Assessing the System Impacts of large scale Pumped Hydropower Storage in a Northern European Market using Stochastic Modelling

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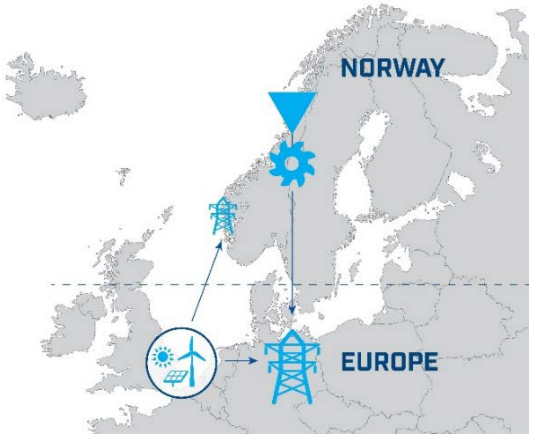
Hydropower Scheduling Conference 2022

HydroConnect

- PhD student contributing
- Effect of connecting Norwegian hydropower to the European market
- Multiple partners
  - Local power companies
  - Universities/research institutes
- Combine different models
  - Capacity expansion, operation scheduling, reservoir impacts



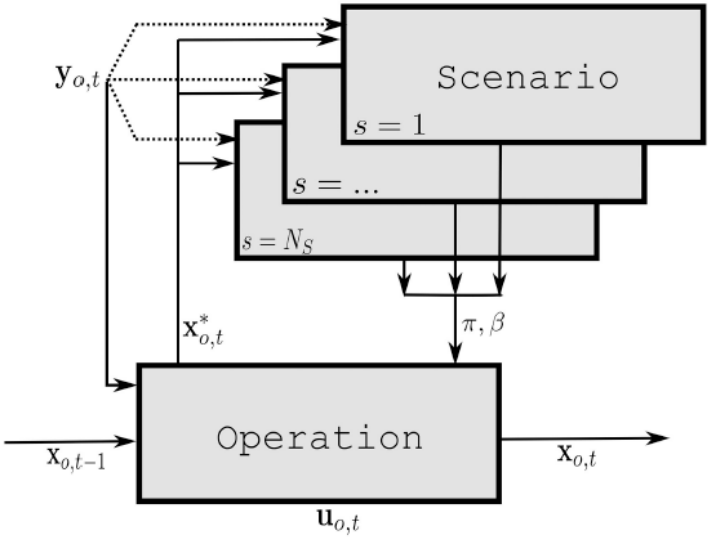
Motivation

- Variable renewable generation
- Flexibility
- Hydropower
  - Seasonal storage
  - Up/down regulation

- Indicators
  - Price distribution
  - Income distribution
  - CO_2 offset
  - Renewable utilization

FanSi

- Fundamental model
- Detailed hydropower representation
- Maintains correlation between weather years
- Two-stage problem
- Rolling horizon

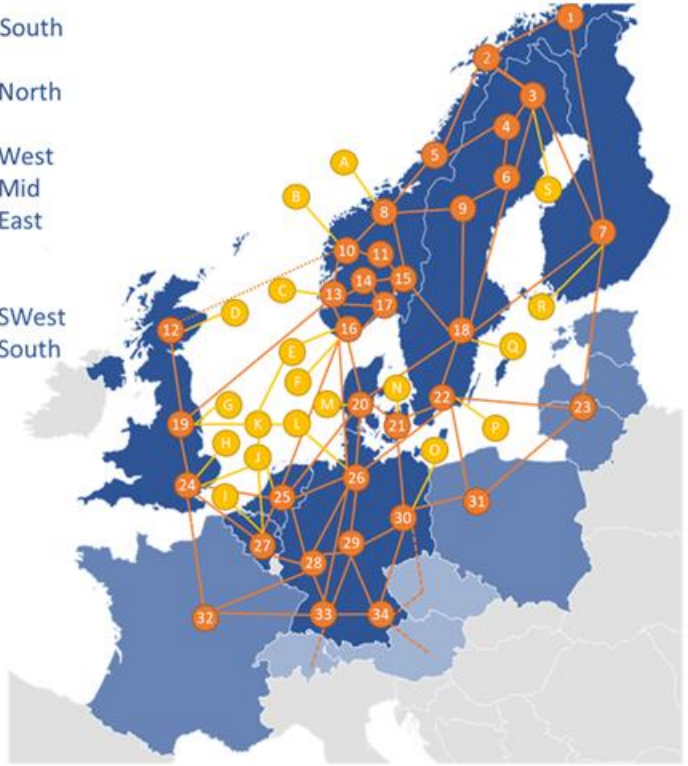


System description

- 2030 scenario considered
- Based on NVE prognosis

Technology	Installed cap. [GW]
Nuclear	60
PV	225
Wind	280
Hydro	100

1 Finnmark
2 Troms
3 SE-ON1
4 SE-ON2
5 Helgeland
6 SE-NN1
7 Finland
8 Norgemidt
9 SE-NN2
10 Vestmidt
11 Hallingdal
12 GB-North
13 Vestsyd
14 Telemark
15 Ostland
16 Sorland
17 Sorost
18 SE-Mid
19 GB-Mid
20 DK-West
21 DK-East
22 SE-South
23 Baltic
24 GB-South
25 NL
26 DE-North
27 BE
28 DE-West
29 DE-Mid
30 DE-East
31 PL
32 FR
33 DE-SWest
34 DE-South



A NORGEM-OWP
B VESTMI-OWP
C VESTSY-OWP
D GB-N-OWP
E SORLAN-OWP
F AEGIR-OWP
G GB-M-OWP
H GB-S-OWP
I BE-OWP
J NL-OWP
K DOGGERBANK
L DE-W-OWP
M DK-W-OWP
N DK-E-OWP
O DE-E-OWP
P SE-S-OWP
Q SE-M-OWP
R FI-OWP
S SE-N-OWP

Cases

I Base case	II Expanded Flex	← +8GW turbine ← +10 GW pump ← +11 GW interconnectors
III Base case High Gas Price	IV Expanded Flex High Gas Price	← +8GW turbine ← +10 GW pump ← +11 GW interconnectors ← Gas fuel cost: 100 €/MWh ← Coal fuel cost:100 €/MWh

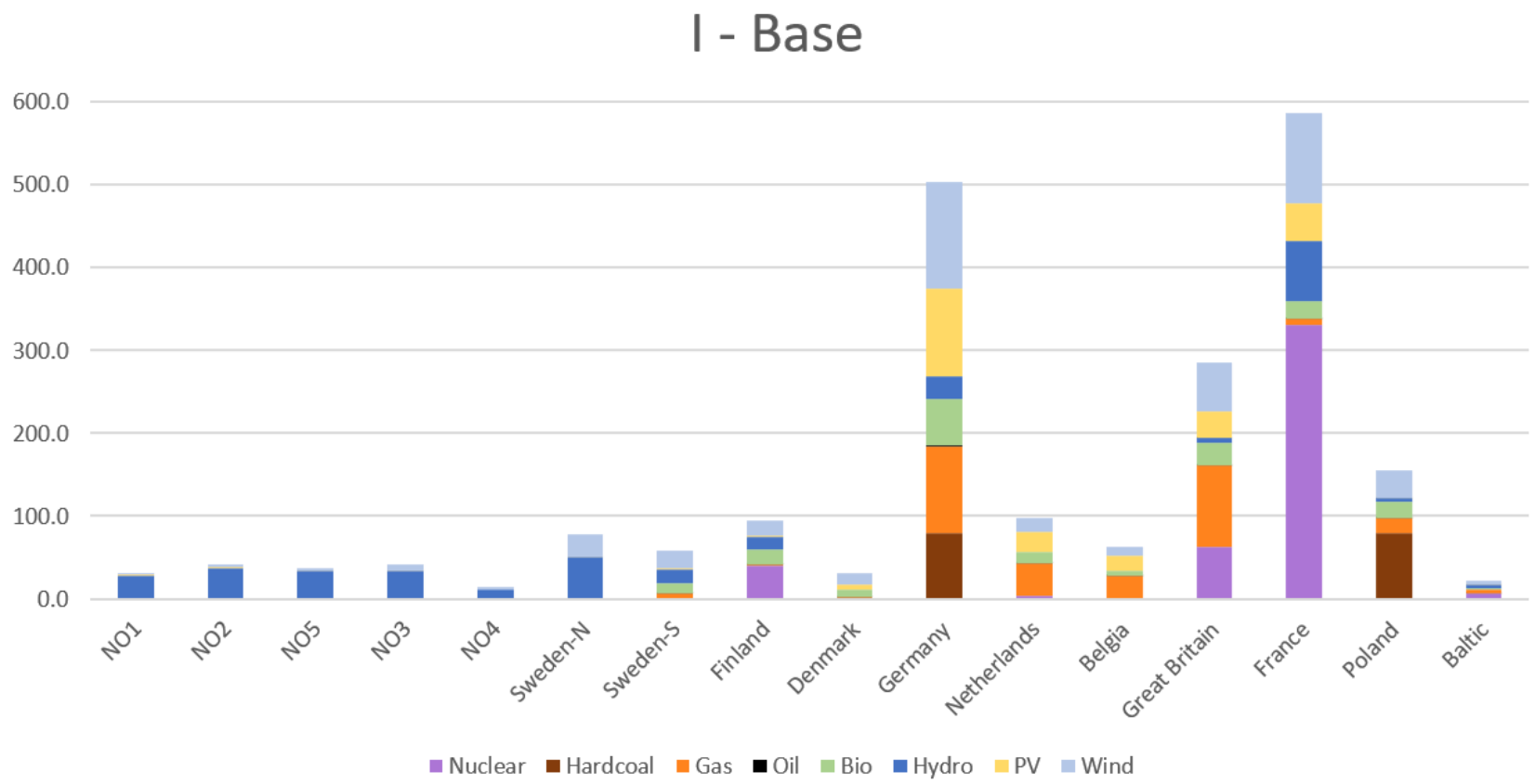
Gas fuel cost: 100 €/MWh →
Coal fuel cost:135 €/MWh →

Results

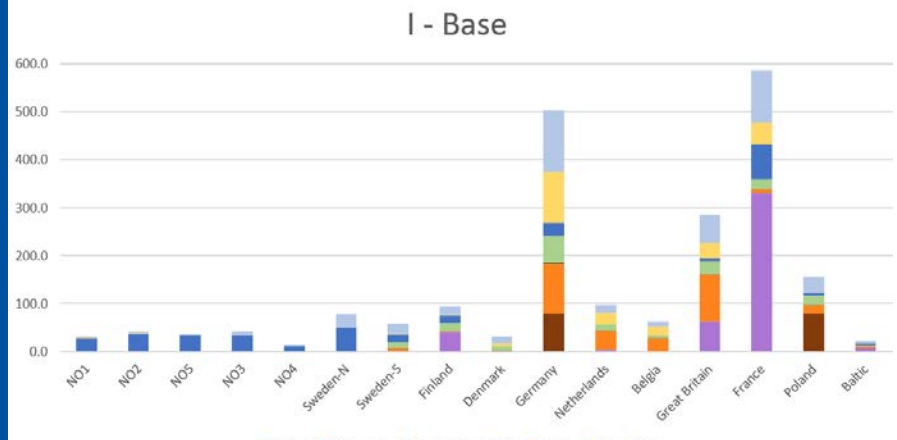
- System
  - Generation mix
  - Power price distribution
  - Area income – who wins?
  - CO_2 offset from thermal generation

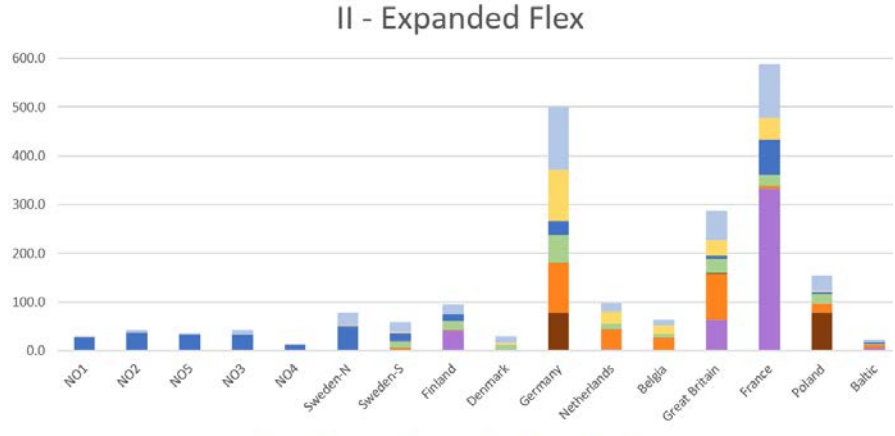
- Operational
  - Transmission utilization
  - Pumping utilization

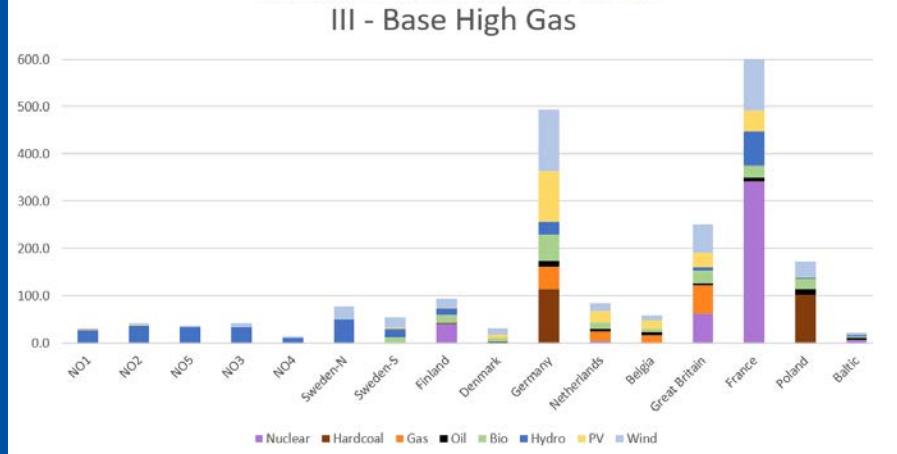
Generation mix in TWh

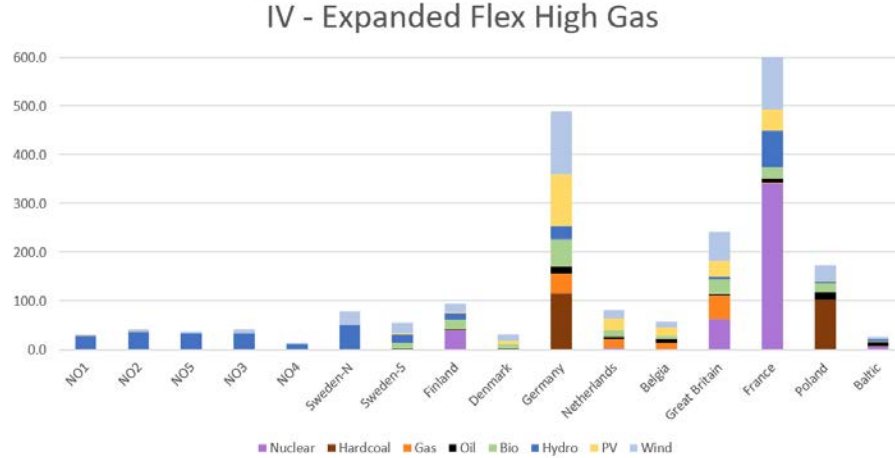


Generation mix in TWh









Generation mix comparison in TWh

Case	Nuclear	Hardcoal	Gas	Oil	Bio	Hydro	Ration	PV	Wind
I-B	444.3	159.6	309.9	1.9	186.7	341.2	0.1	235.8	463.5
II-E	445.7	158.2	304.7	1.8	190.2	340.8	0.0	235.8	463.5
III-BHG	454.1	215.8	145.6	57.5	189.8	339.6	0.1	235.8	463.5
IV-EHG	455.6	219.0	122.3	65.5	193.7	339.2	0.0	235.8	463.5

Deltas

Case	Nuclear	Hardcoal	Gas	Oil	Bio	Hydro	Ration	PV	Wind
I-B	-	-	-	-	-	-	-	-	-
II-E	1.4	-1.4	-5.2	-0.1	3.5	-0.3	0.0	0.0	0.0
III-BHG	9.9	56.1	-164.2	55.6	3.1	-1.6		0.0	0.0
IV-EHG	11.3	59.4	-187.6	63.6	7.0	-2.0	0.0	0.0	0.0

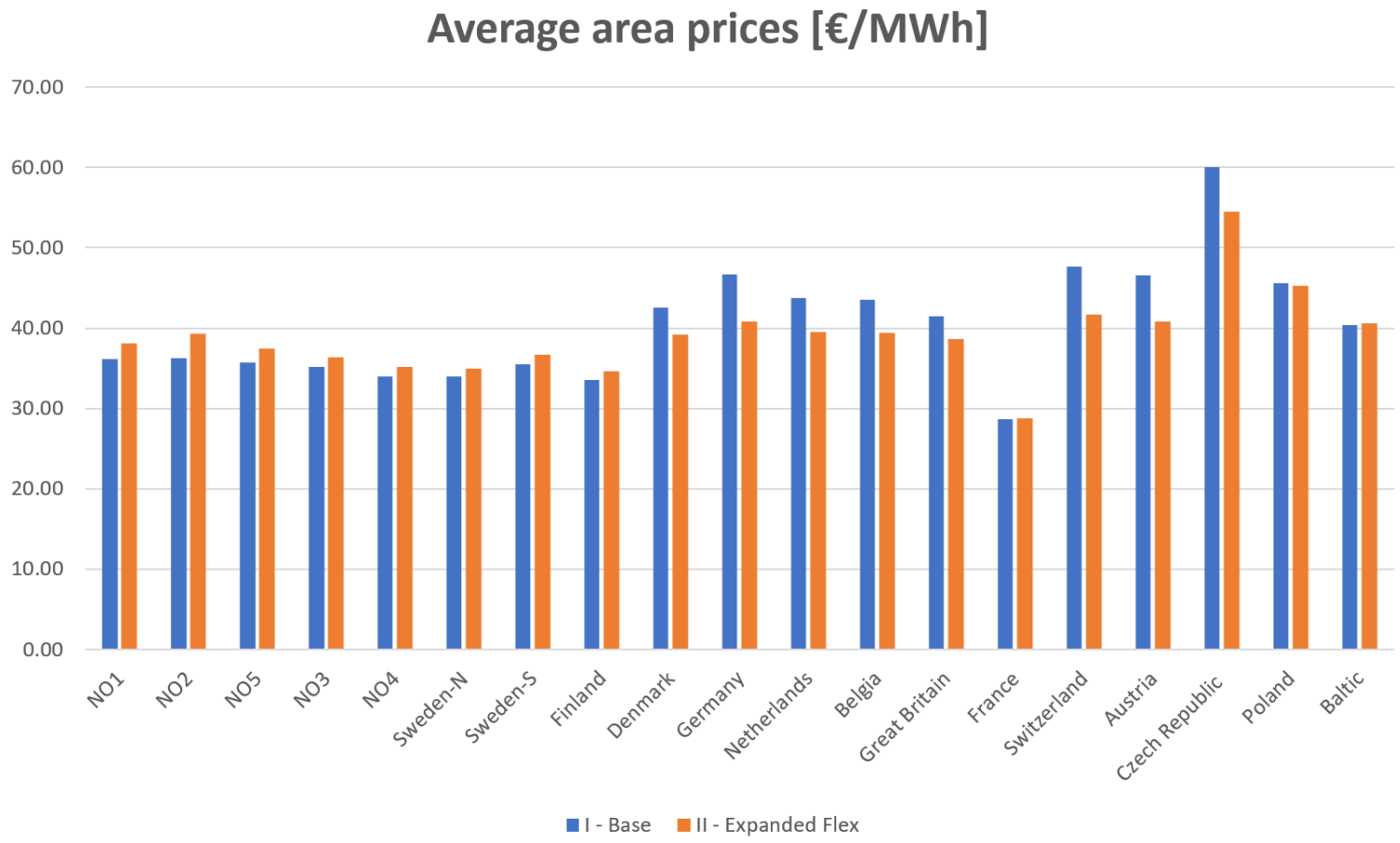
CO_2 emissions offset

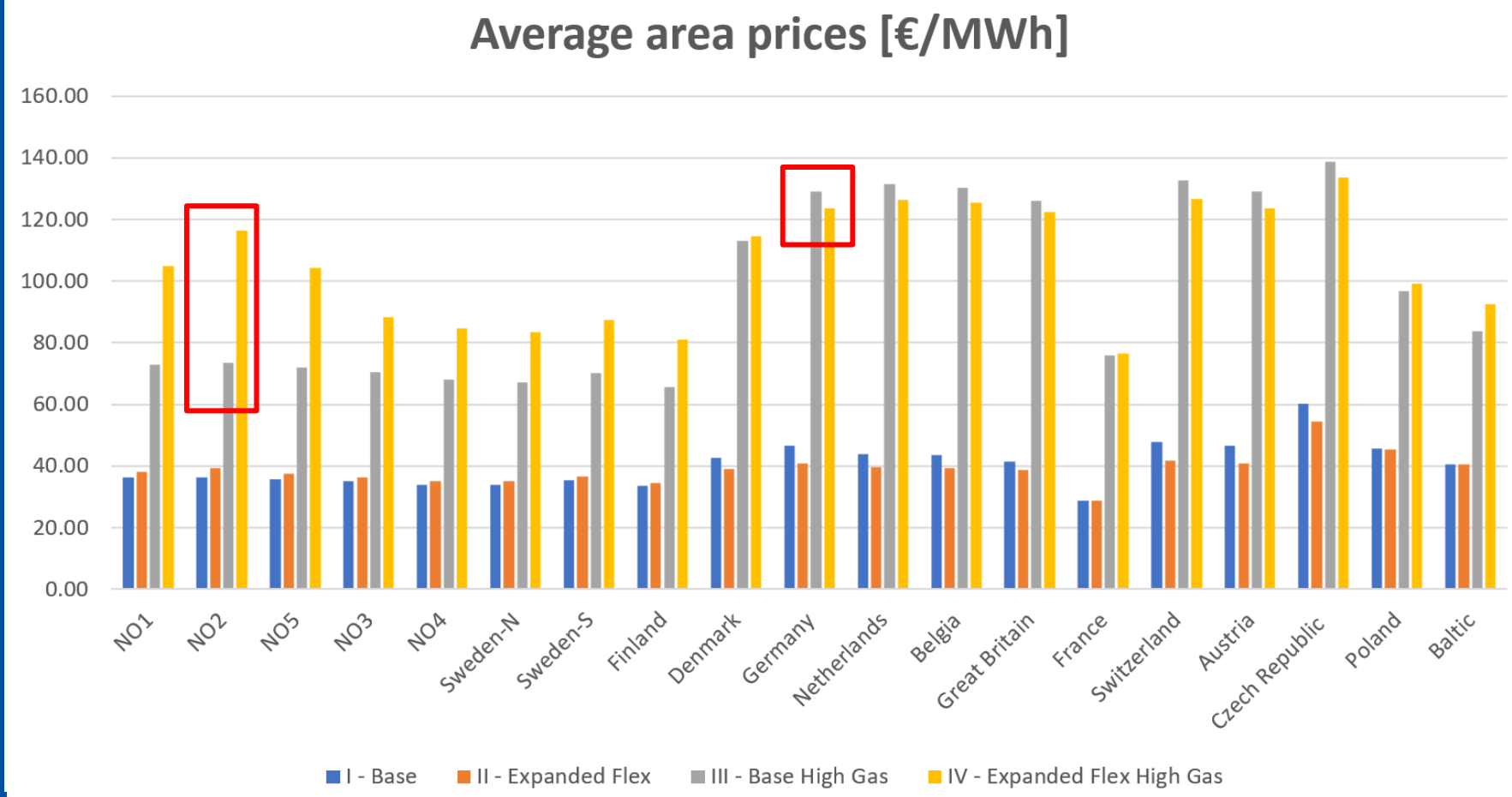
- Production reduced [TWh]

Case	Hardcoal	Gas	Oil
I-B	-	-	-
II-E	-1.4	-5.2	-0.1
III-BHG	56.1	-164.2	55.6
IV-EHG	59.4	-187.6	63.6

- CO2 emissions reduced [Mt]

Case	Hardcoal	Gas	Oil	Sum
I-B	-	-	-	-
II-E	-1.3	-2.1	-0.1	-3.4
III-BHG	50.5	-65.7	41.7	26.5
IV-EHG	53.5	-75.0	47.7	26.1


Average area prices [€/MWh]
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
NO1
NO2
NO5
NO3
NO4
Sweden-N
Sweden-S
Finland
Denmark
Germany
Netherlands
Belgia
Great Britain
France
Switzerland
Austria
Czech Republic
Poland
Baltic
I - Base
II - Expanded Flex


Average area prices [€/MWh]
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
NO1
NO2
NO5
NO3
NO4
Sweden-N
Sweden-S
Finland
Denmark
Germany
Netherlands
Belgia
Great Britain
France
Switzerland
Austria
Czech Republic
Poland
Baltic
I - Base
II - Expanded Flex
III - Base High Gas
IV - Expanded Flex High Gas

System income change I → II

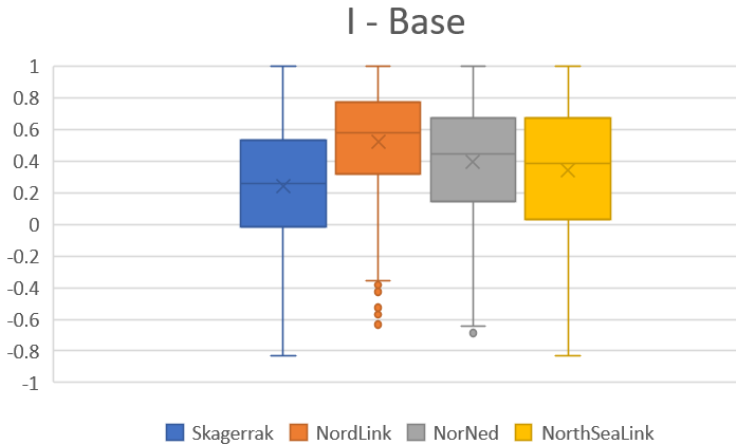
Area	Nuclear	Hardcoal	Gas	Oil	Bio	Hydro	SPP	WPP
NO1						0.042	0.000	0.000
NO2						0.127	0.000	0.002
NO5						0.063	0.000	0.001
NO3						0.028	0.000	0.002
NO4						0.009		0.001
Sweden-N						0.034	0.000	0.008
Sweden-S			0.017	0.001	0.007	0.012	0.001	0.008
Finland	0.019		0.002	0.000	0.011	0.010	0.000	0.006
Denmark			-0.042	-0.004	-0.017		0.002	0.004
Germany		-0.430	-1.000	-0.063	-0.173	-0.066	0.011	-0.086
Netherlands	-0.007		-0.216	-0.015	-0.029		0.008	0.005
Belgia			-0.200	-0.024	-0.014		0.005	0.000
Great Britain	-0.140		-0.705	-0.016	-0.045	-0.024	0.026	0.164 *
France	0.021		-0.012	0.000	0.002	-0.001	0.007	0.006
Switzerland								
Austria								
Czech Republic								
Poland		-0.030	-0.012	0.000	-0.003	-0.001	0.000	-0.003
Baltic	0.001	0.000	0.009		0.000	0.000	0.000	0.001

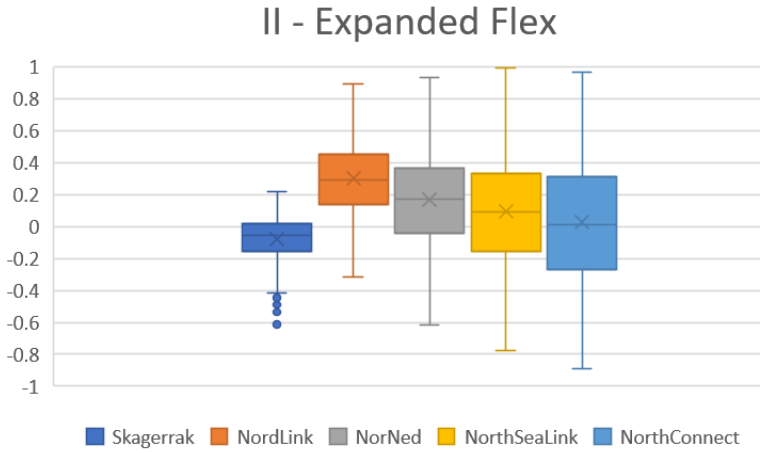
GB-SOUTH	-2.9E+07
GB-MID	-2.8E+07
GB-NORTH	8697957

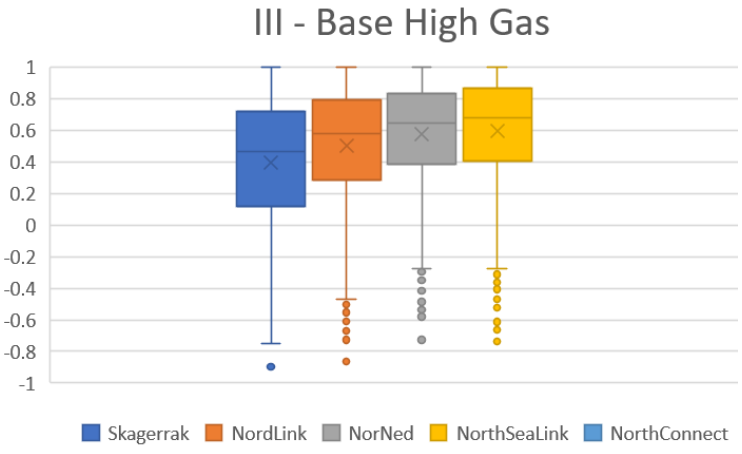
System income change III → IV

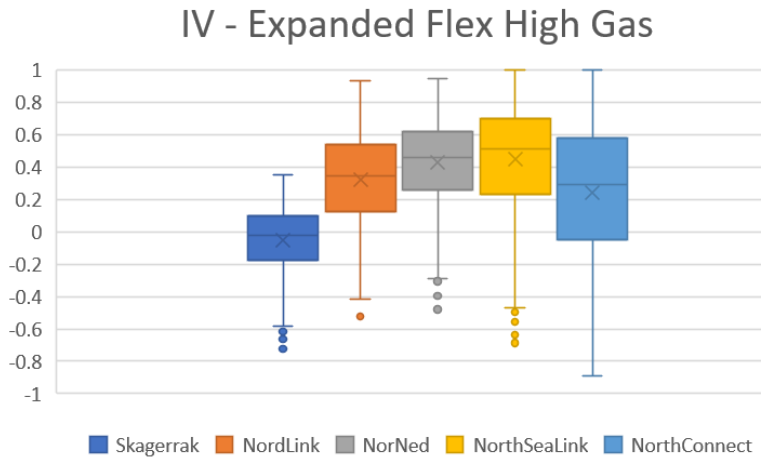
Area	Nuclear	Hardcoal	Gas	Oil	Bio	Hydro	SPP	WPP
NO1						0.313	0.005	0.009
NO2						0.754	0.005	0.035
NO5						0.444	0.002	0.020
NO3			0.000			0.206	0.001	0.036
NO4						0.068		0.009
Sweden-N			0.003	0.000		0.289	0.002	0.085
Sweden-S			0.015	0.039	0.063	0.099	0.009	0.078
Finland	0.176		0.007	0.028	0.090	0.078	0.003	0.059
Denmark			-0.022	0.002	0.005		0.008	0.045
Germany		-0.209	-0.922	-0.049	-0.101	-0.043	0.035	0.047
Netherlands	-0.005		-0.312	-0.008	-0.021		-0.002	0.011
Belgia			-0.214	-0.013	-0.010		-0.001	0.005
Great Britain	-0.105		-1.000	-0.022	-0.032	-0.035	0.003	0.237
France	0.071		-0.012	0.008	0.005	-0.019	0.012	0.014
Switzerland								
Austria								
Czech Republic								
Poland		0.088	-0.001	0.038	0.014	0.001	0.001	0.027
Baltic	0.017	0.000	0.000	0.121	0.006	0.012	0.000	0.011

Transmission utilization []









Pump utilization

- TBC

Further work

- Effect of increased VRE capacity
- Updated scenario matrix

I Base case	* Expanded Flex	* Base case	II Expanded Flex
III Base case High Gas Price	* Only transmission	*	IV Expanded Flex High Gas Price

References

- Helseth et al (2018), *Multi-market Price Forecasting in Hydro-Thermal systems*
- Solvang et. al (2014), *Norwegian hydropower for large-scale electricity balancing needs*

Thanks for your attention!

- Any questions?
- Any ideas?

System capacity mix [GW]

Group name	Nuclear	Lignite	HardCoal	Gas	Oil	Bio	SPP	WPP	Hydro
Norway_South				0.0			1.9	3.1	42.1*
Norway_Mid				0.0			0.2	3.7	7.6
Norway_North								0.6	2.7
Sweden_North				2.5	0.9	1.6	2.6	24.9	16.3
Finland	5.2			3.5	0.7	2.5	0.9	7.9	3.3
Denmark				2.6	0.4	1.8	5.7	13.0	
Germany	0.0		19.2	44.0	3.0	7.4	99.9	82.2	4.8
Netherlands	0.4			12.1	0.8	1.8	23.3	19.7	0.0
Belgium	0.0			10.8	1.3	0.9	16.6	10.6	0.0
Great-Britain	8.1			36.3	0.9	4.1	32.9	44.0	1.2
Sweden_South								0.0	
France	46.3			7.6	2.1	3.9	39.4	58.0	32.3
Switzerland									
Austria									
Czech_Republic									
Poland	0.0	6.4	13.0	4.5	2.4	2.4	1.0	12.4	4.2
Baltic	0.9	0.0	0.0	2.8	1.4	0.3	0.1	1.8	2.8
Sum	**60.8**	**6.4**	**32.2**	**126.7**	**13.9**	**26.6**	**224.5**	**282.0**	**117.4**

*Hydropower upgrade scenario

Generation mix in TWh for case I

Area	Nuclear	Hardcoal	Gas	Oil	Bio	Hydro	Ration	PV	Wind
NO1						28.4		0.7	1.3
NO2						37.7		0.7	3.7
NO5						34.0		0.3	2.9
NO3						33.7		0.2	8.4
NO4						11.7			2.1
Sweden-N						50.5		0.4	27.6
Sweden-S			6.1	0.1	12.2	16.9		2.0	21.5
Finland	40.3		1.7	0.0	18.4	14.7		0.8	18.7
Denmark			1.9	0.2	9.4			5.2	14.1
Germany		79.7	105.0	1.3	55.1	27.6		105.9	129.7
Netherlan	3.0		40.4	0.0	12.9			24.1	16.7
Belgia			28.1	0.1	6.5			17.3	11.1
Great Brita	62.6		98.2	0.2	27.8	5.2	0.0	32.3	59.6
France	331.6		6.1	0.0	22.1	73.2		44.8	109.3
Poland		79.9	18.1	0.0	20.0	3.7		1.0	32.1
Baltic	6.8	0.1	4.3		2.4	4.0		0.1	4.7
Sum I	**444.3**	**159.6**	**309.9**	**1.9**	**186.7**	**341.2**	**0.1**	**235.8**	**463.5**

Hydropower upgrades

- Solvang et al (2014)

Table 2.2 New power generation and pump installations – Scenario 3.

Case	Power station	Output (MW)	Upper reservoir[1]	Lower reservoir[2]
A2	Tonstad pumped storage power station	1,400	Nesjen (14 cm/h)	Sirdalsvatn (3 cm/h)
B3	Holen pumped storage power station	1,000	Urarvatn (10 cm/h)	Bossvatn (12 cm/h)
B6b	Kvilldal pumped storage power station	2,400	Blåsjø (11 cm/h)	Suldalsvatn (6 cm/h)
B7b	Jøsenfjorden hydro storage power station	2,400	Blåsjø (11 cm/h)	Jøsenfjorden (sea)
C2	Tinnsjø pumped storage power station	2,000	Møsvatn (3 cm/h)	Tinnsjø (4 cm/h)
C3	Tinnsjø pumped storage power station	2,400	Kallhovd (7 cm/h)	Tinnsjø (4 cm/h)
D1	Lysebotn hydro storage power station	1,800	Lyngsvatn (12 cm/h)	Lysefjorden (sea)
E1	Mauranger hydro storage power station	400	Juklavatn (14 cm/h)	Hardangerfjorden (sea)
E2	Oksla hydro storage power station	700	Ringedalsvatn (12 cm/h)	Hardangerfjorden (sea)
E3	Tysso pumped storage power station	1,000	Langevatn (13 cm/h)	Ringedalsvatn (11 cm/h)
F1	Sy-Sima hydro storage power station	1,000	Sysenvatn (11 cm/h)	Hardangerfjorden (sea)
G1	Aurland hydro storage power station	700	Viddalsvatn(12 cm/h)	Aurlandsfjorden (sea)
G2	Tyin hydro storage power station	1,000	Tyin (2 cm/h)	Årdalsvatnet[3]
	Total new power generation capacity	18,200		

[1] Water level decrease in parentheses.
[2] Water level increase in parentheses.
[3] Insufficient data to calculate water level increase in Årdalsvatnet

Transmission upgrades

2050 Extended					
	C1	C2	Cap	Additional	Total cap
NordLink	NOR	DEU	1400	4	7000
NorthSeaLink	NOR	GBR	1400	0	1400
NorthConnect	NOR	GBR	1400	2	4200
NordNed	NOR	NLD	700	1	1400
Skagerrak	NOR	DEN	1700	1	3400
			6600	10800	17400