A Comparative Study of High Renewables Penetration Electricity Grids

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***Abstract*—Electricity grids are transforming as renewables proliferate, yet operational concerns due to fluctuations in renewables sources could limit the ultimate potential for high penetrations of renewables. In this paper, we compare three electricity grids – California, Germany, and Ontario – studying the effects of relative cost of solar and wind generation on the selection of the renewables mix, and examine the resulting excess generation. We then observe the effects of the renewables mix and the use of baseload energy generation on the limits to renewables penetration, quantifying what proportion of delivered energy can be provided by renewables. Our study shows that the optimal renewables mix, from the perspective of minimizing total cost of generation, is highly dependent on the relative costs of technology, and that above a certain penetration rate, different for each grid, the optimal mix must contain both solar and wind generation.**

I. INTRODUCTION

Federal, state, and provincial governments have implemented emissions targets and renewables portfolio standards that are accelerating the pace of deployment of renewables generation. Even though progress has been promising, with some grids having added tens of gigawatts of renewables, the longer term is murky; electricity grids are beginning to experience exceptional and challenging events, often caused by sudden and dramatic changes in renewables output. Meanwhile, long-term emissions targets essentially prohibit the use of fossil fuels for firming fluctuating renewables [1], a constraint that fundamentally alters operation of electricity grids.

Many have studied how to make the transition to high renewables penetration on specific electricity grids [2], [3], [4], and have been able to show that extreme levels of penetration, sometimes even 100%, are achievable. What makes our study different is that we compare multiple regions with very different characteristics – we employ generation data from three electricity grids in California, Germany, and Ontario. We describe and employ a scaling methodology that uses time series data by generation type, rather than statistical characterizations that may obscure some of the challenge of especially difficult and long-lasting events, to scale grids to higher levels of renewables penetration. Studying these high penetration models, we examine the effects of the relative cost of wind and solar generation on the mix of renewables capacity and the resulting excess generation. We continue by quantifying the limits to renewables penetration for these grids considering the relative cost of solar and wind, the resulting excess generation, and the selection of non-displaceable baseload generation sources.

II. ELECTRICITY GRIDS

We compare electricity grids for three regions: California, Germany, and Ontario. Statistics about these three grids can be found in Table I. The grids have a range of sizes and renewables penetration levels, and represent geographies with considerably different energy resources. Though the portfolios of existing generation sources differ substantially, the challenge of matching supply to highly-variable electricity demand is common to all electrical grid operators. We continue by further describing each grid, including data sources, the current state of renewables, relevant policy directives, and patterns to supply and demand.

	CAISO California	EEX Germany	IESO Ontario
Mean Power	26.3 GW	50.8 GW	17.1 GW
Min / Max Power, Hourly	18.8 GW / 47.1 GW	24.4 GW / 72.6 GW	11.9 GW / 24.9 GW
Min / Max Power, Daily Mean	21.5 GW / 36.7 GW	32.8 GW / 66.2 GW	14.0 GW / 21.6 GW
Renewables Penetration	10.9 %	26.5 %	24.7 %
Solar Capacity	0.4 GW	30.8 GW	0.0 GW
Wind Capacity	2.8 GW	30.7 GW	1.5 GW
Capacity / Load Factor[1]*, Solar*	28.7 % / 25.3 %	6.2 % / 8.6 %	12.6 %[2] / 15.6 %[2]
Capacity / Load Factor[1]*, Wind*	29.1 % / 33.2 %	16.1 % / 20.6 %	34.8 % / 32.2 %

TABLE I. ELECTRICITY GENERATION STATISTICS OVER ONE YEAR ON THREE ELECTRICITY GRIDS: CALIFORNIA, GERMANY, AND ONTARIO.

A. *CAISO - California*

The California Independent System Operator (CAISO) holds balancing authority over 80% of the electricity grid of California. CAISO began to release hourly supply data for its ten different types of generation sources starting from April, 2010 [5]. Capacity ratings are provided by the California Energy Commission (CEC) for each of the 1007 generators under CA ISO management with the exception of Imports, which reflects power purchased from other operators in the Western U.S. interconnect [6]. Figure 1 shows a yearlong breakdown of the sources of electricity consumed in the CAISO operating region, from August, 2010 to August, 2011[2]. Electricity demand (and, thereby, production) varies on multiple timescales: *daily* with peaks in the late afternoon and nadirs

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[1] Capacity factor is the ratio of mean delivered power to rated power, and load factor is the ratio of mean delivered power to peak power.

[1] The Ontario solar trace is synthesized. Further details in Section II-C.

[2] Note that this period is different from the other two grids. We do not believe that slightly less recent data change our conclusions.

in the night, *weekly* with weekends on average 9.6% lower than weekdays, and *seasonally* with winter load on average 15.8% lower than air-conditioner-driven summer load.

A crucial driver to the creation of the existing blend of generation resources is the state energy policy that governs the economics of supply deployment – chiefly, California has mandated a renewables portfolio standard (RPS) target, whereby 33% of the state's generated electricity (in energy, not capacity) must come from renewable sources by the year 2020, building upon a previous, though unmet, RPS mandate of 20% of generation by 2010 [7].

Of these generation sources, the renewables proportion consists of wind, solar, geothermal, biomass, biogas, and small hydroelectric (only facilities less than 30 MW) generation, a total of 10.9% of annual energy delivered. Additionally, renewables also comprise an unpublished proportion of the imported energy, which itself comprises 28% of total generation during the year under study; we do not consider these renewables, as they are not yet separated and measured. The imported energy comes from the U.S. Southwest (primarily coal and nuclear, with some solar) as well as the U.S. Pacific Northwest (mainly coal and hydroelectricity). Thermal is almost entirely natural gas combined-cycle and single-cycle plants providing base, intermittent, and peaker capacity.

B. EEX - Germany

The European Energy Exchange (EEX) operates the electricity market for Germany. EEX provides a Transparency Platform that publishes hourly data on generation from solar, wind, and conventional energy resources (not broken out), as well as capacity data for all power generation facilities [8]. Using data for annual energy generated from biomass, municipal waste, hydroelectricity, and nuclear, we synthesize traces for these categories assuming constant generation for each source [9]. Figure 2 shows a yearlong breakdown of the sources of electricity consumed in Germany for the year 2012. The installed renewables base of 61.5 GW, split evenly between solar and wind, is the second largest renewables deployment in the world (behind China). Germany has aggressively developed renewable generation sources, particularly by incentivizing a homegrown solar industry via feed-in tariffs. The German grid, which derived 16% of its energy in 2012 from nuclear generation, will see significant changes in the coming years, as recent policy decisions in response to the Fukushima disaster accelerated plans to abolish nuclear power generation from the original target of 2036 to a more ambitious goal of 2022 [10].

Of these generation sources, the renewables proportion consists of wind, solar, biomass, municipal waste, and hydroelectric generation, a total of 26.5% of annual energy delivered. The remaining conventional generation is primarily from lignite, hard coal, and natural gas. Germany does have 7.9 GW of pumped hydroelectricity storage, but we do not consider this in our analysis.

C. IESO - Ontario

The Independent Electricity System Operator (IESO) balances supply and demand across the electricity grid of Canada's most populous province, Ontario. The IESO provides hourly output and capability (capacity) for each of the 88 generation facilities in its territory [11]. Figure 3 shows a yearlong breakdown of the sources of electricity consumed in Ontario for the year 2012. Renewables on this grid, delivering 24.7% of energy, are comprised of hydroelectric and wind generation; a majority (56.6%) of energy is from nuclear generation, representing a very different data point from the other two grids under study. As opposed to Germany, the lack of any utility-scale solar generation is interesting, given that a substantial portion of the province is further south than the southernmost point of Germany and has better solar resources.

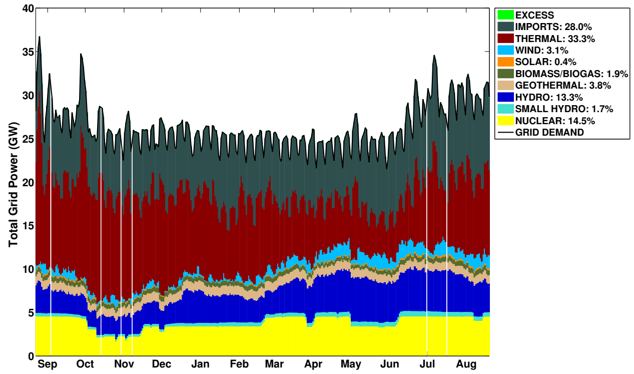

Fig. 1. CAISO - California. A year of daily mean power, by generation type.

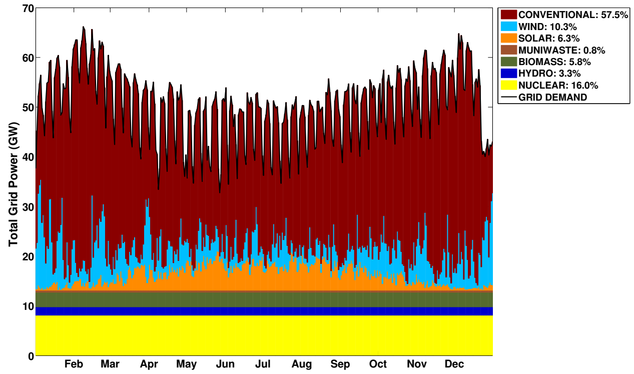

Fig. 2. EEX - Germany. A year of daily mean power, by generation type.

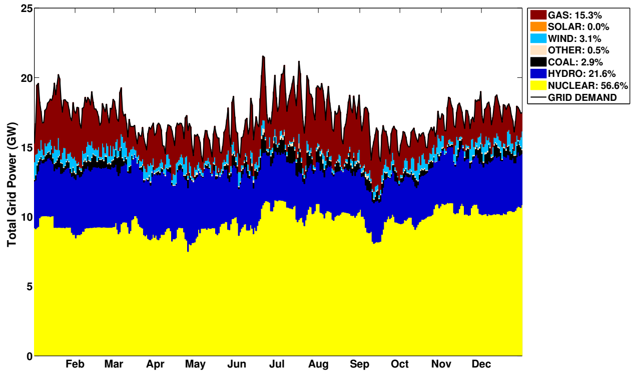

Fig. 3. IESO - Ontario. A year of daily mean power, by generation type.

Since we desire to consider solar generation as a utility-scale generation resource, we synthesized an aggregate solar trace using generation data from PVOutput for twelve solar generation facilities located throughout Ontario [12]. This aggregation is able to provide a trace representing the geographic diversity of the solar resource available in the province, but is vulnerable to the specific characteristics of the small number of installations. In our experiments, we scale this aggregate trace to study the viability of solar generation in Ontario.

The annual load shape for Ontario shows both a summer, air-conditioner driven peak and a winter, heating-driven peak. The magnitudes of these peaks has been changing – until 1998, the winter peak was always higher, but since then, the summer peak has been higher for every year except one [13]. Simultaneously, Ontario has taken significant steps to phase out its coal generation in favor of natural gas generation [14].

III. SCALING RENEWABLES PENETRATION

In this section, we present a methodology for altering renewables penetration on electricity grids using temporal generation data. We make three key assumptions: we are given time series and capacity of each generation type; the demand curve is fixed and unresponsive to availability or cost of electricity (*i.e.*, no demand response), and thus, aggregate supply equals demand; and renewable generation can be scaled proportionally to increase generation. Given these assumptions, we seek to understand how to meet the demand curve by using mixes of energy sources other than the original one.

We assume that time is slotted and the index for a time slot is i. For each grid we are given a yearly supply curve $\mathfrak{S} = (S_1, \ldots, S_K)$, *i.e.*, a time series of what energy was supplied in the grid on an hourly basis. Let $E_d = \sum_{i=1}^{K} S_i$ be the total energy delivered in the year where K is the number of hours in a year. We also know the original mix of sources, *i.e.* $S_i = \sum_{j=1}^{J} s_{i,j}$ where the grid has access to J sources of energy and $s_{i,j}$ is the amount of energy supplied by source j in time slot i.

With fixed demand and no major demand response, we assume the supply curve $\mathfrak{S}$ equals the demand curve $\mathfrak{D} = (D_1, \ldots, D_K)$, ignoring ancillary services. Further, we assume that the regulator is imposing a penetration rate of renewables of p, denoting that the portion of total energy *delivered* to consumers by renewable sources over the year should be pE_d. Though we scale just 2 types of non-dispatchable renewable sources, solar and wind, more types could be considered if needed. For each of these 2 sources, we know the existing capacity in the grid under consideration, say $\mathfrak{C}_{\mathfrak{s}}$ for solar and $\mathfrak{C}_{\mathfrak{w}}$ for wind and the time series $\mathfrak{E}_{\mathfrak{w}} = (e_w(1), \ldots, e_w(K))$ and $\mathfrak{E}_{\mathfrak{s}} = (e_s(1), \ldots, e_s(K))$ where $e_w(i)$ is the energy generated by the wind in time slot i and $e_s(i)$ is the energy generated by solar in time slot i. By selecting a factor $a \geq 0$, we can proportionally scale the existing capacity of either of these sources, resulting in a time series that reflects the geographic diversity of the resource in the grid.

In our methodology with fixed $\mathfrak{D}$, increased renewables generation *displaces* some existing source of energy that may be too polluting, expensive, or dangerous to operate. We group the original mix of energy sources into 3 categories, renewables $\mathfrak{R}$, base load generation $\mathfrak{B}$, *i.e.*, the set of sources of energy that cannot be replaced easily, and displaceable generation $\mathfrak{U}$, *i.e.*, the set of sources of energy that can be replaced. Hence, we can now rewrite S_i as $r_i + b_i + u_i$.

We now consider a mix of renewables $(a\mathfrak{C}_{\mathfrak{s}}, b\mathfrak{C}_{\mathfrak{w}})$. This mix generates in each time slot i a total energy equal to $ae_s(i) + be_w(i)$. We use this energy in this time slot to displace (if possible) u_i. Hence, if $ae_s(i) + be_w(i) - r_i \geq u_i$, we can displace u_i completely and create an excess of renewables in this time slot corresponding to $x_{a,b}(i) = ae_s(i) + be_w(i) - r_i - u_i$. If $ae_s(i) + be_w(i) - r_i < u_i$, then some of the original displaceable energy must be maintained, *i.e.*, $u_i - (ae_s(i) + be_w(i) - r_i)$. Let $Y(a,b)$ be the total amount of displaced energy, *i.e.*, $Y(a,b) = \sum_{i=1}^{K} \min\{u_i, ae_s(i) + be_w(i) - r_i\}$ and $X(a,b)$ be the total amount of excess energy, *i.e.*, $X(a,b) = \sum_{i=1}^{K} (-u_i + (ae_s(i) + be_w(i) - r_i)^+$

A mix of renewable $(a\mathfrak{C}_{\mathfrak{s}}, b\mathfrak{C}_{\mathfrak{w}})$ is **p-feasible** $(0 \leq p \leq 1)$ if $Y(a,b) + \sum_{i=1}^{K} r_i \geq pE_d$ ($a \geq 0$ and $b \geq 0$). Note that p cannot take any values. At best, we can displace the whole existing displaceable energy $E_u = \sum_{i=1}^{K} u_i$. Let $E_r = \sum_{i=1}^{K} r_i$ be the whole existing (in the original mix) renewable energy. Then we can define a *hard limit* to renewables penetration: $p \leq \frac{E_r + E_u}{E_d}$. We discuss this concept further in Section V.

In choosing a generation mix, we seek to find among all the p-feasible mixes of renewables the one that minimizes total cost where we assume that the cost of a renewables category is proportional to its capacity, *i.e.*, the total cost of solar capacity $a\mathfrak{C}_{\mathfrak{s}}$ (resp. $b\mathfrak{C}_{\mathfrak{w}}$) is $\pi_s a\mathfrak{C}_{\mathfrak{s}}$ (resp. $\pi_w a\mathfrak{C}_{\mathfrak{w}}$) where π_s and π_w are known positive numbers. Let the cost obtained through this minimization be Γ_{min}. We are also interested in observing the total excess $X(a,b)$ for a given target cost $\Gamma \geq \Gamma_{min}$.

Hence we can write the problem as: given $\mathfrak{S}$ and the original mix, given $p \leq \frac{E_r + E_u}{E_d}$, given $\mathfrak{E}_{\mathfrak{s}}$ and $\mathfrak{E}_{\mathfrak{w}}$, given the set $\mathfrak{F}$ of p-feasible renewable mixes $m(a,b)$, solve:

$$\mathfrak{P}_{\mathfrak{1}} \quad \min_{m(a,b) \in \mathfrak{F}} \pi_s a\mathfrak{C}_{\mathfrak{s}} + \pi_w b\mathfrak{C}_{\mathfrak{w}} \tag{1}$$

Let Γ_{min} be the solution of $\mathfrak{P}_{\mathfrak{1}}$ and the renewable capacity corresponding to Γ_{min} be $\Delta^*(p) = a^*\mathfrak{C}_{\mathfrak{s}} + b^*\mathfrak{C}_{\mathfrak{w}}$ where a^* and b^* are the solutions of the problem. Note that $\Delta^*(p)$ is a function of $\frac{\pi_w}{\pi_s} \triangleq \Theta$.

IV. EFFECTS OF COST

Regulators, utilities, and independent energy generators consider a host of factors in deciding where, when, and what type of renewable energy generation to deploy. Beyond factors that affect energy output – such as site and transmission availability, weather patterns, and selection of generator technologies – there are a range of economic and policy factors. Weighing all of these inputs and making a rational choice is not straightforward. Tools like levelized cost-of-energy calculators [15] attempt to combine capital, operations and maintenance, performance, and fuel costs to provide a basis for comparison among different generation choices. However, these calculators often do not include costs related to financing, replacement, degradation, as well as possible benefits connected to subsidies and other policy drivers.

In this section, we study the sensitivity of Θ, the ratio of the 'costs' of deploying additional wind generation and additional solar generation. The cost here attempts to encapsulate all of the economic and policy considerations; we do not take a position on how to calculate this cost, but instead provide analysis to choose a mix that minimizes total solar and wind capacity given a particular cost, grid, and renewables penetration rate. Further, Θ may change over time, due to market factors and influence from policymakers. Additionally, our methodology applies to renewables technologies beyond those presented in this work, including variations of solar, wind, and tidal power. We note that for all the experiments in this section, there is no baseload, non-displaceable generation ($\mathfrak{B} = 0$).

A. Effect of cost on renewables mix

Figures 4, 5, and 6 show the solar proportion of the mix of non-dispatchable renewables capacity at various cost and renewables penetration levels for the California, Germany, and Ontario grids, respectively. These graphs result from proportionally scaling the non-dispatchable renewables sources found in each grid to create a range of penetration levels, and then varying the cost parameter Θ and minimizing the total cost at each point, as in Equation 1. A cost of $\Theta = 1/1$ indicates cost parity, and the left side of each graph ($\pi_s > 1$ and $\pi_w = 1$) represents higher-cost solar and the right side ($\pi_s = 1$ and $\pi_w > 1$) represents higher-cost wind. We note that the total capacity $a\mathfrak{C}_\mathfrak{s} + b\mathfrak{C}_\mathfrak{w}$ changes as a function of Θ and p – for more information, see Section IV-B.

In each case, at lower levels of renewables penetration, there is a value of $\Theta = \Theta^*$ across which there is complete substitution of one technology for another. This is because, at lower penetration levels, demand far outstrips renewable supply, and therefore the renewable supply need not match the pattern of consumption. Θ^* reflects the ratio of capacity factors of the technologies in each grid; in the case of Germany and Ontario, wind has a relatively higher capacity factor than solar, whereas in California, capacity factors are closer to parity.

For any penetration where $\pi_s \gg \pi_w$, the chosen mix is all wind; since wind generation, unlike solar, produces power at all hours, an all-wind mix can attain high penetrations. However, when $\pi_w \gg \pi_s$, a mix of both solar and wind is required to reach higher penetrations, as solar does not produce during the night hours. For each grid, there is a maximum penetration p_s for an all-solar mix. For example, p_s is between 50% and 60% for CAISO. Characterization of all-solar blends and p_s is further explored in Section V.

Last, differences in curve shapes at a particular penetration level on different grids reflect the affinity of each type of generation for that grid's demand pattern; for example, if the curves are shallower, as in Germany and Ontario, more wind is required because the solar resource is not as potent. Also, each graph has a convergence cost Θ_C where, regardless of p, the ratio of capacities $\frac{a\mathfrak{C}_\mathfrak{s}}{b\mathfrak{C}_\mathfrak{w}}$ is roughly equal. At Θ_C, the technologies are in balance; further deployment should yield the same proportion of technologies as already exists, regardless of the level of renewables penetration.

B. Effect of cost on renewables capacity and excess generation

The relative cost of different renewables has a significant effect not only on the renewables blend, but also on total renewables capacity and excess generation. Selecting less efficient technologies because of lower costs results in needing more total capacity. To represent this, Figures 7, 8, and 9 show renewables capacity $a\mathfrak{C}_\mathfrak{s} + b\mathfrak{C}_\mathfrak{w}$ and excess generation X for the California, Germany, and Ontario grids for three values of Θ: $1/10$ (more expensive solar), $1/1$ (cost parity), and $10/1$ (more expensive wind).

In each case, cost parity selects the renewables mix to best represent the energy resources available, resulting in minimal total renewables capacity; from this perspective, any Θ besides parity requires either the same or more capacity. In the case

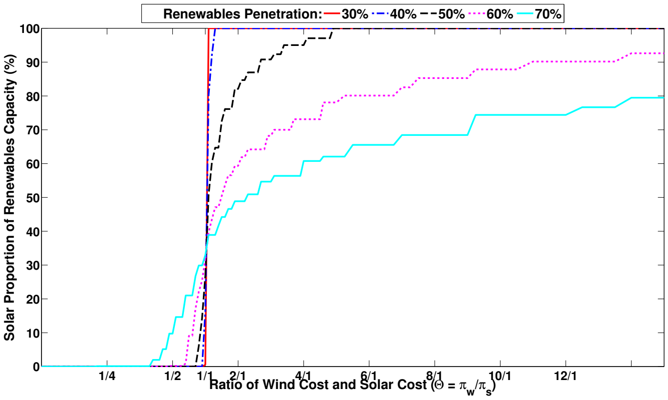

Fig. 4. CAISO - California. Proportion of non-dispatchable capacity that is solar for different renewables penetrations and cost values. Wind is chosen in most scenarios, and required at high renewables penetration levels ($p \geq 60\%$).

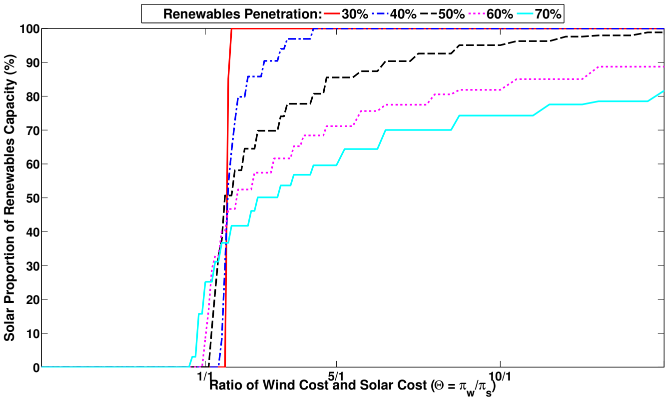

Fig. 5. EEX - Germany. Proportion of non-dispatchable capacity that is solar for different renewables penetrations and cost values. Wind is required to meet renewables penetration levels $p \geq 40\%$. At cost parity ($\Theta = 1/1$), an all-wind blend is always chosen.

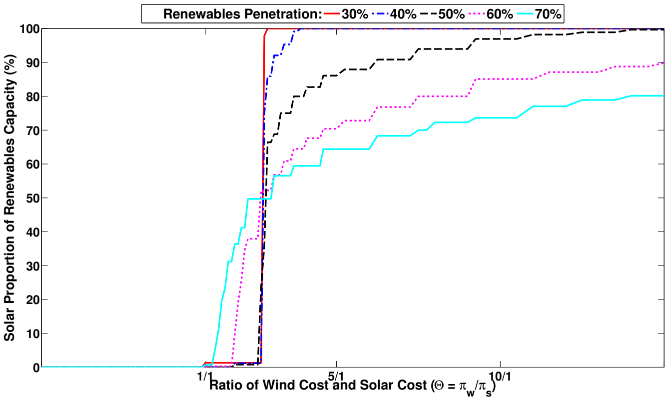

Fig. 6. IESO - Canada. Proportion of non-dispatchable capacity that is solar for different renewables penetrations and cost values. Wind is required to meet renewables penetration levels $p \geq 50\%$. At $p = 40\%$, the cost of wind must be very high ($\pi_w > 10$) to switch from a mixed blend to an all-solar blend.

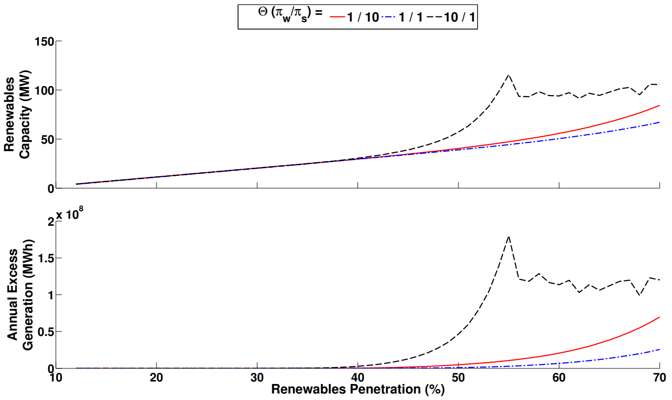

Fig. 7. CAISO - California. Renewables capacity and excess versus renewables penetration at three cost points. The primarily solar blend ($\Theta = 10/1$) incorporates wind generation at $p > 55\%$.

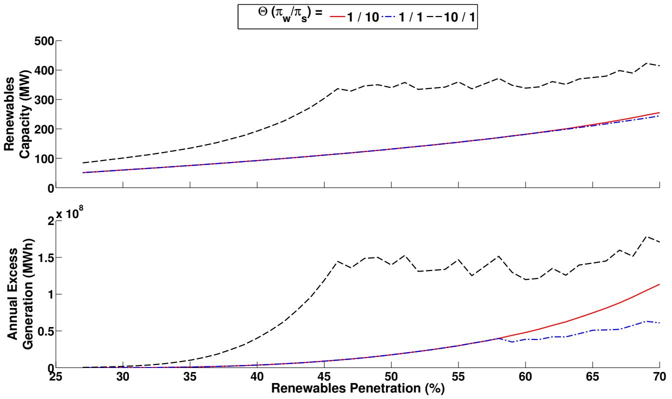

Fig. 8. EEX - Germany. Renewables capacity and excess versus renewables penetration at three cost points. Since wind has a superior capacity factor, the cost parity scenario ($\Theta = 1/1$) chooses the same blend as the scenario where wind is favored ($\Theta = 1/10$).

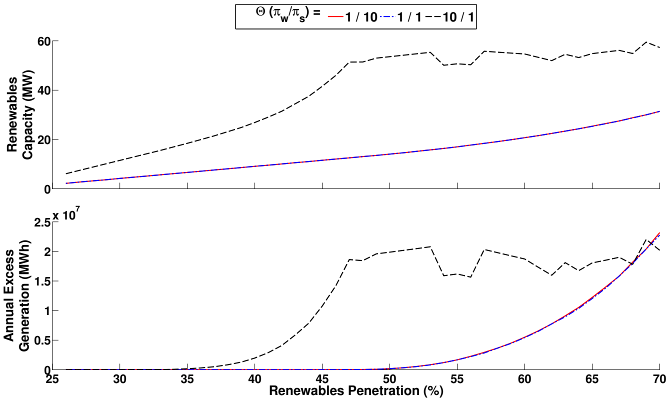

Fig. 9. IESO - Canada. Renewables capacity and excess versus renewables penetration at three cost points. Since wind has a superior capacity factor, the cost parity scenario ($\Theta = 1/1$) chooses the same blend as the scenario where wind is favored ($\Theta = 1/10$). For $\Theta = 10/1$ and $p \geq 40\%$, a mixed solar/wind blend is selected instead of an all-solar blend.

of both Germany and Ontario, wind has a substantially higher capacity factor than solar, such that at cost parity, the capacity mix is all wind generation. Further, in the cases where $\Theta = 10/1$ (more expensive wind), solar is used until a penetration level where the benefit from incremental solar generation is smaller than a tenth of the benefit of adding incremental wind generation, so additional capacity from that point is a mix of solar and wind generation. Of these three grids, with cost parity, only the California grid benefits from having a balance of solar and wind generation. When considering excess generation X, it is important to not only look at the magnitude of generation, but also the capacity required to produce that generation. With this in mind, in each case, the cost-parity blend produces the largest X *per renewables capacity*. Further, more excess from the same capacity may be a benefit; excess could be an opportunity to charge storage, shift loads from other times, or encourage new energy-agile industries.

V. LIMITS TO RENEWABLES PENETRATION

As grids incorporate more fluctuating renewable resources, a critical question is how much renewables capacity can be accommodated. Though the challenges of fluctuating renewables are well known [16], we do not know of any study that studies limits to renewables penetration and their drivers.

Figure 10 presents excess generation X relative to demand $\mathfrak{D}$ in five scenarios from the CAISO grid, the EEX grid, and the IESO grid. Three of the scenarios, all with $\mathfrak{B} = 0$, are identical to those presented in Figures 4– 9. The additional scenarios include non-displaceable baseload generation $\mathfrak{B}$ preventing specific classes of generation like Nuclear and Hydroelectricity from being displaced. We do not present a scenario with nonzero $\mathfrak{B}$ for the EEX grid because German policy aims to eliminate nuclear generation. Additionally, we use a value of $\Theta = 1/1$, the mix of solar and wind generation at cost parity, to allow for comparison among results from different grids. Looking at differences among excess in these five scenarios, we identify two types of limits to renewables penetration: *hard limits*, insurmountable thresholds constrained either by the sum of $\mathfrak{N} + \mathfrak{U}$ or the total demand proportion during available renewable hours, and *soft limits*, arising from how much excess generation X the grid operator is willing to bear. Hard limits are represented by vertical asymptotes on the graph, while soft limits are thresholds on the graph relative to p and are a function of temporal patterns of renewables availability, the amount of non-displaceable generation ($\mathfrak{B}$), and the selected mix of renewables capacity ($a\mathfrak{C}_\mathfrak{s} + b\mathfrak{C}_\mathfrak{w}$). Soft limits are strongly influenced by the minimum value of p for which $X > 0$ and the rate at which X grows thereafter.

To better understand the ramifications of the renewables mix, Table II presents two additional scenarios for each of the five grid configurations: a solar-only grid and a wind-only grid. We can see a wide range of limits to renewables penetration, with soft limits spanning from near 30% all the way up past 90%, and hard limits extending all the way to 100%. A nonzero $\mathfrak{B}$ dictates that renewables have a lower hard limit, providing a narrower range of hours and smaller potential magnitude for renewables generation, resulting in even lower soft limits to penetration. We note that solar generation alone, because of its generation pattern, creates more excess at substantially lower renewables penetrations as compared to wind. All-wind blends tend to perform on par with cost-parity blends, as the generation mix is similar. In all cases, the cost-parity blend can accommodate the most renewables at the lowest generation, a reflection of the effect of Θ. The differences in the grids' blends with $\mathfrak{B} = 0$ shows that the wind generation on the IESO and EEX grids have better affinity to the load shapes on those grids, resulting in soft limits at higher renewables penetrations than the solar-wind CAISO blend.

Renewables Penetrations															
	California - CAISO						*Germany - EEX*			*Ontario - IESO*					
	All Displaceable $\mathfrak{B} = 0$			**Hydro & Nuclear Non-Displaceable** $\mathfrak{B} = 28\%$			**All Displaceable** $\mathfrak{B} = 0$			**All Displaceable** $\mathfrak{B} = 0$			**Nuclear Non-Displaceable** $\mathfrak{B} = 57\%$		
Renewables Mix	**Solar Only**	**Wind Only**	**S/W Mix, Θ=1/1**	**Solar Only**	**Wind Only**	**S/W Mix, Θ=1/1**	**Solar Only**	**Wind Only**	**S/W Mix, Θ=1/1**	**Solar Only**	**Wind Only**	**S/W Mix, Θ=1/1**	**Solar Only**	**Wind Only**	**S/W Mix, Θ=1/1**
10% Excess	46.5%	60.7%	69.0%	35.6%	44.2%	50.4%	40.4%	59.2%	63.6%	46.2%	66.6%	66.6%	31.5%	40.1%	38.0%
25% Excess	50.0%	68.2%	77.1%	38.3%	50.1%	56.6%	44.7%	69.8%	77.1%	49.9%	74.2%	74.4%	32.1%	41.1%	40.6%
50% Excess	52.5%	74.1%	82.8%	40.1%	54.6%	60.8%	48.1%	77.8%	84.6%	52.9%	81.2%	85.4%	32.4%	41.9%	41.9%
100% Excess	55.1%	79.7%	87.7%	42.1%	58.8%	64.3%	51.5%	85.6%	91.0%	55.6%	88.1%	92.2%	32.9%	42.4%	42.8%
Hard Limit	63.5%	100.0%	100.0%	47.1%	72.2%	72.2%	66.6%	100.0%	100.0%	67.7%	100.0%	100.0%	34.9%	43.4%	43.4%

TABLE II. HARD AND SOFT LIMITS TO RENEWABLES PENETRATION IN SCENARIOS ON THE CALIFORNIA, GERMANY, AND ONTARIO GRIDS. THE LEVEL OF EXCESS GENERATION ALLOWED BY THE GRID OPERATOR REPRESENTS SOFT LIMITS ON RENEWABLES PENETRATION, WHEREAS FUNDAMENTAL LIMITS ON RESOURCE AVAILABILITY AND ENERGY DEMAND CONSTITUTE HARD LIMITS ON RENEWABLES PENETRATION.

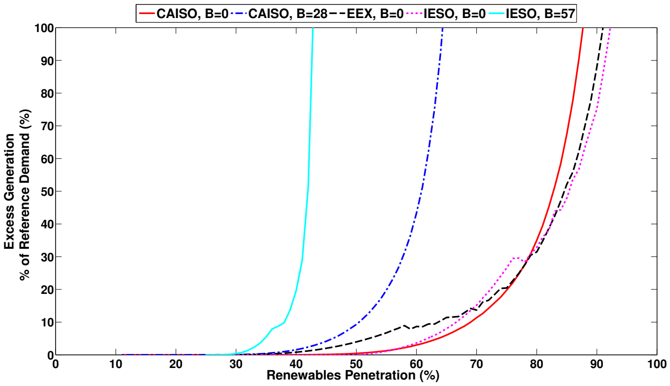

Fig. 10. Excess generation on three electricity grids in scenarios with and without baseload generation. Each line is relative to that grid's total demand.

VI. CONCLUSION

There are a number of extensions that can improve our understanding of limits to renewables penetration. First, the study does not consider unit commitment of energy generation facilities – for example, combined-cycle natural gas generators have limited elasticity, startup times, and maximum ramp rates. Also, dispatchable resources could cooperate with demand management techniques, shifting other dispatchable supplies, or employing utility-scale storage [17]. Second, the study does not incorporate the existing transmission line network, which governs the flow of power from generation sources to regions of demand. Though there is related work that analyzes the limitations of the existing transmission system for incorporating more renewables generation [18], it is difficult to observe nodal limits to penetration without data about nodal demand. Third, our analysis does not consider that the cost of supplying power changes throughout the day; in current economics, this would place higher value on solar generation during the middle of the day rather than wind generation during the middle of the night. However, much higher renewables penetrations are likely to substantially change the economics of the grid, potentially making prices less predictable.

In formalizing a methodology for studying grids at varying levels of renewables penetration and comparing multiple grids using this methodology, we have shown the enormous effect of cost on generation mix, and the transitive effect of generation mix on limits to renewables penetration. We also provide a basis for direct consideration of the factors that influence limits to renewables penetration: baseload generation, the affinity of renewables generation with demand, and the accumulation of excess generation, and discover that limits to renewables penetration are flexible, provided that grid operators are willing to bear moderate quantities of excess generation. Further, we hope to encourage studies beyond this work including the role of energy efficiency and demand flexibility at varying levels of renewables penetration, helping to elucidate a future incorporating unprecedented levels of renewables generation.

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