Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Residual Demand Analysis of South Korea under Deep Penetration of Variable Renewable Energy

Jai Oan Cho[a], Jeong Ik Lee[a]*
[a]*Dept. Nuclear & Quantum Eng., KAIST, 291, Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea*
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

The move towards a society that does not produce carbon emissions is a major concern worldwide. In order to prevent global warming from exceeding 1.5 degrees Celsius, the IPCC (Intergovernmental Panel on Climate Change) has suggested that the world achieve carbon neutrality by 2050 [1]. The South Korean Presidential Committee on Carbon Neutrality has presented two plans to achieve this goal, but the plans have faced criticism for relying on technologies that do not currently exist or are not expected to be available in the near future [2]. Additionally, the plans do not address the need for load following technologies, which are necessary to maintain power output when using Variable Renewable Energy (VRE) sources like wind and solar.

Currently, there are limited options for carbon-free load following power, with hydropower being one of the few available options. However, new technologies are being developed, such as boron-free SMRs (Small Modular Reactor) and gas turbines powered by clean hydrogen, as well as energy storage systems and fuel cells, which could also be used if costs can be reduced. Another potential option is natural gas power with carbon capture and sequestration.

As variable renewable energy becomes more prevalent, there is a greater need for load following plants that can adjust power output to meet demand. Overgeneration of renewable energy can lead to increased costs and reduced environmental benefits, so there is a need for effective energy storage solutions [3, 4, 5, 6, 7, 8]. Energy storage systems like batteries and pumped hydro can help to smooth out the variability of renewable energy sources and provide a backup power source during times of low renewable energy availability. However, these technologies are still relatively expensive and limited in their capacity.

Overall, the progress towards a carbon-neutral society will require a range of different technologies and approaches to balance energy supply and demand. This paper will try to forecast the residual demand in South Korea under conditions of deep variable renewable energy penetration and its implication.

2. Methods and Results

2.1 Methodology and Data Sources

To model the residual demand, the hourly demand of South Korean grid is needed. The data from year 2018 is used as it is the year when Korea reached its peak demand and is before the economic recession due to the COVID-19. The data is then normalized by the hourly average demand as our interest lies on the demand hourly profile.

The hourly capacity factor data of wind and solar power plants for S. Korea was retrieved from a study by Lei Duan et. al. [9]. Modern-Era Retrospective analysis for Research and Application, Version-2 (MERRA-2) reanalysis product was used to model the profile. The world is divided into 207,936 cells and capacity factor for each cell is calculated. Wind capacity factor calculation assumes a 100m high wind turbine hub with a cut-in speed of 3m/s and cut-out speed of 25m/s. For solar PVs, the zenith angle is calculated based on the location and time. For capacity factor of individual countries, the top 25% of grid cells within the country are averaged.

Hydro power plants along with Pumped Hydro Storage (PHS) plants are among the few low carbon power plants with high ramp rates. With increasing penetration of VREs, more intermittency needs to be dealt with. As hydro plants offer fast responses to cope with the sudden increase or decrease of load, the importance of these plants also increases. The total capacity and generation amount of hydro power plants and PHS plants is retrieved from the EPSIS(Electric Power Statistics Information System) of KPX (Korea Power eXchange) [10].

2.2 Residual Demand Modeling

Installed capacity of solar and wind power was set as 83.4% and 16.6% respectively, in accordance with the data from KPX [10]. From the normalized demand, electricity generated from VREs were subtracted on an hourly basis. Three scenarios were tested with VRE proportion of 30%, 50%, and 70%.

After the subtraction, residual demand is left. This residual demand is what needs to be dealt with by load following sources. Peak load following nowadays is mostly done with Open Cycle Gas Turbines (OCGT). In order to maintain a low carbon profile, other means of load following is needed but sudden and big changes in the grid is not a favorable environment for other less flexible energy sources.

Hydro power plants and PHS plants can help flatten the residual demand by only operating when ramp rate of the load following source, which is the change of residual demand over time, is over a certain rate. This will reduce the maximum ramp rate and help the less flexible load following sources to play a role in.

2.3 Results & Discussions

Table I: Results for 3 scenarios

	VRE 30%	VRE 50%	VRE 70%
Peak Residual Demand [GW]	87.8	86.4	81.2
No residual Demand Time [hrs]	525	3238	4720
Curtailed Excess VRE Energy [GWh]	94.1	143.3	203.5
Median Ramp Up Rate [GW/hr]	1.77	1.94	2.77
Median Ramp Down Rate [GW/hr]	-1.86	-2.03	-3.11
Max Ramp Up Rate [GW/hr]	31.8	41.1	40.5
Max Ramp Down Rate[GW/hr]	-27.4	-46.9	-40.4
Max Ramp Up with Hydro [GW/hr]	30.2	41.0	37.2
Max Ramp Down with Hydro [GW/hr]	-27.4	-44.5	-39.5
Average-to-Peak Ramp Up	0.153	0.094	0.067
Average-to-Peak Ramp Down	0.160	0.086	0.065
Min-to-Max Ratio of Ramp Rate	-0.908	-1.085	-1.061

The results are shown in Table I. The modeling was based on normalized values assuming the demand curve profile of the future to be similar to that of 2018. However, in order to grasp an idea on the magnitude of the values, the total generated electricity of year 2018 was used.

As can be seen, regardless of the scenario, peak residual demand remains very high. This means that even with high VRE proportion, large amounts of dispatchable power sources are needed in case VRE generation level drops to near zero.

Residual demand becomes zero when the VRE generation power exceeds the demand, meaning all the electricity of the grid is generated by VREs. The time increases dramatically as the VRE proportion rises.

Curtailed Excess VRE energy was calculated. However, we have not modeled other load following sources. Considering that most dispatchable power sources need to maintain minimum load, actual curtailed energy will be much higher.

Median values of ramp up rates and ramp down rates were compared. Ramp down rates tend to be slightly higher than ramp up rates.

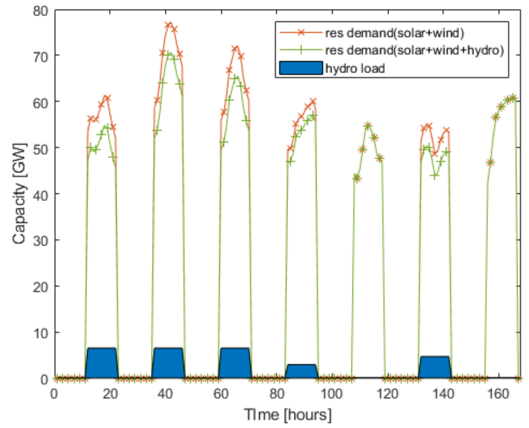

Fig. 1. Residual Demand with and without hydroelectric plants in week 30 for VRE70% scenario

Ramp rates with and without hydro plants were compared. Fig. 1 shows the residual demand with and without hydro plants for VRE70% scenario in week 30 when the increase in residual demand is the highest. We can see that hydro plants can help lower the load and ramp rate in the most volatile days. However, hydro power generation remains very low in Korea(1.34% including PHS). Still, the maximum ramp rates are lowered with the help of hydro plants. Had Korea been generating 30% of electricity with VREs in year 2018, at one point of the year, 30.2GW of additional dispatchable plants would have had to be turned on within an hour to replace the diminishing VRE sources. This is more than 21 APR1400s, the largest nuclear power plants used in Korea, in full load.

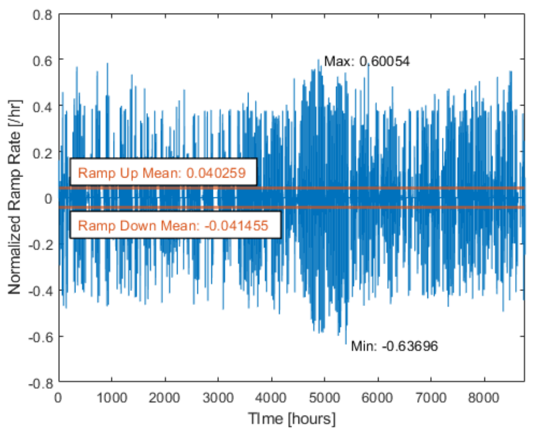

Fig. 2. Normalized Ramp Rate of VRE70% scenario

Average to Peak ratios were compared for ramp rates. The peak values remain relatively similar while the mean value changes much more dramatically depending on the VRE proportion.

3. Summary and Future Works

Three scenarios with different VRE proportion were modelled based on South Korea's 2018 hourly demand data. The residual demand was analyzed in order to understand the operational requirements for future load following low carbon sources under deep VRE penetration. Peak Residual Demand remains very high even when 70% of energy is generated from VREs.

In future studies, load-following sources need to be modelled for more accurate prediction of curtailed energy and reduced GHGs. Start-up time must be incorporated for peak load plants. When load is very volatile, a minimum power level must be maintained to quickly respond to the load variations instead of shutting the plant down completely and restarting. Energy Storage Systems can also mitigate large discrepancies in the load and demand. By specifying the maximum capacity(GWh), power rating(GW), round-trip efficiency, and depth-of-discharge, we can find how much excess VRE energy can be utilized instead of be curtailed.

Demand Management can also be modelled for more detailed analysis. The most straightforward approach would be modeling different electricity prices depending on the residual load level.

Residual load analysis for other countries will also be performed to determine which countries are the most vulnerable in deep VRE penetration scenarios.

REFERENCES

[1] IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

[2] 2050 탄소중립위원회, 2050 탄소중립 시나리오, Oct. 2021

[3] Rose, Stephen, and Jay Apt. "The cost of curtailing wind turbines for frequency regulation and ramp-rate limitation." Proc. 29th USAEE/IAEE North American Conference on Energy and the Environment: Conventional and Unconventional Solutions. 2010.

[4] Denholm, Paul, Matthew O'Connell, Gregory Brinkman, and Jennie Jorgenson. Overgeneration from solar energy in california. a field guide to the duck chart. No. NREL/TP-6A20-65023. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2015.

[5] Golden, Rachel, and Bentham Paulos. "Curtailment of renewable energy in California and beyond." The Electricity Journal 28, no. 6 (2015): 36-50.

[6] Denholm, Paul, and Mark S. Mehos. Enabling greater penetration of solar power via the use of CSP with thermal energy storage. Golden, CO, USA: National Renewable Energy Laboratory, 2011.

[7] Marcos, J., O. Storkël, Luis Marroyo, M. Garcia, and E. Lorenzo. "Storage requirements for PV power ramp-rate control." Solar Energy 99, 28-35, 2014

[8] Alvaro, Daniel, Rafael Arranz, and Jose A. Aguado. "Sizing and operation of hybrid energy storage systems to perform ramp-rate control in PV power plants." International Journal of Electrical Power & Energy Systems 107, 589-596, 2019

[9] Duan, L., Petroski, R., Wood, L., & Caldeira, K., Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide. Nature Energy, 7, 260-269, 2022

[10] Korea Power Exchange, "EPSIS," [Online]. Available: https://epsis.kpx.or.kr/.