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Integrating renewables into the Japanese power grid by 2030

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

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egi elia grid international
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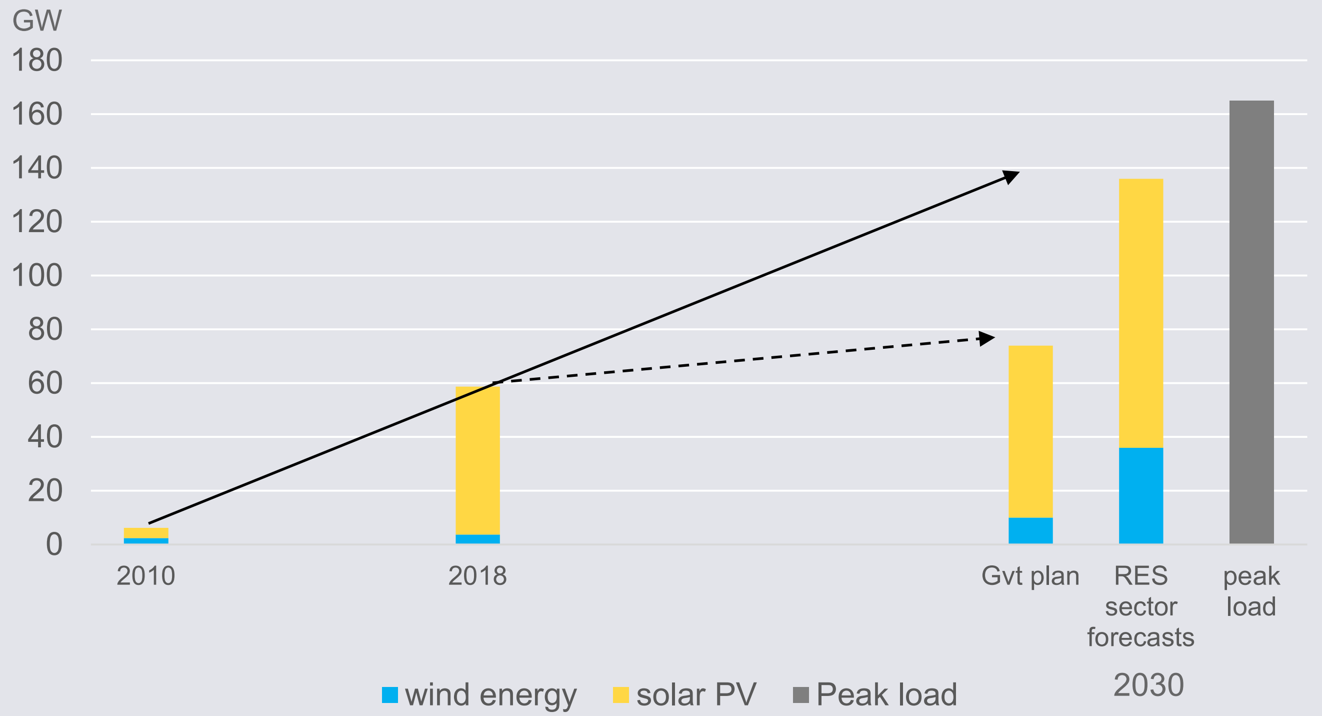
Framework : Is Japan more sensitive to grid instabilities than other power systems?

Solar PV has risen rapidly in Japan over the last five years, but concerns regarding grid integration could raise the possibility of a renewables slow-down

Installed solar and wind capacities in Japan in 2010 and 2018. Projection for 2030 according to the government plan and the forecast of RES sector



Source (REI, BP, GWEC, METI), data for 2018 are preliminary, peak load data from 2017, Gvt plans 2030 represents current targets, RES 2030 forecasts from the RES sector (2017)

Solar PV has risen rapidly over the last five years in Japan (55* GW installed capacity end of 2018), making the country one of the most dynamic PV markets outside of China.

In Kyushu and Shikoku islands, hourly VRES infeed already covered respectively 84% and 79% of demand in summer (~ over 55% of hourly production)

However, the annual share of VRES is still rather low (~7%) and governmental renewables targets for 2030 (22-24% RES, i.e. ~10% VRES) are significantly below international averages.

Concerns over whether RES can be efficiently integrated into Japan's power grid without endangering grid stability raised the possibility of renewables slow-down in the country.

* preliminary data (BP, 2019)

Renewable integration is more challenging in island systems than in interconnected systems. But Japan is actually made up of large, interconnected islands

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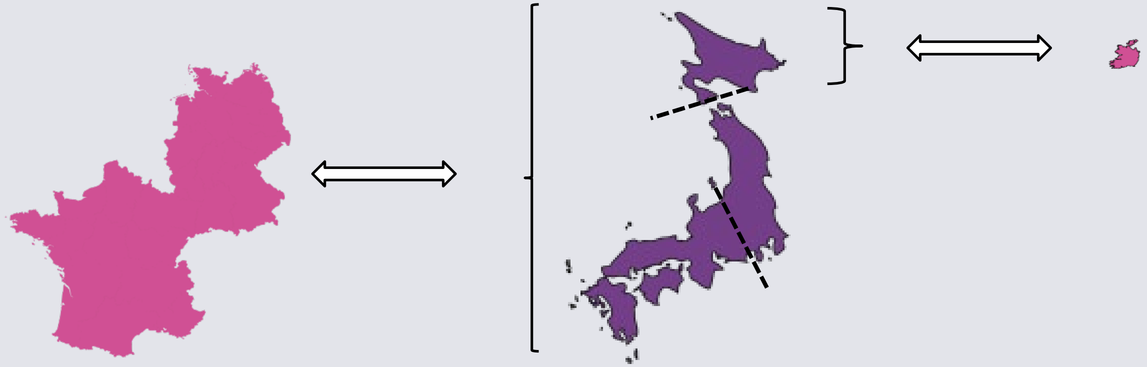
Comparative energy data between Japan, France and Germany (as one region) and Ireland.



Country*	Peak load (GW)	Yearly consumption (TWh)	Share of VRES	Share of coal and nuclear	Wind and solar capacities (GW)
Japan	165	979	6%	35%	52 GW
Sum of France and Germany	172	1100	14%	52%	129 GW
Ireland	4,4	31	25%	19%	3 GW

Source: Meti (2016), Entsoe (2017), RTE (2018), Agora /Sandbag (2018), REI (2018), SEAI (2018)

Island systems cannot benefit from cross-border exchange to balance the system at lower costs. Furthermore, the available inertia is lower in islands than in large interconnected systems.

The Japanese power system is comprised of three main AC synchronous areas : Western Japan (50 Hz), Easter Japan (60 Hz), Hokkaido (60 Hz).

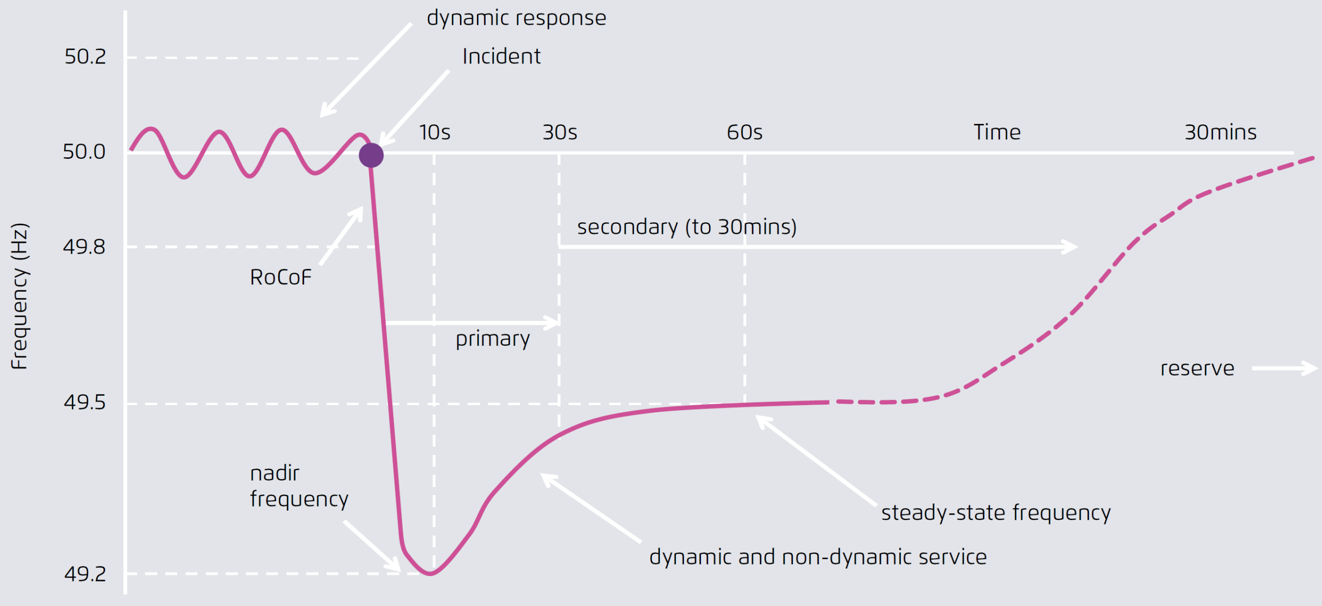
Japan is an island system but it is not Ireland! The Japanese power system is comparable – in size – to the sum of France and Germany. Hokkaido alone is comparable to Ireland.

As a result, renewables grid integration and grid stability is more challenging in Japan than in both France and Germany (since Japan is not interconnected) but easier than in Ireland.

*2017 data for Japan. 2018 data for the European countries.

Maintaining power system stability is one of the most critical task of transmission system operators

Typical frequency response behaviour in the event of a loss of generation



EGI (2019)

Power system stability refers to the capacity of an electric system to regain a state of operating equilibrium after being subject to a physical disturbance.

In order to test system stability, the dynamic (or transient) behavior of key physical values (frequency, voltage, generator rotor angle) is analyzed after a triggering event. <u>This study focuses only on the frequency stability in Japan.</u>

Key physical values must remain in safe operating range after disturbance as to avoid damages and serious consequences for the system (cascading effects, local black-outs, system splits,…)

The system inertia* and the control reserves prevent the frequency from dropping. Frequency nadir and RoCOF** are important parameters to monitor, in order to limit frequency deviation incidents.

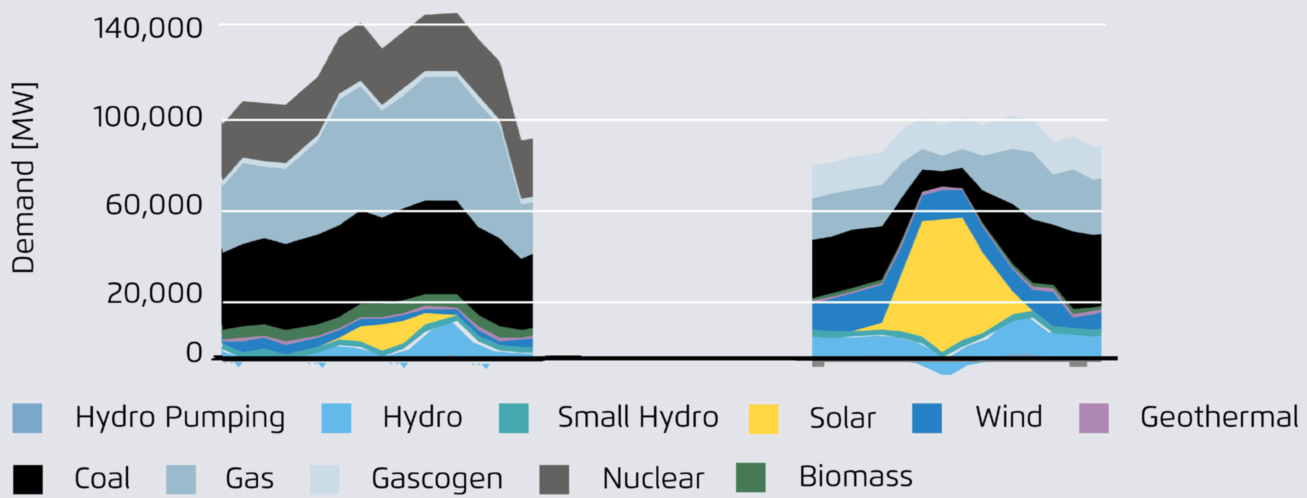
*Inertia is the kinetic energy stored in the rotating part of synchronous machines.
**RoCoF is Rate of Change of Frequency. RoCOF is inversely proportional to inertia.

High vRES infeed can challenge stable grid operation in isolated systems by pushing down the system inertia limits

Hourly generation in Japan in 2030 (left: one day in December in the government scenario; right: one day in May in the +RES scenario)

Day in December
8% vRES West JP, inertia: 440 GWs
5% vRES East JP, inertia : 300 GWs

Day in May
65% vRES West JP, inertia : 100 GWs)
72% vRES East JP, inertia : 60 GWs)



REI, Agora, EGI, gridlab

By default, VRES is a non-synchronously connected generator and does not provide inertia.

High VRES infeed displaces synchronous generators (nuclear, coal and gas power plants), leading to a loss of system inertia.

Without additional counter-measures, an isolated system with high vRES infeed can become more vulnerable to frequency instabilities.

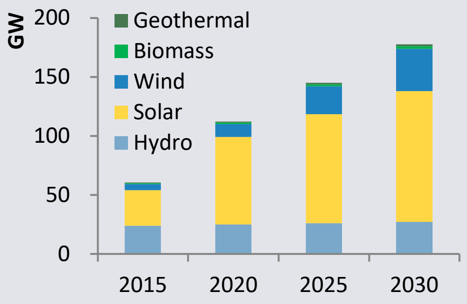
International experiences (Ireland, Denmark, Texas,…) have shown that several technical solutions exist to support frequency stability. This study investigates the situation for Japan.

Model set-up for the Japan grid study

Independent and transparent grid integration studies contribute to a factually grounded debate

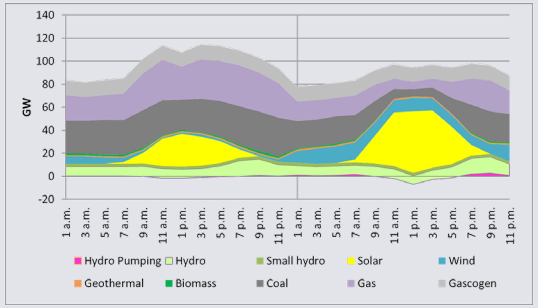
Scenario development

- Database
- Projection of generation capacity
- Estimation of RE output



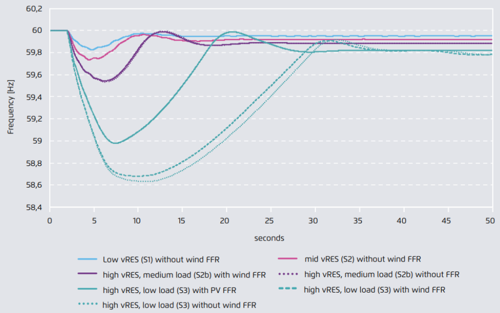
Dispatch modelling

- Evaluation of hourly demand-supply structure
- Selecting snapshot assessed in grid model



Grid modelling

- Evaluation of frequency stability
- Load flow analysis
- Impact evaluation of higher VRE penetration



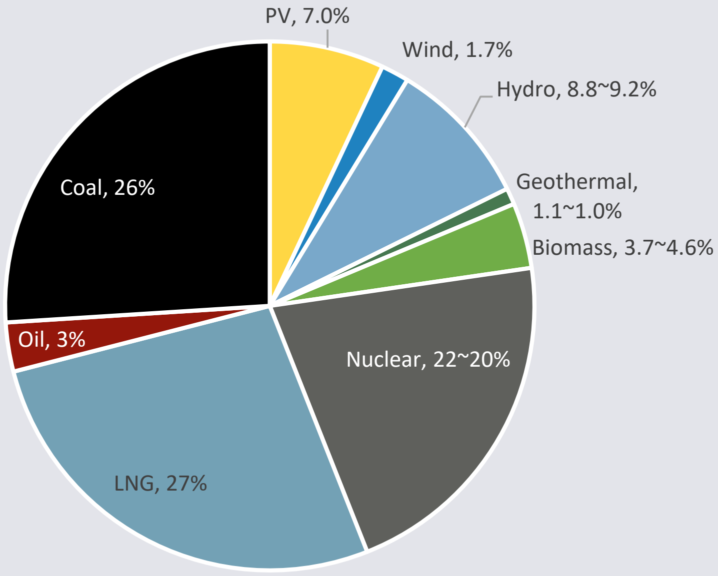
Integrated discussion: Issues and countermeasures to expansion of RE capacity

1. Scenario development : two scenarios were investigated for the Japanese power system in 2030

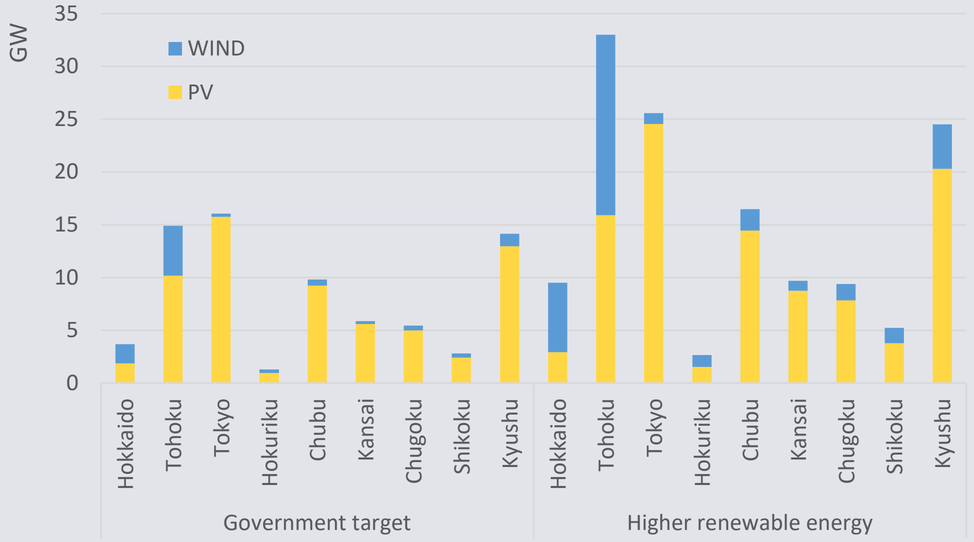
Government target scenario: long-term projection by government (PV:64GW, Wind:10GW; 60GW total coal + nuclear）

Higher renewable energy scenario: based on target by RE industrial association (PV:100GW, Wind36GW; 37 GW total coal + nuclear*

Energy mix in FY2030 based on the government long-term energy projection published in 2015

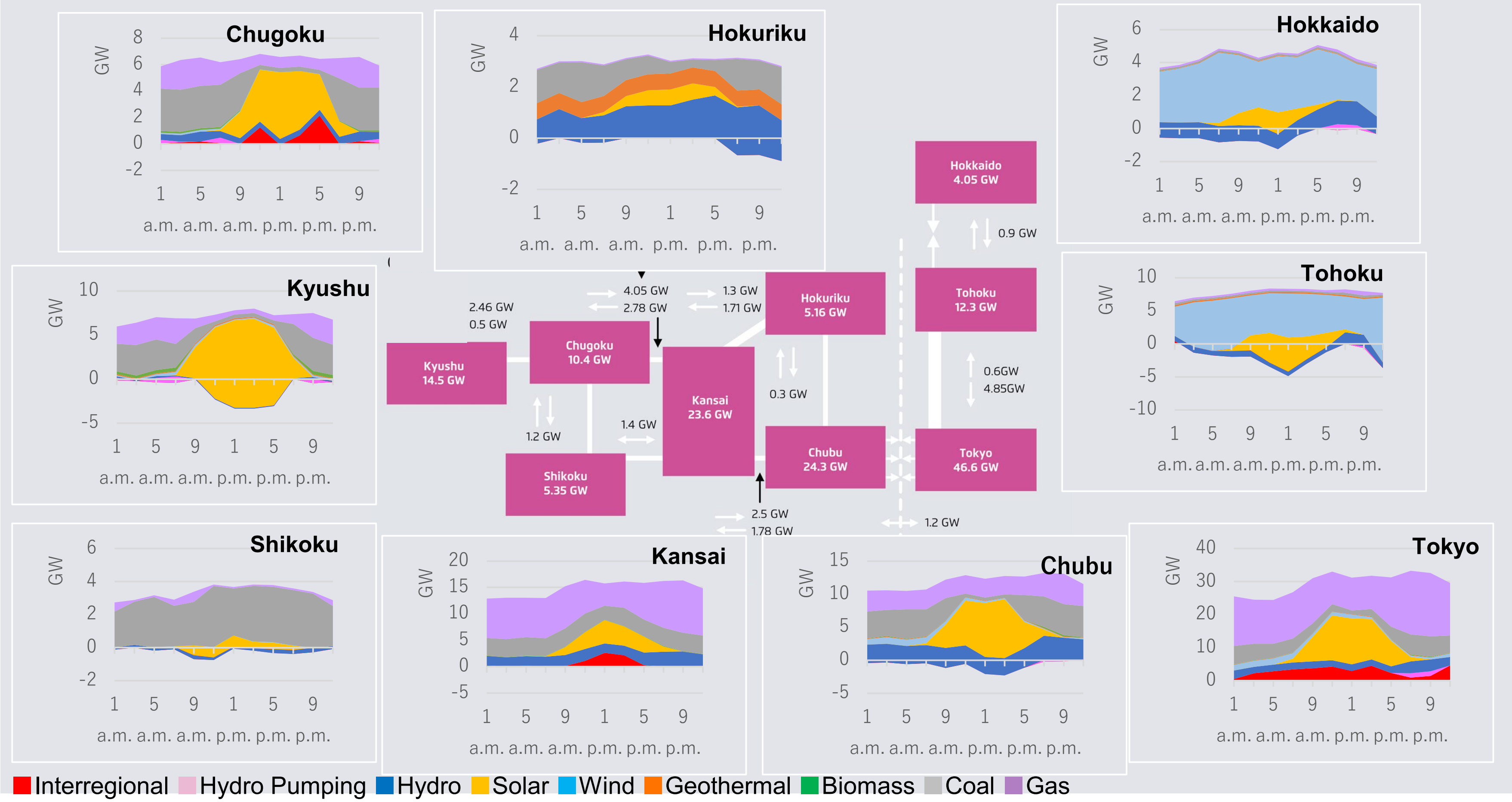


Distribution of PV and Wind capacity in 2030



* The investigated scenario considered 0 GW nuclear and 37 GW coal. However, the dimensioning parameter for the frequency analysis is not the level of nuclear and coal capacities taken individually but rather the sum of both. The +RES scenario is therefore comparable to an alternative scenario were some coal generators have been replaced by nuclear reactors located in the same area.

2. Dispatch modelling: Hourly demand-supply was simulated in minimum/maximum demand day in each month in 2030 by using the SWITCH model*



Main flexibility : pumped-hydro (16 GW), cross-region exchanges, thermal power plants (coal and gas). Nuclear cannot operate flexibly in Japan.

In +RES scenario, the max. PV in-feed for all Japan reaches 64 GWh/h and 26 GWh/h for wind**

Wind energy is produced almost exclusively in East Japan

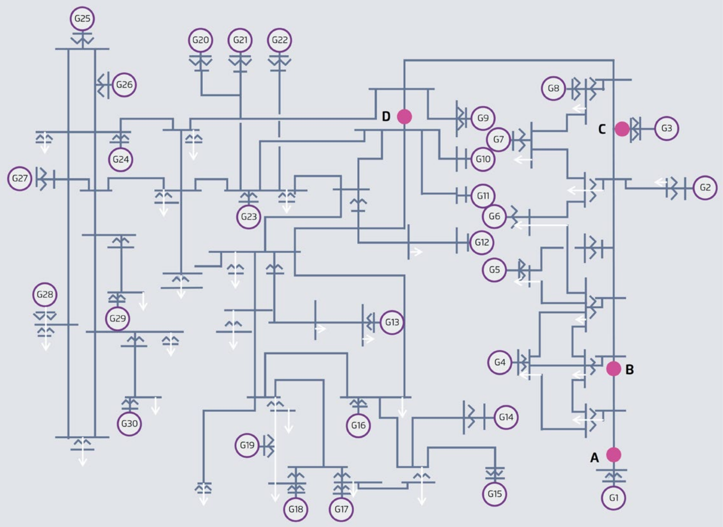
In Kyushu, Shikoku, Hokkaido and Tohoku hourly VRES infeed can be above demand levels

*SWITCH model was developed by Dr. Fripp Mathiass (Assistant professor at Hawaii University) and maintained by Renewable & Appropriate Energy Laboratory of UC Berkeley. Hourly supply-demand of each area is simulated to minimize cost considering interregional electricity trade.

** For installed PV and wind capacities of respectively 100 GW and 36 GW.

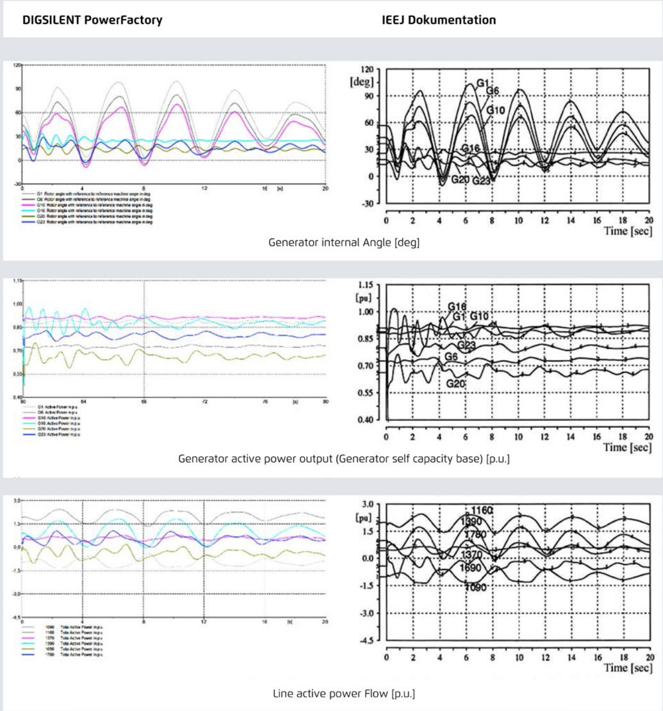
3. Grid model analysis : Evaluation of the impact of increasing instantaneous VRE penetration on frequency stability and load flow

IEEJ power system model (EAST30)



IEE Japan (2001)

Example of results validation in Powerfactory



IEE Japan, Gridlab

Frequency stability analysis : frequency variation caused by an incident must be kept within a tolerable range

Methodology：
IEEJ power system model (2001 is reconstructed and validated in Powerfactroy (DIgSILENT) for this analysis).

The constraint of frequency stability is set to maintain frequency nadir within the range of 0.98 p.u., which equals to the threshold of 58.8Hz in the Western grid and 49 Hz in the Eastern Grid.

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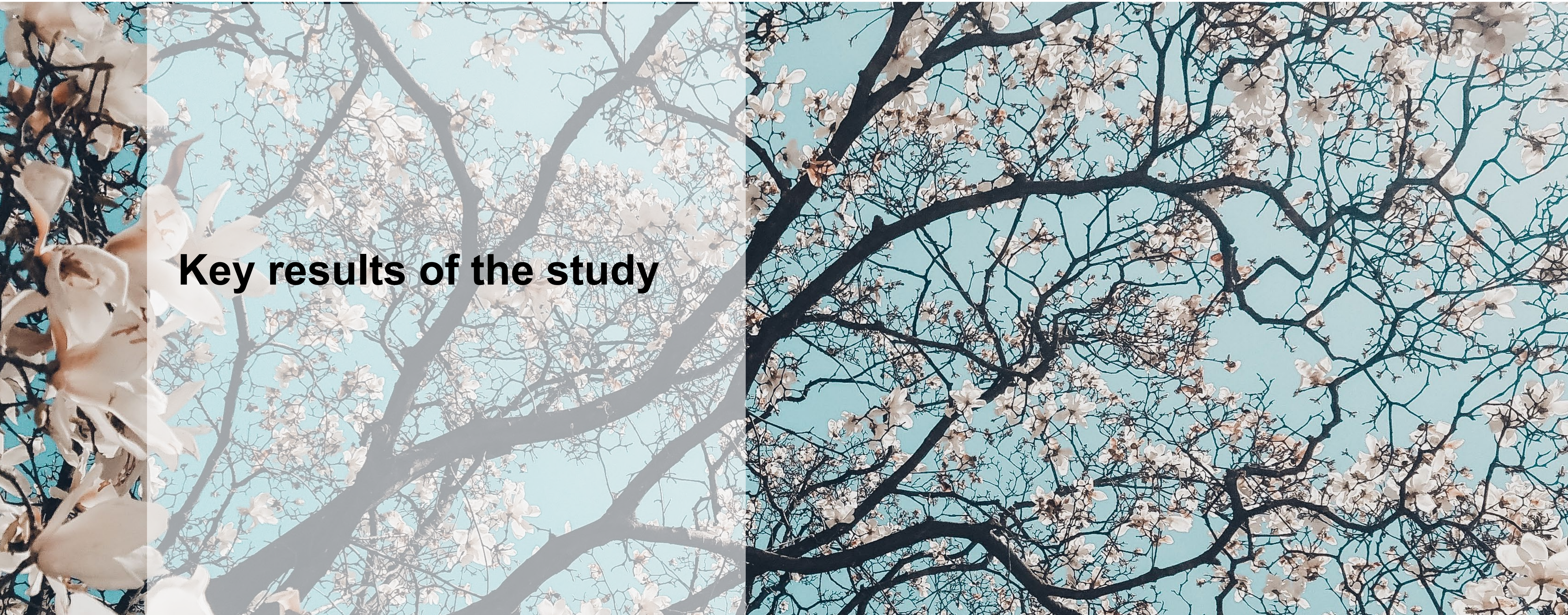
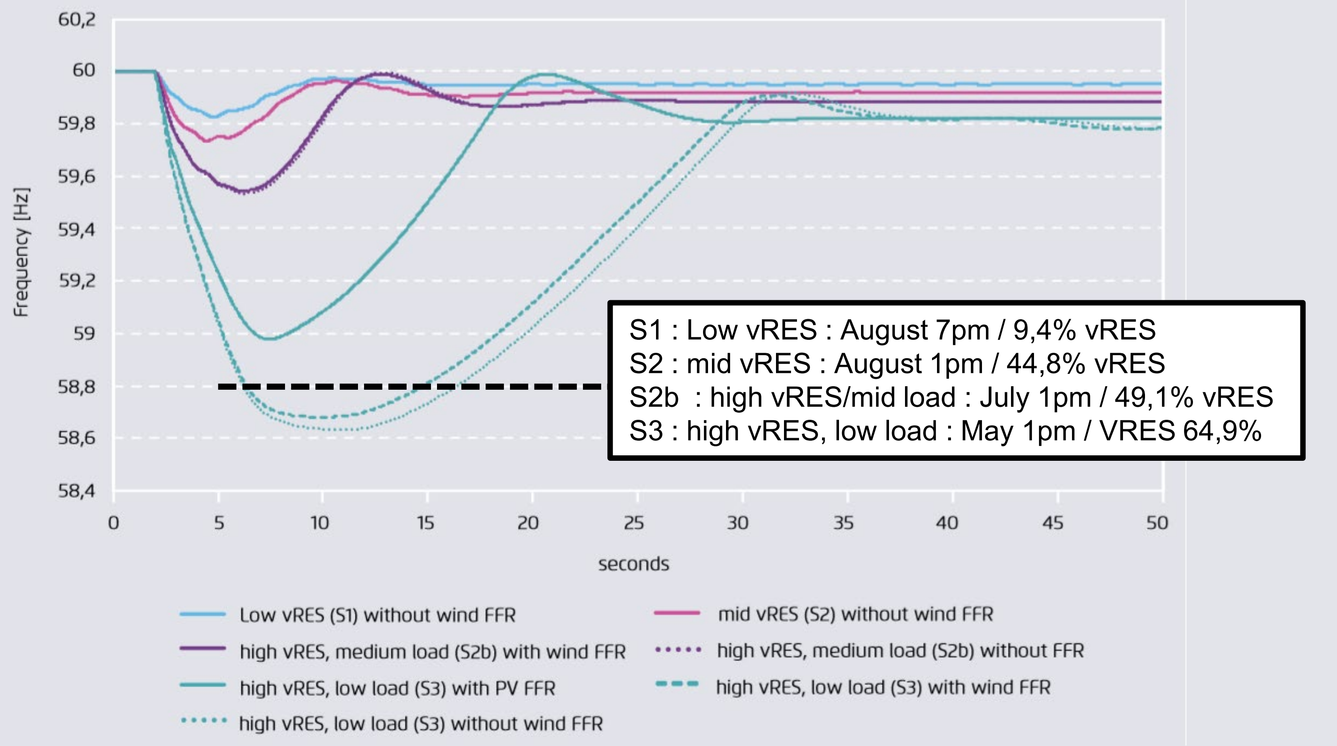
Key results of the study



There are already existing technical measures to improve grid stability in situations where high VRES infeed may place a strain on grid operation

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



EGI, Gridlab (2019)

Instantaneous penetration of VRES above a certain threshold may violate the frequency stability limits of the Japanese power system (frequency nadir > 58,8 Hz in West Japan and > 49 Hz in East Japan* and RoCoF < -0.2 Hz/s)

The use of renewables-based Fast Frequency Response (FFR) services may allow higher instantaneous penetration levels, while still maintaining frequency stability in tolerable ranges

FFR is a super fast (<1s) ancillary service providing/consuming power in cases of grid frequency deviations. It can be provided by many different technologies, including wind mills, solar PV, batteries, DSR, synchronous condensers

In many power systems, especially electrically isolated systems, FFR solutions is already state of the art (for example in the UK, Ireland, Texas (Ercot/US))

* This correspond to a limit of 0.98 p.u. in both areas.

The existing Japanese transmission grid can incorporate instantaneous VRES penetration of up to 60% in East Japan and 70% in West Japan, while maintaining frequency stability

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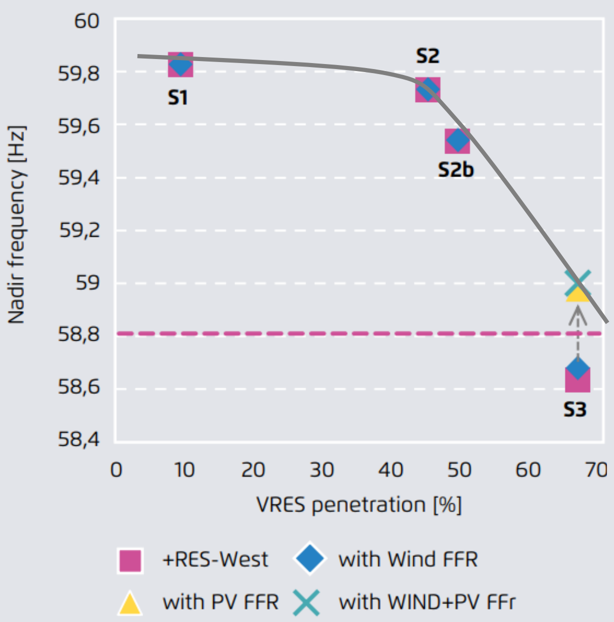
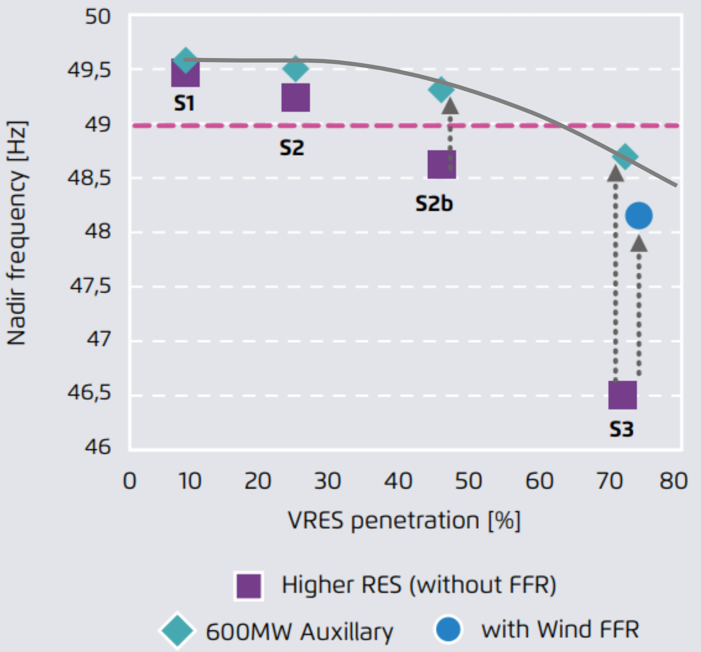
Evaluation of the frequency nadir for the western synchronous area (left) and in eastern Japan (right) under various vRES infeed





EGI, Gridlab, Agora, REI

Under conservative assumptions on grid stability and without any other technical counter-measures, VRES infeed above ~60% in West Japan and above ~50% in East Japan could begin to challenge the system frequency stability limit.

The use of renewables-based FFR* services may allow instantaneous VRES penetration to rise to ~70% in West Japan and ~60% in East Japan, while still maintaining frequency stability in tolerable ranges.

These assessment confirm trends observed in Kyushu and Shikoku in 2018 where hourly VRES infeed covered already respectively 84% and 79% of demand (and accounts for over 55% of production). By 2030, those high regional infeed would become the norm for Japan as a whole.

* Fast Frequency Response

The Western grid is more robust in withstanding internal incidents than the Eastern grid

Comparison of factors influencing stability between the eastern and western synchronous areas

Contributor to system stability	Reason	East	West
Grid			
Grid topology	Better meshed, more lines → more stable	–	+
Grid size	More transmission lines / More damping	–	+
Remaining system inertia	Less inertia → less stable		
Generation technologies	Different technologies have different inertia constants	○	○
Generator operating points / dispatch	If load distributed to more generators with less loading, inertia is higher	–	+
Peak load / load level in general	For higher loads, the same level of SNSP means more system inertia	–	+
Pumped hydro & hydro installations	pumped hydro & hydro is always on and always provides inertia	–	+
Counter measures			
Amount of primary control	More primary control, more stability	○	○
Response time for primary control	More ancillary support more stability	○	○
Auxiliary support services (600MW)	More ancillary support more stability	○	○
Fast frequency response services	The more RE installed, the greater	–	+
Event			
Dimensioning incident	The bigger the incident event [in GW], the bigger the impact on frequency stability	○	○
Incident location		○	○

EGI/Gridlab (2019)

An annual share of at least 30% VRES can easily be integrated, while maintaining grid stability within tolerable ranges and with very low curtailment levels.

Estimation of curtailment level in 2030 by introducing an upper SNSP limit of 60% in East Japan and 70% in West Japan

	JAPAN ~33% RES			JAPAN ~ 40% RES		
	JAPAN	EAST	WEST	JAPAN	EAST	WEST
Annual demand (TWh)	916	412	503	916	412	503
PV (GW)	100	44.7	55.3	125	44.8	80,2
Wind (GW)	36	24.9	11.1	54	37.5	16.5
Pumped hydro (GW)	22.3	8.9	13.3	22.3	8.9	13.3
SNSP limit*	60% for East 70% for West	60%	70%	60% for East 70% for West	60%	70%
Annual VRES share	22,1%	28,4%	16,9%	28.9%	34.7%	24.1%
Annual RE incl. hydro share	33,0%	38,9%	28,3%	39.8%	45.2%	35.5%
Annual VRES curtailment	1,8%	3%	0%	3.9%	5.1%	2.5%

* The SNSP limit is defined as the hourly upper limit of variable renewables penetration.

EGI, Agora, REI

One solution to ensure stable system operation is to introduce instantaneous penetration (SNSP*) limits and curtail VRES infeed above those thresholds. This is for example applied in Ireland (today SNSP limit 65%. Objective to reach 75%)

Applying SNSP limits in line with the results of this study (60% in East Japan and 70% in West Japan) would lead to curtailment levels below 2% in the +RES scenario**.

A higher renewable shares of 40% (corresponding to 30% VRES) could also be achieved on the same stability limit assumptions with only a very small increase in the curtailment level to 4% of annual VRES generation

Further VRES expansion entails considering additional measures to maintain stability. This should be implemented in the form of ancillary services and provided by other technologies (DSR, storage, synchronous condensers,…)

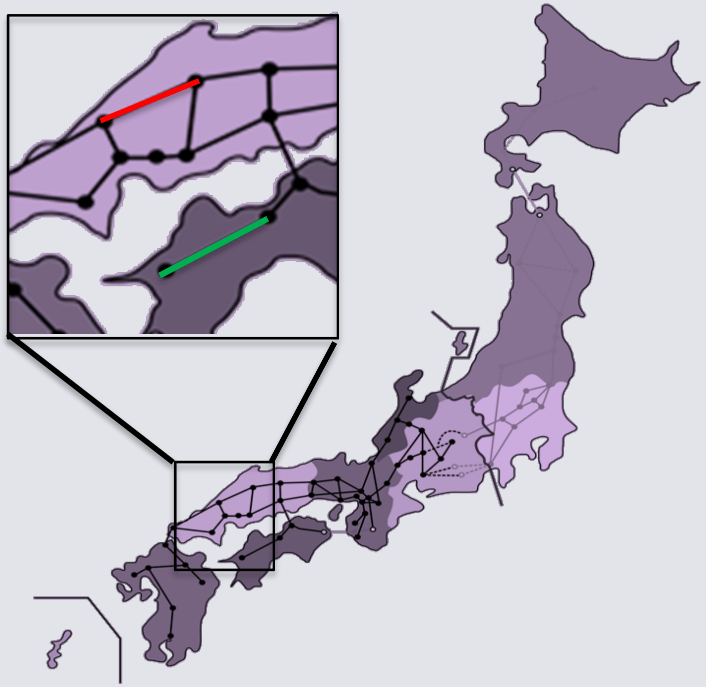
*SNSP : System Non-Synchronous Penetration

**The +RES scenario has a share of ~33% RES in 2030 (22% wind and solar energy)

Integrated grid and resource planning can help mitigate the impact of wind and solar PV deployment on intraregional and interregional load flows

Line loading tendencies by region in 2030 the +RES scenario

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



EGI, Gridlab (2019)

More renewables does not necessarily mean more congestion!

Location is key.

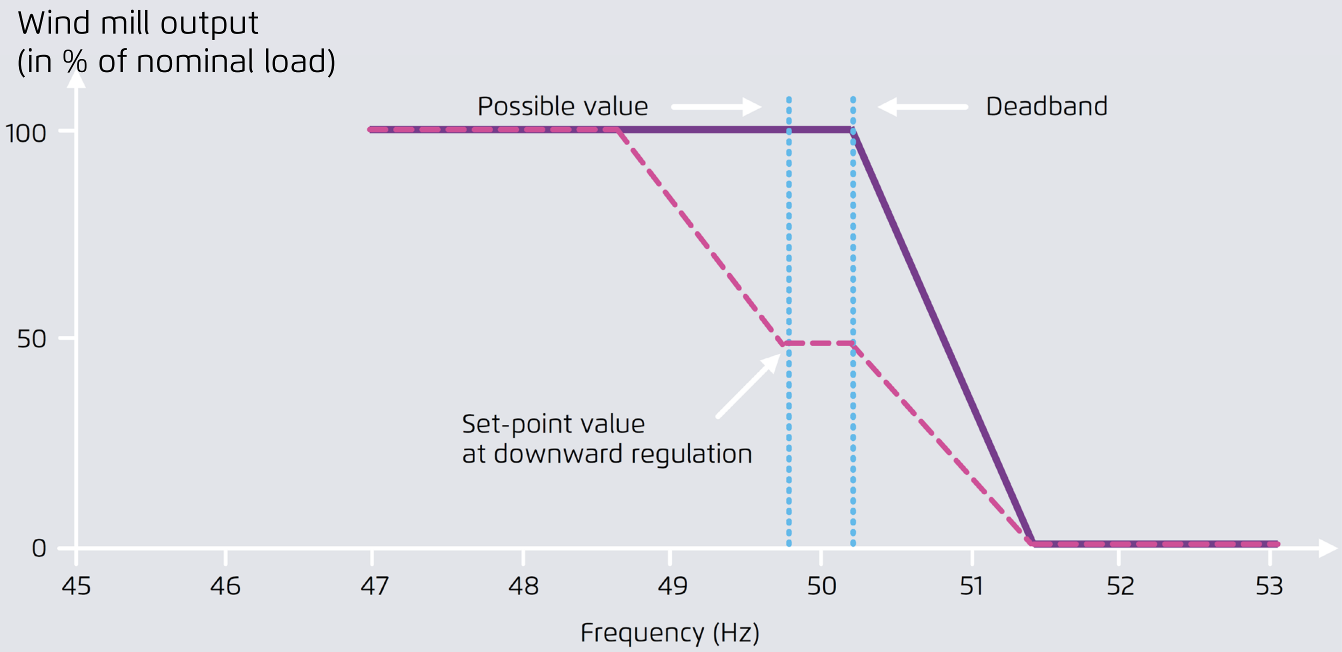
Increasing the proportion of VRES in the mix is indeed expected to reduce power line loading in some regions (Kyushu, Chugoku, Tohoku) and increase it in other parts of the system (Tokyo, Chubu, Kansai, Hokuriku)*

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

*This study could only assess high-level line-loading tendencies. A detailed evaluation of grid reinforcement measures would call for further investigation. This would require greater transparency and improved data access.

Non-discriminatory market regulations, enhanced transparency and state-of the art of operation and planning practices facilitate RES integration

Excerpt from Danish regulations for wind farms connected at a voltage level above 100kV



DEA (2004)

Variable renewables are not only bringing new challenges in term of power system operation, but also provide solutions, for example to ensure system stability.

RES should be integrated in ancillary service provision, since they can contribute to frequency stability, balancing and voltage control, in tandem with other technologies (DSR, conventional generation, storage)

Integrating renewables in ancillary services can contribute to reducing the overall cost for ancillary services procurement.

Non-discriminatory regulations must be implemented in order to facilitate renewable integration (through the definition of grid codes provisions, but also in designing the different short-term and ancillary market segments)

Conclusion - Key insights of the study


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

STUDY

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Key insights

1	**The Japanese power system can accommodate a larger proportion of wind and solar energy than is currently provided for in the government's 2030 targets, while still maintaining grid stability.** An annual share of at least 30% variable renewables (VRES) in Japan (in excess of the 2030 target which currently assigns less than 10% of power consumption to VRES) can easily be integrated, while still maintaining grid stability within a tolerable range and 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).

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