Empirical Evidence from Bayesian Structural Time Series Model: Small Hydropower Responses to Increasing Solar PV in CAISO

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Abstract

To achieve the 100% green electricity goal, we need to understand the relationship between renewable resources in the market and identify clean sources of flexibility to integrate intermittent resources. In this paper we reveal a complementary relationship, within the same day but may not in the same hour, between small hydro power plants and solar PVs in CAISO based on the system-wide hourly generation data from 2013-2017. Through a Bayesian structural time series model, we find that when the solar PV increases its portion in the generation mix by 1%, small hydro will also increase its generation portion by 0.01-0.06%. Such response is more obvious in the morning net demand peak hours and the afternoon net demand peak hours. The coefficients are small but statistically significant. The reason behind such relationship is the low operation cost, high flexibility, and dispatchability of small hydro in CAISO. Due to its benefit in emission and low LCOE, we suggest considering more small hydro projects to accommodate the additional solar PV. To integrate additional solar PV for the 100% green electricity goal, our estimation indicates that the current feasible potential of small hydro 3.4 GW, is larger than the required capacity addition of 3,375MW, if the relation stays the same over years. Moreover, if small hydro developers can limit the environmental impact, more technical potential (7.5GW in total) will become feasible. Thus, small hydro has the potential to integrate more solar PV and reduce the demand for natural gas plants and batteries.

Introduction

In recent years, scientists have proposed to use 100% renewable energy to meet the electricity demand for the world[1,2] and the U.S.[3,4]. However, these results strike controversy due to the unconvincing underlying assumptions and modeling tools[5]. Besides these critics, the models ignore the impacts from electricity market operation and resource interaction. A convincing model would have solid assumptions about the relationship between different energy sources in the electricity market. We believe that any new findings on how different energy sources interact with each other in the market would provide critical insight into the model and would facilitate better energy policy.

A challenge for the grid to integrate more intermittent resources is how to increase the flexibility[6,7] and adding more flexible generating resources is one solution. Common flexible generators include hydropower units, natural gas combustion turbines, and batteries. Researchers[8] found that natural gas plants create a synergy with wind plants due to their flexibility and the synergy also drives the reduction in the generation of coal plants. However, there is still a gap in understanding the interaction between hydropower and intermittent resources. Regarding carbon emissions, there is more incentive to use hydropower, rather than combustion turbines, to provide flexibility. While large hydropower plants are often considered as non-renewable due to their considerable environmental impact, small hydro provides an alternative source of flexibility with relatively low environmental impact.

Small hydropower plants, usually defined as hydropower plants with less than 10 MW of capacity, are eligible for the renewable portfolio standard in 25 states. In 2017, the U.S. had about 3.6 GW of capacity from small hydropower plants, most of which lies in the Northeast and Southwest regions[9]. In addition, reports from the Oak Ridge National Lab (ORNL) estimate that retrofitting non-powered dams (NPDs) could attribute an additional 2,500 MW of potential capacity nationwide[10], while new stream-reach development (NSD) has 4,321 MW of capacity[11].

California issued Senate Bill 100 (SB-100) in 2018, promising 100% of electricity from eligible renewable energy resources and zero-carbon resources by 2045. High renewable penetration has already created numerous problems for grid operation, one of which is the notorious duck curve[12]. Solar PV generation increases the need for ramping up and ramping down products to maintain the stability of the system. The following analysis explores how small hydropower could help integrate the intermittent resource in the California electricity market where many small hydropower facilities already exist.

Data and Methods

Regression model

The California Independent System Operator (CAISO) discloses their hourly generation portfolio on a daily basis[i]. The data used in the model is from 2013 Jan 1st to 2017 Dec 31th, accounting for 1826 days. There are five main categories: import, thermal, hydro, nuclear and renewable. Hydro, in this dataset, refers only to large hydropower plants. Small hydro, which California defines as smaller than 30MW, belongs to the renewable category along with solar PV, solar thermal, wind, biomass, biogas and geothermal. Since demand may affect all generation plants and lead to confusion about the interaction between different generation sources, we do not target the amount of generation, but the portion of demand met by a certain resource. The portion of resource *i* at hour H on day t is the generation of *i* divided by the sum of all the main categories as indicated by

$$\mathrm{p_{i,H,t}} = \frac{\mathrm{G_{i,H,t}}}{\mathrm{G_{import,H,t}} + \mathrm{G_{Thermal,H,t}} + \mathrm{G_{Hydro,H,t}} + \mathrm{G_{Renewable,H,t}} + \mathrm{G_{Nuclear,H,t}}} \tag{1}$$

The Bayesian structural time series model[13] is adopted to analyze the relationship between small hydro generation proportion and solar PV generation proportion. It is believed that the learning process of the system operator resembles a Bayesian learning process. The operator learns the flaws of the schedule today and then updates next day's schedule. It should be kept in mind that

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[i] http://www.caiso.com/TodaysOutlook/Pages/Supply.aspx

this model ignores the relationship between the output of the current hour and the next hour and it only aims to explain the daily variance of the energy generation. The daily variance rather than the hourly variation, could also be a better representation of the solar PV penetration.

This model utilizes the Kalman filter for time series decomposition and the spike-and-slab method for variable selection.

$$y_{H,t} = f(\beta^T X_t) + \mu_t + \gamma_t + \epsilon_t \tag{2}$$

$y_{H,t}$ is the daily time series data of small hydro proportion at hour H of the day t; $H \in \{1,2,\ldots,24\}$

$\beta^T X_t$ is a regression component. X_t is a 24x1826 matrix and each row represents the daily solar PV proportion of the hour. β is the 24x1 static coefficient matrix.

f is the spike-and-slab method for variable selection. In this model only one variable, one column of X, is chosen to explain $y_{H,t}$. This method assigns a Bernoulli prior probability of inclusion and then, condition to that, a normal distribution prior on the coefficient with mean as zero. When observing the data, the expectation is updated

μ_t is the trend component. In this paper, its level components move as random walk and the slope component follows the AR1 process.

$$\mu_{t+1} = \mu_t + \delta_t + \varepsilon_t \qquad \varepsilon_t \sim N(0, \sigma_\varepsilon^2) \tag{3}$$

$$\delta_{t+1} = D + \phi(\delta_t - D) + \eta_t \qquad \eta_t \sim N(0, \sigma_\eta^2) \tag{4}$$

γ_t is the seasonality component. In this model, it represents the contribution of each month to the annual cycle. Hence, the seasonality could be expressed as following:

$$\gamma_{t+1} = -\sum_{i=0}^{10} \gamma_{t-i} + \tau_t \qquad \tau_t \sim N(0, \sigma_\tau^2) \tag{5}$$

The iteration limit is 10,000 times.

Future potential estimation

Assuming the relation between small hydro's portion and solar PV's portion remains the same by 2050, an estimation of the average small hydro generation ($SH_{M,H,2050}$) at hour H in month M in 2050 is based on the revealed relation, estimated solar generation ($Solar_{M,h}$), and estimated total demand ($D_{M,H}$ and $D_{M,h}$). The highest estimated generation of small hydro should be no larger than the required small hydro capacity in 2050. To be more conservative, a capacity factor at month M in 2017 ($CF_{M,2017}$) is applied to convert the highest generation into the needed capacity. β_H is the coefficient between the small hydro generation portion at hour H with the corresponding solar generation portion at hour h. H may not be equal to h.

$$\begin{aligned} \text{SH Capacity Need} &= \max_{M,H}\left(\text{SH}_{M,H,2050}\right)/\text{CF}_{M,2017} \\ &= \max_{M,H}\left(\beta_H * \left(\frac{\text{Solar}_{M,h}}{D_{M,h}} - \frac{\text{Solar}_{M,h,2017}}{D_{M,h,2017}}\right) * D_{M,H}\right)/\text{CF}_{M,2017} \end{aligned} \tag{6}$$

When projecting the 2050 electricity demand, a simplification is to assume the mean day demand profiles remain the same for each month and scale linearly with the ratio between current and future annual demand. The demand scale factor of 1.33 was determined from 2017 CAISO data and projections from the Advanced Energy Pathway project, which projected 390,629GWh of annual electricity consumption in 2050[14]. Similarly, the future mean day hourly solar generation is assumed to scale proportionally with the total solar capacity increase. According to projections by the California Council on Science and Technology, California requires 87GW of solar capacity by 2050 to meet their electricity demands and environmental goals[15].

$$D_{M,H} = D_{M,H,2017} * \frac{D_{total,2050}}{D_{total,2017}} \qquad Solar_{M,H} = Solar_{M,H,2017} * \frac{\text{Solar Cap}_{total,2050}}{\text{Solar Cap}_{total,2017}} \tag{7}$$

Without the availability of verified and holistic models concerning CAISO future resource planning, this analysis only intends to frame high-level discussion of the feasibility of pairing small hydro with solar in the future.

Result and Discussion

Observation

The figure below (Figure *1*) is the daily averaged generation profile of solar PV and small hydro in CAISO on a normalized scale for June and November in 2013 and 2017, while these two are just the examples of their changes over the years. The most interesting change is the shape of their daily generation profile. In the early years, the shape of small hydro is relatively flat but in the recent years, the two peaks become evident. The peak in the morning is about 6:00 a.m. to 10:00 a.m. and the peak in the afternoon is about 6:00 p.m. to 10:00 p.m. When comparing the shape of small hydro and solar PV, the peaks of small hydro just lay at the edges of the solar generation. It is conjectured that the emerging of two peaks are the responses of small hydro to the increasing solar PV.

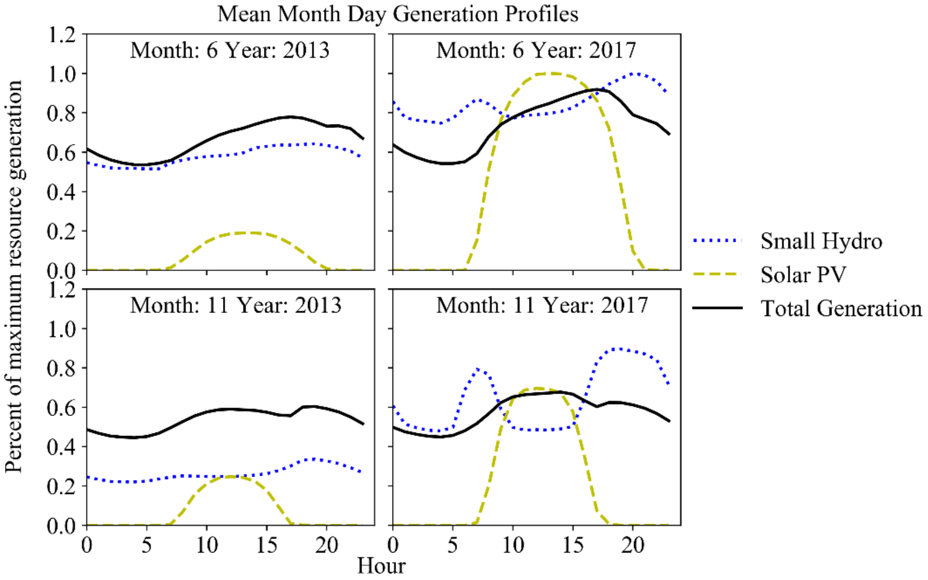

Figure 1: Generation profile change over the years

Generation profile change

Besides the generation change, the change of generation mix is more influential. The graph below (Figure 2) summarizes the probability to include solar PV generation portion into the Bayesian structural time series model for a better explanation of the daily variation of small hydro generation portion. All the coefficients are also positive (see Appendix A for details). Fourteen of the total twenty-four hours of small hydro have at least 90% probability of being affected by the solar PV. Since various other factors drive up the solar PV generation, there is little possibility that the small hydro drives up the solar PV. Thus, the association could be intepreted as small hydro increasing its portion in the generation mix as a response to the increase of solar PV.

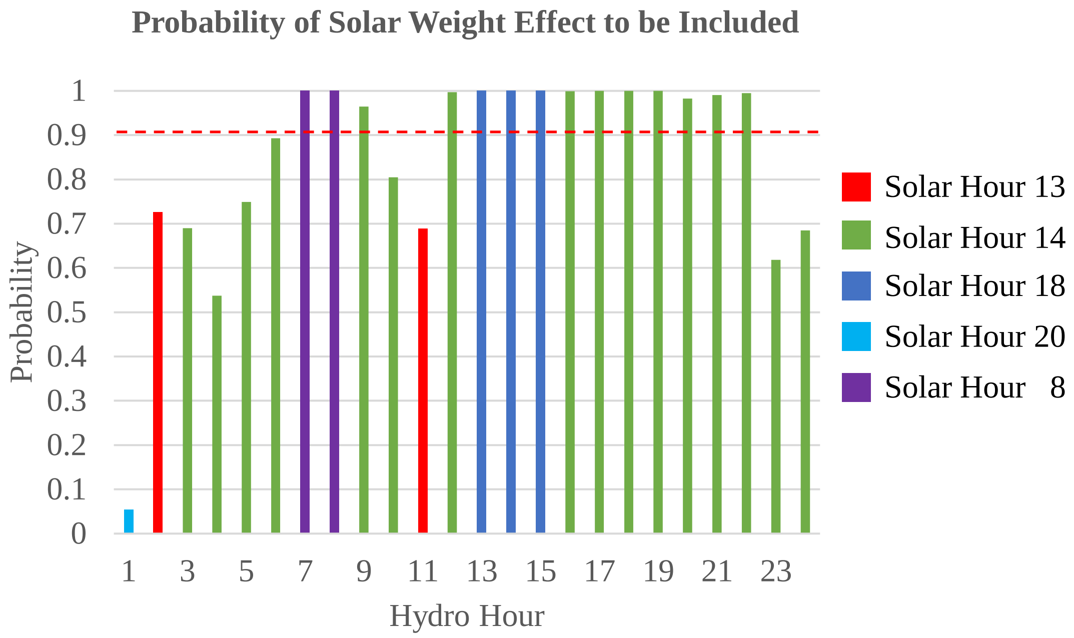

Figure 2: Probability of small hydro's weight affected by solar PV's weight

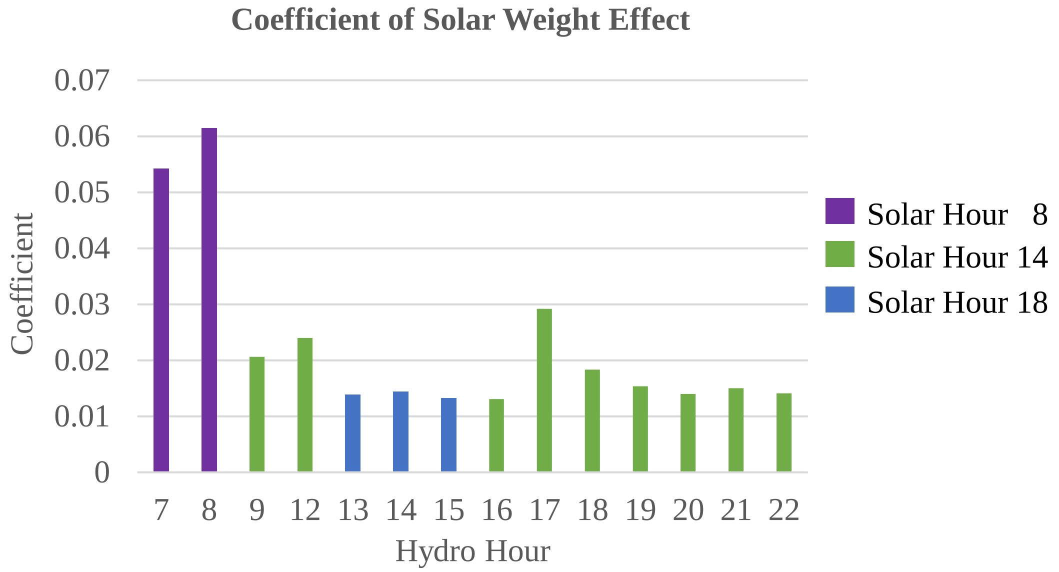

Figure 3: coefficients of Solar’s weight on small hydro's weight

When looking specifically at the hours with at least a 90% probability of inclusion, the small hydro’s portion in the generation mix will increase 0.01%~0.06% with 1% increase of solar PV.

The largest coefficient is the near-term effect in the morning. Small hydro's weights in the generation mix during hour 7 and 8 are largely affected by the solar PV's weight in hour 8. It shows that small hydro would take some responsibilities to prepare for the morning net demand peak hours. The flexible resources at this time need first to ramp up to meet the morning peak demand and then ramp down to meet the decreasing net load caused by solar PV. Similarly, around 5-7 p.m. another net load peak, the flexible resources need to ramp up quickly to deal with the decreasing solar and the increasing demand. However, this process is simpler than the morning ramping process because it is one-direction ramping and the ramp amount is larger which could be handled by some large units rather than small hydro. Hence, the coefficient at these hours are relatively small.

Uncertainties caused by solar PV, from hour 9 to hour 20, could explain the general positive relations during the day. When high uncertainties exist, flexible resources, such as small hydro, are preferred in the generation portfolio.

When solar PV has the highest portion in the generation mix (1-3 p.m.), the small hydro generation portion is associated more significantly with the solar PV at 6 p.m. Considering that the sunset time in California varies from 5 p.m. to 8 p.m. across the year, the solar PV output at 6 p.m. could tell when the solar PV will disappear. In other words, the system operator of small hydro at noon will begin to prepare for the decrease of solar PV. On the other hand, this coefficient could also be partly explained by the slow ramping up process of some resources like the coal plant (<100 MW since 2015[ii]). When the solar generation disappears, they could not ramp up quickly and need to begin the ramping process three hours or more before they reach their maximum output.

The small hydro's weight after sunset is still associated with the peak of solar PV's weight (2p.m.). Slow starting processes and minimum downtime constraints of some plants may contribute to this effect. When solar PV's weight is high, for example at 2p.m., some plants are forced to shut down, but when solar PV decreases, they are not able to restart so quickly. Small hydro, at this time, would increase the weight in the generation portfolio even after sunset.

Explanation –Flexibility and Cost

The relationship revealed above in CAISO suggests that small hydro is able to respond to the rising solar PV generation by increasing its weight in the total generation mix. However, small hydro is not always considered as a flexible resource since many of them are small run-of-river plants with limited ramping capabilities. On the contrary, it is not the truth in CAISO.

In CAISO, the small hydro is defined as less than 30MW rather than 10MW. By capacity, a large portion (58%) of the small hydro asset in CAISO are not run-of-river nor canal/conduit, according to their FERC licenses. Moreover, an International Energy Agency's (IEA) report[16] states that even the run-of-river hydropower plants can have load gradients as high as 5% of the installed capacity per minute. By number of the plants, 49.5% of the small hydro plants is smaller than 1.5 MW. The small capacity limits the ramping capability, but as a fleet containing many plants, the dispatchability of the plants is also the source of flexibility, additional to the ramping capability.

People usually recognize the natural gas plants, but not the small hydropower fleets, for their ability to take the ramping responsibility, despite small hydro's flexibility. In the market process,

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[ii] https://www.energy.ca.gov/almanac/electricity_data/electric_generation_capacity.html

the decisive factor is the bidding price, which is similar to the operation cost. Small hydro's price advantage will enable it to provide the flexibility along with the natural gas plants.

According to the annual technology baseline (ATB) published by NREL[17], the operation and maintenance (O&M) cost of hydropower less than 30MW is 31-125$/kw-yr. The fixed O&M cost for a battery is over 9000 $/kw-yr, not so economic for now. The O&M cost of natural gas plants along with the fuel cost is about 23-50$/kW-yr if the capacity factor is 60%. It is not a surprise that some small hydro plants, with less operational constraints comparing to large hydro plants, are dispatched to meet the system ramping need caused by solar PV along with some cheap natural gas plants.

Metric	*Natural Gas Plant*	*Hydropower Plant*
O&M Cost ($/kW-yr)	23-50	31-125
LCOE ($/MWh)	30-119	36-69
LCOE with Carbon Tax($/MWh)	46-144	36-69

Table 1: Cost comparison

Suggestions for Resource Planning

During resource planning, the system planner frequently uses the levelized cost of electricity (LCOE) which measures the cost of generating one megawatt hour of electricity. The LCOE of natural gas plants ranges from 30-119$/MWh with an average of 58$/MWh while hydro (<30MW) ranges from 36-69$/MWh with an average of 53$/MWh[17]. Moreover, to account for the costs of carbon emissions, a carbon tax equal to the country level social cost of carbon (SCC) is imposed on the LCOE of natural gas plants. For the United States, the cost is approximately 48$/t$CO_2$ [18]. According to the EIA[iii], the emission rate for natural gas plants is 53.07kg/MMBtu. With the heat rate and other related assumptions from ATB, the LCOE of natural gas plants is 46-144$/MWh with an average at 79$/MWh, almost 50% more expensive than the average LCOE of small hydro. Therefore, it is attractive to consider more small hydro plants rather than natural gas plants to provide the flexibility during the resource planning phase of the electricity system.

It may be unfair to only consider the emissions caused by generation. However even if we compare the life cycle carbon emissions, small hydro is still lower. IEA [19] estimated the life cycle carbon emissions of small hydro as approximately 9 g/kWh, compared to combined cycle natural gas turbines at 430 g/kWh. Besides the emissions, small hydro development also contributes to various negative environmental impacts including, disruption of river connectivity and flow patterns, degradation from construction, and water quality changes[20]. In recent years, researchers are working to mitigate these negative effects through developing concentrated development principles[21], a standard modular hydropower framework[22], and new multiscale approaches to guide project development[23]. Hence, the environmental impact of small hydro development will continue to decrease in the future.

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[iii] https://www.eia.gov/environment/emissions/co2_vol_mass.php

Conclusion

Historical data tells that the small hydro generation responds to the increasing solar PV generation during the five-year span (2013-2017) in CAISO. The hourly generation portion of small hydro in the generation portfolio will increase 0.01%-0.06% when solar PV's portion increase 1%. The change in the morning peak hours of net demand is the most significant one, followed by the increase in the evening peak hours. The reason behind is that the increasing solar PV brings the need of flexible resources, especially at the sunrise and sunset periods. Due to the flexibility, dispatchability, and relatively low operation cost, small hydro's portion in the generation mix increases during these hours along with other flexible resources.

Considering the low LCOE, low emissions, and relatively low and controllable environmental impact, we suggest considering more small hydro projects during the integrated resource planning in systems with large amounts of solar irradiation and small hydro potential like CAISO. To achieve the 100% green electricity in CAISO, the current small hydro feasible potential can help integrate all projected additional solar PV with the current small-hydro-solar-PV relation. If technology advancement can reduce the environmental impact of small hydro, much more potential of small hydro can be developed to integrate solar PV and reduce the demand for natural gas plants and batteries.

Author contributions

R.S. conceptualized the research idea and built the time series model; R.S. and X.W. contributed to the model result explanation; C.S. conducted the discussion about environmental impact; R.S. and C.S. conducted the future potential estimation; R.S. and C.S. contribute to the data collection and data visualization.

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Disclaimer

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Appendix A- BSTS model result

The result of 24 models are presented below:

Small Hydro Time (y)	Solar PV Time (x)	Inclusion probability	Coefficient	Standard deviation	Residual	R^2
Hydro hour 8	solar8	1	0.061478754	0.012769816	0.000950278	0.9754669
Hydro hour 7	solar8	1	0.054220456	0.013996524	0.00095207	0.9751898
Hydro hour 19	solar14	1	0.015343213	0.001906289	0.000851091	0.967893
Hydro hour 18	solar14	1	0.018325689	0.003101018	0.000784237	0.9726829
Hydro hour 17	solar14	1	0.029191005	0.006475693	0.000842618	0.9658167
Hydro hour 15	solar18	1	0.013235683	0.003653169	0.000797695	0.967155
Hydro hour 14	solar18	1	0.014399291	0.003832385	0.00081655	0.9654648
Hydro hour 13	solar18	1	0.013888695	0.003225666	0.000827376	0.9651161
Hydro hour 16	solar14	0.999484	0.013080644	0.003530135	0.000799456	0.9671838
Hydro hour 12	solar14	0.99735674	0.023979399	0.005289254	0.000858016	0.9636804
Hydro hour 22	solar14	0.99476123	0.014079985	0.002005615	0.000771536	0.975352
Hydro hour 21	solar14	0.99063044	0.015003917	0.003783403	0.000818432	0.9712243
Hydro hour 20	solar14	0.98281266	0.014010527	0.00260358	0.000813539	0.9703619
Hydro hour 9	solar14	0.96431092	0.020605912	0.007968539	0.001019078	0.9680348
Hydro hour 6	solar14	0.89286075	0.029499847	0.011161123	0.001026208	0.9696299
Hydro hour 10	solar14	0.80492233	0.023060783	0.012981579	0.00093299	0.9676969
Hydro hour 5	solar14	0.74917273	0.022952164	0.014045171	0.000974086	0.9722446
Hydro hour 2	solar13	0.72585227	0.004561038	0.002970726	0.000682442	0.9831801
Hydro hour 3	solar14	0.68995589	0.010145797	0.008168421	0.001144565	0.9573632
Hydro hour 11	solar13	0.68888441	0.011175247	0.007617163	0.000924551	0.9612825
Hydro hour 24	solar14	0.68468468	0.009658559	0.006920367	0.00068079	0.9831284
Hydro hour 23	solar14	0.61840379	0.008627048	0.007070171	0.000698393	0.9809792
Hydro hour 4	solar14	0.53747366	0.008717295	0.009056738	0.001125523	0.9619235
Hydro hour 1	solar20	0.05453087	0.00041704	0.001891573	0.000422751	0.9938414

Appendix B – Estimated Future Generation

June Mean Day Comparison (2017 & 2050) in GW

Hour	2017 Small Hydro	2017 Demand	2017 Solar PV	2050 Small Hydro addition	2050 Demand	2050 Solar PV
1	0.543667	32.40513	0.000533	0.001794	43.34484	0.003185
2	0.491833	30.40223	0.000533	0.171752	40.66578	0.003185
3	0.482867	29.0725	0.000567	0.354409	38.88714	0.003384
4	0.478367	28.0716	0.0002	0.294025	37.54834	0.001194
5	0.4734	27.5253	0	0.759087	36.81762	0
6	0.489733	27.52987	0	0.975797	36.82373	0
7	0.522333	28.00027	0.0029	1.201478	37.45293	0.017319

8	0.551433	30.0792	1.359767	1.463464	40.23369	8.120515
9	0.5347	34.50383	4.6317	0.85427	46.15205	27.66047
10	0.506167	37.59033	6.856433	1.041564	50.28053	40.94656
11	0.489067	39.41057	7.9752	0.54551	52.71525	47.62783
12	0.498067	40.8644	8.608167	1.177387	54.65989	51.4079
13	0.501	42.04383	8.945867	0.491149	56.23749	53.42464
14	0.5047	42.9832	8.990033	0.520582	57.49398	53.68841
15	0.511033	44.1736	8.967533	0.491766	59.08625	53.55404
16	0.523367	45.26007	8.8287	0.711345	60.5395	52.72492
17	0.5473	46.18917	8.432833	1.620037	61.78226	50.36081
18	0.569033	46.6494	7.757567	1.02717	62.39786	46.32812
19	0.598933	46.1169	6.506333	0.850183	61.68559	38.85577
20	0.617233	43.6112	3.876667	0.734156	58.33399	23.15142
21	0.633667	40.09273	0.880533	0.72278	53.62772	5.258538
22	0.627767	38.9395	0.016767	0.658762	52.08516	0.10013
23	0.608133	37.79827	0.004833	0.391805	50.55866	0.028865
24	0.5636	35.20413	0.000533	0.408547	47.08876	0.003185