form 1 June 2018; Accepted 21 August 2018

Nomenclature

$a_{i,j}$	Performance parameters of technologies in the model
b_i	Limits on installed capacity and operating parameters
BC_j	Balancing costs as defined by Hirth et al
c_j	Cost vector for each possible decision in the model
c_j^c	Curtailment cost per unit energy for generator *j*
C_C	Total curtailment cost
$CF_{i,j}$	Capacity factor for generator *j* in time slice *i*
C_T	Total system cost with curtailment costs included
D_i	Adjusted demand in time slice *i* to model dispatchable load
D_i^0	Initial demand in time slice *i*
	Energy available from generator *j* in time slice *i*
$E_{i,j}^C$	Amount of energy constrained for generator *j* in time slice *i*
E_i^D	Total demand in each time slice, *i*
$E_{i,j}^G$	Total generation for generator *j* in each time slice *i*
GC_j	Grid related costs as defined by Hirth et al
i	Index of time slices in the model
I_j	Installed capacity of generator *j*
j	Index of decisions (generators) in the model
P	Amount of energy the dispatchable load must provide
P_i	Power of the dispatchable load in time slice *i*
PC_j	Profile costs as defined by Hirth et al
S_V	Size of infrastructure investment
v	Specific value of infrastructure investment to the system, scaled to size of infrastructure investment
v_C	Component of the specific value attributable to the inclusion of curtailment cost
V	Value of an infrastructure investment to the system
x_j	Vector of all possible decisions in the model

generation. We provide a brief review of these studies before reviewing the literature on curtailment in short and medium term studies.

In long term studies, the effect of demand side management, transmission expansion and storage on the penetration of VR energy have been addressed. Salpkari et al. [8] model demand side management of heating loads and other flexibility solutions to increase VR penetration for a system in Finland. Lamadrid et al. [9] assess the effects of investments in transmission on the ability of the grid to integrate VR generation and find a corresponding increase in VR penetration with transmission expansion. Denholm and Hand [10] study the effect of ramping capability of non-VR generators on VR penetration and show that a more flexible system allows more VR generation in the system. Studies of storage often optimize the size of the storage system and, in some cases, other generators to meet a given demand with specified costs for both the generators and the storage system [1,7,11–23]. Braff et al. [24] present a method for sizing hybrid wind/storage installations to obtain the highest market value from the power sold. As noted above, these long term studies can include integration costs using the framework presented by Ueckerdt [3] and Hirth et al. [4].

As in long term studies, short and medium term studies have addressed the effect of demand side management, transmission expansion and storage on the penetration of VR energy. Arteconi et al. [25] evaluate the use of active heating demand response to deal with VR variability and find that demand response reduces system operating costs and curtailment. Xiong et al. [26] consider controlled heating loads in Northeast China to enable reduced wind curtailment. Brouwer et al. [27] compare the system cost when the system is permitted to curtail VR generation with the system cost of adding demand response, storage or interconnection for a system with high penetrations of intermittent resources. They find that only curtailment and demand response are economically viable. Denholm et al. [28] investigate load shifting, demand response and increased ramping flexibility in a system with 50% solar energy penetration and show that implementing these technologies reduces curtailment. Although each of these studies considers demand response investments to reduce curtailment, none place an economic value on the curtailment when it occurs.

Only two studies were identified that consider transmission expansion in short or medium term models and the impact on curtailment. Lamy et al. [29], rather than considering transmission expansion explicitly, compare potential VR generation locations when transmission constraints are included and find that different locations have different levels of curtailment. As noted above, Brouwer et al. [27] compare the system cost when the system is permitted to curtail VR generation with the system cost of interconnection and find that transmission expansion to reduce curtailment is not economically viable. Neither of these studies consider the cost to the system of curtailing generation.

There are many studies of the impacts of storage investments on the curtailment of VR generation. Johnson et al. [30] evaluate storage batteries to determine the value of reducing curtailment and transmission requirements. This value is used to determine storage cost curves based only on the value of the additional revenue from energy sales that is enabled by including battery storage. Denholm [31] evaluates energy storage to reduce curtailment and shows that even medium duration storage, on the order of 4–8 h, results in significantly reduced curtailment. The value of the thermal storage that is integral to concentrated solar power plants and its effect on VR curtailment, has also been studied [32–34]. Other works evaluate the potential for power-to-gas technologies to reduce curtailment [35–41]. All these studies optimize the size of storage infrastructure but none explicitly considers the value of resulting curtailment reduction.

To summarize, integration costs for VR generation have been included in some long term energy planning models, but the cost of curtailment can, at best, be only implicitly included in these models. In the short and medium term, most studies have only considered the reduced curtailment that can be achieved with infrastructure investments but not the cost of curtailing this generation.

2.2. *Integration costs and model frameworks*

To show how long term models implicitly include curtailment costs but that shorter term studies, to date, haven't included them we first provide a review of the major work on integration costs in long term models. This is followed up with a review of the few papers that discuss integration costs in shorter term models and shows how our addition of curtailment costs into shorter term modelling contributes to the energy modelling literature.

For long term energy planning, Hirth et al. [4] provide a summary of VR integration costs, noting that these costs are a combination of increased requirements for balancing services, increased cycling of thermal plants, reduced utilization of capital stock and other system level impacts. They organise these costs into three categories:

1. *Balancing costs* reduce the value of VR generation due to deviations of actual VR generation from forecast generation. These costs include the requirement to have standby generators available should the VR generation not meet the forecast and the costs of curtailing generators should the VR generator produce more than forecast.
2. *Profile cost* is the differential market value of VR generation due to the timing of the generation. At times of high VR penetration, the price of energy may be depressed due to the effect of VR energy on the market. VR generators, therefore, may provide lower value on average than dispatchable generators.
3. *Grid related costs* are the differential market value of VR generation