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Initial Perspective on a 100% Renewable Electricity Supply for Prince Edward Island

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Abstract

Prince Edward Island, already with the highest wind energy penetration of any province in Canada, aims to increase its renewable energy generation. A challenge is realizing better matching of intermittent wind and solar power with on-island electricity demand. This paper provides an initial perspective by considering the case of a 100% renewable island electricity system. Using time-series power data of wind, solar, and electricity demand for the province, varying capacities of wind and solar power along with battery energy storage and biomass are considered to model 100% renewable electrical energy scenarios. Wind, solar, and storage combinations without curtailment show how complementary supply combinations can reduce seasonal variations. Scenarios including curtailment demonstrate significantly reduced storage requirements. Scenarios that include biomass suggest little value in combining biomass and storage. Least-cost solar, wind, and storage capacities are estimated and storage cost reductions appear to be transformative in enabling greater renewable energy integration.

Keywords: renewable energy, integration, wind, solar, energy storage

Introduction

Prince Edward Island (PEI), like every province or territory in Canada, is challenged with reducing its greenhouse gas emissions as the country takes steps toward its commitments under the Paris Agreement [1]. Carbon pricing is already on the horizon following the Pan-Canadian Framework [2]. PEI is unique in its small geographic area, single connection point with other electrical grids, and almost exclusively wind power for its own electric energy generation. From a power-flow perspective, just over half of the electricity used on PEI is supplied via undersea cable from neighbouring province New Brunswick. As Canada's smallest province, PEI's emissions are miniscule in comparative terms yet it faces the same upcoming carbon pricing pressures. As well, PEI's electricity prices are roughly 20% higher than the population-weighted national average [3] and the prevalence of wind farms on PEI suggests relatively good public acceptance toward renewable energy. The PEI Energy Accord of 2011 mandated an increase in wind energy for the sake of greater energy independence and price stability [4]. Together, these factors make a strong incentive for increased renewable energy in the PEI electrical supply. In May 2016, the Standing Committee on Infrastructure and Energy recommended a strategy to meet all energy use with renewables by 2050 [5]. This was not listed in the Provincial Energy Strategy released later that year, but the strategy does list increasing wind energy generation as a top priority, while mentioning the rising potential of solar power and smart grid technologies [6]. For reasons of energy security and striving for a 100% island-generated renewable energy supply, it is informative to consider a stand-alone island electrical power supply where a mix of technologies are required to allow the energy produced from available intermittent renewable sources to be kept on-island. This paper uses measured 15 minute wind generation and demand data to present an initial study on the prospects of converting PEI's electricity system to be supplied entirely by local renewable energy sources and where there is no exchange of energy with New Brunswick.

1.1 PEI's Electricity System

Future possibilities should be considered relative to the existing energy system. The current PEI grid spans the island from tip to tip. It is connected to New Brunswick though undersea cables–two 100 MW cables that are well into their useful lifetime and two new 180 MW cables [7]. Most of the grid is operated by Maritime Electric, the provincial utility, while the portion covering PEI's second-largest city, Summerside, is run by a city-owned utility [8]. Sub-hourly data of electrical load and wind energy generation on PEI is available from a provincially-run energy data website [9], providing a data-rich view into the province's electrical energy situation. The load duration curve for PEI in 2014 is shown in Figure 1. This indicates the number of days per year that the load exceeds a certain amount. For example, the left side of the curve indicates that the load exceeded 200 MW for a total time of roughly 30 days. The right end of the curve shows that the load was greater than -70 MW for the full duration of the year.

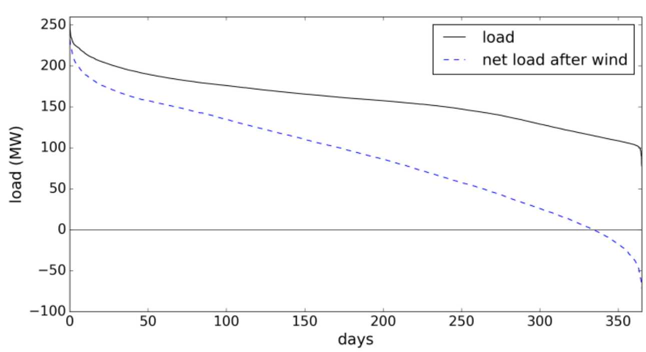

Figure 1. Load duration curve in 2014.

According to the data, PEI's electrical demand in 2014 was 160 MW on average and 260 MW at peak. Total on-island wind capacity is currently 204 MW. Wind energy represents the vast majority of on-island electricity generation. Previously, a small amount came from now-unnecessary fossil-fuel peaking generators. Currently, there is a small but growing amount of net-metered grid-connected solar photovoltaic capacity being deployed. Logged data shows that wind generation meets over 40% of on-island electric energy demand in a real-time energy-flow sense, though roughly half is under power purchase agreement off-island. The load duration curve for PEI after on-island wind power generation is subtracted is also shown in Figure 1.The remaining load is met by imports from New Brunswick under an agreement with NB Power [4]. The result is that intermittency in on-island wind generation is compensated for from the New Brunswick grid. From a conventional perspective, dealing with the highly sloped net load duration curve is the challenge with including more renewables, or in integrating the existing renewables without relying on the New Brunswick connection. The small negative portion of the net load duration curve in Figure 1 reflects that very little of the on-island wind-generated electricity actually leaves the province in terms of energy flow. According to the x-intercept of the curve, electricity is only exported from PEI 8.5% of the time.

1.2 Relevant Technologies and Strategies

Beyond what is already implemented, a range of technologies as well as the strategies to integrate them exist to enable greater renewable energy integration. These range from renewable energy generation combinations to power conversion, energy storage, and flexible or efficient end use technologies. This paper endeavours to consider those which are most plausible for PEI.

The cost of solar photovoltaic (PV) technology is steadily declining [10], approaching the cost competitiveness of wind power. Solar PV also has the important advantage of scalability, being suitable for residential and commercial rooftop applications in urban areas as well as utility-scale farms. Solar energy is also particularly well-suited for ‘behind the meter’ installations where its economic viability is more influenced by higher retail costs of electric energy. Wind energy, which is already competitive with conventional generation at large scales, sees further projected improvements in cost and capacity factor as turbine designs evolve [11]. Other renewable generation technologies such as wave and tidal power lack the local scale or technological maturity to be considered significant contenders at present, though that may change. Biomass-based generation does have potential as a resource, but limited land area which is already used for agriculture limits the scale that could be practical [12]. However, biomass-based fuels offer the advantage of dispatchability, meaning they could play a role in meeting occasional supply shortfalls even if the annual consumption is relatively small.

In terms of electrical energy storage, lithium ion batteries have quickly become the leading option across a range of conditions and scales. Current statistics suggest they are cost competitive with other electrical energy storage technologies that don’t rely on specific geographies [13]. Furthermore, their high discharge rates, ease of deployment, and declining cost mean that their future potential appears strong. Storage technologies that do rely on geography, such as pumped hydro or compressed air energy storage, offer lower costs but do not hold obvious promise for PEI given the Island’s flat geography. Thermal energy storage may be a compelling option, especially because of the high heating needs of PEI during the winter. As electrification of household heating continues, demand response through thermal load shifting could also play a large role in helping demand meet supply [14]. The city of Summerside, PEI already implements such a program, which could be replicated across the province with the required infrastructure. Smart-grid coordination of electric vehicle charging and flexible loads at the municipal, commercial, and industrial level offer additional means of adjusting demand to better accommodate renewables.

The general rationale for emphasizing multiple renewable energy sources is the potential to smooth out fluctuations in energy supply by combining energy sources with complementary seasonal variations. This is applicable on PEI; Figure 2 shows the complementary seasonal trends of solar and wind power available on PEI, with more wind in winter and more solar in summer.

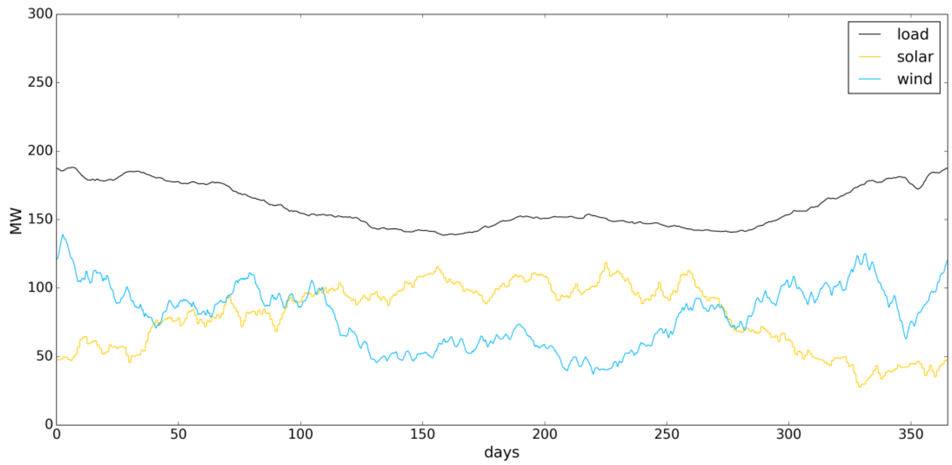

Figure 2. Seasonal trends in load, solar power, and wind power, illustrated with wind and solar each providing half of total energy demand, and all data smoothed by 10 day moving average.

In seeking high penetrations of renewable energy, especially in an "islanded-grid" scenario where exchange with New Brunswick is not considered, it can make economic sense to curtail, or not harness, some of the available renewable energy at times of excess. Having a wind or solar farm not convert all of the available energy would represent a loss of revenue to the farm owner. However, at high penetration levels there can be little practical alternative and it is a common practice in some places.

2. Methodology

This study explores 100% renewable energy scenarios for PEI's electricity system by running year-long time-series simulations and modelling electricity generation, storage, and load. This modelling approach, which works on 30 minute time intervals, allows accounting for the issues of integrating intermittent supply and demand which are at the crux of the renewable energy integration challenge. With reasonable cost assumptions, different scenarios can be compared quantitatively and the most cost-effective possibilities identified.

2.1 Time Series Data Sources

The analysis uses historical data for the PEI load and wind generation in 2014 archived from 15 minute web-based updates of a provincial energy data website [9]. The electric load from the archived data is used as-is. The wind generation time series are taken as representative of the intermittency of the resource and are normalized and then scaled to represent different possibilities for increased wind capacity. To account for a new wind farm coming online in the fall of 2014, the wind power data before this date is scaled up proportionally to simulate the same installed capacity throughout the time series.

Normalized hourly solar electric power data was produced using HOMER Energy software's synthetic hourly data generation feature [15] and then output through HOMER's generic fixed-tilt PV module and inverter model. The necessary monthly average values for PEI's geographical coordinates were sourced from NASA's solar energy database. The annual yield from this normalized dataset is 1.2 MWh/kWpk of installed solar, which corresponds with the expected resource availability [16]. Though this data is synthetic, it captures key temporal aspects including longer days in the summer, shorter days in the winter, angular effects of the changing position of the sun and impacts of weather variability, all of which are of interest for the analysis. The algorithm HOMER uses to generate hourly data from monthly averages is based on work by Graham and Hollands [17]. It uses statistics that are global averages and does not perfectly replicate the solar resource for a given region. For example, there is no specific accounting for events such as morning coastal fog or regular afternoon showers. However, the algorithm is thought to provide reasonably accurate solar resource information that includes typical intermittency due to weather patterns. According to [18], there is typically less than 5% difference between the synthesized PV output and measured data, which is acceptable for the purposes of this initial perspective study.

Samples of the measured load and wind data and the synthesized solar data are shown in Figure 3. The wind and solar power time series are normalized to a maximum value of one to facilitate scaling to represent different installed capacities. The capacity factor from the recorded data for wind is 35.4% and that for the synthesized solar data is 13.4%.

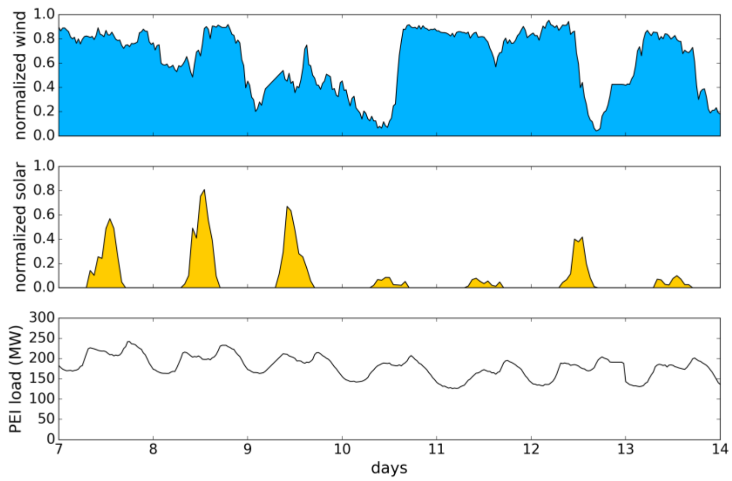

Figure 3. One week (Jan 7-14, 2014) of data for normalized wind power, normalized solar power, and PEI load.

2.2 Scenario Simulation

A scenario is defined by the time series already mentioned, the choice of which technologies to consider, and assumed costs of the technologies. The installed capacities of wind, solar, storage, and biomass as applicable are the design variables which are optimized to minimize the cost of energy in the scenario.

Simulation begins by comparing the total generation with the load at every half-hour time step. Battery energy storage is simulated using a simple causal model where the energy surplus or shortfall at each time step is stored or taken from the battery, within the battery's capacity limit. Limits in charge/discharge rates and efficiency are not considered at this stage. Any remaining excesses can be considered as calling for either wind and solar curtailment or for use in non-electric applications which fall outside the electrical system such as seasonal thermal storage for use in district heating. These are not currently accounted for.

The model can address shortages by considering the costs of a dispatchable fuel-based tertiary generation source. In keeping with the 100% renewable scope of the study, this is considered to be a biomass fuel source. It is important to note that, with sufficient storage capacity present, the lead-up time before these backup fuel sources are needed could be in the order of hours. This raises the possibility of having these generation sources in a non-running state most of the time, avoiding the inefficiency disadvantages of typical "spinning" reserves. Because the simulated scenarios contain a significant amount of energy storage – or are insensitive to its addition – this softening of the ramping requirements on biomass plants can be reasonably assumed. With that in mind, biomass generation is modelled as instantly dispatchable without ramping limits, and this simplification is thought to have negligible influence on the results.

2.3 Costs

Costs of generation and storage technologies are calculated based on capital, operating, and fuel costs from several published sources. These are summarized in Table 1. Costs for wind are based on rounded mean values from the Open Energy Information Transparent Cost Database curated by the US National Renewable Energy Laboratory [19]. Wind turbines are taken to be MW-scale as currently exist on the island. The cost for solar power represents utility scale plants at a similar scale to the wind farms currently on PEI and are in line with [20]. However, smaller PV installations at the residential and commercial scale often compete 'behind the meter' in retail rate electricity markets. These smaller systems can be double the cost of utility scale systems but they are usually offsetting higher, often double, the cost of electricity. In this respect all PV deployed on the island can be approximated by utility-scale costs [10]. Biomass costs are based on numbers from [21] and [22]. Fuel costs, which are heavily location dependent, are estimated from nearby New England wood chip prices assuming an electrical conversion efficiency of 30%. Details such as location-specific transportation costs are neglected in light of the approximations made for additional costs associated with biomass.

Table 1: Cost Assumptions

	Wind	Solar	Biomass	Battery
Capital cost	2000 $/kW	2000 $/kW	5000 $/kW	500 $/kWh
Fixed operating ($/yr/kW)	30	20	120	
Variable operating (excluding fuel) ($/MWh)	8	0	11	
Fuel Cost ($/MWh)			40	
Lifetime (years)	20	30	20	5000 times capacity divided by throughput

Because using biomass as a main source of generation raises a number of issues (e.g. [12]), an additional cost of $100/MWh is placed on it in the model. For context, this is similar to the cost that would arise if the Carbon tax amounts currently being discussed for Canada were implemented immediately and applied to biomass generation. This cost could also be interpreted as the social cost of air quality impacts from such large amounts of biomass combustion, or the expense of equipment to mitigate pollutants that would damage air quality.

The cost of energy storage in lithium batteries is calculated by assuming a capital cost of $500/kWh of storage capacity and that the battery end of life occurs when its total energy throughput reaches 5000 times its storage capacity. The levelized cost of battery storage then depends on both the installed capacity and the rate of use.

Once a scenario has been simulated, the installed capacities and resulting energy production quantities are input into the cost model. Capital costs are calculated for each technology and then amortized over the technology's expected lifetime using a discount rate of 6%. These are combined with operating costs and then divided by overall electrical demand to calculate the levelized cost of energy, which is the objective function of the optimization.

2.4 Optimization Approach

Subject to assumptions about how shortages and surpluses of power are accounted for, capacities of wind, solar, and storage can be varied in an attempt to find the lowest cost way of meeting electrical demand. For scenarios where curtailment and biomass generation were not considered, the least-cost configuration was found by a parameter sweep of the range of capacity options. For more complex cases, a genetic algorithm optimization approach [23] was used to avoid having to sweep the full design space when additional variables were at play.

3. Results and Discussion

Three types of scenarios for the electricity system are considered:

- 100% renewable generation with wind, solar and storage only, without curtailment;

- Wind, solar and storage, with the option of curtailment;
- Wind, solar and storage, with curtailment and biomass to provide dispatchable generation.

This progressive increase in the options considered is informative in showing the cost reductions enabled from each. The second approach builds on the first by considering curtailment, which would be an adjustment from current renewable energy power purchase agreement norms on PEI. The third option builds further by allowing a fuel-based source of generation which dramatically reduces the energy storage requirements.

3.1 100% Renewable Generation Scenarios Without Curtailment

This first scenario-based approach allows for an initial perspective on what defines an independent, 100% renewable electricity system in the absence of renewable energy curtailment or a dispatchable fuel source. Three scenarios are explored which permit the total island load to be powered by either 100% solar, 100% wind or an optimal combination of both. In each of these scenarios the annual renewable energy generation equals the load energy. Integrating the net load over time, the peak-to-peak value of this accumulated energy balance defines the storage capacity required.

To no surprise, the required battery sizes are large and the system costs far from economic at today's pricing. However, these results are informative in revealing a distinct minimum in storage size requirement when solar and wind installed capacity are optimally combined due to their complimentary nature. As well, considering an order-of-magnitude reduction in battery cost shows how future technology developments may make these scenarios feasible. The results are discussed below and summarized in Table 2.

Scenario 1a: Wind with storage

According to the data and model assumptions, meeting PEI's electricity needs with 100% wind, with battery energy storage and no curtailment requires 448MW of wind, a bit over double today's installed wind capacity, and 132 GWh of batteries. Figure 4 shows time series of wind, load, net load, and storage state of charge. The net load is simply the difference between load and generation. The noticeable seasonal variation in stored energy illustrates a relative lack of wind in the summer season as compared to the winter. Statistics including costs are given in Table 2.

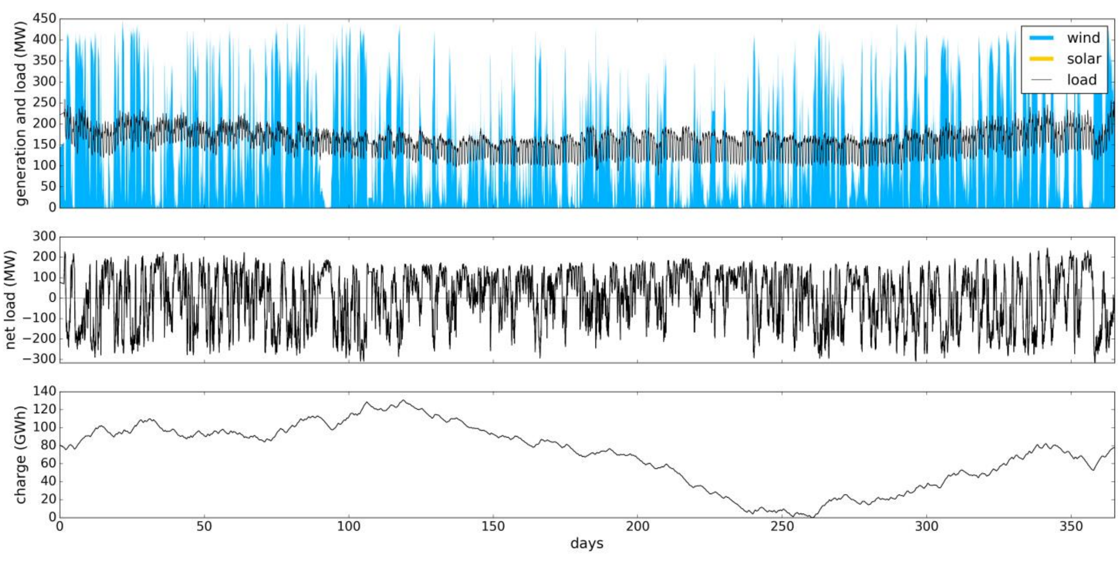

Figure 4: Wind with storage scenario.

Scenario 1b: Solar with storage

If powering PEI with 100% solar, the seasonal storage requirement is pronounced and nearly sinusoidal. The required solar capacity is 1150 MW and the storage required is the largest of the three scenarios at 235 GWh. As shown in Figure 5, energy is stored from the summer and used in the winter and the battery makes one large annual cycle. This is the opposite as is shown with the wind resource and suggests both wind and solar may be complimentary. It is also worth noting that 1.1GW of solar photovoltaic generation causes a potentially disruptive net power flow that is likely beyond what the PEI grid can tolerate. This disruption could be minimized, however, by co-locating energy storage with the solar generation.

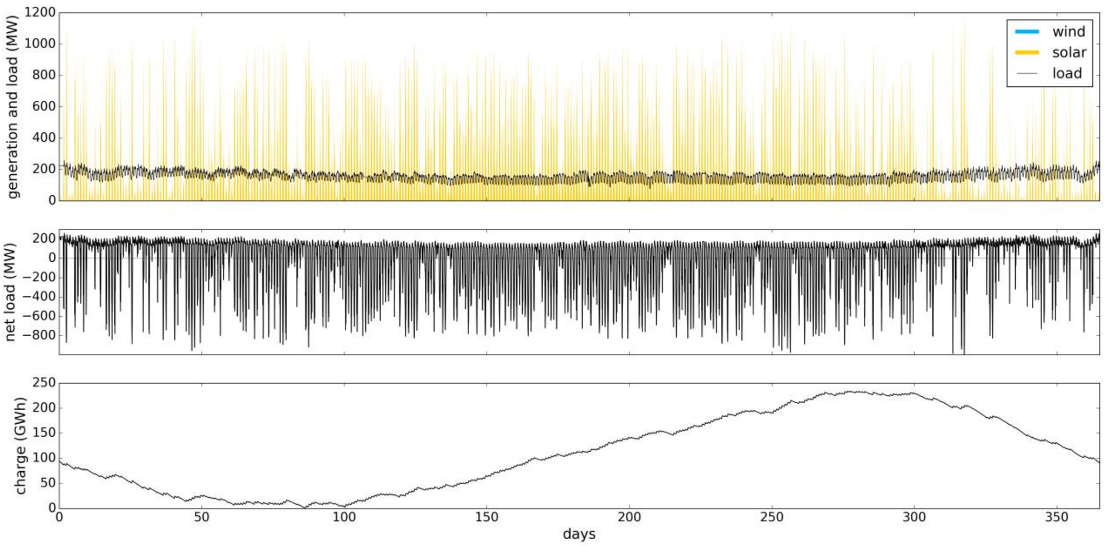

Figure 5: Solar with storage scenario.

Scenario 1c: Solar and wind with storage

Considering integrating wind and solar in combination reveals the complimentary relationship between wind and solar and its effect on the required battery size. Results are show in Figure 6, where wind increases from 0 to 450 MW and solar decreases from 1150 MW to 0 as one moves along the x-axis. In all combinations the total renewable generation equals the annual load. The results show a distinct storage required minimum at 313 MW of wind and 350 MW of solar.

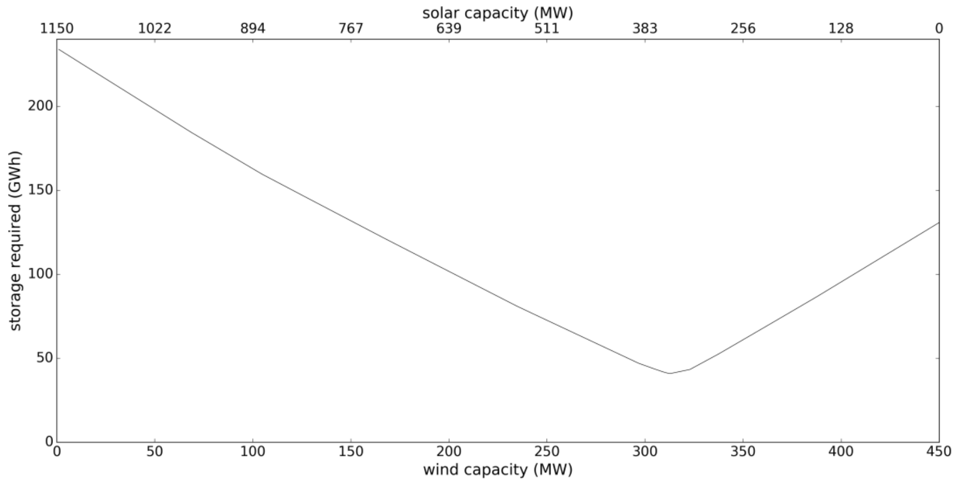

Figure 6: Energy storage capacity required as a function of wind capacity in wind-solar combined supply.

The 41 GWh storage requirement for the optimal wind and solar combination is detailed in Figure 7. The main seasonal component is no longer present and the storage is required to operate at a seemingly higher frequency and thus a greater cycle rate. Even so, the battery in this scenario experiences 9.5 times its 41 GWh capacity in annual energy throughput, which is less than 200 full energy cycles in 20 years. This result suggests that new lower cost and lower cycle life battery technologies might be applicable to future energy systems or that partial secondary utilization of electric vehicle batteries could economically contribute to the storage mix. Scenario 1d listed in Table 2 shows the results if storage costs dropped by an order of magnitude. For perspective on the storage requirement, it should be noted that with PEI's population of roughly 150,000 people, 41 GWh of storage translates into a 270 kWh battery per capita. In comparison, electric cars with 400 km range are equipped with approximately 100 kWh batteries.

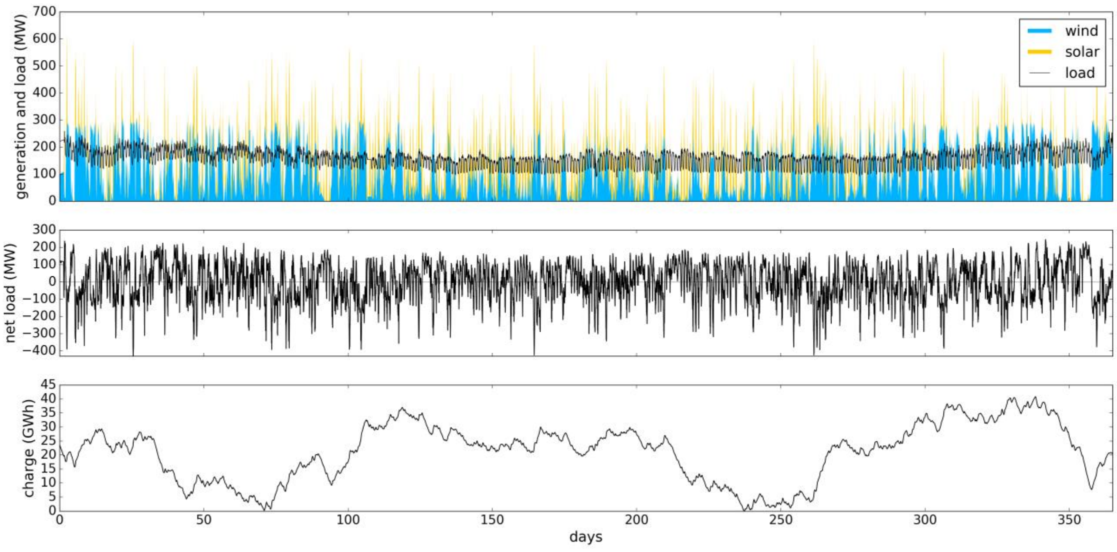

Figure 7: Wind and solar with storage scenario.

While scenarios with wind, solar, and storage without curtailment are prohibitively expensive at current cost assumptions, the cost of the scenario where storage is an order of magnitude cheaper is not uncompetitive to other scenarios at this storage cost, as explored in the next sections.

Table 2: Summary of results with no curtailment

Scenario		1a Wind only	1b Solar only	1c Wind + solar	1d Wind+solar (low cost storage)*
Installed capacity	wind (MW)	448	0	313	313
	solar (MW)	0	1150	350	350
	battery (MWh)	132000	235000	41000	41000
Fraction of load	wind	0%	100%	70%	70%
	solar	100%	0%	30%	30%
Annual cost (M$)	wind	103	0	72	72
	solar	0	190	58	58
	battery	3960	7050	1230	123
Cost of energy ($/kWh)		2.91		0.975	0.181

*the low cost storage scenario reduces the storage cost from 500 $/kWh to 50 $/kWh

3.2 100% Renewable Generation Scenarios Including Curtailment

When curtailment is permitted, wind and solar power capacities can be explored independently without needing to constrain the overall annual renewable energy production to match demand. These scenarios therefor include three parameters – wind, solar, and storage capacity – which are optimized to find the least-cost configuration in a given economic context. Significant surpluses of available power can exist. These are assumed to represent curtailed (avoided) generation in the current work, though future work might consider alternate uses for this excess energy. The following scenarios show the significant reductions in storage requirement that can be enabled by allowing wind and solar power to be curtailed. Similarly to the previous section, four scenarios are considered: wind only, solar only, wind-solar, and wind-solar with reduced storage cost. The results are summarized in Table 3.

Scenario 2a: Wind with storage and curtailment

When only wind and storage are considered, the least-cost configuration is 967 MW of wind and 17 GWh of storage. The time series are shown in Figure 8. The middle sub-plot shows the excess power available after generation, load, and storage are accounted for. This indicates the amount of curtailment taking place. By allowing curtailment, the storage size and cost of energy are significantly reduced relative to the wind-only scenario without curtailment.

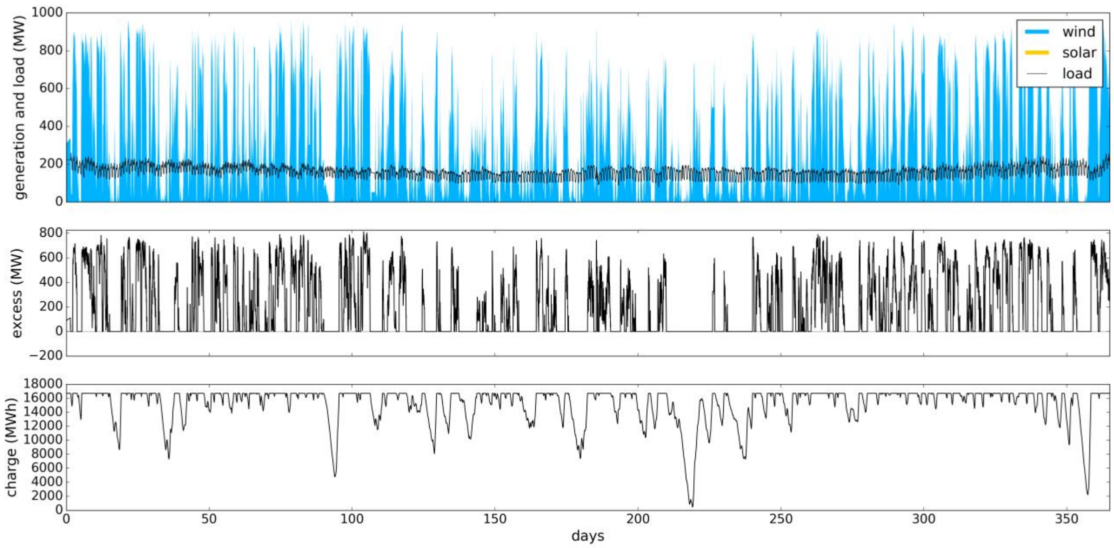

Figure 8: Wind and storage with curtailment.

Scenario 2b: Solar with storage and curtailment

When only solar and storage are considered, the least-cost mixture is to have 3320 MW of solar and 25 GWh of storage. The lack of symmetry with the wind-storage scenario arises because of the different capacity factors and seasonal variations between wind and solar. Figure 9 shows the time series, with the battery depletion occurring in winter, whereas it was in summer for the wind power case. As with wind, the use of curtailment reduces storage requirements dramatically, in this case reducing the cost of energy by a factor of three. As well, the power flows in this scenario with curtailment are much lower than those without curtailment, representing less demand to the grid.

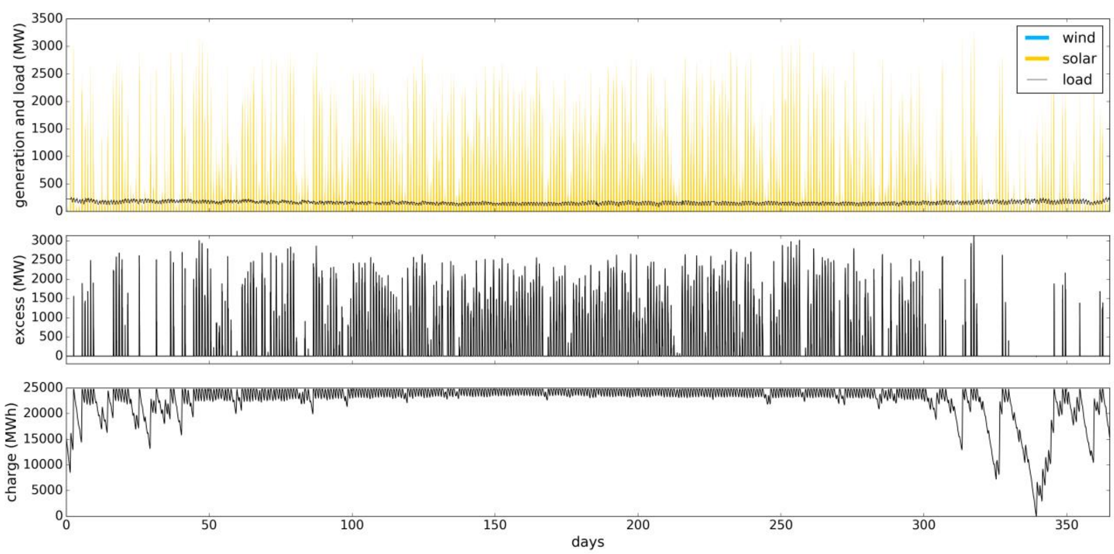

Figure 9: Solar and storage with curtailment.

Scenario 2c: Wind and solar with storage and curtailment

Combining wind and solar gives the lowest storage requirement, similarly to the previous section, except that the use of curtailment allows cost savings by oversizing the wind and solar capacities to reduce the storage requirement even further. The optimized capacities in this scenario are 351 MW of wind, 1220 MW of solar, and 12 GWh of storage. With solar's lower capacity factor, these capacities give a roughly even energy split between solar and wind in terms of meeting the load. Figure 10 shows the time series. Once again, curtailment allows a much lower cost of energy. However, the savings relative to the wind-only case of Scenario 2a are relatively small.

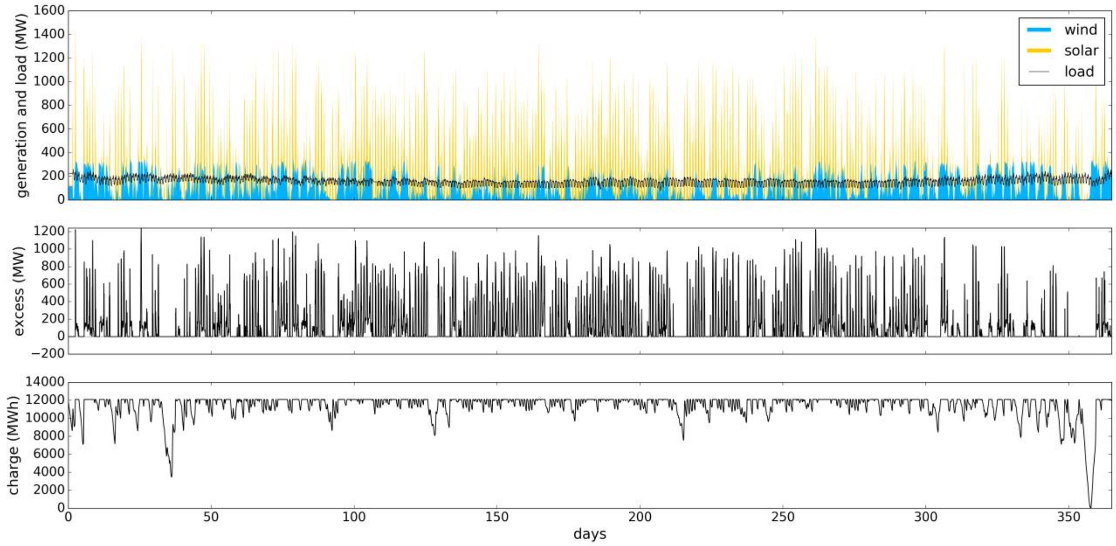

Figure 10: Wind, solar, and storage with curtailment.

Scenario 2d: Wind and solar with storage and curtailment at reduced storage cost

When the battery cost is reduced by an order of magnitude, the minimum cost arrangement changes considerably. The capacity of wind increases to 584 MW while solar is reduced to 219 MW. Storage capacity is increased to 19 GWh and the cost of energy reduces from 0.46 $/kWh to 0.16 $/kWh. It is noteworthy that at the reduced storage cost, use of curtailment gives only a small savings in cost of energy relative to the no-curtailment case of Scenario 1d in the previous section. In fact, there is relatively little cost sensitivity with respect to changes in renewable generation sizing and the storage required. More renewables simply results in less required storage whereas less renewables results in more required storage and the overall costs of energy are relatively unchanged.

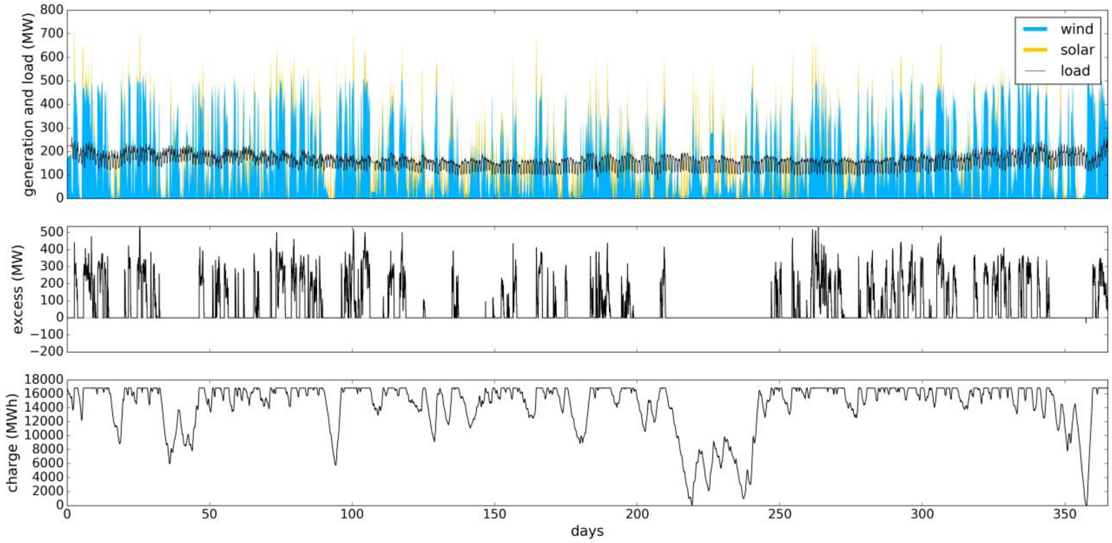

Figure 11: Wind, solar, and storage with curtailment at order-of-magnitude reduced storage cost.

Looking at the time series for each of the scenarios, it is clear that the storage capacity is determined by multi-day periods of renewable energy shortage. The principal benefit of combining wind and solar is that it reduces the length and frequency of these periods.

Table 3: Summary of results with curtailment

Scenario		2a Wind only	2b Solar only	2c Wind + solar	2d Wind+solar (low cost storage)
Installed capacity	wind (MW)	967	0	351	537
	solar (MW)	0	3321	1220	246
	battery (MWh)	16694	24760	12087	16845
Fraction of load	wind	100%	0%	53%	83%
	solar	0%	100%	47%	17%
Energy curtailed	wind	54%		32%	31%
	solar		64%	55%	17%
Annual cost (M$)	wind	209	0	78	119
	solar	0	549	202	41
	battery	502	748	364	51
Cost of energy ($/kWh)		0.510	0.931	0.461	0.151

The costs of energy in Table 3 show that allowing curtailment can dramatically reduce the storage requirements and therefore the overall costs of a 100% renewable energy scenario, given the cost assumptions of Table 1. The significant cost difference between wind and solar is apparent in the resulting costs of energy. Also, the solar-only case with curtailment is similar in cost to the wind and solar without curtailment case presented in the previous section.

3.3 100% Renewable Generation Scenarios Including Curtailment and Dispatchable Biomass Generation

Allowing curtailment reduces the storage requirements from seasonal to on the order of days. Storage is needed to only cover those periods with abnormally low solar and/or wind energy. The total energy required in these periods is relatively little, as can be seen from Figure 10, especially when solar and wind power are optimally balanced. Yet satisfying these periods with stored energy entails a large increase in the required storage capacity. If instead dispatchable, fuel-based generation was used to meet this demand, it could reduce the overall cost with only a small amount of combustion. In keeping with the goal of 100% renewable electricity supply, biomass-based generation is considered for this purpose. The cost assumptions for a stoker boiler are given in Table 1. The results are summarized in Table 4.

Scenario 3a: Wind and biomass with storage and curtailment

For a scenario where wind and biomass are the two energy sources, the least-cost result sees 279 MW of wind capacity, with no storage, and biomass providing the remaining 46% of energy required to meet demand. Figure 11 shows the time series results. In the middle pane, positive values represent excess wind power that would be curtailed, while negative values represent a shortage that would be met with biomass generation. The shaded area indicates the amount of energy required from biomass.

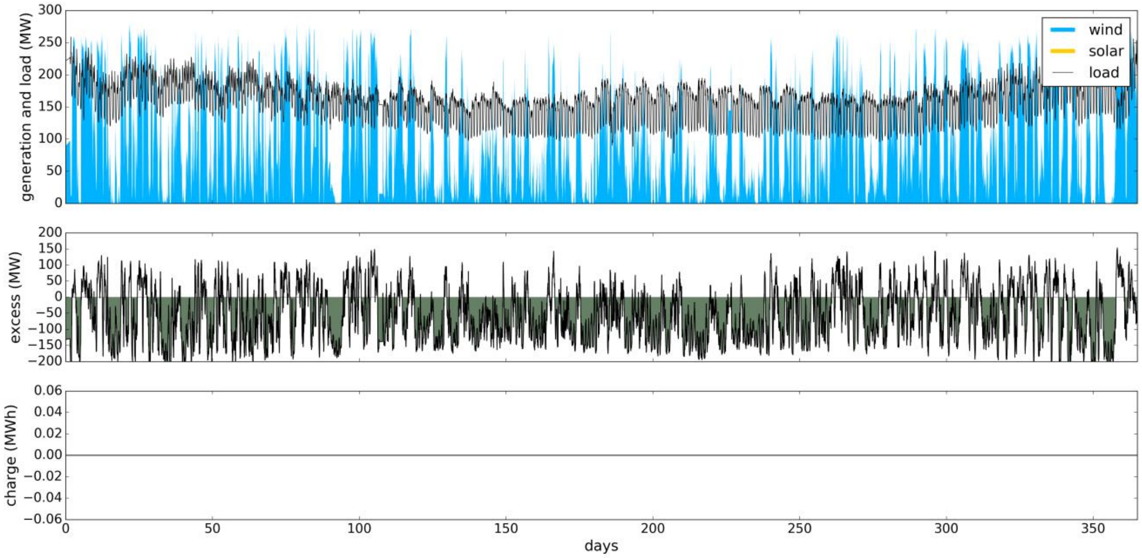

Figure 11: Baseline cost scenario with wind, biomass, storage, and curtailment.

The optimization shows some curtailment of wind is more cost-effective than reducing the wind capacity and using more biomass. Storage is still not cost-effective in this scenario. Biomass for backup remains more affordable than using batteries. A driver for this is that, as shown in Table 4, the cost of biomass generation is dominated by fixed rather than operating cost, so once the biomass capacity is sized to meet the worst supply shortage, there is little cost savings to reducing the biomass energy use.

Scenario 3b: Solar and biomass with storage and curtailment

In a scenario of solar, biomass, and storage, the least-cost result sees 256 MW of solar capacity. Similarly to the previous case, there is no storage and biomass provides the remaining energy required. The higher expense of solar leads the scenario to rely on a greater portion of biomass (79%) in meeting the annual energy demand.

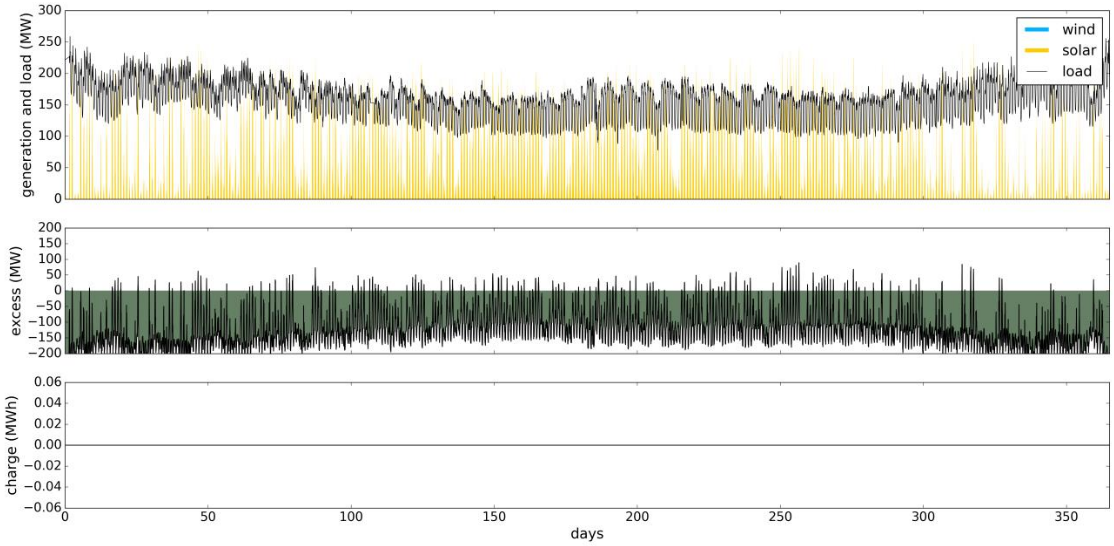

Figure 12: Baseline cost scenario with solar, biomass, storage, and curtailment.

Scenario 3c: Wind, solar and biomass with storage and curtailment

In a scenario where both wind and solar are considered, along with biomass and storage, the least cost result is identical to Scenario 3a: 279 MW of wind with the remainder provided by biomass. Based on the costs estimated in Table 1, when meeting the full load with biomass generation is considered an option, solar power and battery storage do not offer a cost reduction.

Although the above result might be seen to favour heavy use of biomass, it should be noted that using more wind power, or adding solar power, has only a small increase in the estimated cost of energy. Figure 13 shows how the cost of energy changes when up to 280 MW of additional solar or wind power are added to the least-cost scenario of 279 MW wind. These show that this scenario is relatively flexible to further increasing the share of wind or solar in the mix. Similarly, the addition of 520 MWh of storage capacity – enough to supply the peak load for two hours – increases the cost of energy by only 5%.

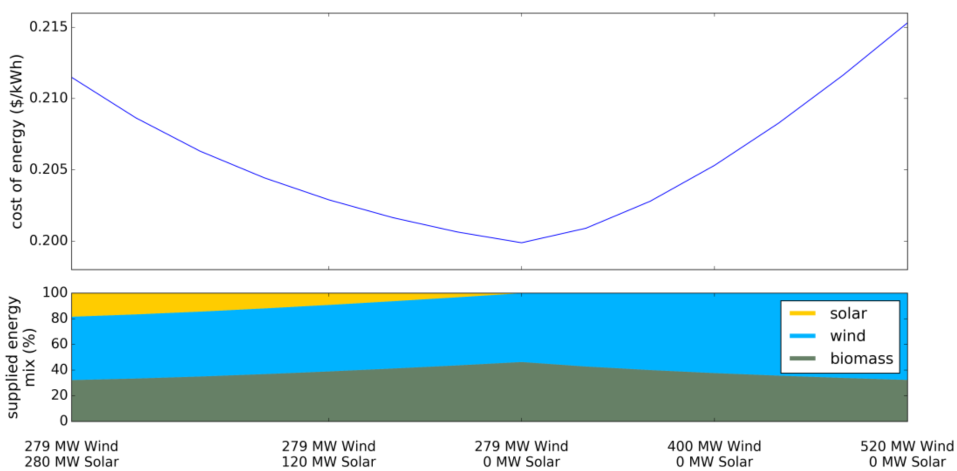

Figure 13: Change in cost of energy with added solar or wind power relative to least-cost solution using baseline cost assumptions.

Scenario 3d: Wind, solar and biomass with storage and curtailment at reduced storage cost

If the energy storage cost is reduced from $500/kWh to $50/kWh, the least-cost solution changes entirely. Biomass is completely removed from the solution and a mixture of 537 MW of wind, 246 MW of solar, and 17 GWh of low-cost battery storage gives a cost of energy of 0.15 $/kWh – this is the same solution as for the wind-solar case of Scenario 2d with curtailment from the previous section when the storage price is reduced. Clearly, the price of storage has a dramatic effect on what the least-cost electricity generation solution is. An order of magnitude cost reduction in storage costs would appear generally enabling to wind and solar and deterring to biomass combustion-based electricity generation.

Table 4: Summary of results that include curtailment and biomass generation

Scenario		3a Wind only	3b Solar only	3c (same as 3a) Wind + solar	3d (same as 2d) Wind+solar (low cost storage)
Installed capacity	wind (MW)	279	0	279	537
	solar (MW)	0	256	0	246
	battery (MWh)	0	0	0	16845
	backup (MW)	244	259	244	0
Fraction of load	wind	54%	0%	54%	83%
	solar	0%	21%	0%	17%
	fuel	46%	79%	46%	0%
Energy curtailed	wind	14%		14%	31%
	solar	4%	3%	4%	17%
Annual cost (M$)	wind	63	0	63	119
	solar	0	42	0	41
	battery	0	0	0	51
	backup plant	118	125	118	0
	backup fuel	33	56	33	0
Cost of energy ($/kWh)		0.200	0.239	0.200	0.151

To explore the situation with low-cost storage further, Figure 14 shows how the minimum cost of energy and corresponding storage requirement change for different ratios of wind and solar power. The data is plotted with respect to installed wind capacity – at any given x value, the solar and storage capacities are optimized for minimum cost of energy. Relative to the already-discussed least-cost combination with 537 MW of wind, the cost of energy increases mildly as the mix is adjusted toward more wind or more solar. The price increases more dramatically as the wind capacity goes below 200 MW and solar supply mix rises above 50%. The somewhat erratic character of the energy storage requirement may be an indication of the complexity of the optimization; because both wind and solar supply are stochastic signals, as their balance is varied, the design-driving shortage event can change unpredictably. The figure also suggests that an energy mix initially heavy on wind could be incrementally supported with smaller scale deployments of solar resources without much consequence to cost of energy. These solar resources could be integrated into urban environments and deployed over time to match growth in demand without the land use of industry-scale energy farms.

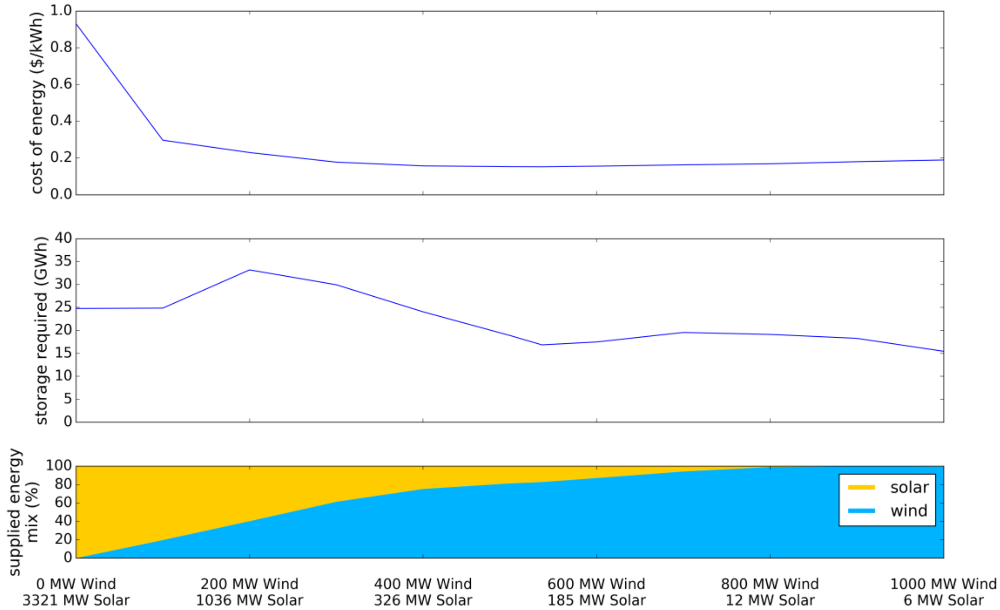

Figure 14: Change in cost of energy and battery capacity for minimum-cost solutions with different wind capacities when storage cost is reduced.

4. Conclusions

Models of 100% renewable electrical energy supply on PEI were created using time series power data of recorded wind generation and electrical demand as well as simulated solar generation potential. These models allow study of different scenarios and exploration of cost-minimizing combinations of wind power, solar power, and energy storage based on different cost and operation assumptions.

Results of wind and solar generation without the possibility of curtailment show very large storage requirements and consequentially high costs of energy. However, the results show that a certain combination of wind and solar gives a distinct reduction in storage size by balancing the complimentary seasonality of the two sources. Reducing the battery cost by an order of magnitude yields results that are of similar cost to the later discussed scenarios and without the need for renewable generation curtailment or complex and scale-sensitive biomass generation plants. While the storage cost reduction might appear to be unrealistic, battery-based grid storage technology is in its infancy and new energy storage technology developments are arising such that a 10 times reduction in cost is worth considering for future perspectives.

Under current price assumptions, the use of curtailment in wind and solar generation allows for a dramatic reduction in energy storage requirement, from seasonal time scales to multi-day time scales. By oversizing the wind and solar capacity, the storage size becomes driven by occasional multi-day wind and solar supply shortages rather than seasonal variations. This gives a significant cost of energy reduction, down to the order of 0.50 $/kWh for wind or wind-solar scenarios. With the storage cost reduced by 10 times, the cost of energy is reduced to 0.15 $/kWh which is only a small reduction compared to the no-curtailment case under the same assumed cost inputs.

The addition of biomass generation that is assumed dispatchable does not appear to serve a complementary role with battery storage by filling in the multi-day shortages. Instead, presumably because of its high capital to operating cost ratio, it acts as an alternative to storage. Under current cost assumptions, the least-cost mixture is a combination of wind and biomass, each providing a similar fraction of the total energy demand. However, the economics are such that increases in wind or addition of solar in this scenario by up to 200 MW do little to increase the cost of energy.

There are also practical limitations to large-scale biomass generation that warrant further consideration in such scenarios. When the storage cost is reduced, the minimum-cost solution does not include biomass and is identical to the solution of the wind, solar, and curtailment case. The cost of energy in this scenario is relatively insensitive to further increases in wind and solar generation, suggesting a degree of flexibility for future growth in renewable energy generation.

Acknowledgements

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