The Electricity Journal 30 (2017) 58–63

Contents lists available at ScienceDirect

The Electricity Journal

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

Reliably integrating variable renewables: Moving grid flexibility resources from models to results

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A R T I C L E I N F O

Keywords:
Grid integration
Renewables
Variable
Solar
Wind
Storage

A B S T R A C T

At least eight kinds of demand- and supply-side grid flexibility resources can complement and firm variable renewables (wind and photovoltaics) at generally lower cost than fossil-fuel backup or bulk electrical storage, supporting largely if not wholly renewable electricity without a battery revolution. Validating dozens of simulation studies, at least 10 nations with modest or no hydropower now reliably use many times the US variable and total renewable fraction with attractive economics and improved reliability.

1. Introduction

The most widespread and persistent myth about electricity is that scaling up variable renewables (wind and solar photovoltaics [PV]) to provide much or most of our electricity will require bulk electrical storage—often claimed to be of equal capacity—for when the sun doesn't shine and the wind doesn't blow. Since such storage today would be costly, some commentators claim that scaling the renewable revolution much further is impractical. But a rising preponderance of industry experts rejects this view, and extensive global experience unambiguously disproves it, for reasons explained below.

A 2015 survey of 1600 stakeholders in 71 countries found the electricity industry rapidly converging on a consensus that with systematic grid integration, high-renewables futures (~70% by 2050) are indeed feasible (Trabish, 2015). By 2017, over 80% of 600 North American utility professionals expected moderate-to-significant renewable increases in their systems over the next decade—and their grid integration concerns had halved in just a year (Trabish, 2017a). Realization is growing that, as the CEO of National Grid said (Beckman and Holliday, 2015a), for integrating variable renewables "It's simplistic to only look at storage. We will have the intelligence available…to ensure power is consumed when it's there and not when it's not there." Such behind-the-meter elements of the modern grid-flexibility portfolio—efficiency, flexible loads, and distributed storage—can combine with onsite PVs to create striking economic value (Rocky Mountain Institute and Reznick, 2014; Rocky Mountain Institute, 2015a, 2015b; Bronski et al., 2015).

Objections that high-renewables futures require breakthroughs in affordable bulk electrical storage have been voiced even by several recent US Secretaries of Energy, but are not consistent with modern literature (Bird et al., 2013; Milligan et al., 2009; American Wind Energy Association, 2015; Goggin, 2017; Solar Energy Industries Association, 2017; Advanced Energy Economy Institute, 2017), and experience. Careful analyses consistently find that largely or wholly renewable power supply can be delivered with little or no bulk storage and at reasonable cost by integrating at least seven kinds of "grid flexibility resources." These generally cost less than bulk electrical storage or fossil-fueled backup. In approximate order of increasing cost, grid flexibility resources comprise:

1. efficient use, which often disproportionately reduces peak load, and whose practical and profitable potential could double US electric end-use efficiency through 2030 (National Academies, 2009), yet was found in 2011 to be twice as big (through 2050) and four times cheaper (Lovins and 60 Rocky Mountain Institute (RMI) coauthors, 2011), then became even bigger and cheaper by 2017 (Lovins, 2017a);
2. unobtrusively flexible demand ("flexiwatts") (Bronski et al., 2015), which also offers cheap primary frequency control (Molina-García et al., 2011; Donnelly et al., 2012);
3. modern forecasting (National Renewable Energy Laboratory (NREL), 2016; Lange, 2017), of variable renewables' output (often more accurately than demand);
4. diversifying those variable renewables—wind and PV—by type and location (just diversifying windpower sites can halve their variability or double their firm output from the same capacity (Palmintier et al., 2008), and wind and PV are often complementary);
5. dispatchability—integrating wind and PV portfolios with the other

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https://doi.org/10.1016/j.tej.2017.11.006

renewables that generated ~54% of modern renewables' 2016 global output (Goldfield et al., 2017) (not counting big hydropower, which could also be integrated more effectively than now (Karier and Fazio, 2017)) and with cogeneration that must run anyhow to satisfy its thermal loads;

6. distributed thermal storage worth buying anyway (*e.g.* ice-storage air-conditioning, perhaps high-temperature heat storage (Forsberg et al., 2016), or managed thermal storage in buildings' existing thermal mass; and
7. distributed electrical storage that's worth buying anyway (*e.g.* smart charging and discharging of electric vehicles bought to provide mobility).

An eighth option—producing hydrogen (Lovins, 2003) from cheap surplus renewable electricity and storing it (*e.g.* in old gasfields) for later use in fuel cells, process heat, or cogeneration—is becoming attractive at recent renewable prices, particularly for seasonal balancing, and can scale almost without limit. Now that unsubsidized renewables in good sites can produce electricity for ~3¢/kWh, heading for 2¢ and perhaps for 1¢, the hydrogen option becomes imaginable because the heat content of 1¢/kWh electricity is equivalent to oil at $17/bbl. Of course this equivalency must be adjusted for the end-use efficiency of both oil and electricity (the latter being far higher), the losses of the electrolyzer and fuel cell, and their costs (less demand response credit for the electrolyzer), but at such low electricity prices, hydrogen could become attractive, especially for process heat and heavy vehicles.

2. Analytic examples of high variable-renewable fractions with little or no bulk storage

A heuristic hourly simulation illustrates grid integration for 100%-renewable 2050 supply of Texas's ERCOT power pool, a difficult case (hot, often humid, electrically isolated from the rest of the US, and only 1% hydro-powered), leaving only 5% of renewable output as surplus to be spilled (Lovins, 2014). Far more detailed state-of-the-art modelling of an 80%-renewable lower-48-states US electricity system in 2050 found a need for storage equivalent to 11% of renewable capacity (National Renewable Energy Laboratory, 2012). Yet changing the renewables from all-centralized to half-distributed cut those storage needs to 5% (Lovins and 60 Rocky Mountain Institute coauthors, 2011), which could be largely or wholly distributed, mostly or entirely in electric vehicles bought for personal mobility.

Thus inexpensive bulk electrical storage would be very useful, and seems to be emerging (as mentioned at the end of Section 6 below), but is not necessary. Along with fossil-fueled backup generation, bulk storage is currently the costliest way to add flexibility to the grid, so it should be bought last, not first. The supply curve of grid flexibility resources will shift, but even if batteries become very cheap, some major grid flexibility resources will remain even cheaper, such as end-use efficiency at negative cost. Even on the very conservative assumption of current battery costs, grid operators have gradually learned (Martinot, 2015) that the cheaper kinds of flexibility resources generally suffice if (to use my colleague Clay Stranger's metaphor) the grid is run as a conductor leads a symphony orchestra: no instrument plays all the time, but the ensemble continuously produces beautiful music.

This approach has been thoroughly modeled for 80%-renewable electricity in the US (National Renewable Energy Laboratory, 2012; Lovins and 60 Rocky Mountain Institute (RMI) coauthors, 2011) and EU (European Climate Foundation, 2013). as well as in China (ERI et al., 2017). Both US studies and the China study used the National Renewable Energy Laboratory's peer-reviewed state-of-the-art ReEDS model—whose US version has 134 balancing areas, 356 wind/solar resource areas, conservative 2010 exogenous costs, and sophisticated nonlinear dynamics—for hourly economic optimization of regional and national electricity investment and dispatch, further validated with ABB's GridView model. A 2013 NREL update with generation 80% renewable and half variable-renewable (at 2012 renewable costs well above today's) found retail electricity prices indistinguishable from business-as-usual (Mai et al., 2014).

Shorter-term, a 2014 General Electric assessment for the PJM power pool found "no significant issues" and virtually unchanged regulating reserve requirements with up to 30% wind-plus-PVs, *i.e.* > 100 GW of new variable renewables (GE Energy Consulting, 2014). The US Southwest Power Pool averaged 21.5% windpowered in March–May 2016 and has approached 40%, but found it could handle up to 60%, with lower cost and less price volatility, by straightforward conventional improvements not including new bulk storage (US Department of Energy, 2017a). The US Eastern Interconnection—by some metrics the world's largest power system—can likewise reliably raise its renewables by more than tenfold (Bloom et al., 2016). More than 30 US studies, some reviewed by a metastudy (Cochran et al., 2014), have validated high-renewable futures' feasibility (US Department of Energy, 2017b) in addition to the first four references in the previous paragraph and many national or regional analyses in Europe, such as those cited below for Germany. Even if options are confined to wind, gas, bulk battery storage, and a dispatchable zero-carbon technology (nuclear or dispatchable renewables), > 70% global decarbonization is feasible without batteries' cost becoming important (Safaei and Keith, 2015).

Illustrating the value of a diversified generating portfolio, during 2008–14, Germany's balancing reserves fell 15% while its wind-plus-solar capacity tripled (Hirth, 2015). A Siemens-funded analysis confirmed that in Germany, whose 2016 renewable electricity was 39% dispatchable (*i.e.* neither wind nor PVs), even the one-fourth renewable fraction of a few years ago reduced the need for winter reserves while dramatically cutting electricity's net costs, especially for heavy industry (Dillig and Karl, 2015). A further German study (Henning, 2014) carefully integrating electric with thermal uses found a modest need for storage of both (Morris, 2014a, 2014b). Two 2014 German studies using an Aachen University hourly optimization model for European power markets found that "no, or very little, new storage will be required to build a grid that is powered almost entirely by renewable energy sources"(Trempier, 2015). A deep German analysis found low grid-balancing costs for high renewables (Fürstenwerth et al., 2014). The International Energy Agency confirmed similarly low grid-balancing costs in eight European countries and the US—on the order of a few $/MWh—for 20–30% windpower (International Energy Agency, 2014). And Australian simulations showed a reliable 100%-renewable mix including 46% wind and 20% PVs (Diesendorf, 2014). Queensland and South Australia (which has only ~20% interchange capacity with Victoria) are already achieving reliable supply with world-class variable-renewable fractions, though coal advocates falsely blamed windpower for a blackout that more of it could have averted (Australian Energy Market Operator, 2017).

A 100%-renewable analysis for Denmark (Danish Energy Agency, 2015), found substantial use for heat storage but concluded that swapping power with the hydro-rich Nordic grid, as Denmark now does, would cost far less than bulk electricity storage. Thermal storage, already common and profitable with hot water and air conditioning, can become a grid resource with energy management using buildings' existing thermal mass as a storage medium. That costs almost zero. In general, it costs far less to store heat or coolth than to store electricity. For decades, New Zealand has used simple electric-water-heating storage, controlled by over- and under-frequency relays, to stabilize its hydro-dominated grid.

3. Empirical international examples of high variable-renewable fractions

Successful grid integration has been *empirically* demonstrated in several European countries with modest or no hydropower, yet getting about half their 2014 electricity consumption from renewables without adding bulk storage or degrading reliability (Morris, 2013): dividing net