Integrating renewables into the Japanese power grid by 2030

A frequency stability and load flow analysis of the Japanese system in response to high renewables penetration levels

EXECUTIVE SUMMARY

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IMPRINT

STUDY
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A frequency stability and load flow analysis
of the Japanese system in response
to high renewables penetration levels

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Proofreading: WordSolid, Berlin
Layout: RadiCon | Berlin · Kerstin Conradi,
UKEX GRAPHI, Urs Karcher, Cover: Meriç Dağlı

This publication is available for
download under this QR code.

148/1-S-2019/EN
Publication: December 2018

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ACKNOLWEDGEMENTS
We would like to thank all those who participated in the expert workshops for their valuable input and in particular Yukari Takamura, Professsor, Integrated Research System for Sustainability Science (IR3S), University of Tokyo Institutes for Advanced Study (UTIAS) – Yoh Yasuda, Project Professor, Graduate School of Economics, Faculty of Economics, Kyoto University, Takao Tsuji, Associate Professor, Faculty of Engineering, Yokohama National University – Tetsuo SAITO, University of Tokyo, Institute of Industrial Science – Nobuyuki Honjo, Leader, Power System Committee, Japan Wind Power Association (JWPA) – Takeaki Masukawa, Secretary General, Japan Photovoltaic Energy Association (JPEA) – Hideyuki Ohnishi, Regional General Manager, GE Renewables, North Asia.

We are grateful to the support provided by Adelphi.

Please cite as:
Renewable Energy Institute, Agora Energiewende (2018): *Integrating renewables into the Japanese power grid by 2030.* Study on behalf of Renewable Energy Institute and Agora Energiewende

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Preface

Dear readers,

As the cost of wind and solar power generation has drastically fallen, these technologies have come to make a major contribution to the decarbonisation of power systems. In Japan, solar photovoltaic uptake has risen rapidly over the last five years, making the country one of the most dynamic photovoltaic markets outside China. While the proportion of variable renewables in the Japanese system is increasing, however, it remains rather low, at around 7%.

Concerns over whether renewables can be efficiently integrated into Japan's power grids without endangering grid stability have raised the spectre of a renewables slowdown in the country. International experience has shown, however, that a number of technical measures that are not yet widespread in Japan can be safely implemented to improve grid stability. Unfortunately, there are very few studies in the public domain on these aspects of Japan's power system.

In this study, Japan's Renewable Energy Institute (REI) and Agora Energiewende attempt to partially fill this lacuna. As well as providing new insights into grid stability in Japan, the study also promotes data transparency. We are firmly convinced that third party analysis on the basis of transparent data can contribute to a more robust discussion and ultimately raise societal awareness of the importance of the energy transition.

Yours sincerely,
Patrick Graichen,
Executive Director of Agora Energiewende
and **Mika Ohbayashi,**
Director of the Renewable Energy Institute

Key insights

1. **The Japanese power system can accommodate a larger proportion of renewables (RES) than is currently provided for in the government's 2030 targets, while still maintaining grid stability.** An annual share of at least 33% RES (22% variable renewables – VRES) can easily be integrated, while still maintaining grid stability within a tolerable range. A higher renewable share of 40% (30% VRES) could also be achieved with very low curtailment level.

2. **There already exist a number of technical measures to improve grid stability in situations where a high proportion of variable renewables could place a strain on grid operations.** Indeed, VRES can contribute to maintaining grid stability by providing fast frequency response (FFR). On conservative assumptions, this study shows that such FFR services would enable the existing Japanese transmission grid to incorporate instantaneous VRES penetration levels of up to 60% in eastern Japan and around 70% in western Japan, while still maintaining frequency stability. These assessments confirm the trends observed in 2018 in regions such as Kyushu or Shikoku, where hourly VRES penetration satisfied more than 80% of demand (corresponding to more than 55% of all power generation). By 2030, these high regional infeed levels could become the norm for the Japanese system as a whole. Furthermore, implementing additional technical measures would allow even higher penetration levels to be reached.

3. **Integrated grid and resource planning can help mitigate the impact of wind and solar PV deployment on intraregional and interregional load flows.** Increasing the proportion of VRES in the mix is expected to reduce power line loading in some regions and increase it in other parts of the system. The impact of VRES distribution on the grid must therefore be systematically taken into account in future grid development plans, in order to avoid creating line-loading hotspots.

4. **Non-discriminatory market regulations, enhanced transparency, and state-of-the-art operational and planning practices facilitate the integration of a higher proportion of variable renewables.** In particular, renewables should be incorporated into ancillary service provision, since they can contribute to frequency stability, balancing, and voltage control in tandem with other technologies (such as demand side response, conventional generation, and storage).

Executive summary

Independent and transparent grid integration studies contribute to factually grounded debate on the future of the Japanese power system

The task of integrating a high level of renewables into the power mix while reducing the proportion of conventional generation such as coal and nuclear presents Japan's power system with new challenges. Increased uptake of variable renewables, and particularly solar PV (49 GW total installed capacity at the end of 2017), has heightened concern over the impact of variable renewables (VRES) on grid stability. This has prompted investigations into various possibilities of incentivising sufficient system flexibility. Against this backdrop, grid integration studies have become an invaluable means of facilitating informed debate and guiding national policy.

This study, jointly conducted by Japan's Renewable Energy Institute and Agora Energiewende, investigates the impact of the integration of renewables in Japan on frequency stability and – to a lesser extent – power flows. It is based on a modelling and simulating tool chain of the Japanese power system developed for this project by Elia Grid International and Gridlab, which aims to facilitate independent third-party research. The study compares two scenarios for the year 2030: the government's target scenario, which provides for a renewables penetration level of 22–24% (64 GW solar and 10 GW wind), and a more ambitious scenario (100 GW solar and 36 GW wind). The study examines how the system responds at a number of extreme snapshots involving very high nonsynchronous renewables penetration levels (i.e. wind and solar energy). At these levels, conventional power plants are displaced, thereby pushing down the inertia limits that play a key part in ensuring the Japanese power system's frequency stability.

The study simulates frequency stability and power flows for Japan's western and eastern synchronous areas. Additional analysis was carried out on the extent to which system stability is boosted by VRES-based fast frequency response (FFR) services and by the provision of fast ancillary support using the HVDC interconnection between the eastern and western synchronous areas, which is already in place to cope with certain emergency situations.

Particular emphasis was placed on developing a transparent methodology that could address two major challenges facing countries undertaking studies on renewables integration: (1) significant constraints on data availability (despite the improvements initiated by Japan's energy regulator), and (2) the need to establish a sustainable tool chain for the purposes of modelling and simulating the power system – particularly for third parties wishing to conduct independent research. All of the input and output data generated during the course of this project are hereby made public. We intend this study to contribute to further discussion on renewable energy integration and data transparency.[1]

The Japanese system can accommodate a larger proportion of variable renewables in the energy mix than is currently provided for in the government's 2030 targets, while still maintaining grid stability.

On conservative assumptions, this study suggests that the use of renewables-based FFR services may allow instantaneous variable renewables penetration levels to rise to around 70% in western Japan and up to 60% in the eastern synchronous area, while still

1 The dynamic investigations undertaken in this project are based on the bulk power system models for Japan provided by the country's Institute of Electrical Engineers (IEE model). The IEE model used for this analysis is a simplified model of the Japanese power system. An analysis based on a more detailed model would likely improve the quality of the results.

maintaining frequency stability within tolerable ranges.[2] These figures imply that even greater renewables penetration may be possible in certain regions. In the absence of fast frequency response (FFR) services, instantaneous penetration levels would only reach around 60% in western Japan and 50% in eastern Japan. These assessments confirm the trends observed in 2018 in regions such as Kyushu and Shikoku, where hourly VRES infeed already covers 84% and 79%[3] of demand, respectively (and accounts for over 55% of production). By 2030, these high regional infeed levels could become the norm for the Japanese system as a whole.

Instantaneous infeed levels above these thresholds would begin to challenge the system's frequency stability limits. This situation would only rarely ensue in the more ambitious renewables scenario, however, and would almost never occur in the governmental scenario. One solution could therefore be to introduce instantaneous penetration (SNSP) limits and curtail renewables infeed above these thresholds. This approach would lead to curtailment levels of under 2%[4] of annual renewable generation in the more ambitious renewables scenario.

The analysis implies that, on conservative assumptions concerning renewable energy developments, the annual share of renewables in Japan can be increased to at least 33%[5] by 2030, while still maintaining grid stability within a tolerable range and without additional transmission line reinforcement.

2 These penetration levels do not take into account any additional technical countermeasures, except the 600 MW ancillary support delivered via the HVDC lines from the western synchronous area to the eastern synchronous area.

3 When taking into account biomass energy and hydropower during these hours, renewables satisfied close to 100% of power demand.

4 Assuming that variable renewable energy generation is curtailed above the instantaneous penetration level of 70% in western Japan and 60% in eastern Japan.

5 Corresponding to 22% wind and solar energy

A higher renewable share of 40%[6] could also be achieved on the same stability limit assumptions (SNSP limit of 60% VRES in eastern Japan and 70% in western Japan) with only a very small increase in the curtailment level to 4% of annual renewable generation. Such a scenario would be possible even on the assumption of a significant reduction in conventional thermal generation (i.e. coal and nuclear) by 2030. Furthermore, given the rapid growth of renewables over the last 5 years, even the 40% share would seem a conservative figure and could be reached before 2030.

In order to further expand variable renewables, it is necessary to consider the additional measures that might be adopted to maintain system stability. These should be implemented in the form of ancillary services (such as FFR or virtual inertia) and may be provided by a range of technologies such as batteries, variable renewables, conventional power plants, synchronous condensers, HVDC links, demand response, and flywheels.[7] Modifying service provision requirements for both conventional and renewable generators is also key to improving grid stability while increasing the proportion of variable renewables in Japan.

Wind and solar energy systems can contribute to maintaining grid stability in situations where high levels of variable renewables may pose a challenge for grid operations

Maintaining power system stability is one of the most critical tasks of transmission system operators. Frequency stability must be maintained at all times, even during major system disturbances.[8] In this

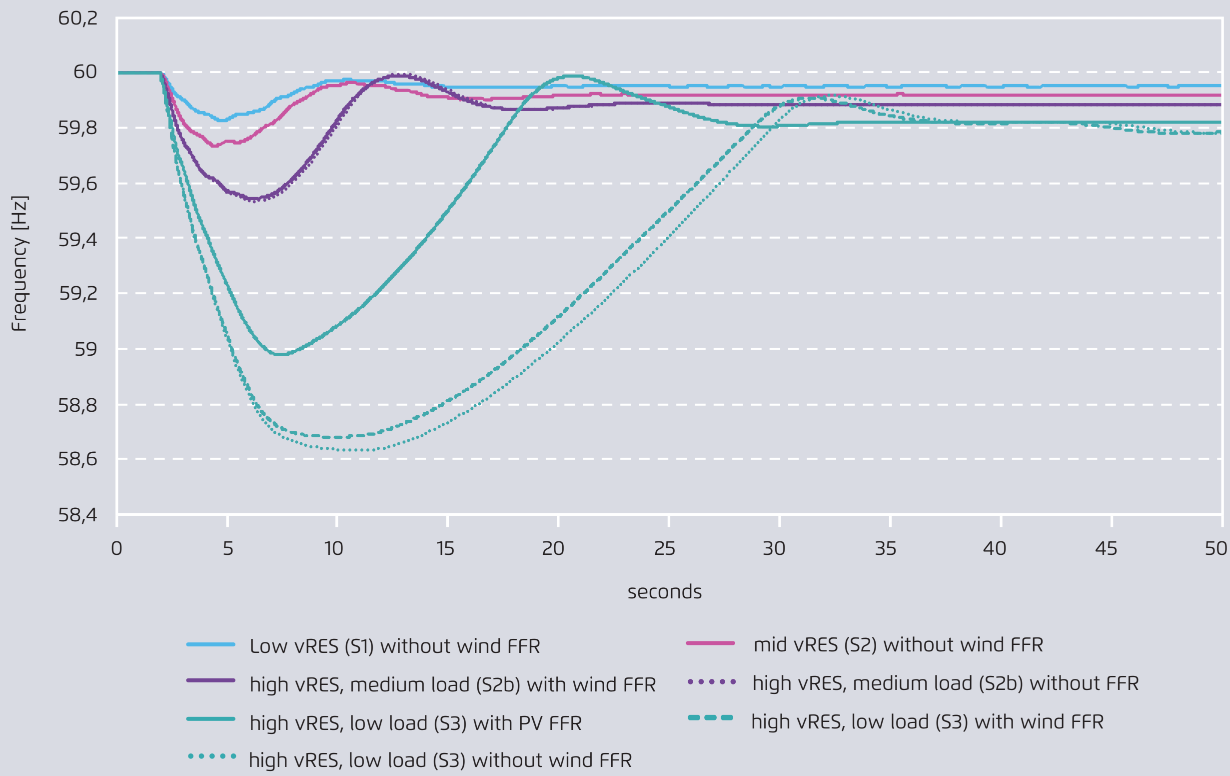
6 Corresponding to about 30% wind and solar energy

7 Quantifying the benefits of these various measures would require more detailed analyses than were possible in the context of this project, given the data available.

8 Other stability criteria, such as voltage stability, rotor angle stability, short circuits, and power quality, are also relevant but were not assessed in detail in this project due to the limited quantity of publicly available data.

Frequency response after loss of 1 500 MW for western Japan +RES scenario; with and without wind and solar FFR

Figure E1



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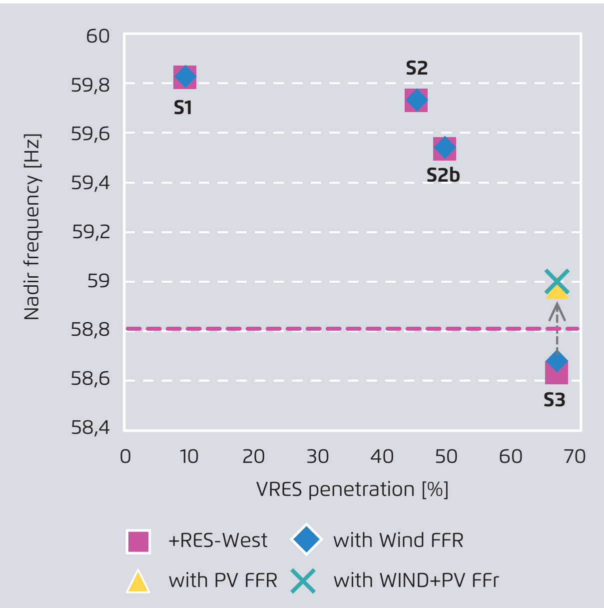
study, frequency stability was assessed in the event of a 1.5 GW generation loss, which was identified as the extreme dimensioning reference incident. System frequency response was assessed in different snapshots involving increasing levels of variable renewables penetration (from 9% to 65%), as illustrated in Figure E1. With respect to the evaluation criteria, the system was assessed on its capacity to maintain frequency drops above 58.8 Hz in western Japan and above 49 Hz in eastern Japan (i.e. a threshold of 0.98 pu). Should the frequency nadir fall below this level, this may result in generators and loads disconnecting, which could in turn lead to local blackouts or cascade effects. Monitoring the remaining inertia in the system is important to guard against critical system states and frequency stability issues.

The results for the frequency nadir in the western area are shown in Figure E1. It can be seen here that the frequency nadir remains above the critical threshold of 58.8 Hz in snapshots S1 (9% VRES), S2 (45% VRES), and S2b (49% VRES) in the western synchronous area. This is the case when the only corrective measures applied are the remaining system inertia and primary control of thermal generators. Snapshot S3 (65% vRES) falls slightly below the critical threshold. With a minimal solar PV contribution to fast frequency service (at a total of 250 MW, which equates to only 0.75% of the actual PV infeed), however, the system can maintain the frequency nadir within the safe operating area (i.e. above 58.8Hz). This highlights the positive impact of VRES-based FFR services in this particular case.

Evaluation of the frequency nadir for the western synchronous area — Figure E2



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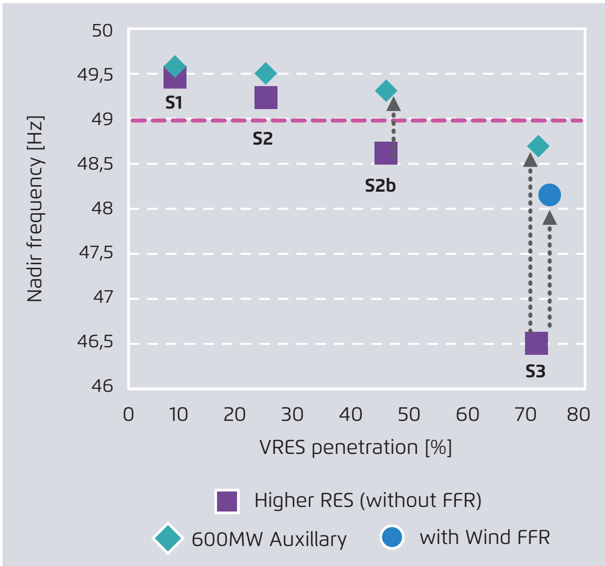
Nadir frequency and VRES penetration in eastern Japan with and without the 600MW ancillary service — Figure E3



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Alongside renewables-based fast frequency response – which is not yet widespread[9] – a range of other technical solutions and modifications to service provision requirements may be implemented to improve grid stability. The technologies that may be employed include ancillary support via HVDC lines, synchronous condensers (created for example by converting decommissioned nuclear reactors[10]), demand side response, and batteries. In Japan, the existing 600MW ancillary support delivered by the HVDC lines from the western synchronous area to the eastern area help to mitigate the loss of frequency in the system. The contribution made by this service to renewable energy integration has been assessed in detail in this study, as can be seen in Figure E2.[11] Snapshot 2b again shows how critical situations can be mitigated and how the nadir can be raised above the critical threshold of 49.0 Hz. In snapshot E3, the nadir remains below the critical threshold, yet it can be raised by a remarkable 2.2 Hz. Similarly, fast frequency response from wind turbines (wind FFR) can maintain frequency levels above 48.0 Hz.

9 The technology already exists but since it is not yet required in most markets, its deployment is limited to a few systems which have very high levels of variable renewables (such as Denmark and Ireland).

10 Such a transformation was undertaken at the Biblis A power plant in Germany, after the electricity generating part of the nuclear reactor was definitively switched off.

11 In order to demonstrate the effect of this mechanism, only the eastern synchronous area was investigated. During the critical snapshots, power flowed from east to west which suggests that an additional injection from west to east would also be possible.

Wind and solar PV deployment have a significant impact on intraregional and interregional load flow. While line loading may decrease in some regions, it is expected to increase in other parts of the system.

This study also investigates the impact of increasing renewables penetration on load flows at the inter-regional and intraregional levels.[12] Aggregated results for the higher RES scenario are given in Table 1, which shows the loading tendencies for interregional lines. These tendencies are divided into three categories: increasing, decreasing and same range.[13] An increase indicates a potential need for grid reinforcement but could also highlight the benefits of improving operational practices. Indeed, higher loads could be achieved in some cases by delivering higher grid capacities (NTC values) to market participants participating in cross-regional exchange. While a detailed evaluation of grid reinforcement measures would call for further investigation,[14] our study shows that the power flow from Kyushu to Chugoku and from Chugoku to Kansai increases in response to an increase in variable renewables penetration. By contrast, power flow from Shikoku to Kansai and from Hokuriku to Kansai decreases. These trends are to be expected, since the significant solar PV installations in Kyushu, Chugoku, and Shikoku serve to reduce the import dependency of these regions' and turn them into net exporters. Finally, increased VRES penetration is accompanied by an increase in exports via the Hokkaido – Tohoku and Chubu – Tokyo HVDC links. Both links are at their maximum loading in the highest VRES penetration snapshots.

Line loading tendencies at higher RE levels — Table E1

Interconnection	Loading tendency
Western area	
Chugoku to Kyushu	Increasing
Shikoku to Chugoku	Decreasing
Chugoku to Kansai	Increasing
Hokuriku to Kansai	Decreasing
Kansai to Chubu	Same range
Shikoku to Kansai	Decreasing
Eastern area	
Tohoku to Tokyo	Increasing
HVDC links	
Hokkaido – Tohoku	Increasing
Chubu – Tokyo	Increasing

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The study further assessed the impact of greater renewables levels on the general loading on the meshed[15] transmission lines within each region. The results for the higher RES scenario are shown in Table E2. In general, we can observe that in certain regions (such as Kyushu, Chugoku, Shikoku and Tohoku), the line loadings and thus the need for energy transmission increases. This indicates a potential need for grid reinforcement. In certain regions, however, the average line loading decreases. This is due to the fact that, in these regions, consumption and generation are moving closer to each other as installed capacities and the overall share of renewables in the energy mix increase.

12 Due to a lack of data in the public domain, our load-flow analysis was only able to assess line loading tendencies.

13 A change within the same range is a loading difference of up to 100MW.

14 This would require greater transparency and improved data access.

15 Meshed lines were chosen here because they more clearly indicate the need for additional energy transportation. In contrast to feeder or generator lines, reinforcement is triggered only by additional generation capacities.

Line loading tendencies by region in response to higher RE levels — Table E2

EPCO region	Loading tendency
West	
Kyushu	Increasing
Chugoku	Increasing
Kansai	Decreasing
Hokuriku	Decreasing
Chubu	Decreasing
Shikoku	Increasing
East	
Tohoku	Increasing
Tokyo	Decreasing

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Variable renewables can deliver some of the additional ancillary services required, particularly additional reactive power

Increased penetration of inverter-based renewable technologies (predominantly consisting of wind and solar power) has the effect of displacing conventional synchronous machines (i.e. coal, nuclear and gas power plants). This displacement of thermal generation not only has implications for frequency stability but also for ancillary services that are important in ensuring system reliability, such as reactive power/voltage support, control power, short circuit currents, and system restoration. The study gives an indication of how high renewables infeed levels in Japan may affect demand for reactive power. The overall results are given in Table E3.[16]

Additional reactive power demand in the +RES scenario — Table E3

	+RES scenario			
	West		East	
	Q_L (Mvar)	Q_C (Mvar)	Q_L (Mvar)	Q_C (Mvar)
Low RES (S1)	–	1300	–	–
Med. RES (S2)	–	1000	–	–
High RES (S3)	220	180	740	1960

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It can be seen here that the additional demand for reactive power remains within a moderate range of < 2GVAr in the eastern and western areas. This range is moderate to the extent that 2GVAr represents only a small fraction of the assumed renewable energy installations of 36GW of wind and 100GW of PV. State-of-the-art wind farms and PV solar parks also have a default feature that allows them to provide reactive power. On the conservative assumption that variable renewables can contribute only 10% of their installed active power in the form of reactive power (i.e. 100GW of PV can provide 10GVAr of reactive power) the additional 2GVAr of reactive power demand can easily be satisfied by VRES. Variable renewables may then actively contribute to reactive power management (along with other ancillary services such as control power).

Non-discriminatory market rules, enhanced transparency, and state-of-the-art operational and planning practices can facilitate the integration of variable renewables in Japan

In light of the experience of various other countries, a number of recommendations can be derived from our analysis. These recommendations aim to facilitate the integration of renewables at a reduced cost while maintaining a high level of reliability in the power system.

16 Q_L indicates demand for inductive reactive power; Q_C for capacitive reactive power.

Recommendations for policy planners and regulatory bodies

- **Implement non-discriminatory market rules for renewable integration:** consider the potential role of RES in ancillary services such as balancing markets and reactive power provision. This would boost the new business case for RES and allow RES to assume greater responsibilities within the power system as a whole.
- **Foster data transparency** to enable third parties to carry out meaningful studies on the Japanese energy sector. This will eventually result in more robust debate and help to raise public awareness.
- **Encourage further power system studies involving independent parties:** Integrating renewables is an interdisciplinary project and further studies should be conducted on congestion management, adequacy, market integration, operational planning adaptation, connection requirements, and system defence.

Recommendations for system operators

- **Establish inertia monitoring:** inertia is a key parameter in ensuring system stability. By monitoring it, system operators can actively limit the consequences of frequency deviation incidents.
- **Integrate renewables into ancillary service provision**: system operators can make use of the capacity of VRES to maintain frequency stability and provide balancing power and voltage control. In all such cases, system operators should diversify their portfolio of service providers.
- **Increase the transparency of the grid and power system data** required for long-term planning.

Recommendations for renewable developers

- **Anticipate grid service requirements:** the Japanese energy sector is set to undergo major changes in the near future as a result of unbundling and the establishment of new markets. Developers should actively define their role in this process and seek out new opportunities.
- **Explore the additional services renewables may provide:** renewable energy sources are already capable of providing other services beyond mere energy supply. We recommend carrying out further studies and defining use cases for services such as FFR, balancing, and reactive power. This will allow innovative solutions to be developed for the benefit of all parties.

149/12-S-2018/EN

How do we accomplish the clean-energy transition?

Agora Energiewende develops scientifically based and politically feasible approaches for ensuring successful energy transition in Germany, Europe and worldwide. We see ourselves as a think-tank and policy laboratory, centered around dialogue with energy policy stakeholders. Together with participants from public policy, civil society, business and academia, we develop a common understanding of energy transitions, its challenges and courses of action.

Renewable Energy Institute was established in the aftermath of Fukushima Nuclear Accident, in August 2011, to establish renewable energy based society in Japan and other countries. REI conducts scientific studies on renewable energy policies, advocates the policy makers and introduces global knowledges of renewables to the public.

Agora Energiewende and Renewable Energy Institute initiated in 2016 a partnership with the goal to transfer expertise and deepen information exchanges about the ongoing energy transition in Germany and Japan.

Agora Energiewende

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Agora Energiewende is a joint initiative of the Mercator Foundation and the European Climate Foundation.