Stability Considerations at 100% Instantaneous Penetration

Session 1: Managing a High Penetration Converter-fed Power System

ESIG 2018 Fall Technical Workshop
Denver, USA, 1-3 October 2018

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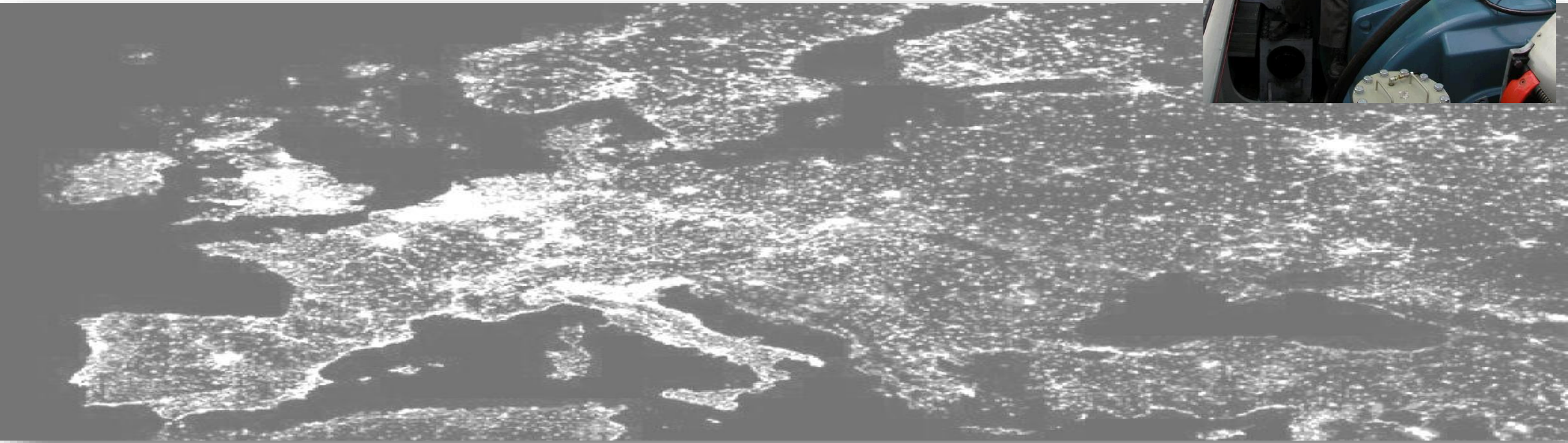


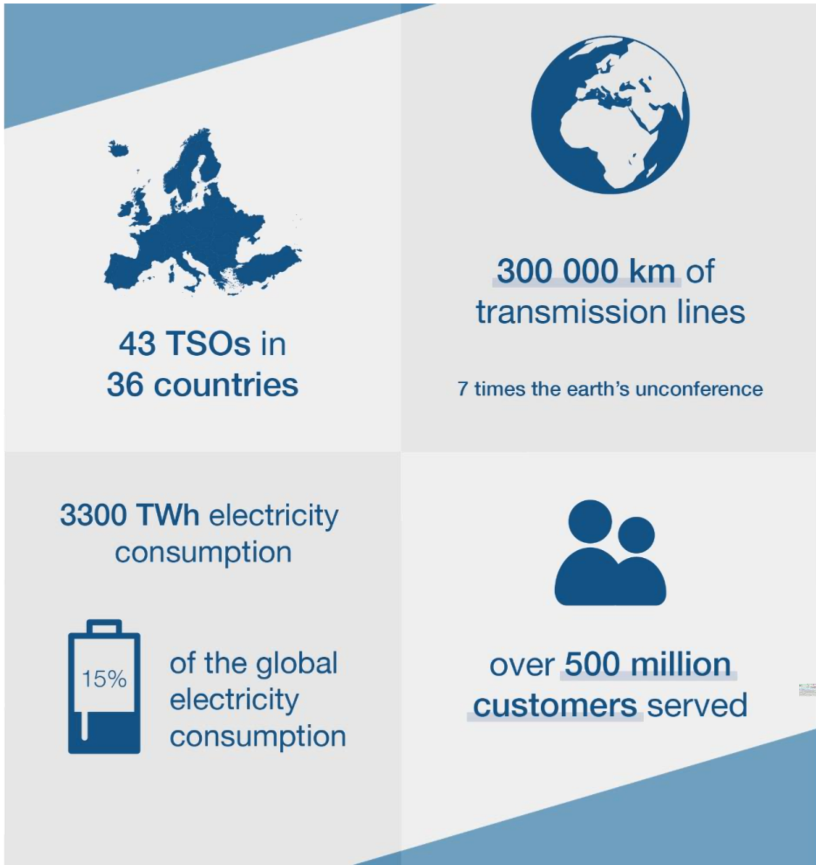
Urdal Power Solutions Ltd

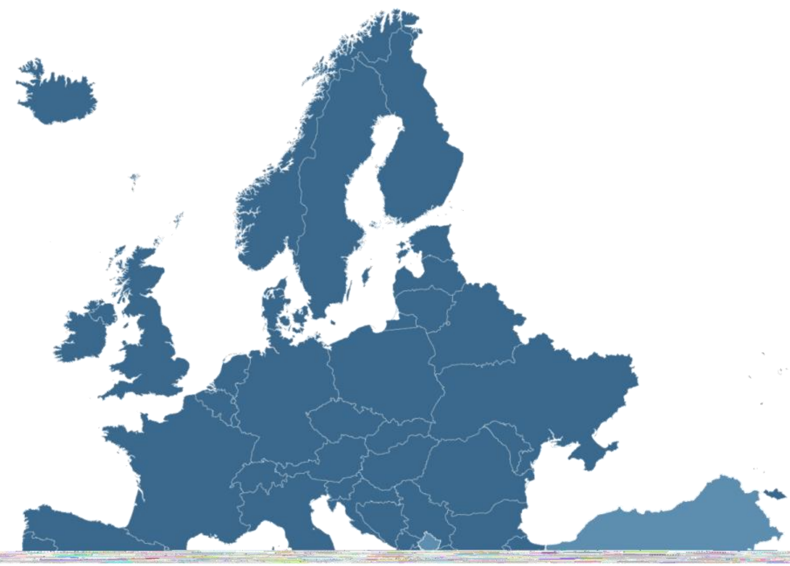
Keeping the lights on in a low carbon future

AGENDA

- Instantaneous penetration - PEIPS scenario examples
- Early SO limits established – Costs looking forward
- Dynamic studies undertaken for GB
  - Consequences of BAU – no change in Converter Control Strategies
  - What can be done if some converters starts LEADING
- Summary of System Technical Challenges with 100% PLLs
- Options to get to Stable Operation at 100% PEIPS
- Developments in Progress
- Conclusions

ENTSO-E
WHO?


300 000 km of
transmission lines
7 times the earth's unconference
43 TSOs in
36 countries
3300 TWh electricity
consumption
15%
of the global
electricity
consumption
over 500 million
customers served



Penetration of Wind & Solar in Europe's 2030 Energy Scenarios updated to 2018

The wind and PV installations continue to grow in GB & Europe

2018 scenarios (by ENTSO-E's in TYNDP) suggests an expansion of RES in EU28 to achieve an electricity share of

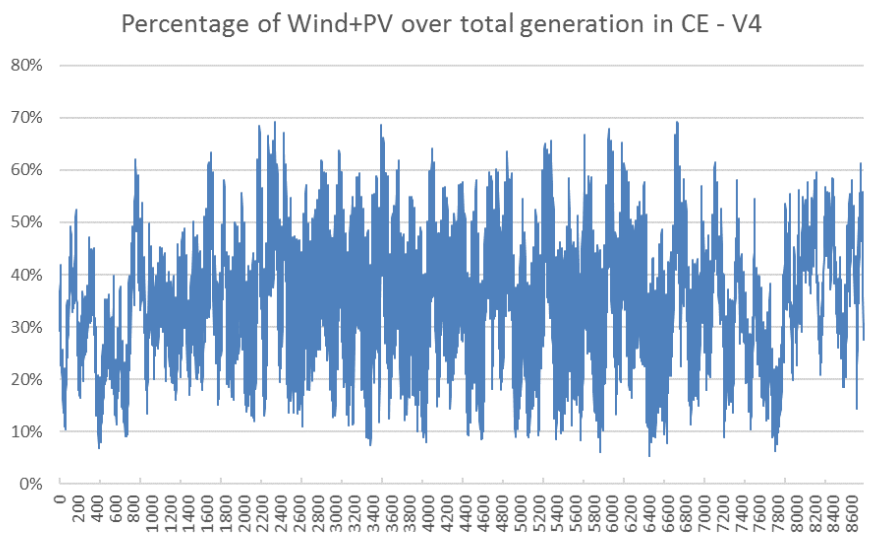
41% in 2020,

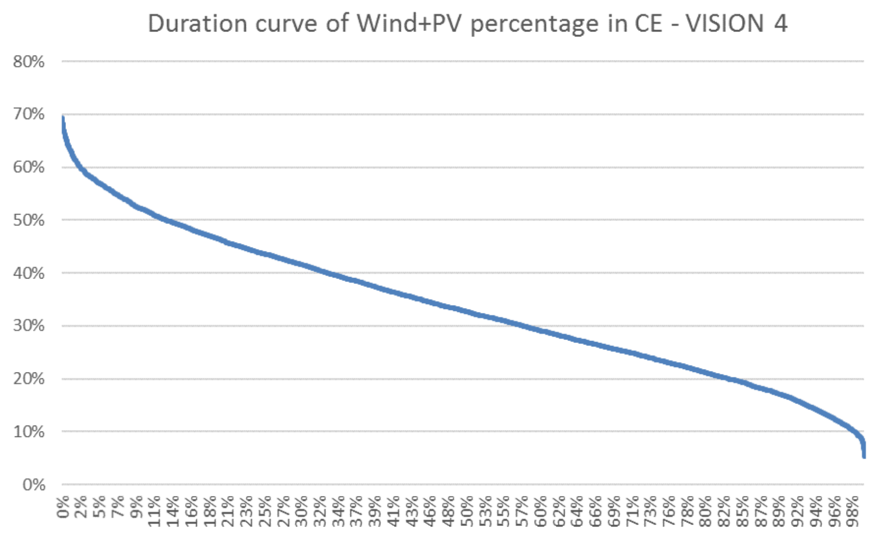
50-58% by 2030

and between 62 and 77% by 2040

(with a CO_2 reduction by 2040 between 60and 70%),

Variability & penetration data for Continental Europe from IGD HPoPEIPS with 2016 Wind + PV penetration data (by ENTSO-E) – Vision 4 scenario 2030.





Penetration getting high even in CE

Smallest synchronous areas, Ireland and GB much higher penetration still. These will soon hit 100% for some hours in the year, unless constrained.

Diminishing System Strength including Total System Inertia

- System strength is an important indicator for stability. It is expressed in different ways, dependent upon the users
  - TSI - Total System Inertia - Used for Frequency management
  - FL - Fault Level - Used in Protection context
  - SCR - Short Circuit Ratio - Used in Converter control context

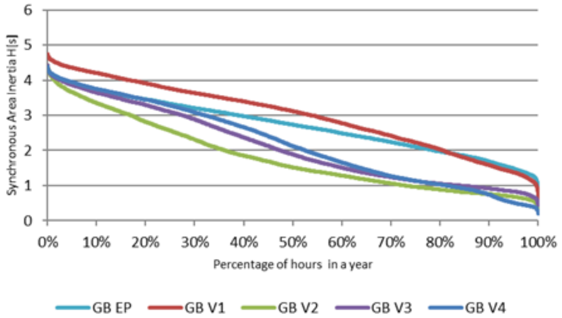
- Availability of TSI data
  - TSI data for 2030 scenarios is available for all 5 European Synchronous Areas (SAs)
  - Data also for TSI contributions from each country to its SA
  - TSI expressed as H (pu). Prior to RES, H was typically 5-6 s.
  - If TSI is reduced, the impact increases of step changes in power. Less time to take counter measures before it is too late
  - Low TSI usually associated with low FL/SCR

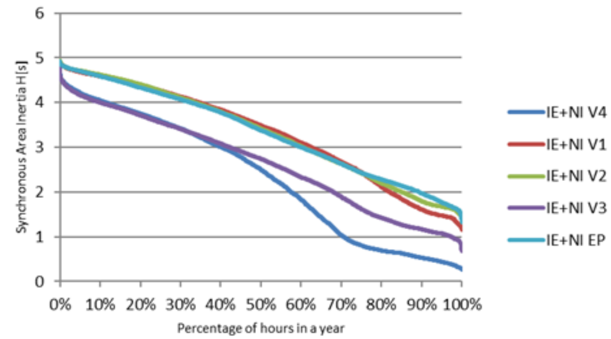
Duration Charts for Total System Inertia (H) in Europe's 5 Synchronous Areas (SAs)
Three SAs Ok'ish while two SAs have big concerns

From IGD HPoPEIPS with 2016 market study results for all synchronous areas for 2020 and 4 different visions for 2030

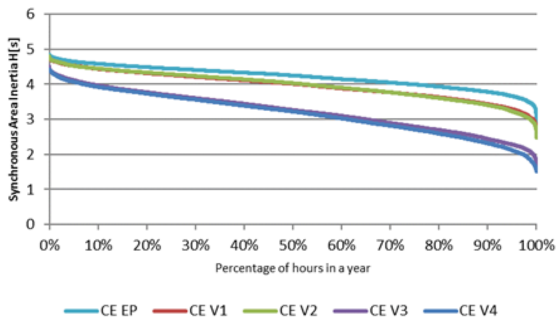
GB & IE+NI have BIG CONCERN at SA level.

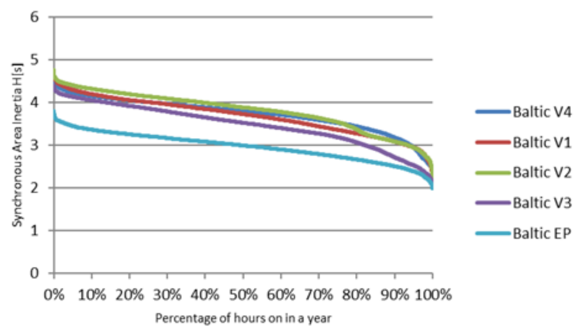
Some scenarios with H<1s for 30% of time! Dramatic reduction in H

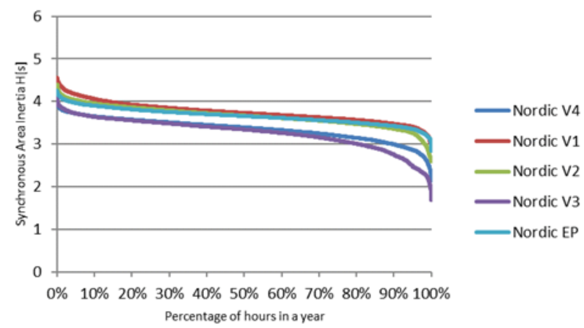




Three SAs ok'ish at SA level with modest reductions in H in all scenarios.







National per unit contributions to Synchronous Area TSI at time of minimum TSI for the SA - INDICATIVE

Inertia contribution colouring code:

- Green H>4s contribution — Very good
- Black 3s<H<4s contribution — Good
- Purple 2s<H <3s contribution — Marginal
- Red H <2s contribution. — Limited Action needed?

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  - Consequences of BAU – no change in Converter Control Strategies
  - What can be done if some converters starts LEADING, using VSM
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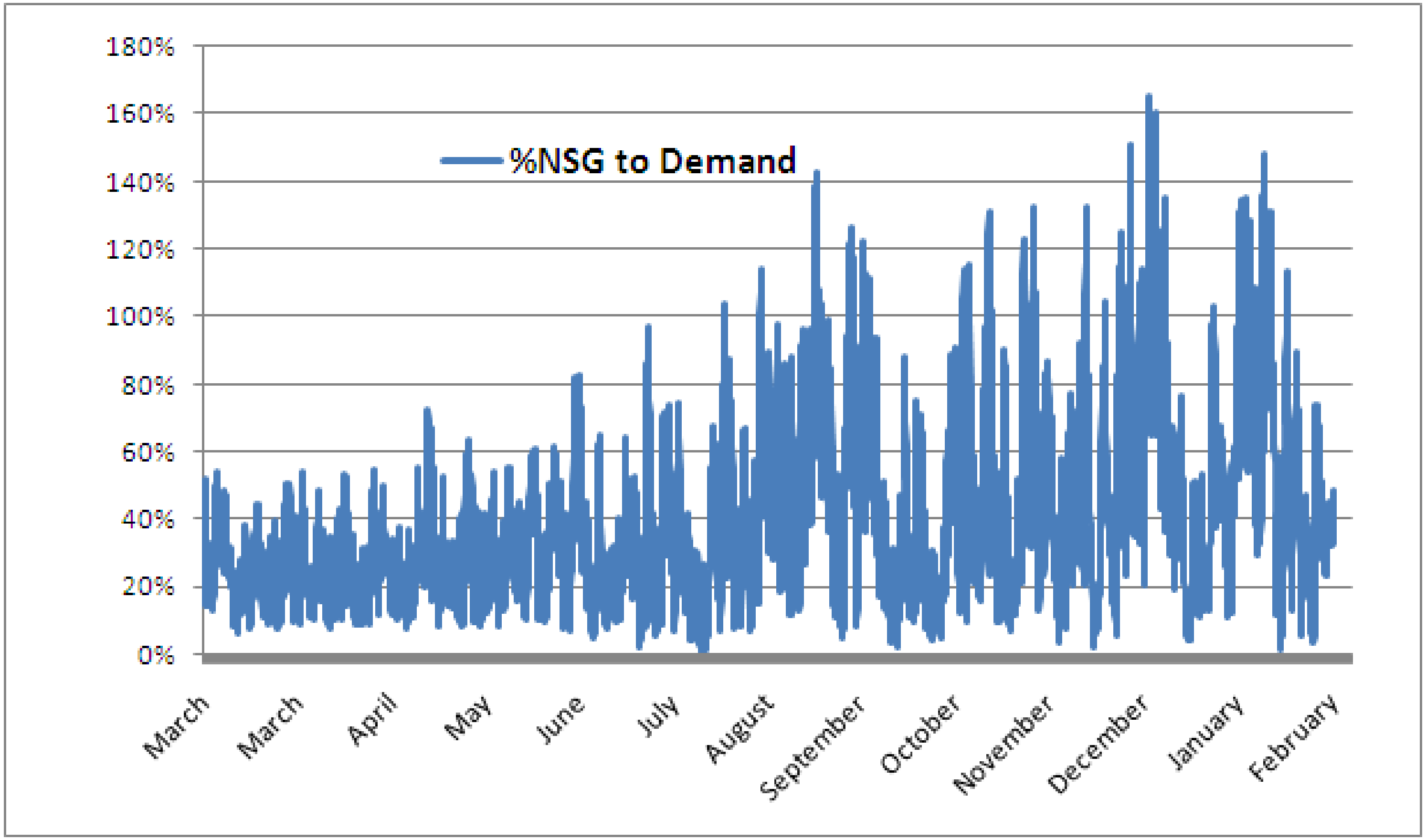
Hourly % Non Synchronous Generation

2030 Gone Green (in 2013) – GB in isolation

Varying from 0% to 165% of demand



Level of RES substitution (TWh) needed with different penetration limits. Improvements from raising GB limit from 50% to 95% NSG/PEIPS

Indicative Annual costs of substitution. Based on £100/MWh substituted. This gives 1TWH=£100M

Red R>£500M/Y

Amber £100<A<£500

Green G<£100M/Y

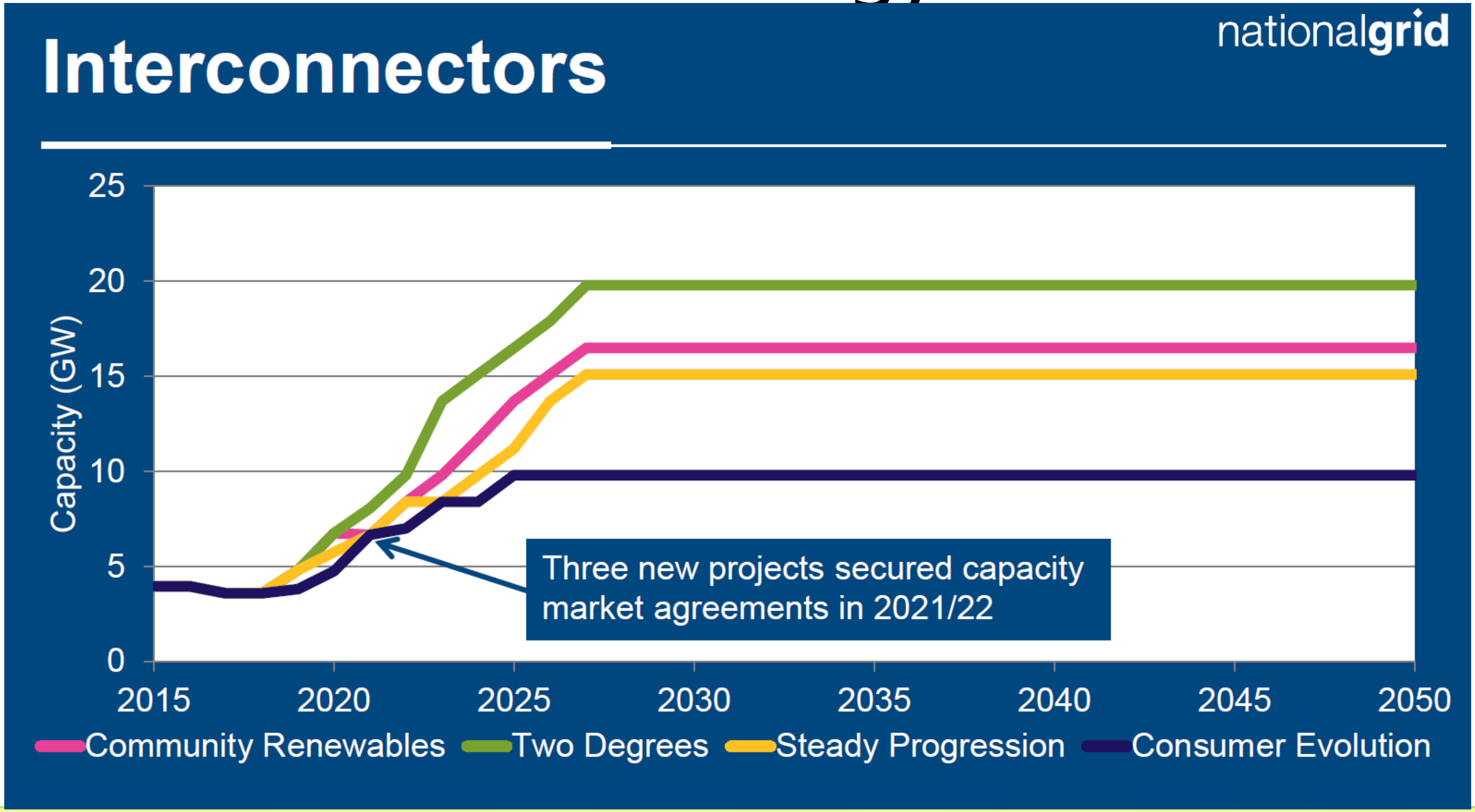
	Worse Import	Base case	Better	Best Export
NSG% (TWh)	3GW Imp. 0 Exp.	No Imp./Ex.	3GW Imp. 10GW Exp.	0 Imp. 10GW exp.
50	31.04	23.14	18.81	13.54
60	21.04	15.25	10.74	7.22
75	10.99	7.46	3.81	2.29
80	8.66	5.68	2.59	1.49
85	6.71	4.31	1.72	0.94
90	5.16	3.27	1.11	0.55
95	3.95	2.45	0.68	0.28

Limit in System Operators' freedom to operate at High Penetration of Power Interfaced Power Sources (HPoPEIPS)

- The GB 2013 economic analysis concluded that
  - On its own GB needs by 2030 to be stable for 95% PEIPS with respect to the load, in order to have a reasonable level of constraints (2TWh or £200M constraint payments)
  - With 10GW export to help, this falls to 85%
- These are both well above the level of 65% where super synchronous instabilities are predicted from rms studies.
- Additionally, recent complex EMT studies for Southern England with HP shows Sub-Synchronous Instability (at 6Hz) see http://www.smarternetworks.org/project/nia_nget0187/documents

PS From Texas 4Hz instability experienced – Texas & GB many similarities re size and RES penetration

Interconnector capacities expected in 2018 Future Energy Scenarios GB



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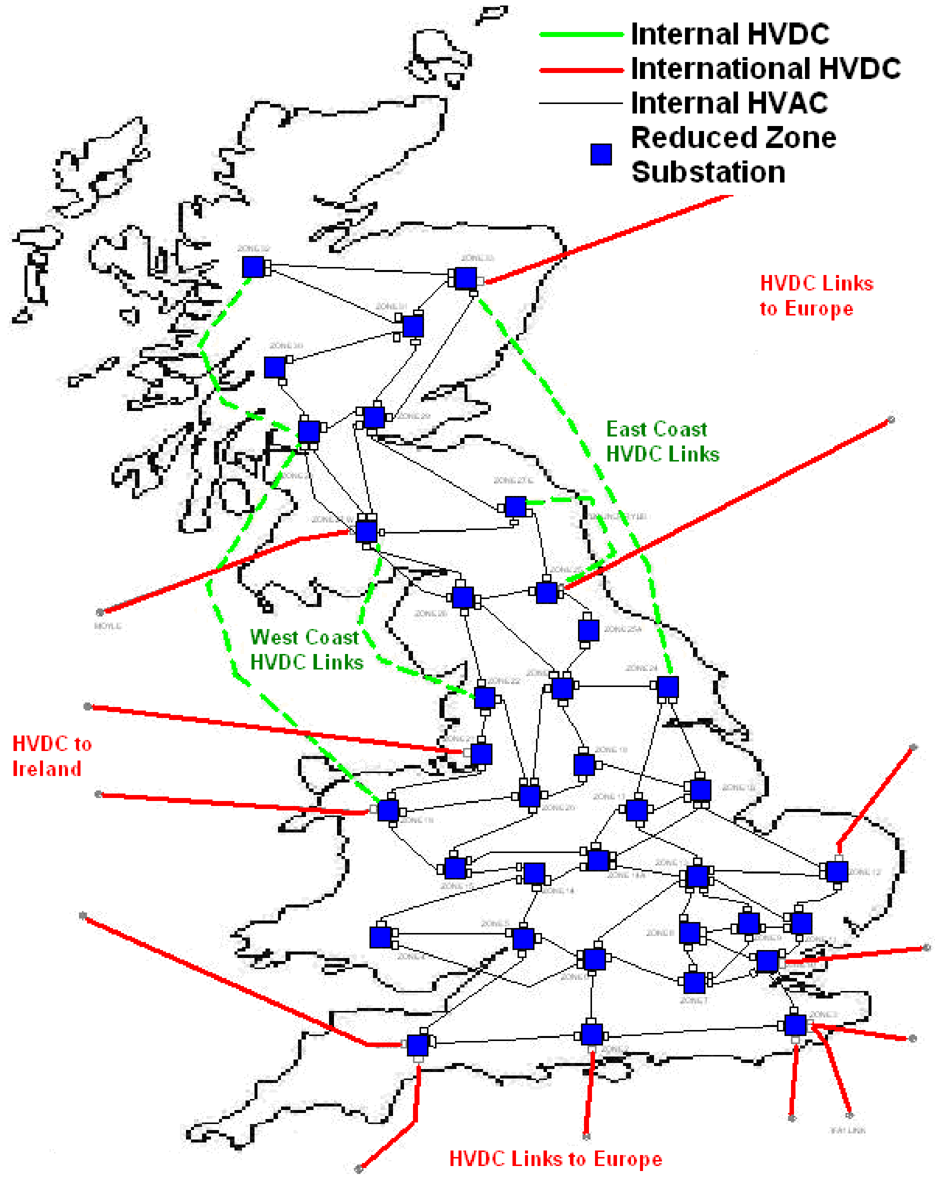
Angular stability analysis for NSG >50%; network used

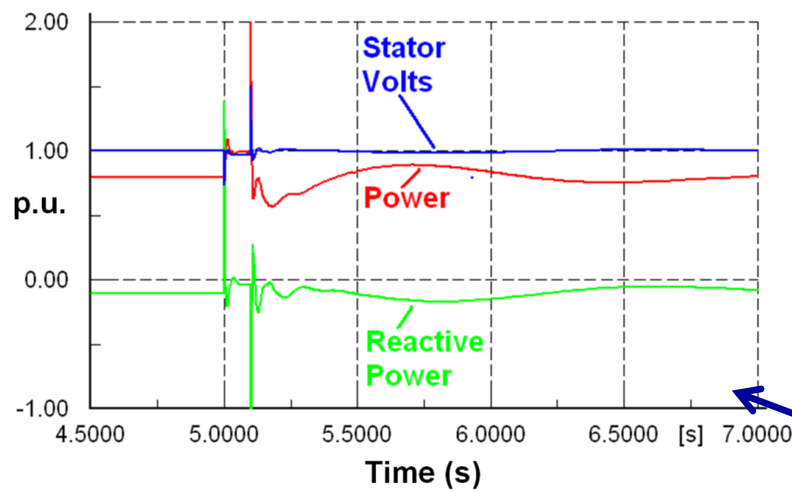


Reduced GB 2030 - 36 Node Transmission System Model

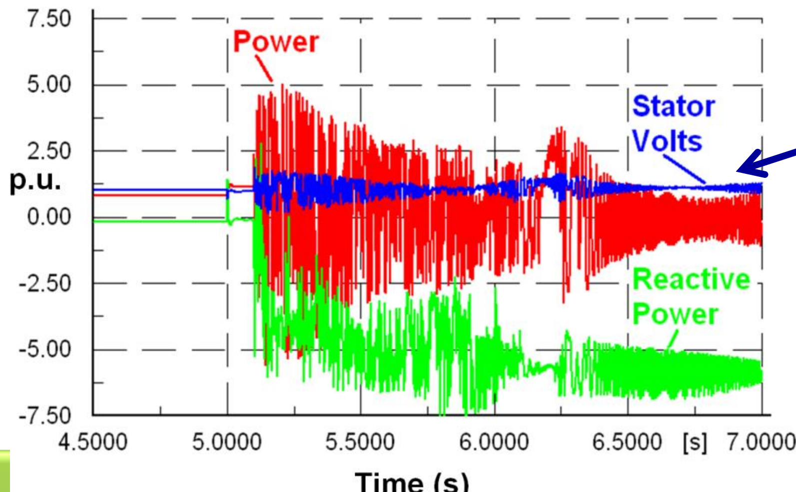
- Network reinforced to accommodate the high levels of NSG in 2030, including current and proposed works e.g. the series capacitors between England and Scotland and East and West Coast HVDC links. Absence of voltage support in the central parts of the system was first remedied by blocks of 2GVA STATCOMs
- Included dynamic controllers for Statcoms, Convertors, Governors, AVRs and PSSs.
- The case chosen was a double circuit 3 phase fault of 100ms duration on 2 of the 4 HVAC links between Scotland and England.
- **Dispatching > 65% NSG (on MW) created angular instability**
- Reduced model including dynamic data available on request by e-mailing Richard.Ierna@nationalgrid.com

2013 Results

2013 – Stable Result



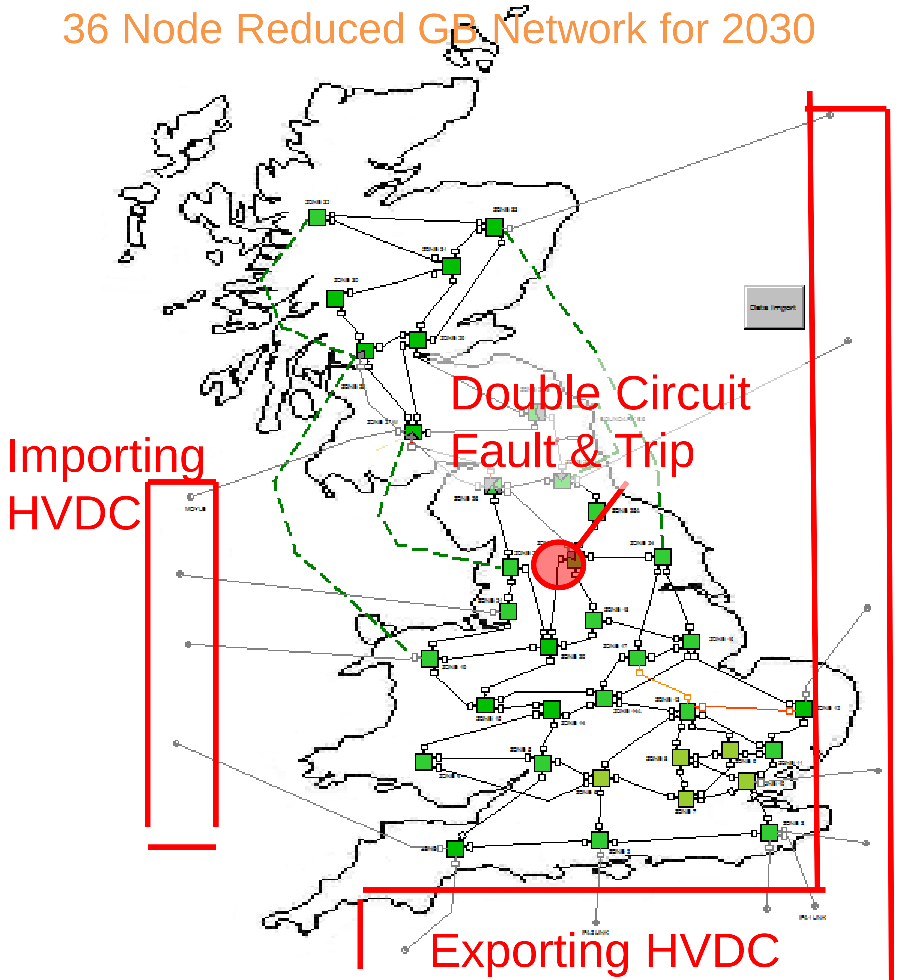
2013 – Unstable Result



NSG	0 Import HVDC 0 Export HVDC			3GW Import HVDC 10GW Export HVDC			0 Import HVDC 10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	OK			OK	OK		OK	OK	OK
Mid				OK			OK	OK	
High			N/A						

2013 Studies
Only 9/26 high NSG scenarios ok

36 Node Reduced GB Network for 2030



NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export HVDC			10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	OK			OK	OK		OK	OK	OK
Mid				OK			OK	OK	
High			N/A						

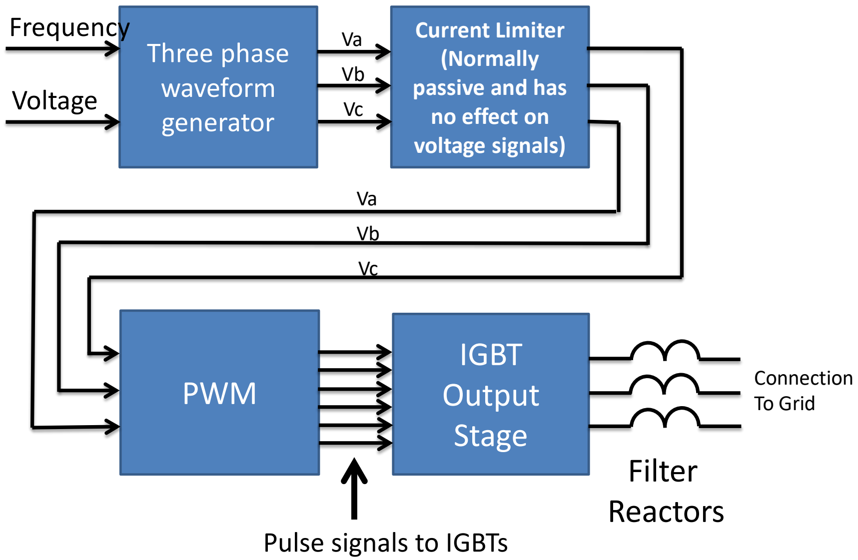
NSG is 8GW Solar +
Low: 16.0GW Wind
Mid: 20.5GW Wind
High: 28.5GW Wind

Brown cells ok in 2013
Grey cells produced HF instability

HP Studies with Grid Forming Converter Controls – VSM / VSM0H

Both VSM & VSM0H use similar output stages

3 Phase VSM / VSM0H Output Stage



<u>Changes for VSM</u>

1. Simulate inertia
2. Reduce the bandwidth of F and V to 5Hz

<u>Advantages (main)</u>

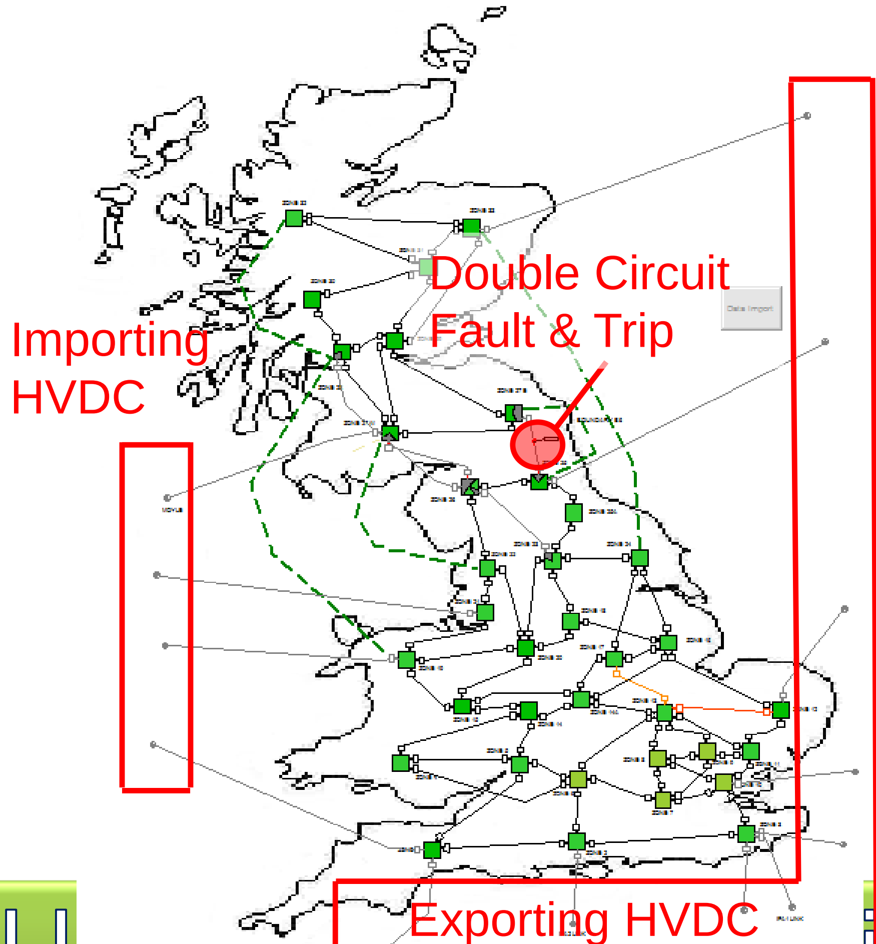
1. Contributes to RoCoF
2. Compatible with SG
3. Reduced interaction and HF instability risks
4. Can be modelled in RMS system studies

<u>Disadvantages</u>

1. Requires additional energy
2. Possibility of traditional power system instability

2016 Studies
All high NSG scenarios stable

36 Node Reduced GB Network for 2030



With VSM all scenarios are stable & 100% NSG is possible

NSG	0 Import HVDC 0 Export HVDC			3GW Import HVDC 10GW Export HVDC			0 Import HVDC 10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	1% 60%	10% 25% 69%	10% 25% 80%	1% 54%	1% 60%	10% 68%	1% 48%	1% 15% 53%	1% 60%
Mid	5% 25% 73%	5% 83%	10% 97%	1% 64%	10% 25% 71%	10% 80%	1% 58%	1% 20% 64%	10% 73%
High	15% 97%	20% 30% 103%	N/A	10% 80%	10% 89%	15% 35% 100%	10% 25% 74%	10% 82%	10% 30% 93%

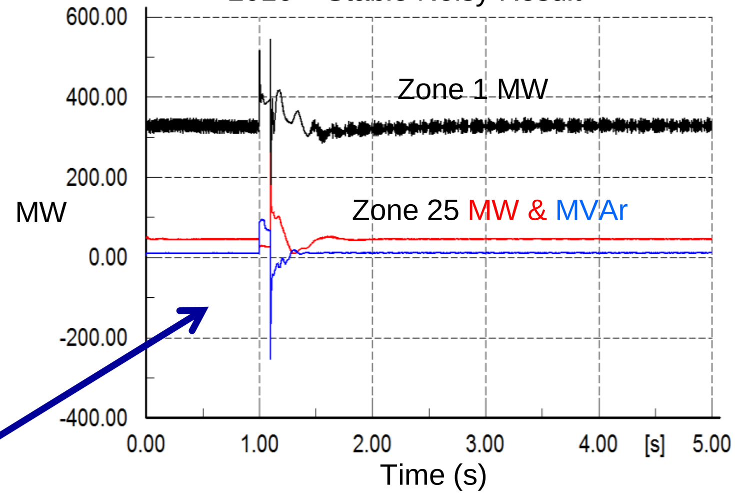
NSG is 8GW Solar +
Low: 16.0GW Wind
Mid: 20.5GW Wind
High: 28.5GW Wind

Brown cells ok in 2013
All cells now ok with VSM
% of NSG which is VSM
10% VSM for stability
30% VSM for low noise
93% NSG (7%SG)

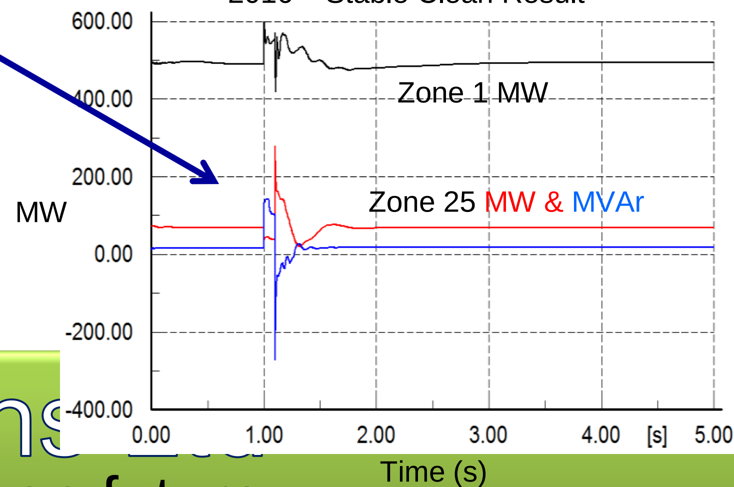
Typical results from 2016 studies

NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export HVDC			10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	1% 60%	10% 25% 69%	10% 25% 80%	1% 54%	1% 60%	10% 68%	1% 48%	1% 15% 53%	1% 60%
Mid	5% 25% 73%	5% 83%	10% 97%	1% 64%	10% 25% 71%	10% 80%	1% 58%	1% 20% 64%	10% 73%
High	15% 97%	20% 30% 103%	N/A	10% 80%	10% 89%	15% 35% 100%	10% 25% 74%	10% 82%	10% 30% 93%

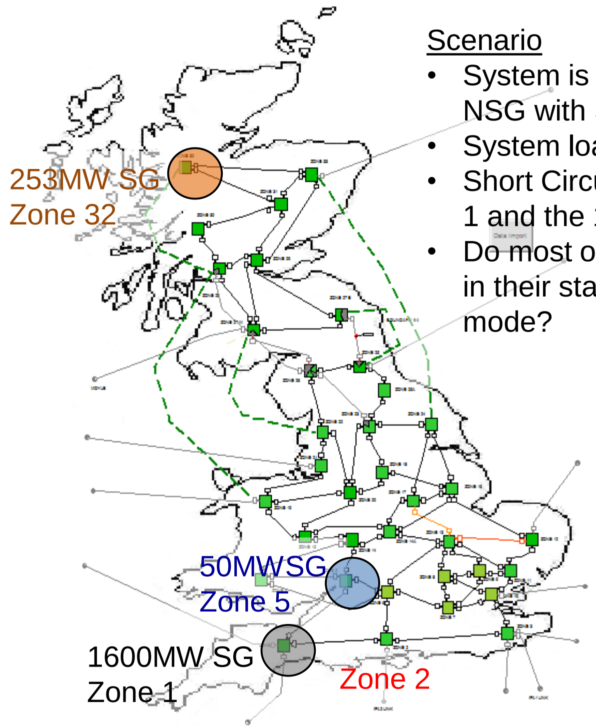
2016 – Stable Noisy Result



2016 – Stable Clean Result

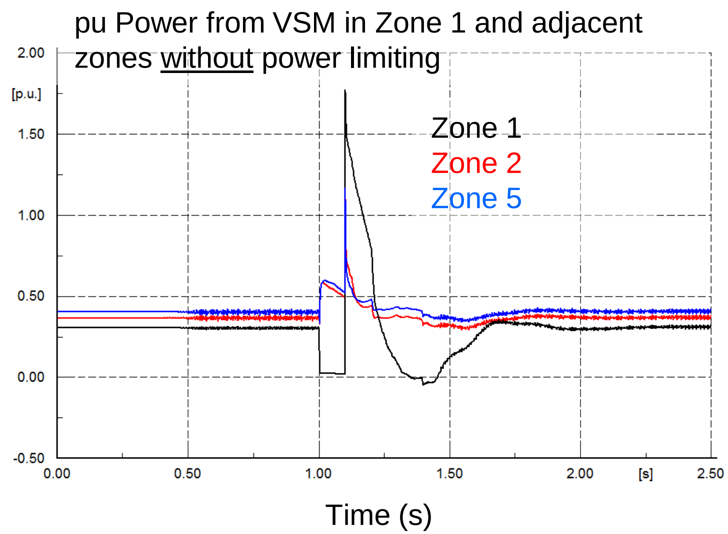


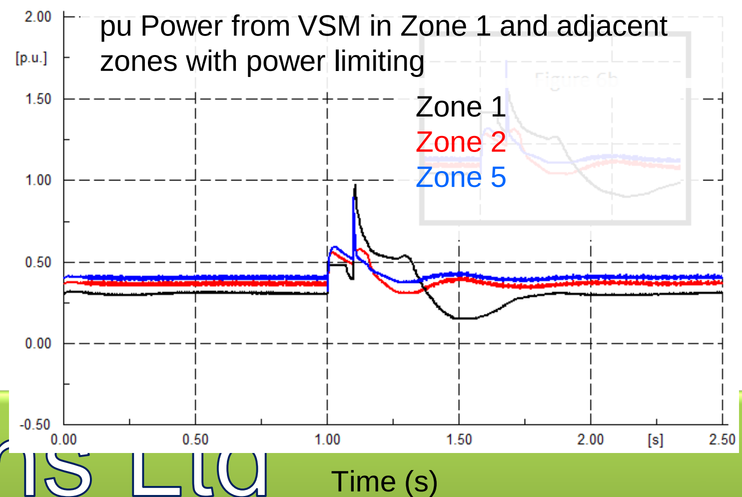
1600MW Trip at 97% NSG with 30GW of Load



Scenario

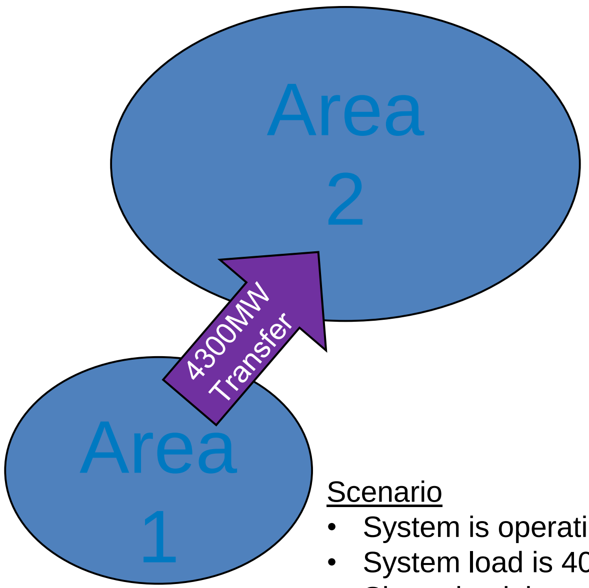
- System is operating at 97% NSG with SG as shown
- System load is 30GW
- Short Circuit is applied at Zone 1 and the 1600MWSG is tripped
- Do most of the VSM remain with in their stable region i.e. VSM mode?



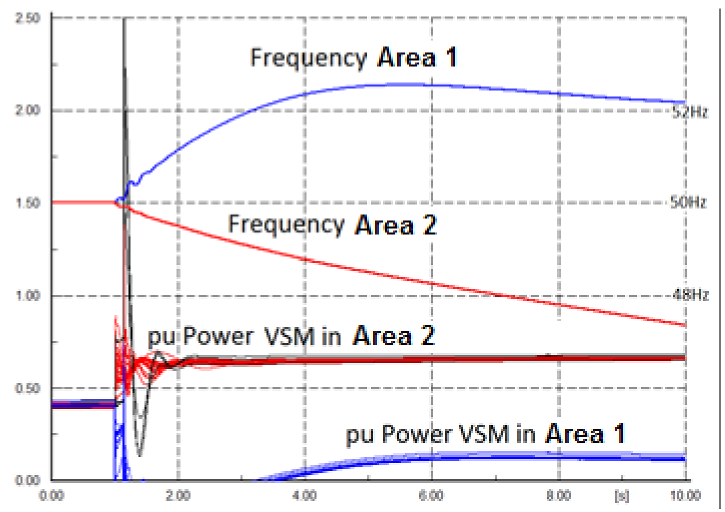


System Islanding at 93% NSG with 40GW load

CC.6.3.7 and CP.A.3.6



pu Power from VSM (all zones) without power limiting



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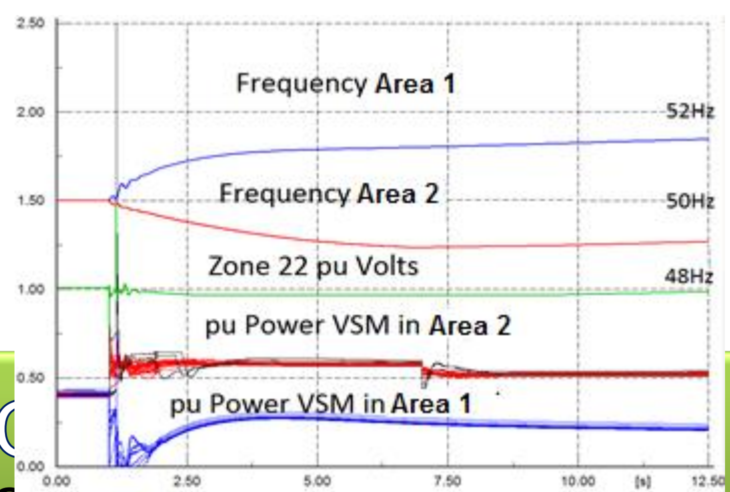

Scenario

- System is operating at 93% NSG
- System load is 40GW
- Short circuit is applied to AC interconnection
- Loss of AC interconnection between exporting Area 1 and importing Area 2
- Does LFDD work?

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Wider stability Challenges & system Needs during high penetration (HP)

Challenges with low System Strength

C1 Lack of synchronising torque with distorted voltage

C2 Inadequate system inertia

C3 Failure to survive major disturbances (allow time for LFDD + support system restoration)

C4 Adverse control system interactions, sub & super synch + simplify dynamic analysis

C5 Absence of sinks for harmonics & unbalance without synch gens

System Needs to cope even at high penetration

N1 Need converters to lead, shape voltage (PLLs just follow)

N2 RES contribute to TSI

N3 Aid system stability by locking frequency & angle during fault

N4 Limit f bandwidth of active controls, e.g. <5Hz avoiding high frequency analysis

N5 Converters act as sinks to harmonics & unbalance, act as a voltage behind an impedance

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Summary of high penetration challenges & potential solns in GB

With current technology/models, the system may become unstable when more than 65% of generation is Non-Synchronous

For the FES 2Degrees, Consumer Power and Slow Progression scenarios, it is currently forecast this level could be exceeded for 800-1800Hrs p.a. in 2023/24 and for 2100-2750Hrs p.a.in 2026/27.

Key

No	Doesn't Resolve Issue
P I	Potential Improves
Yes	Resolves Issue

Solution	**Estimated Cost**	RoCoF	Vector Shift	Sync Torque/Power (Voltage Stability/Ref)	Prevent Voltage Collapse	Prevent Sub-Sync Osc. / SG Compitable	Hi Freq Stability	RMS Modelling	Fault Level	Post Fault Over Volts	Black Start	Harmonic & Imbalance	System Level Maturity	Notes
Constrain Asyncronous Generation	Hgh	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	These technologies are or have the potential to be Grid Forming / Option 1
Syncronous Compensation	High	P	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	P	Yes	Proven	
VSM	Medium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	P	P	Modelled	
VSM0H	Low	No	No	Yes	Yes	No	P	P	P	Yes	P	P	Modelled	Has the potential to contribute but relies on the above Solutions
Synthetic Inertia	Medium	Yes	No	No	No	P	No	No	No	No	No	No	Modelled	
Other NG Projects	Low	Yes	No	P	Yes	No	No	No	P	P	No	No	Theoretical	

Timescale (Based on work by SOF team)	RoCoF	Vector Shift	Sync Torque/Power (Voltage Stability/Ref)	Prevent Voltage Collapse	Prevent Sub-Sync Osc. / SG Compitable	Hi Freq Stability	RMS Modelling	Fault Level	Post Fault Over Volts	Black Start	Harmonic & Imbalance
	Now		2019	2019	Now	2020	Now	Now	2025		2025

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HP Technical/Expert Groups in Europe and in GB

European HP TG: Stage 1 done: Produced two IGDs, including HPoPEIPS

https://consultations.entsoe.eu/system-development/entso-e-connection-codes-implementation-guidance-d-3/user_uploads/igd-high-penetration-of-power-electronic-interfaced-power-sources.pdf

Stage 2 Draft report due Dec 2018, final report Summer 2019

- Describe individual aspects of grid forming capability
- Describe design/sizing consequences for Power Electronic interfaces
- Describe possibilities and limits of grid forming with respect to size of storage and/or current headroom
- Set up benchmarks for evaluation of compliance including testing
- Publish results

GB Expert Group on HP

- Develop Option 1 from previous details during Consultation Summer 2017
- Analysis to-date shows Grid Forming capabilities needed by 2021
- Aim to complete Grid Code proposal by end 2018 with study based CBA

Grid Forming option
– what can it achieve?
- holistic approach?

Capabilities of Class 1 / Grid Forming Converters

- Class 1 Converters shall be capable of supporting the operation of the ac power system (from EHV to LV) under normal, disturbed and emergency states without having to rely on services from synchronous generators.
- This shall include the capabilities for stable operation for the extreme operating case of supplying the complete demand from 100% converter based power sources.
- Grid Forming Converters provide an inherent performance resulting from presenting to the system at the Connection Point a voltage behind an impedance (true voltage source).
- The support services expected are limited by boundaries of defined capabilities (such as short term current carrying capacity and stored energy).
- Transient change to defensive converter control strategy is allowed (if it is not possible to defend the boundaries), but immediate return is required.

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Conclusions

- Total system strength is reducing as Synchronous Generators (SGs) are increasingly being replaced by Power Electronic Interfaced Power Sources (PEIPS)
- Unless restriction applied / market intervention taken, hours of operation with total absence of SGs will become common place in Europe.
- The largest Synchronous Areas (SAs) have more time to prepare than the smallest SAs, such as GB & Ireland.
- Analysis has identified a range of services needed from PEIPS in the future. The foremost candidate to deliver: Grid Forming (true voltage source) / VSM
- The longer delay in introduction of Grid Forming requirements, the more severe parameters will be needed (as a smaller part of PEIPS has to deliver)
- Aware that VSM was installed as early as 1996.
- Main focus is dealing with novel stability aspects associated with operation close to 100% PEIPS.
- Is Grid Forming capabilities (e.g. VSM) the optimal answer? Looks likely.
- Do we have realistic means for TSO Grid wide stability studies?

  Are the present rms models fit for purpose?

  Beyond about 65% penetration, I suggest not, unless bandwidth limited.

Thank you for your attention

Questions

Additional material
Back-up

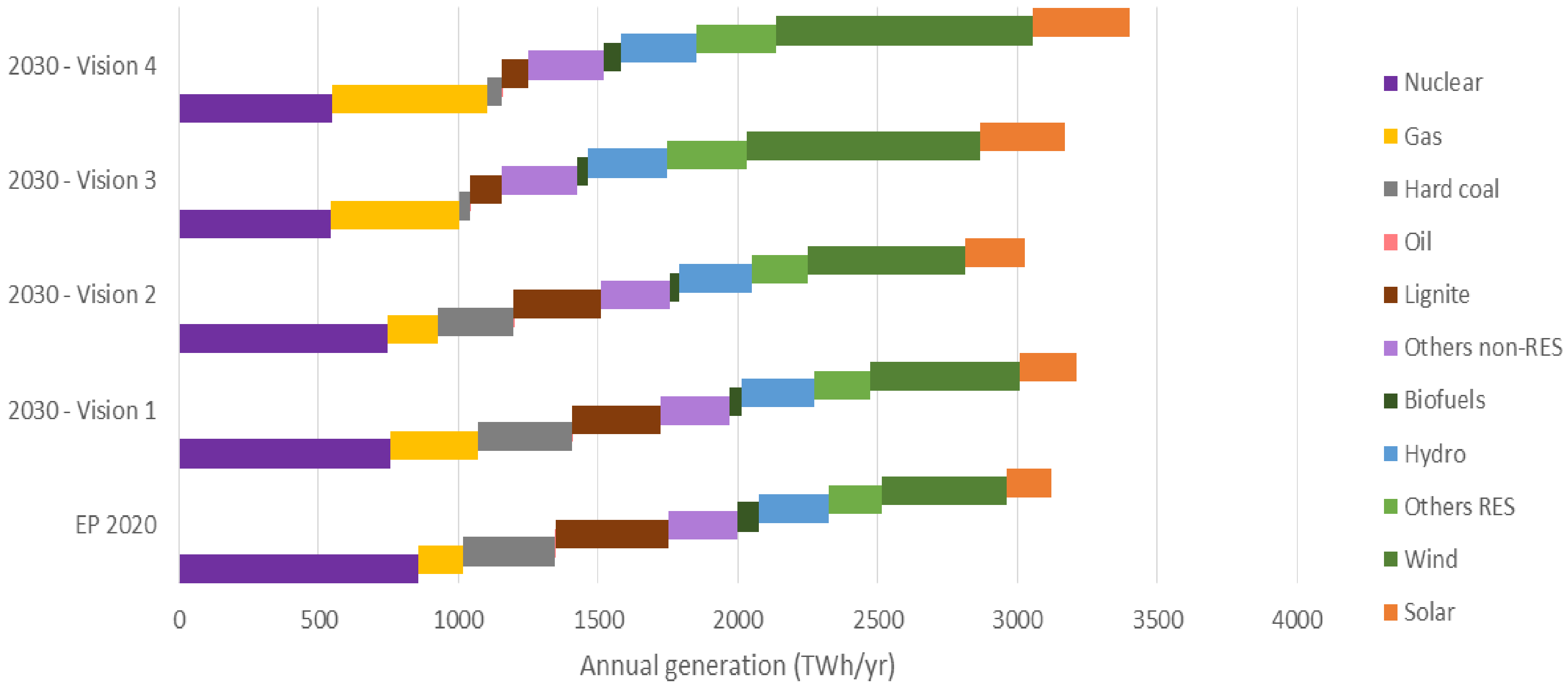
Work on High Penetration

HPoPEIPS

Intro to Helge Urdal *

- Borne in Kristiansand, Norway. 1950
- Varied short jobs in mechanical, smelting, shipping and electricity industry
- Studied E&E Eng at Newcastle Univ – 1st Class Honours in 1974
- Worked in Oslo for Statkraft / Statnet / Power Pool – 74-77
  - Protection of T, D & G / HVDC
- Design & tendering for world's first SVCs – 77-79
  - Created Power oscillation Damping (POD) principle
- CEGB – Protection & Control Systems of Generation & Transmission – 1979-90
  - Design / settings / site services / labs / AVRs with on site tuning + mobile standby excitation
- National Grid 1990-2013
  - Business systems for construction
  - Design across engineering (110 staff) for national Project Management (construction)
  - Generator Compliance – All GB generation + dev of Grid Code for wind / RES
  - Training Development Manager for technical staff
  - SMARTer System Performance Manager & Future specialist
  - National Grid lead with ENTSO-E on Connection Network Codes – 2009 -2013
- Independent Power System Consultant – 2013 onwards
  - Contracted to ENTSO-E until end 2017 – Convener for NC HVDC justification
  - Convener for Implementation Project Team – support for national implementation
  - Engaged in support of University Research – main focus: weak power systems at UoS, Glasgow

TYNDP SCENARIOS: Annual Generation by power source
A WIDE RANGE OF PLAUSIBLE FUTURES



Annual generation in each scenario – breakdown per technology

EP= Expected Progress scenario

System Stability Studies with low System Strength using PLL based converter controls approaching 100% penetration

- PLL Phase Locked Loops – following externally provided system voltage
- By 2013 operational impact of high RES penetration had emerged in GB with wind farms tripping for high RoCoF.
- Concerns over various stability aspects with future weaker power system
- TSO need for system wide dynamic studies
- What is the limit of stable system wide operation with higher level of penetration of power electronic interfaced power sources?
- Are the models including generic models fit for purpose?

- Penetration levels predicted for 2030 based on hourly recorded weather data for 3 years for 36 zones including offshore, main focus wind.
- RES in 2030 could deliver 165% of demand in most challenging hour
- Need to be prepared in all operational aspects to come close to 100% RES at times and at other times close to 0%

Recommendations in terms of getting RE ready to replace SG services - principle

- As % RE largely connected via converters increases and conventional Synchronous Generators (SG) at times of high RE output are disconnected, the RE increasingly need to deliver the steady state, dynamic and general stability support (V & f) to ensure all forms of system stability, without constraining off RE.
- In my experience introduction of such services needs to be anticipated by evaluating scenarios at the minimum through half the life time of the RE, i.e. at least 10 years ahead.
- Introducing such capabilities when the problems have already arisen is generally too late.
- In Europe the aim was to have connection requirements fit for purpose out to 2030, i.e. 20 years ahead of the initial proposals.

First the basics or even advanced capabilities

IGD HPoPEIPS identifies:

Basic expectations for converters – calling it Class 3, already common

Advanced capabilities for converters – calling it Class 2, on its way in

Focuses on needs for Class 1 – to be self sufficient where, when and under which circumstances needed

<u>Why a holistic approach for Class1?</u>

- The TSO analysis of fast dynamics associated with extremely low System Strength show strong inter relations between different topics.
- Management of one issue is bound to affect management of several others.
- A holistic approach is needed to prepare a path towards full RES penetration.

Recommendations in terms of getting RE ready to replace SG services – rules of thumb

- RE penetration on average as in production of annual TWh is typically 4 times lower than the hour with the highest penetration. (Vary in range 3-5)
- In Denmark in 2008, when annual penetration was 20%, total demand was already being exceeded by wind power alone. In GB, unlike Denmark, nearly all RE is connected via power electronic. In Europe preparation is made for High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS).

Annual % RE	max PEIPS as % of D	HU view of RE Support Service need
Up to 5%	<20%	1 Basics: No simultaneous trips. FRT
Up to 10%	<40%	2 Basics+: Add Q capability & V control
Up to 15%	<60%	3 Advanced: Add frequency controls
Up to 20%	<80%	4 Advanced+: Add fast f controls + HF stab
Up to 25%	<100%	5 Full SG services: Introduce Grid Forming
>25%	Constrain/store RE	6 Widespread use of Grid Forming or equiv

Process extract from draft IGD HPoPEIPS (abbreviated) Steps for Synchronous Area & Individual Countries

Step 1 - Define extent of the challenge.

Establish penetration of PEIPS in area at least to 2030.

Step 2A - If PEIPS > 75% for the SA for >10% of the hours in the year. →

A strategy needed to make improvements to contributions from PEIPS.

If the SA H is < 1s for more than 10% of time consider urgently to implement the converter control capabilities defined as Grid Forming.

If 2A conditions do not apply:

Step 2B - If PEIPS > 50% for your COUNTRY, discuss within SA.

If your country inertia <1s for >10% of time, consider if your inertia contribution is acceptable, and resilience for system splits is adequate.

Consider the possibility of implementing Grid Forming capabilities.

Step 3 - Detail requirements including parameters for the implementation and models to study the effectiveness as well as compliance tests → Introduce new requirements at national level

Network codes are the foundation of a secure, competitive and low carbon European Internal Energy Market

Challenges

RES variability
> Ensure adequacy despite resource variability
> Maintain system stability with less conventional plants
> Manage increased uncertainties
> Need for market close to real time

Distributed generation
> Connect thousand of units, mostly to distribution grids
> Develop visibility on distributed generation
> Coordinate with DSOs

Need / value of cross-border trade and coordination
> Need for an integrated EU market
> Transit huge flows across Europe
> Manage flow changes following weather conditions
> Connect HVDC lines
> Use infrastructures efficiently and safely

Network codes as enablers

Market
- Capacity allocation and congestion management (CACM)
- Forward capacity allocation (FCA)
- Electricity balancing (EB)

Operation
- System operation (SOGL)
- Emergency and restoration (ER)

Connection
- Requirements for generators (RfG)
- Demand connection (DCC)
- HVDC connection

Network codes (or Commission Regulations) are a set of binding rules addressing cross-border issues enabling a European Internal Energy Market to deliver a secure, competitive and low carbon energy supply.

Access to the final Regulations at European level via ENTSO-E – EC also access to translations

General from ENTSO-E (with onwards access to all 8 codes – in force)

- https://electricity.network-codes.eu/network_codes/

Specifics on Connection: NC RfG full text (+DCC + HVDC)

- https://electricity.network-codes.eu/network_codes/rfg/

IGDs and IGD HPoPEIPS

- https://electricity.network-codes.eu/network_codes/cnc/cnc-igds/
- https://docstore.entsoe.eu/Documents/Network%20codes%20documents/Implementation/CNC/170322_IGD25_HPoPEIPS.pdf

Specifics on System Operation – SOGL & E&R

- https://electricity.network-codes.eu/network_codes/sys-ops/
- https://electricity.network-codes.eu/network_codes/er/

Specifics on Markets – CACM (+FCA + EB)

- https://electricity.network-codes.eu/network_codes/cacm/

EU network codes
National implementation

Extensive process at national level to update pre-existing national code.

Lots of further working groups with stakeholder representations

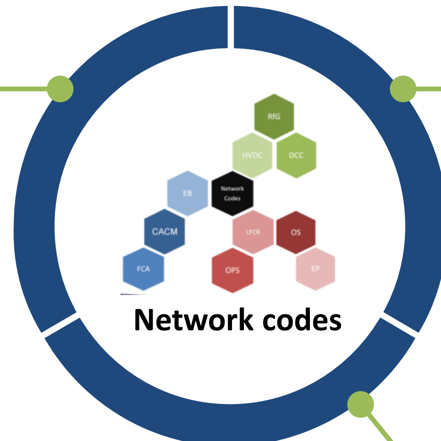
For access to processes in some of the 34 countries, see

https://docs.entsoe.eu/cnc-al/

Measures included in the Network Codes contribute – amongst other measures – to the three main pillars of the EU Energy Policy

Sustainability

- **260 GW** of solar photovoltaic and wind generation capacity connected to the EU networks
- **24.5 GW connected in 2016** (86% of RES units) – same pace expected in the next decade
- **>11 GW of demand-side response** across Europe



Competitiveness & Social Welfare

- **23 countries** (19+4) are participating in day-ahead market coupling
- **0.7-1 B€ p.a.** of increase in social welfare thanks to market coupling (**80%** already achieved)
- **About 120 TWh p.a. exchanged in intraday** on power exchanges' platforms (**x2** for continuous trading in 4 years)
- **10 million data files** made available each year, for around **2000-2500 active users per day** on ENTSO-E website
- **Up to 40 new HVDC interconnections** in the TYNDP

Security of supply

- **NO major interruption** across several countries over the past decade
- **300** coordinated tasks per day for TSCNET / **200** for Coreso
- **30** employees in TSCNET **/ 40** in CORESO (1 over 4 in 24/7 shift)

Update with Coreso

Case study 1 – Implementation of market coupling (CACM)

3

Benefits associated with the integration of wholesale markets

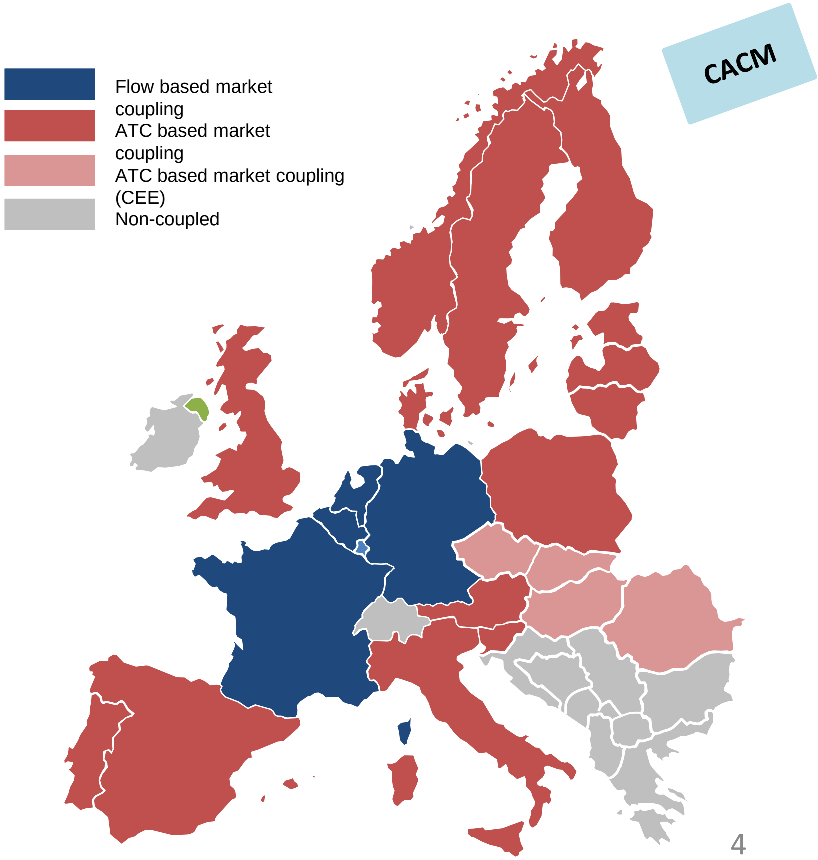
0.7-1 B€/year of potential welfare gains from market coupling.

~80% of the benefits of market coupling already obtained in 2016.

2/3 of efficient utilization of interconnector already achieved.

>100 M€/year of additional benefits thanks to flow-based in CWE.

1500 TWh traded in day-ahead on power exchanges in 2016



Case study 2 – Integration of balancing market (EBGL)

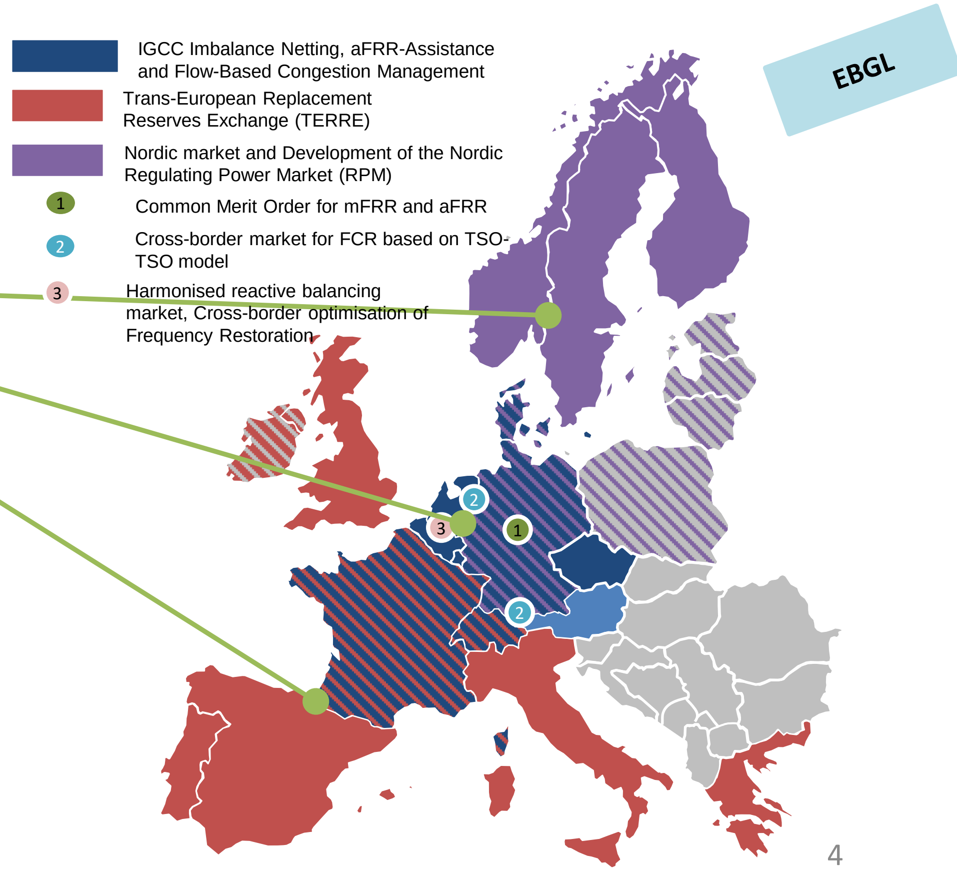
Benefits associated with upgrading and integrating balancing markets

Estimated benefits of pilot projects for the integration of balancing markets:

Nordic RPM: **~220 M€ p.a.**
IGCC: **~80 M€ p.a.**
TERRE: **~120 M€ p.a.**

Net expected benefits of full integration of energy balancing markets (forward-looking/2030):

500 – 800 M€

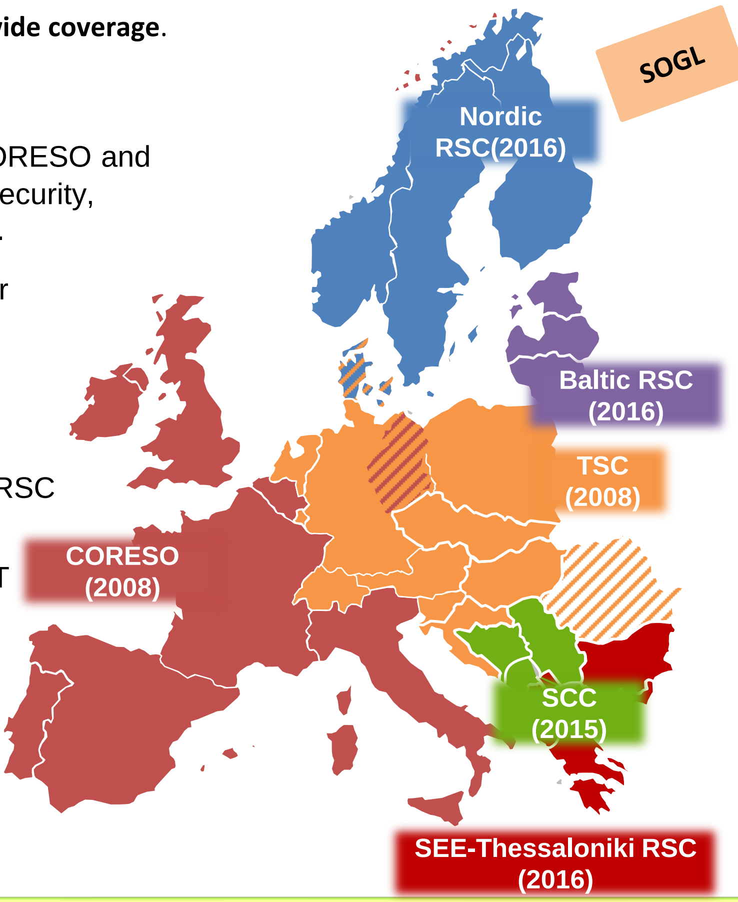


The integration of energy balancing markets carries the **promise of welfare gains for european electricity sector**.

Case study 3 – Regional coordination (SOGL)

3 Benefits associated with system operation coordination

- The coordination of TSOs has strengthened significantly with the creation of RSCs:
  - ⇒ From a **voluntary TSO initiative**… …. to a **EU-wide coverage**.



3 key services are already partially operational in CORESO and TSCNET (out of 5 foreseen in SOGL) to ensure system security, improve market functioning and facilitate RES integration.

100% performance for day-ahead congestion forecst for capacity calculation (**99.6%** for intraday)

x7 red flag (i.e. potentially critical) situations detected by CORESO (2015 vs. 2014)

>10,000 data files exchanged daily between TSOs & its RSC
4000 remedial actions proposed/year by CORESO
134 Multilateral Remedial Actions coordinated by TSCNET

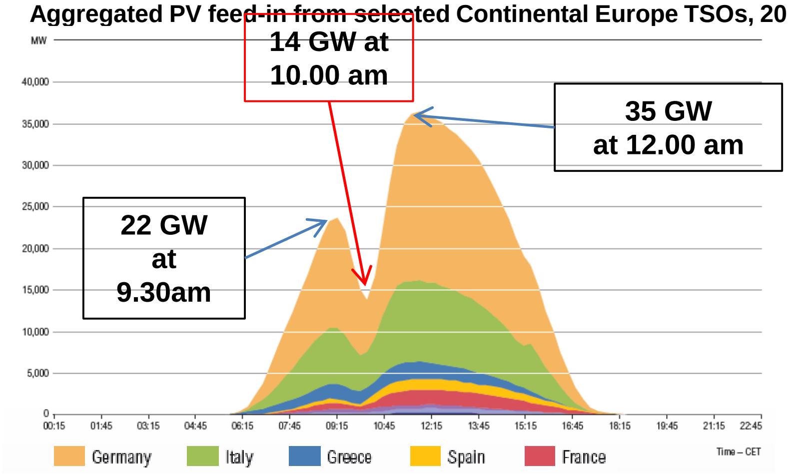
30 employees at TSCNET
40 employees at CORESO (3 over 4 in 24/7 shift)
150 employees trained in TSCNET programs

Significant progress…
… but **quite a busy agenda** to implement the SOGL by 2019!

Case study 3 – Regional coordination (SOGL)

The 2015 solar eclipse as a test for the future challenges

Situation



Solutions

SOGL

1 Coordinated security analysis

> TSOs coordinated their assessment of the situation

2 Coordinated planning

> Anticipation of issues
> Secured reserves and emergency plans

3 Real-time coordination between TSOs

> Real-time communication between TSOs during the eclipse
> Frequency quality was maintained

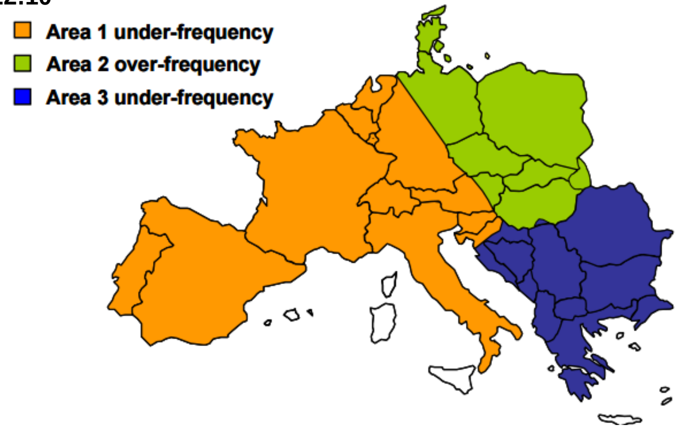
- **Successful preparation and cooperation** avoiding disturbances
- **Minimum cost**: **4.2 M€ for additional reserves**, cost of a **black-out (~450-600 M€ / hour for Germany)**
- **Increasing risks**: expected **RES ramping of 32GW/h** after the eclipse in August 2027 (14GW/h in 2015)

Case study 4 – Requirements for generators (RfG) + Coordination (SOGL / E&R)

Lessons from the 2006 event (system split)

Situation

Schematic map of UCTE area split into three areas – 4 November 2006 at 22:10



Solutions identified and integrated in NCs

1. **Adapted requirements for generators** — RfG
   - > Including on distributed generation
2. **Improved scheduling procedures** — SOGL
3. **TSO coordination and enhanced security analysis** — SOGL
   - > Data exchanges and common grid model
   - > Coordinated security analysis and remedial actions
   - > Training of operators (esp. neighbouring systems)
   - > TSO-DSO coordination
4. **Enhancing emergency and restoration plans** — E&R

Network codes, if implemented at the time of the 2006 event, would have contributed to avoid:

17 GW of load and **1.6 GW** of pumps shed

15 million European households cut off

300-500 M€ of economic losses due to load shedding

> 20 GW of generation tripped or disconnected

Source: http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/2007/E06-BAG-01-06_Blackout-FinalReport_2007-02-06.pdf, https://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/Final-Report-20070130.pdf

4

The network codes are a source of value creation and key enablers of the IEM, but substantial works still ahead for the full implementation

1 The network codes are a source of value creation for European customers

> Preliminary indicators and case studies show that the benefits of network codes are very substantial.

> ENTSO-E will continue to assess these benefits through a value creation study and through the NC monitoring afterwards.

2 The proactivity of TSOs and ENTSO-E has enabled to achieve an early implementation of the network codes, delivering already significant benefits.

> Thanks to the early implementation of CACM, market coupling extends to 23 countries (19 + 4), continuous cross-border implicit intraday trading develops and flow-based has been introduced in CWE.

> Pilot projects were launched in 2014, extending/upgrading existing projects, to develop cross-border balancing.

> RSCs stem from voluntary initiatives of TSOs and all RSCs are now established.

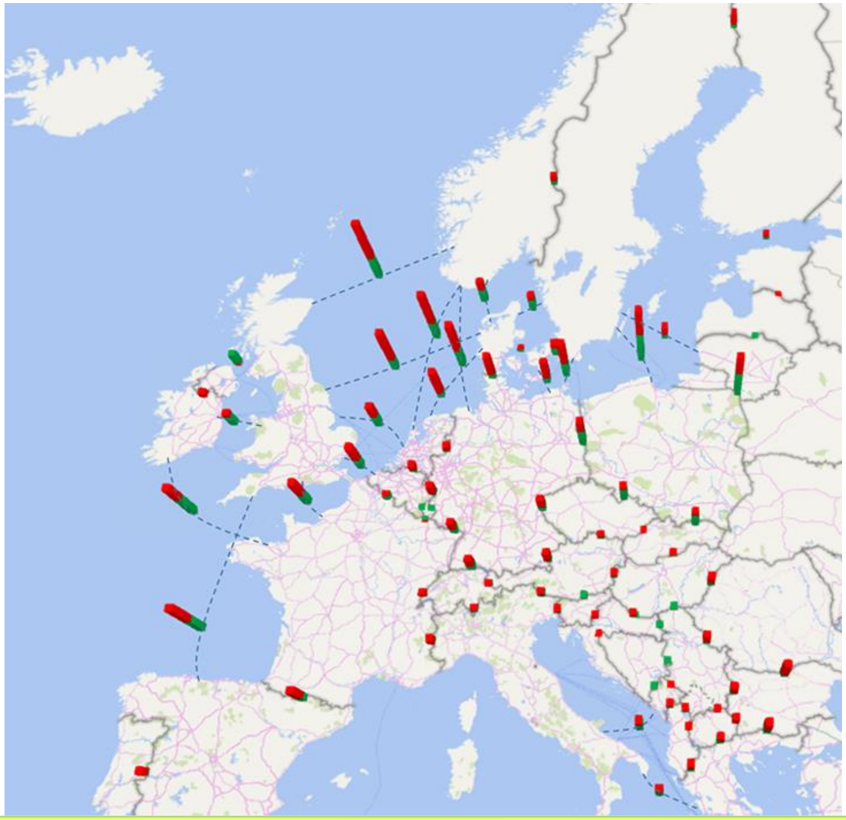
3 However, the full implementation of network codes represents a significant challenge but also new opportunities in years to come for TSOs and ENTSO-E.

> The full implementation of CACM is complex: significant work is ongoing from TSOs and ENTSO-E e.g. on all approval procedures, on capacity calculation or on the bidding zone review.

> The full implementation of the balancing guideline will take at least 6 years, implying considerable changes in operations and market designs.

> RSCs need to develop the five services for all TSOs: achieving it by 2019 is a challenging deadline, but RSCs, TSOs and ENTSO-E are fully committed to it.

BENEFITS OF TYNDP INVESTMENTS FOR EUROPEAN MARKET INTEGRATION



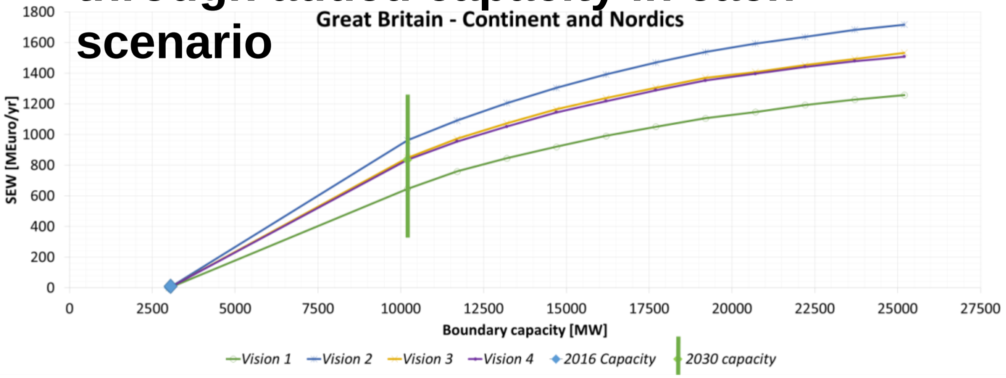
Average price spread at each border in Vision 3

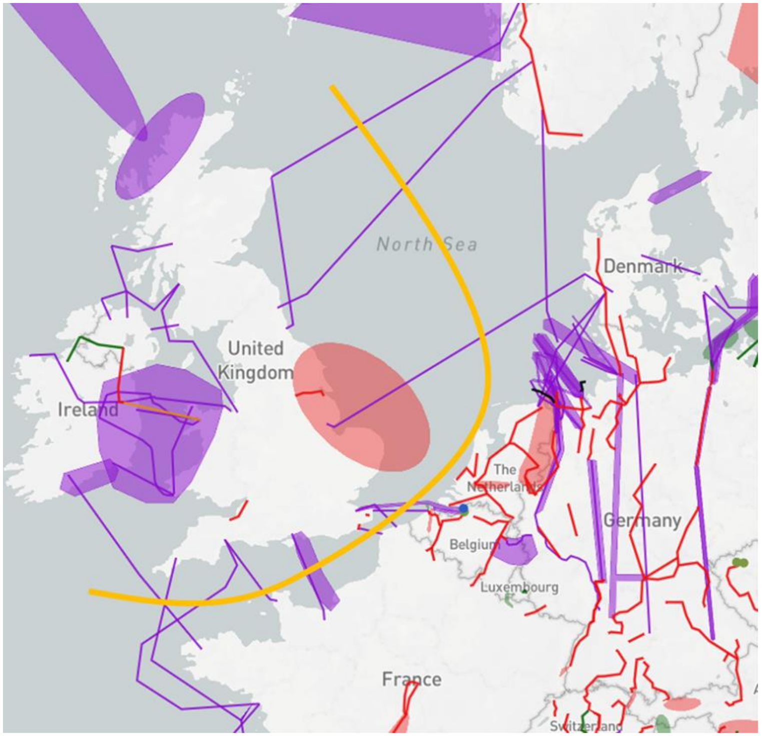
Without TYNDP 2016 investments

With TYNDP investments

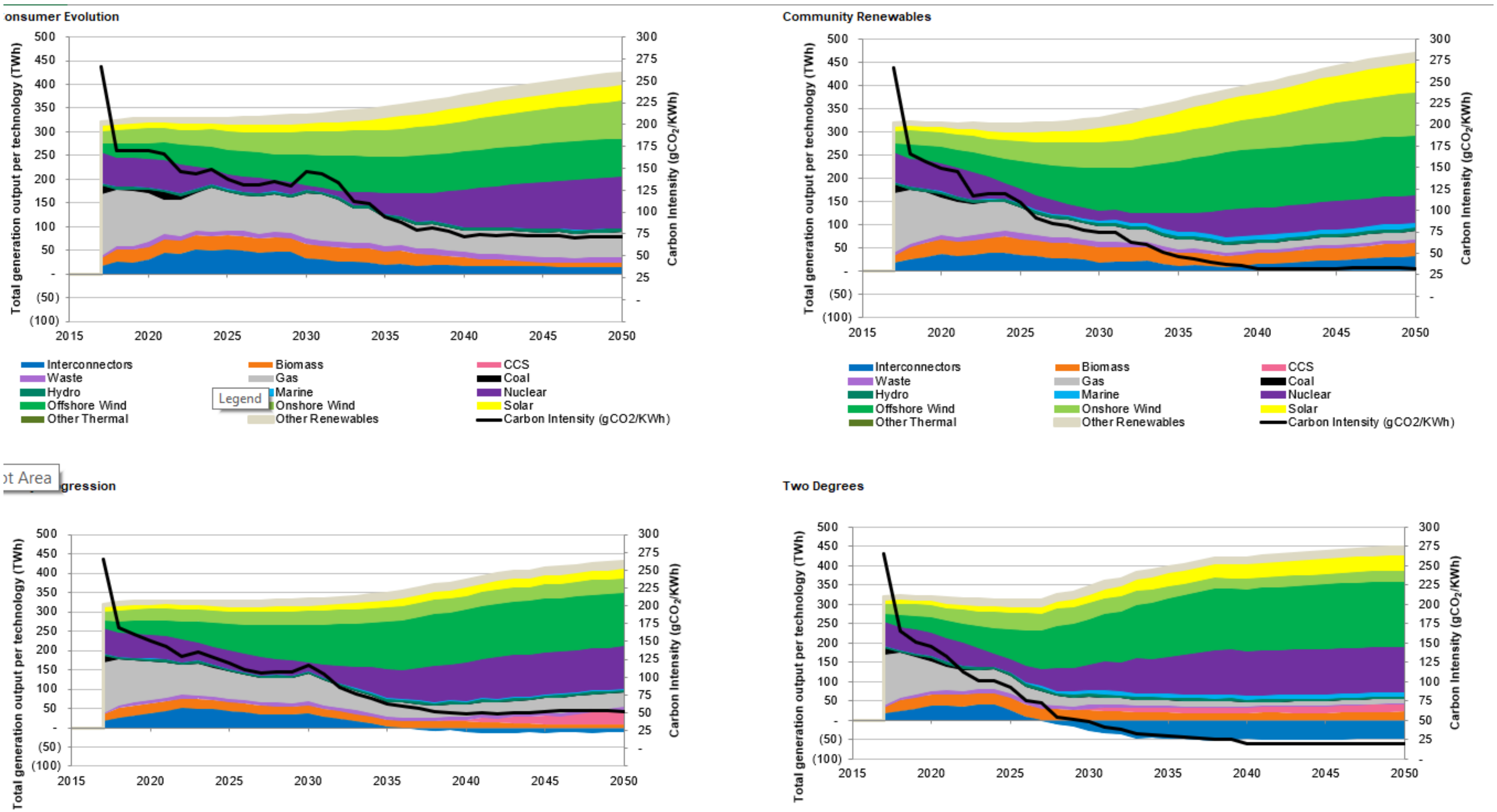
GB – CONTINENTAL EUROPE AND NORDICS

Socio-economic welfare gains through added capacity in each scenario





FES 2018 Generation Scenarios (TWh) to 2050 Type and Carbon Intensity (g/KWh)



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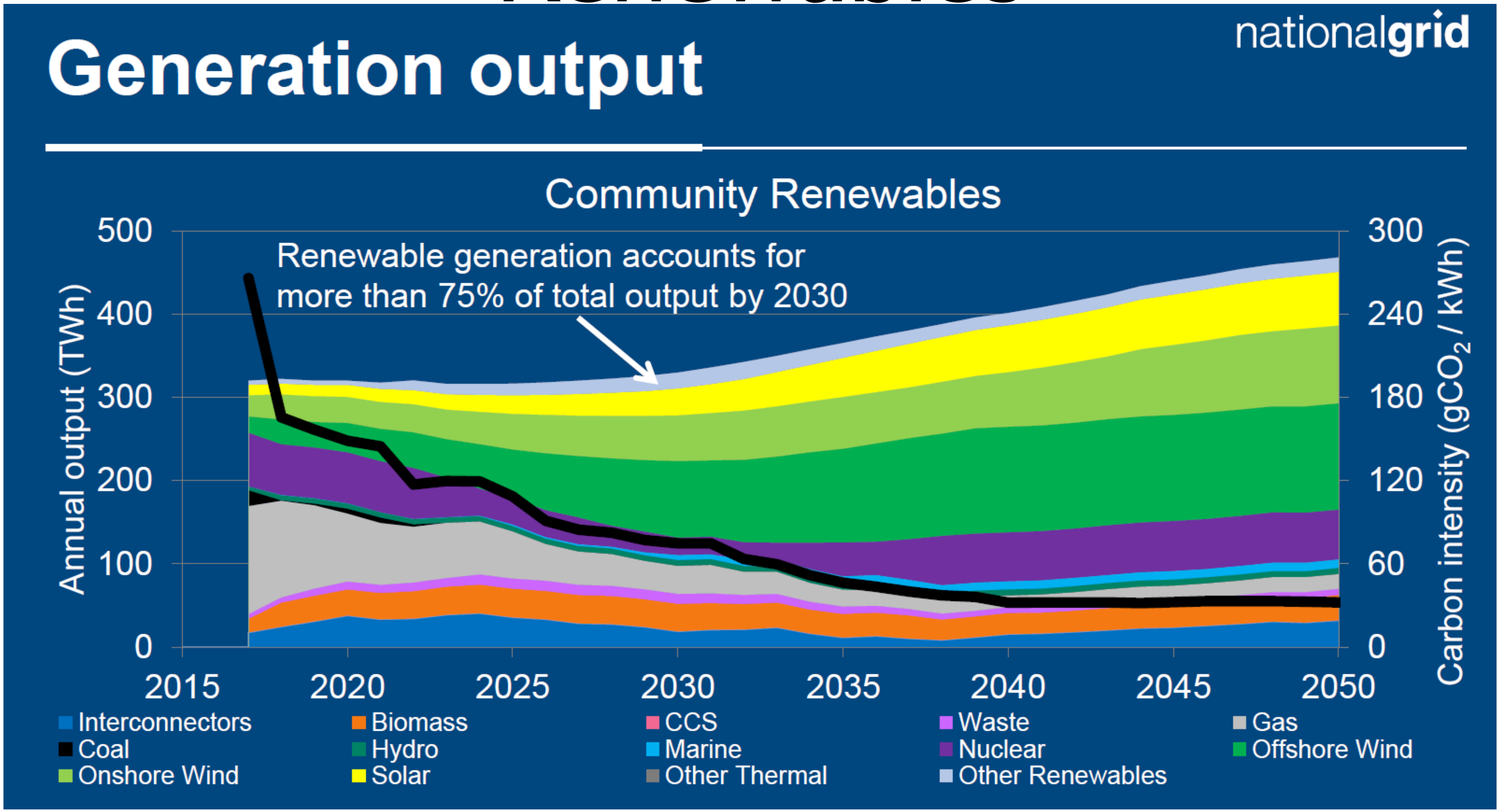
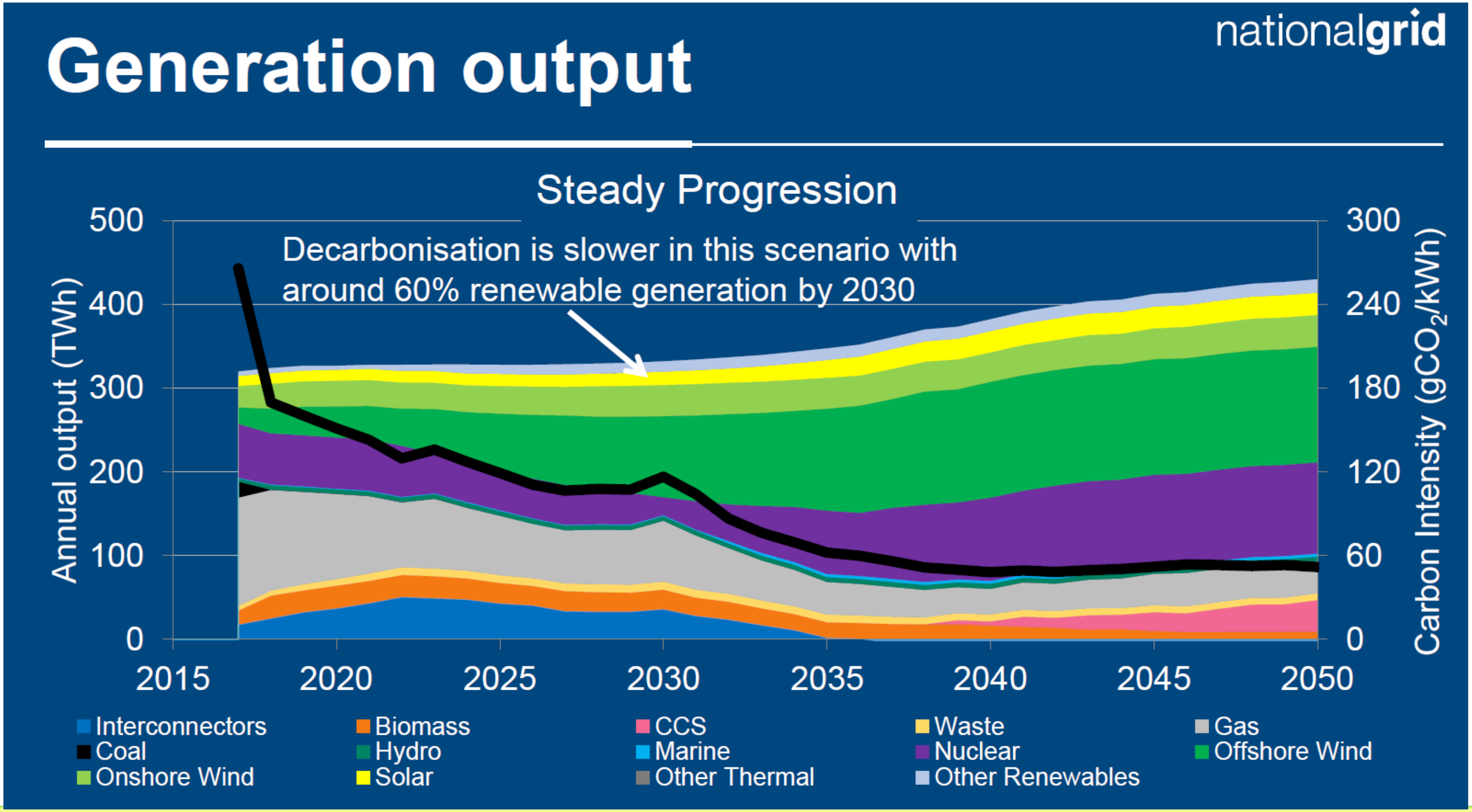
Keeping the lights on in a low carbon future

FES 2018 Community Renewables



FES2018 Steady Progression



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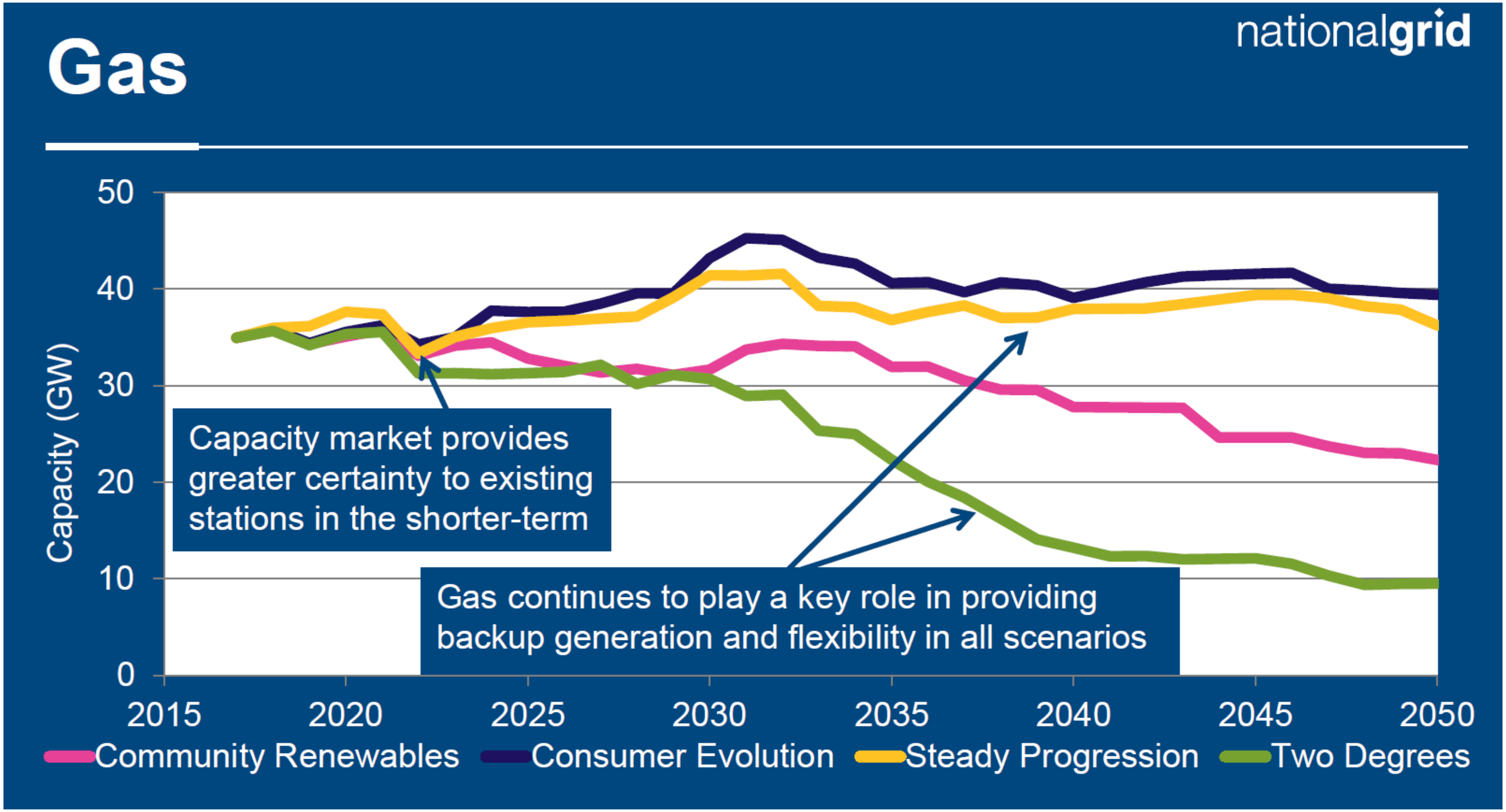
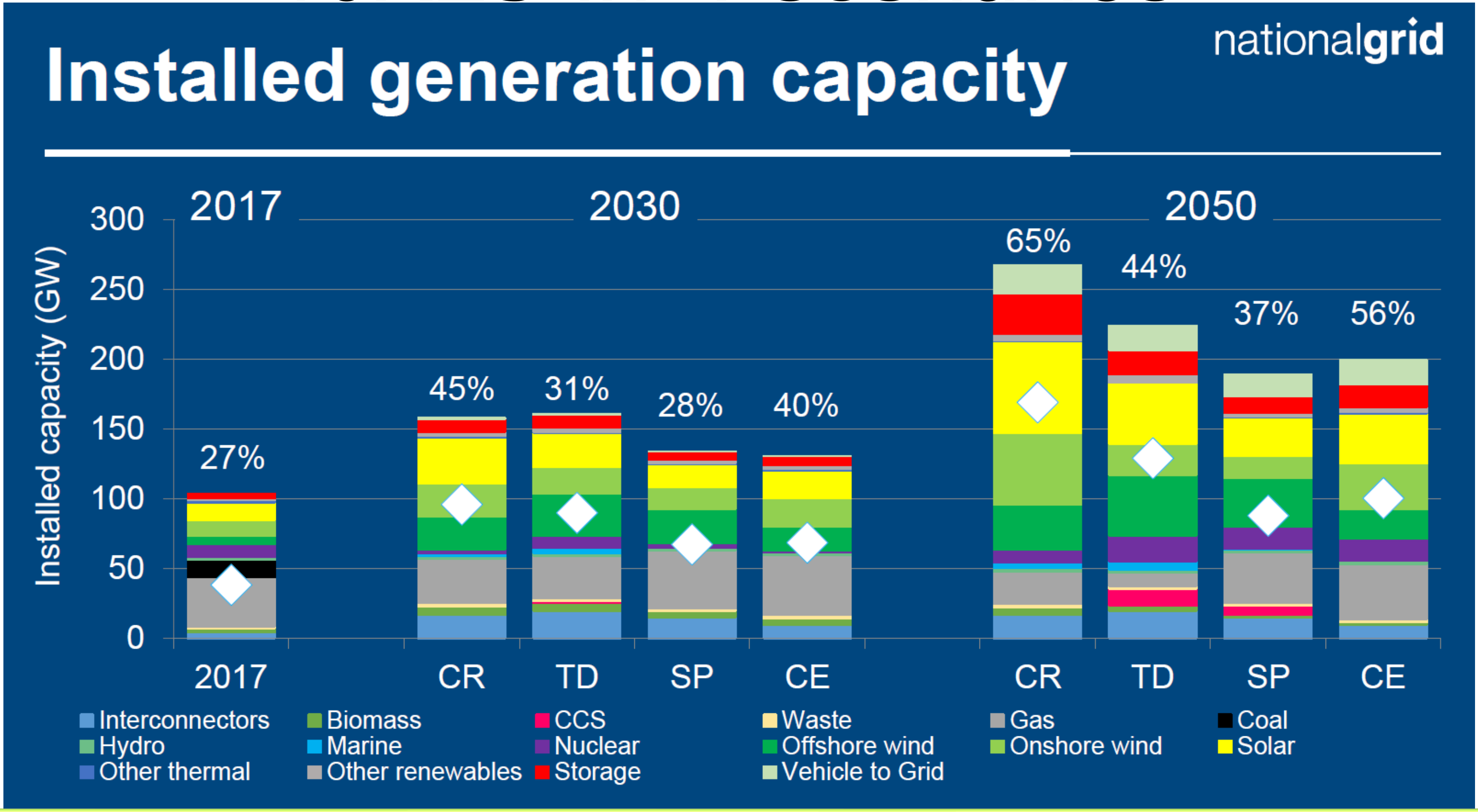
Gas a key factor to cope with variability
Introduction of capacity market



FES 2018 Development of %RES in 4 scenarios



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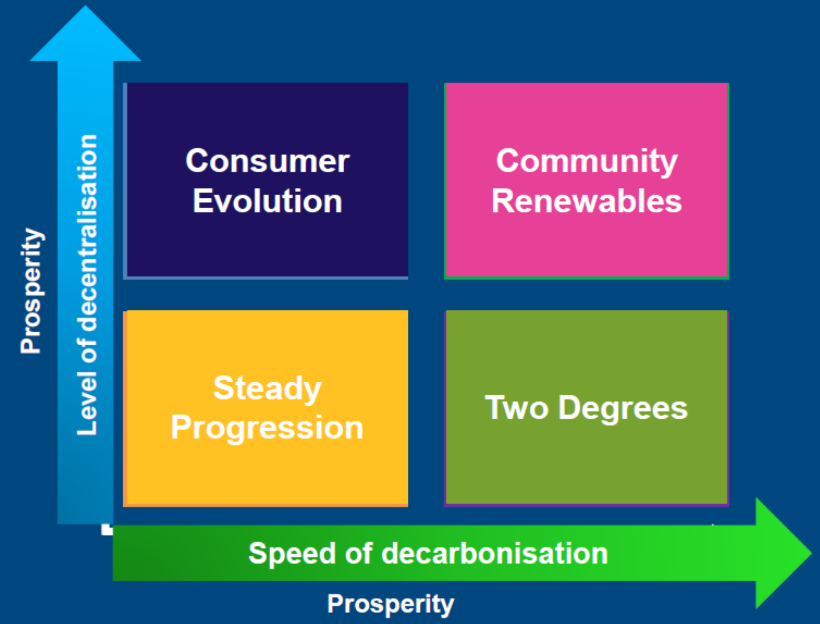
FES 2017 to FES 2018

nationalgrid



Electricity Demand: Peak GW

nationalgrid