RENEWABLES ARE BLOOMING; IS THE POWER SYSTEM READY?

A Prognosis on Residual Load Flexibility in Taiwan by 2025

Dung-Bai Yen/ ID: 4552781

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Introduction

Taiwan is ongoing its Energiewende. With a goal of 20% share of renewable energy in electricity by 2025 [1], the question of whether conventional power plants can adapt to the more volatile load variation will become a major concern.

To more properly analyze such issue, the concept of *residual load (RL)* gradually replaces the conventional term "baseload"[1] in recent years [2]. In this paper, RL is defined by the following equation [3]:

$$RL = DL - VRE \quad (1)$$

Where DL stands for demand load, and VRE stands for variable renewable energy such as wind and solar.

Traditionally, the variation of RL matches that of the DL. According to [4], as the share of renewable energy grows, it will gradually change the characteristic of RL and affect how a power system works. To describe such characteristic change more precisely, we introduce the concept of *residual load flexibility (RLF)*, defined as the capability of a power system to adjust power output according to the variation of RL. This definition is in line with various sources [5, 6]. It has been shown also in these literature that more VRE requires more RLF in the system.

Although commonly misunderstood as a pure technical issue, the technical limit of RLF is still far from reached even in nations with large amount of VRE [7]; to the contrary, many sources have pointed out that market design and policy setting are more important in improving RLF of a power system [6, 8].

An example of how market affects RLF can be seen recently in Germany. The minimum RL during Sturmtief Herwart was about 10 GW less than that during Sturmtief Sebastian (Fig. 1a), but the net electricity export during Sturmtief Herwart did not increase significantly (Fig. 1b). Since the average wholesale price when Herwart hit remained negative (Fig. 2b), conventional power plants operators reduced power output more or simply shut down the plants to prevent further loss [9].

Knowing this, this paper aims to investigate two questions: *1) What will the RL curve look like in Taiwan by 2025?* and *2) Are the policies and power system in Taiwan ready for such RL curve?*

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[1] Throughout the paper we will add a quotation mark on the term "baseload". We believe "inflexible capacity" is more suitable to describe both nuclear and coal.

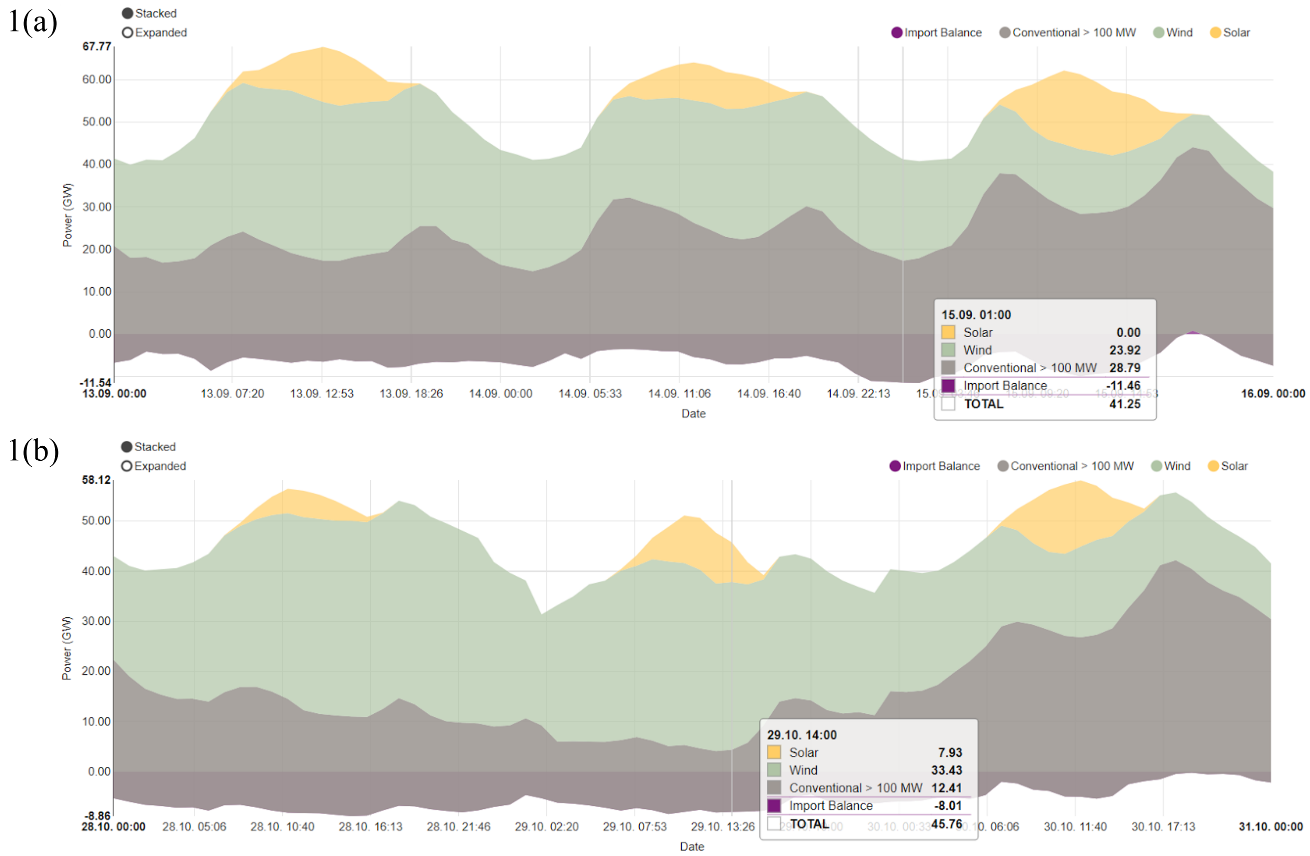
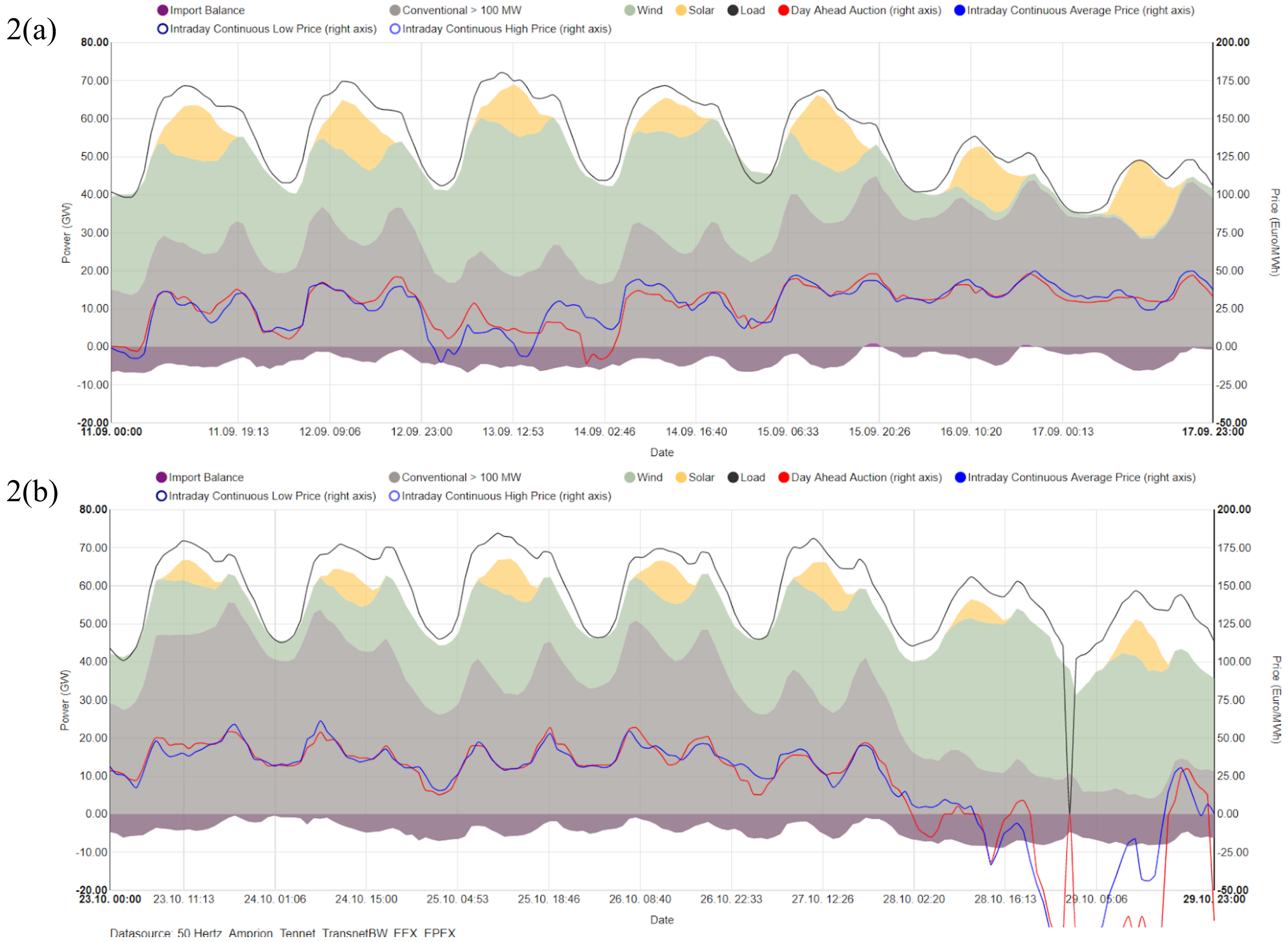


Fig. 1. Power output in Germany during Sturmtief Sebastian (1a) and Sturmtief Herwart (1b). [10]



Datasource: 50 Hertz, Amprion, Tennet, TransnetBW, EEX, EPEX

Fig. 2. Wholesale prices in Germany during Sturmtief Sebastian (2a) and Sturmtief Herwart (2b). [11]

Methodology

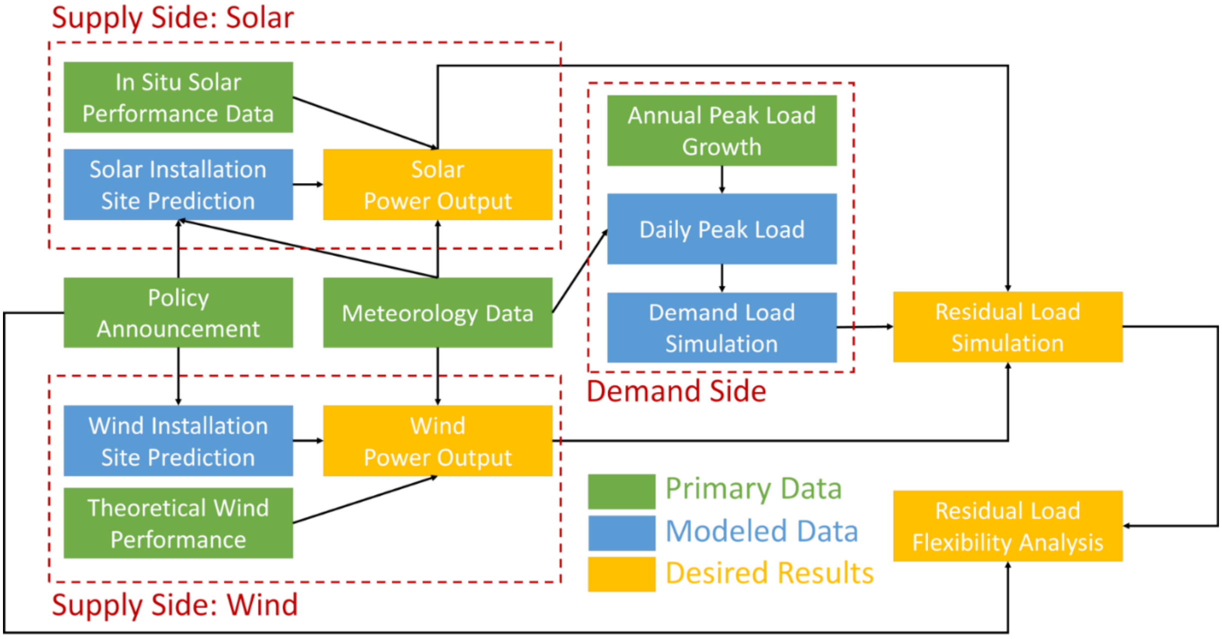


Fig. 3. Flowchart of the simulation and analysis of RLF

Scenario for VRE Installation

We assumed that the governmental goals of different VRE would be achieved by 2025, as shown in (Table 1).

VRE Installation Density Prediction

We assumed that solar panels were installed proportionally to the annual total solar insolation of the site, which was interpolated from [12] (Fig. 4a). The interpolation formulas were based on a RBFK approach [13]:

$$\hat{z}\,(\vec{r}) = \frac{\sum_i z(\vec{r_i})w_i}{\sum_i w_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$w_i = |\nabla d(\vec{r_i})| e^{-(\vec{r}-\vec{r_i})^2 \cdot (\nabla d(\vec{r_i}))|\nabla d(\vec{r_i})|^2 - \frac{\left((\vec{r}-\vec{r_i})^2 - \left(\frac{(\vec{r}-\vec{r_i})\cdot \nabla d(\vec{r_i})}{|\nabla d(\vec{r_i})|}\right)^2\right)}{b}} \ldots\ldots\ldots(3)$$

Where z is the desired interpolate value, r the position vectors, i the dummy notations indicating different observation sites, d the distance to the coast, and b an arbitrary bandwidth (we chose 0.5).

The resulting solar installation density is shown in (Fig. 4b). Locations higher than 200 meters were not considered suitable for building grid connected solar panels and therefore filtered.

For offshore and onshore wind, we predicted future installation based on development plans announced by [14] (Fig. 4c & 4d).

VRE Output Simulation

We simulated VRE output under the meteorological conditions [15] of July and August 2016. Data interpolation methods were again equations (2) and (3). Surface wind speed data was adjusted via the following wind profile power law [16] before interpolation:

$$u(z) = u(z_0)\left(\frac{z}{z_0}\right)^{\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where z is the height, u the wind speed, and alpha a constant (which we assumed to be 1/9 for offshore wind and 1/7 for onshore wind as suggested [17]).

Table 1. Assumed scenario for VRE installation

VRE Sources	Current Capacity (15.Nov 2017)	Capacity by 2025	Release Date
Solar	1.286 GW [18]	20 GW [1]	22 June 2016
Offshore Wind FIT	0.136 GW [19]	3 GW [1]	22 June 2016
Offshore Wind Auction	-	2.5 GW [20]	12 Oct 2017
Onshore Wind	0.682 GW [1]	1.2 GW [1]	22 June 2016

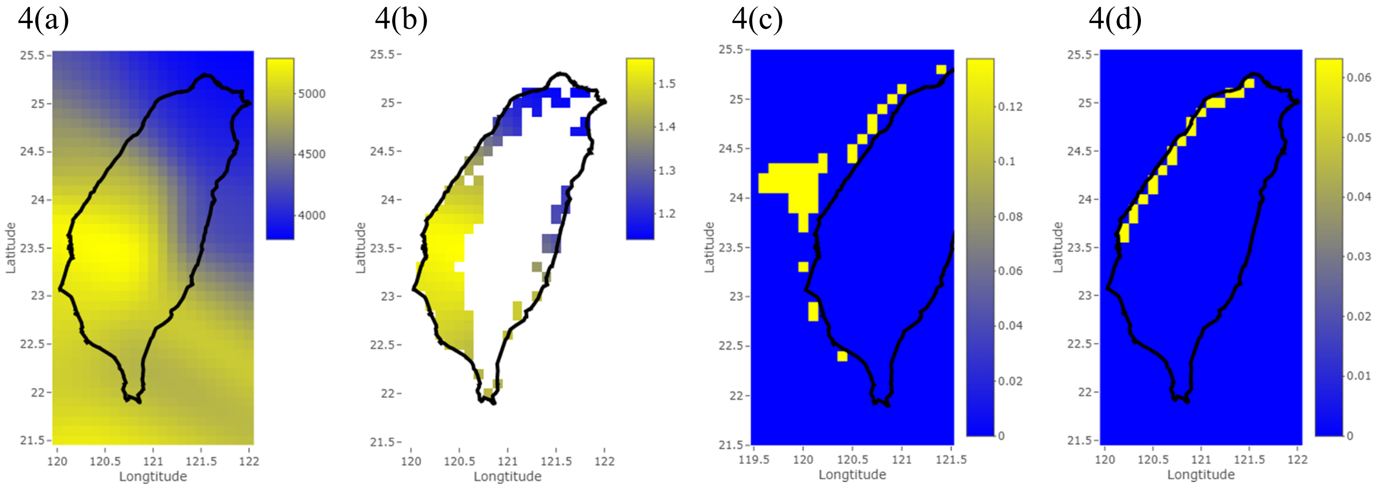


Fig. 4. Interpolated solar insolation in MJ/km^2 per year (4a), predicted solar capacity density by 2025 in MW/km^2 (4b), predicted offshore wind capacity density by 2025 in GW/km^2 (4c), and predicted onshore wind capacity density by 2025 in GW/km^2 (4d)

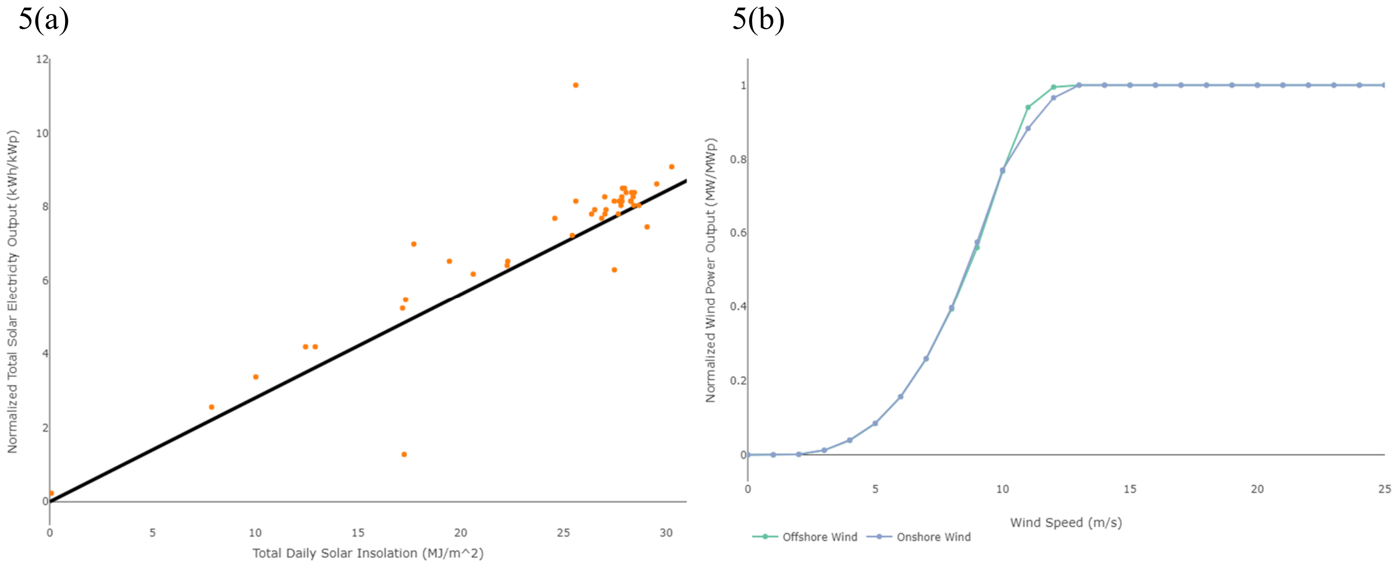


Fig. 5. Normalized performance curve of solar panels (5a) and wind turbines (5b).

The performance curve of solar panels was derived empirically via in situ data in Penghu [21] (Fig. 5a) under the following model:

$$P = m \times S \text{ ....} (5)$$

Where P is the power output (in kW/kWp) of the solar panel, m an empirically obtained slope, and S the solar insolation (in MW/m^2).

For the power output of wind, a typical performance curve [22] of wind turbines was used (Fig. 5b). We assumed the cut-out speed as 30 m/s.

Demand Load Simulation

The following model was proposed to predict the daily peak load (DPL):

$$DPL = (\alpha_1\zeta_1 + \alpha_2\zeta_2 + \alpha_3) \times (1 + r)^{yr - yr_0} \text{ ....} (6)$$

Where r is the annual peak load growth predicted by [23], zeta the first two principal component (PC) scores [24] of daily maximum temperature variations among the observation sites, and alpha the coefficients obtained empirically, varying for weekdays and weekends.

Having the DPL predicted, we estimated the PC scores of the loads via MLE [25] under fixed DPL and continuity conditions. The empirical data used to obtain the PCs of DL was collected between 26th of July to 16th of August 2017 from [26]. Part of the validation time series is shown below (Fig. 6).

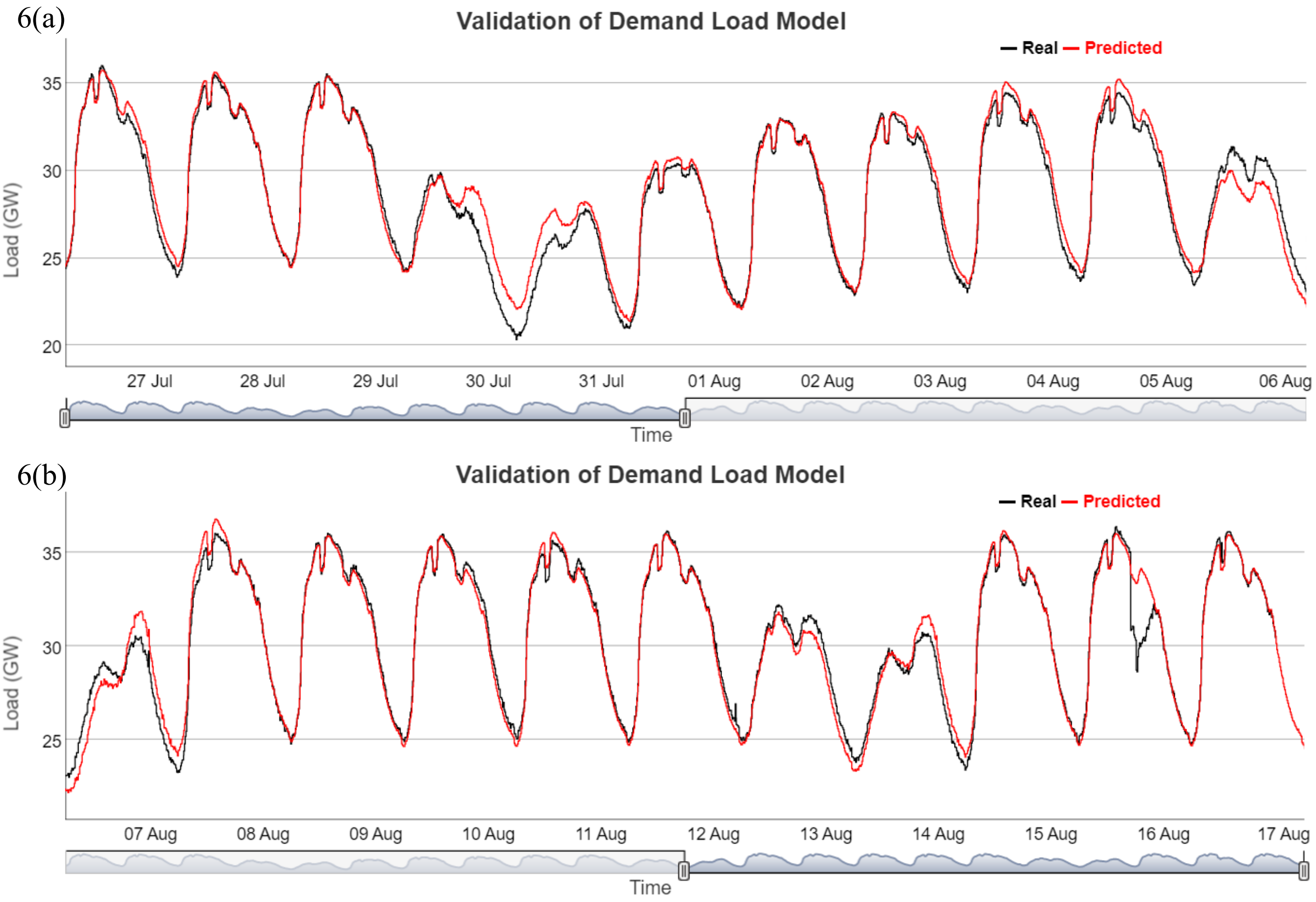


Fig. 6. Comparison between the modeled and empirical load. Note that the model tended to overestimate the load on Sunday. On the 15th of August an operation error occurred in a natural gas station, causing the load to suddenly drop 5.2 GW.

Results and Analysis

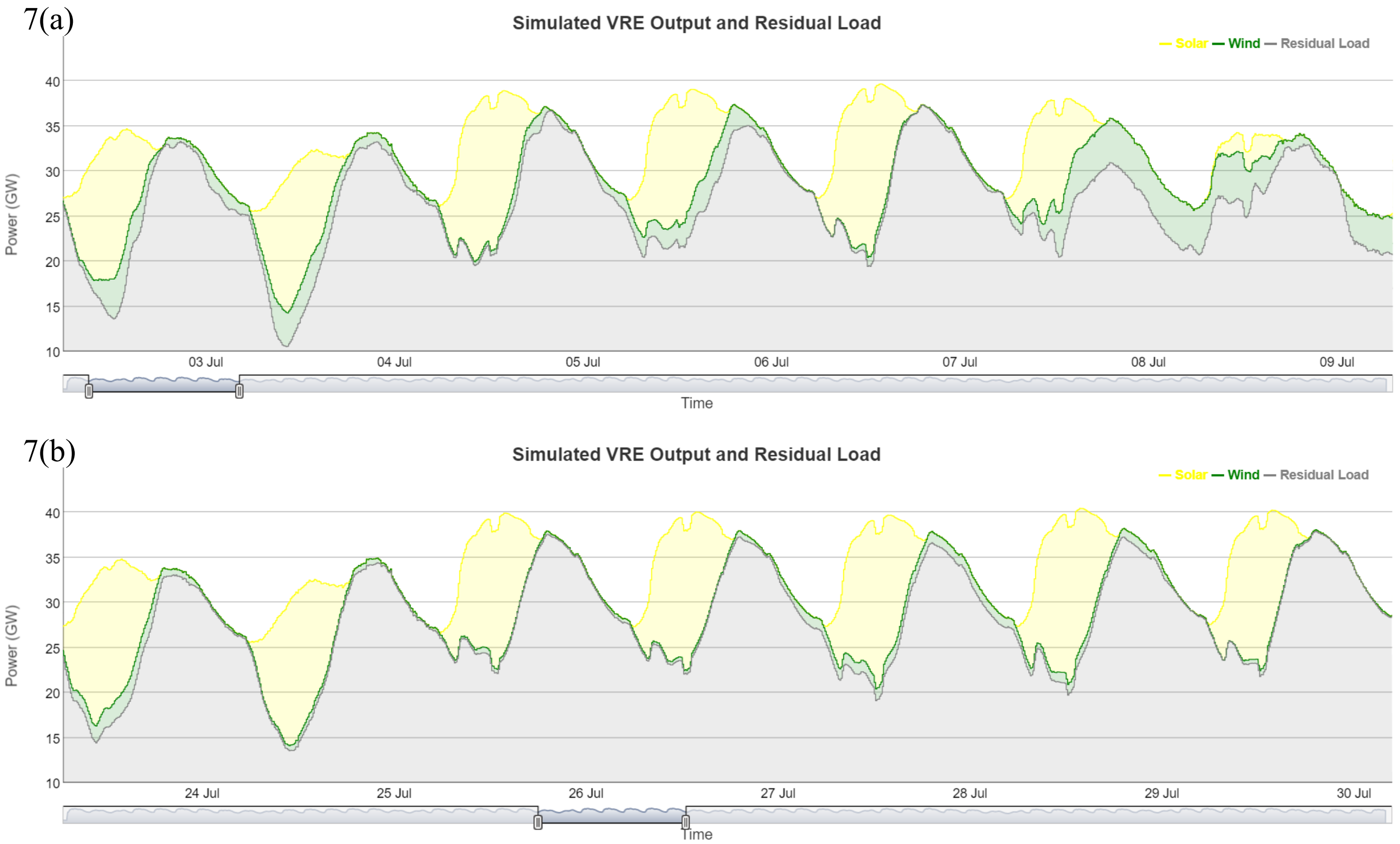


Fig. 7. Simulated VRE output and RL curve during the weeks where maximum (7b) and minimum (7a) RL occurred.

VRE Output and Residual Load Curve

After the model was built as described in the previous section, we used meteorological data [15] of July and August 2016 to simulate VRE output and RL. (Figure 7 & 8) shows some of the characteristics of the VRE output and the RL curve.

There exist three maxima on the average DL curve (Fig. 8a); these maxima represent daily temperature trend and the schedule of office hours.

Traditionally, daily peak RL coincides with the second daily maxima of the load curve. In the simulation, large amount of solar capacity changed the characteristic of RL curve dramatically. The daily minimum of the RL curve shifted to noontime, while the daily peak RL shifted to the evening. The resulting RL curve is known as the “duck curve”, and has been studied thoroughly in regions with large installations of solar panels such as California [27].

Offshore and onshore wind power output, on the other hand, affected little on the characteristics of the RL curve because of smaller capacity and also weaker wind during summer. In our simulation, solar produced 3.5 more electricity than wind, and VRE as a whole accounted for 16.45% of the total electricity demand (Figure 9a).

Dispatchable Capacity and Flexibility Requirements

Annual reserved capacity (ARC) is commonly used in the assessment of conventional capacity requirements. Since the simulated peak RL in summer would still be higher than projected peak load in winter [28], we can use it as a reference in predicting the ARC. The resulting reduction percentage of ARC due to large scale VRE installation, about 6.27% (Fig. 10 a, b & Table 2), is in line with [29], which suggested the value to be 8.3% under very similar scenario assumptions with this paper.

Flexibility requirements, on the other hand, have not been discussed much in Taiwan. (Fig. 11) is the empirical cumulative distribution function (ECDF) of simulated 6-hour[2] average RL variations. One extreme case occurred right after the minimum RL (3rd of July in Fig. 7); about 23 GW of RLF was required during a period of 12 hours. Overall, more abrupt variations in RL reduced the demand for fixed RL (defined as the average daily minimum RL here) by about 21.3%, while increased the demand for variable RL (the rest of RL) by about 4.8% (Fig. 9a & b).

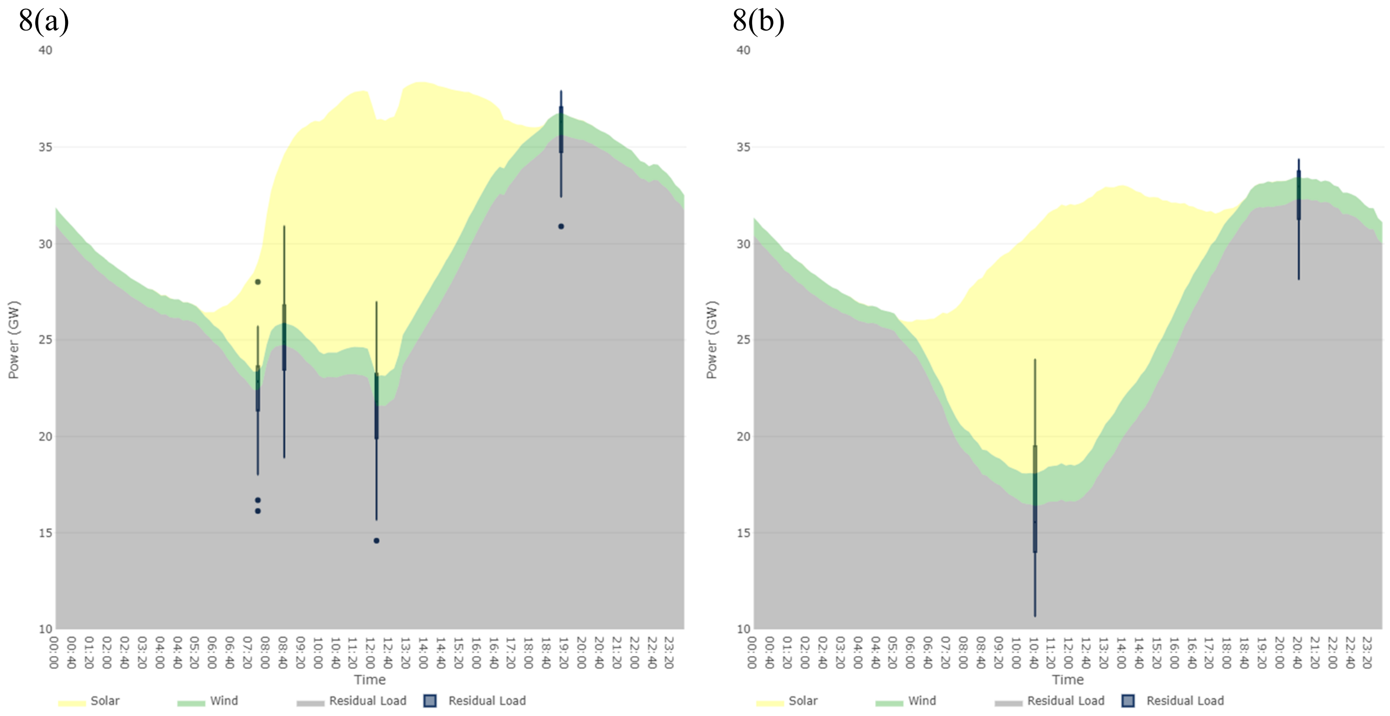


Fig. 8. Average weekday (8a) and weekend (8b) trends of the simulated VRE output and RL curve.

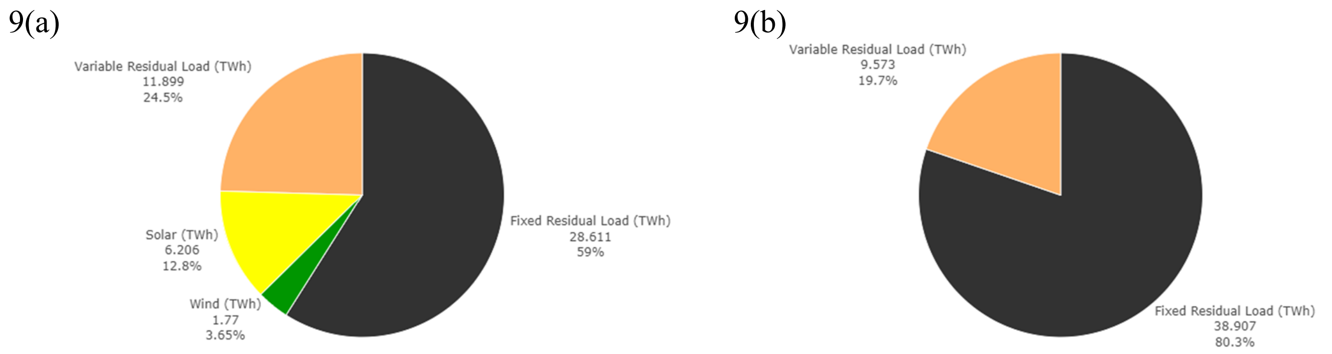


Fig. 9. Total power share of different sources with (9a) or without (9b) large scale implementation of VRE.

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[2] We have chosen the time interval of 6 hours because according to [8], this is about the minimum cold start-up time for hard coal power plants, which means that RLF during the time interval could not be performed by hard coal power plants that were out of operation for more than two hours.

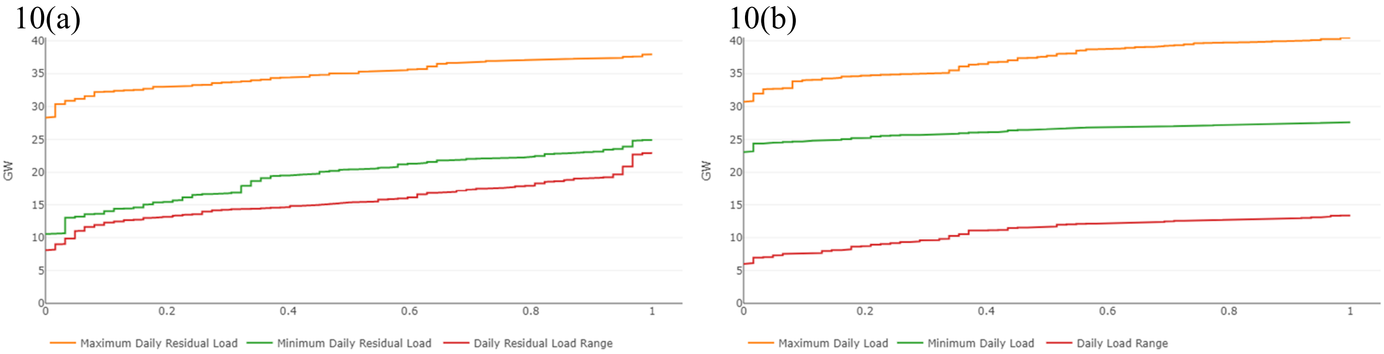

Fig. 10. ECDF of maximum, minimum and range of daily RL (10a) and DL (10b).

Table 2. Basic Statistic for Simulated DL and RL

VRE Sources	Max. (GW)	Min. (GW)	Mean (GW)	SD (GW)
Daily Maximum DL	40.464	30.732	37.137	2.576
Daily Maximum RL	37.902	28.332	34.870	2.149
Daily Minimum DL	27.596	23.088	26.253	1.034
Daily Minimum RL	24.914	10.553	19.306	3.653
Daily DL Range	13.360	6.016	10.884	2.060
Daily RL Range	22.921	8.087	15.565	2.987

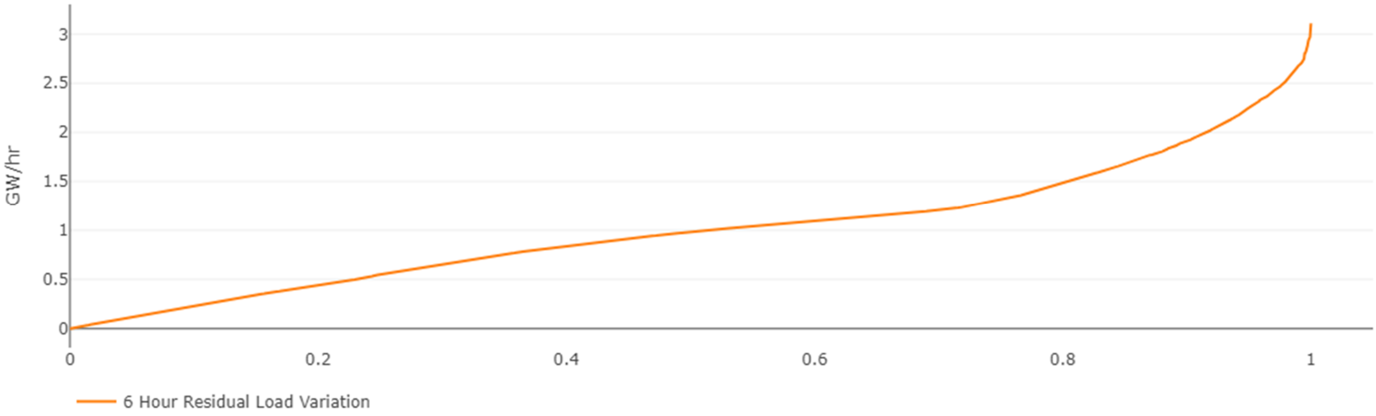

Fig. 11. ECDF of 6-hour RL variation.

Challenges and Policies Review

As shown previously, large scale implementation of VRE would slightly reduce the ARC demand, and we can see from [30] that sufficient capacity will be built by 2025 to meet the rest of the demand[3]. However, the sufficiency of RLF should also be considered.

Our simulation suggested during summer, a maximum 18 GW of RLF must be achieved within 6 hours, which, besides the 4.5 GW hydroelectricity power plants and demand side measures[4], would have to be mostly done by the natural gas[5] (NG) power plants. Currently there is about 10 GW of NG capacity in Taiwan, and another 15GW is planned within ten years [30]. This should be more than enough to perform the required RLF.

But besides the question of installation amount, the electricity market design will also play a role. For example, state of art hard coal plants can also show greater RLF [8]. In theory, leveraging this potential could reduce total coal use. However, the ongoing liberalization of the electricity market poses uncertainty; without a proper carbon price, hard coal power plants operators might take advantage of better flexibility performance and compete with NG power plants for load matching, as seen in Germany [31].

If the future government is to achieve its goal of reducing electricity share of coal to 30% and electricity carbon intensity to 0.394 kg CO2 eq/kWh[6] [32], such scenario should be avoided; hard coal power plants should perform RLF mainly when VRE output booms, but remain capped at around 10 GW[7] when RL demand is high.

Future Improvements for the Model

We acknowledge some shortcomings of our simulation, and list some of them below for potential improvements in the future.

Installation sites prediction:

1. Transmission and distribution issues were not held into account. This was a greater problem when estimating the capacity installation of offshore wind.
2. The assumptions of PV installation were very naïve. A LCoE based model taking distribution lines, land price, and incentive into account should yield a better prediction.

Power output simulation:

3. Higher temperature should yield lower efficiency for solar panels, which was not considered.
4. Wind speed in higher altitudes might not obey the wind profile power law given.

Load simulation:

5. The change in meteorological parameters was not considered; future modeling should include a typical meteorology year modeling.
6. Demand side management, an important aspect when discussing RLF, was not discussed in this paper.

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[3] Conventional capacity will increase to around 43.5 GW by 2025.

[4] 2.6 GW of the hydroelectricity plants can perform pump storage. In addition, according to [1] there also might be some biogas and geothermal power plants by 2025, but the capacity would be only about 1 GW in total; from a viewpoint of carbon reduction, they would be better used to replace some coal power output in serving the fixed RL, as how Germany has been using them.

[5] The term "natural" gas is quite controversial, since it is also a fossil fuel; "fossil gas" lock-in has become a major concern in places where coal is being effectively replaced by NG. We acknowledge the role of NG as a bridging fuel should not be overemphasized, and the primary target of a successful Energiewende is to integrate the most amount of VRE as fast as possible while reducing fossil fuel usage. For more details, one can refer to the report on global gas lock-in by Rosa-Luxemburg Stiftung: *Natural Gas Lock-in: Current politics in the European Union*

http://www.carbontradewatch.org/downloads/publications/Natural-gas-lock-in.pdf

A recent study by 風險社會與政策研究中心(Risk Society and Policy Research Center) also suggested that by 2030, the electricity output of NG should begin to decrease in Taiwan: *〈加速建構轉型量能，邁向深度低碳社會 「溫室氣體減量推動方案」研擬建議〉(Recommendations on GHG Reduction Plan)*

http://rsprc.ntu.edu.tw/fordownload/1061123/20171123_greenhouse_gas_reduction.pdf

[6] According to [32], coal had a share of 45% in the total electricity production in 2016 and the electricity carbon intensity was 0.529 kg CO2 eq/kWh.

[7] With an average power output of 10 GW, the total electricity share of coal during the simulation would be roughly about 30%.

Conclusions

This paper reviewed discussions regarding residual load flexibility of advanced nations in Energiewende, and simulated the residual load flexibility required in Taiwan by 2025. The conclusion was that current policies regarding both flexible and inflexible conventional capacity were sufficient to meet the residual load requirements under the considered scenario; however, to achieve other policy goals such as reduction in coal use, we stressed the importance of a proper market design. Finally, we discussed how to improve the simulation in the future to obtain better results for similar analysis.

A paradigm-shift from focusing on “baseload” capacity towards more emphasis on residual load flexibility is necessary for a successful Energiewende. We hope that with our work and similar studies, such shift can occur in Taiwan as soon as possible.

Reference

[1] Executive Yuan. (2016). *綠能政策目標、未來規劃及執行現況書面報告（Report on Policy Targets, Future Plans and Current Status of Renewable Energy）*. Available: https://ws.ndc.gov.tw/001/administrator/10/relfile/5653/26083/1050622%E7%B6%A0%E8%83%BD%E6%9B%B8%E9%9D%A2%E5%A0%B1%E5%91%8A.pdf

[2] M. Farmer. (2017). *Debunking Three Myths About “Baseload”*. Available: http://www.energycentral.com/c/gr/three-myths-about-%E2%80%9Cbaseload%E2%80%9D-renewable-energy-and-grid-reliability

[3] L. P. C. Do, "Demand and residual demand modelling using quantile regression," *Renewable Energy and Environmental Sustainability,* Research Article vol. 1, no. 41, 2016.

[4] I. E. Agency, "Getting Wind and Sun onto the Grid,　A Manual for Policy Makers," 2017, Available: https://www.iea.org/publications/insights/insightpublications/Getting_Wind_and_Sun.pdf.

[5] R. A. Verzijlbergh, "Institutional challenges caused by the integration of renewable energy sources in the European electricity sector," *Renewable and Sustainable Energy Reviews,* vol. 75, p. 8, 2017.

[6] EURELECTRIC, "Flexibility and Aggregation Requirements for their interaction in the market," 2014, Available: http://www.eurelectric.org/media/115877/tf_bal-agr_report_final_je_as-2014-030-0026-01-e.pdf.

[7] Bundesnetzagentur, "Bericht über die Mindesterzeugung (Report over the Minimum Supply)," 2017, Available: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Mindesterzeugung/BerichtMindesterzeugung_2017.pdf?__blob=publicationFile&v=1.

[8] A. Energiewende, "Flexibility in thermal power plants," 2017, Available: https://www.agora-energiewende.de/fileadmin/Projekte/2017/Flexibility_in_thermal_plants/115_flexibility-report-WEB.pdf.

[9] F. ISE. (2017). *Energy Charts (Unitwise electricity production from lignite in Germany)*. Available: https://www.energy-charts.de/power.htm?source=ligniteAll&week=43&year=2017

[10] F. ISE. (2017). *Energy Charts (Electricity production in Germany)*. Available: https://www.energy-charts.de/power.htm?source=conventional&week=43&year=2017

[11] F. ISE. (2017). *Energy Charts (Electricity production and spot prices in Germany)*. Available: https://www.energy-charts.de/price.htm?year=2017&auction=1h&week=43

[12] K. C. Chang, "國內 2004-2013 年間經典氣象年之日射量調查分析 (Analysis of Solar Insolation of a Typical Meteorological Year of Taiwan 2004-2013)," *台灣能源期刊 (Journal of Taiwan Energy),* vol. 3, no. 1, p. 12, 2016.

[13] "Radial basis function kernel," in *Wikipedia*, ed.

[14] (2017). *風力發電 4 年推動計畫 (4 year promotion plan for wind power)*. Available: http://web3.moeaboe.gov.tw/ecw/populace/content/ContentDesc.aspx?menu_id=5493

[15] T. T. a. F. R. Institute. *大氣水文研究資料庫(Data Bank for Atmospheric and Hydrologic Research)*. Available: https://dbahr.narlabs.org.tw/

[16] "Wind profile power law," in *Wikipedia*, ed.

[17] S. A. Hsu, "Determining the power-law wind-profile exponent under near-neutral stability conditions at sea," *Journal of Applied Meteorology,* vol. 33, 1994.

[18] 台灣電力股份有限公司(Taipower). (2017). *太陽光電發電 (Power Output from Solar Panels)*. Available: http://www.taipower.com.tw/content/new_info/new_info-b36-2.aspx

[19] Renews, "James Fisher ticks Taiwan box," in *Cable de-burying and retrenching work complete at Formosa 1 project* ed, 2017.

[20] Chinatimes. (2017). *2025 目標量擬升至 5.5GW 能源局加碼拚離岸風電 (Bureau of Energy pushes offshore wind, target to rise to 5.5 GW)*. Available: http://www.chinatimes.com/newspapers/20171013000066-260202

[21] Sunnyfounder. (2016). *Penghu Project Nr. 4*. Available: https://www.sunnyfounder.com/projects/47

[22] Enercon, "ENERCON Produktübersicht (Enercon Product Overview)," Available: https://www.enercon.de/fileadmin/Redakteur/Medien-Portal/broschueren/pdf/ENERCON_Produkt_de_6_2015.pdf.

[23] Ministry of Economic Affairs. (2017). *產業缺電現況與對策 (Electricity insufficiency in the industry sector: current situation and Measurements)*. Available: https://www.slideshare.net/OpenMic1/20171108-81732743

[24] "Principal component analysis," in *Wikipedia*, ed.

[25] "Maximum likelihood estimation," in *Wikipedia*, ed.

[26] Taipower. *今日電力資訊 (Information of Today's Electricity)*. Available: http://www.taipower.com.tw/content/new_info/new_info_in.aspx?LinkID=30

[27] C. I. S. Operator, "What the duck curve tells us about managing a green grid," 2016, Available: https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

[28] Taipower. *近期備轉容量曲線 (Operational Reserved Capacity Curve)*. Available: https://www.taipower.com.tw/content/new_info/new_info_in.aspx?LinkID=26

[29] 李佩珊, "Impact Analysis of Large Scale Wind and PV Power Installations on Taipower System Generation Reserve," Department of Electrical Engineering, Chungyuan University, Taiwan, 2016.

[30] Taipower. (2017). *106-117 年大型火力、核能機組除役及新增情形(Retirement and Installation of Large Scale Conventional Power Plants 2017-2028)*. Available: http://www.taipower.com.tw/content/new_info/images/c40/c40_10605.png

[31] A. Energiewende, "Das deutsche Energiewende-Paradox: Ursachen und Herausforderungen (The

Germany Energiewende Paradox: Causes and Challenges)," Germany2014, Available: https://www.agora-energiewende.de/fileadmin/Projekte/2014/Energiewende-Paradox/Analyse_Energiewende_Paradox_web.pdf.

[32] E. P. Administration. (2017). *「能源轉型 減污減碳」 記者會 (Press Conference for the road map of energy transition and reduction of pollutants and carbon emission)*. Available: https://www.facebook.com/thomas0126/videos/1497105477048035/