Enhancing Offshore Wind Integration by Integrated Electricity and Gas Systems With Hydrogen Blending

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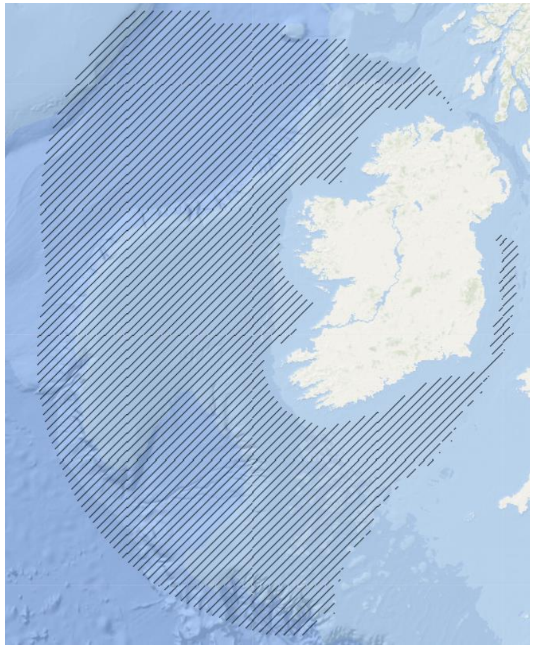
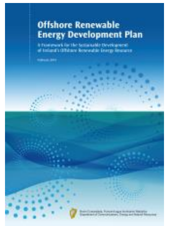
1.1 Offshore wind in Ireland

Ireland has a sea area of 490,000 km^2—approximately seven times the size of its landmass—and one of the best offshore renewable resources in the world.



Exclusive economic zone



2014 Offshore Renewable Energy Development Plan (OREDP)

- Opportunity identification

2023 CLIMATE ACTION PLAN 2023

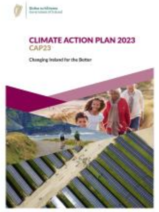
- Set out 5GW goal for offshore wind

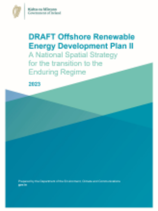
2023 Policy Statement on the Framework for Phase Two Offshore Wind

- Clarify three phases and long-term plans of offshore wind development

2023 DRAFT Offshore Renewable Energy Development Plan II

- Assessment in OREDP2





1.1 Offshore wind in Ireland

2023

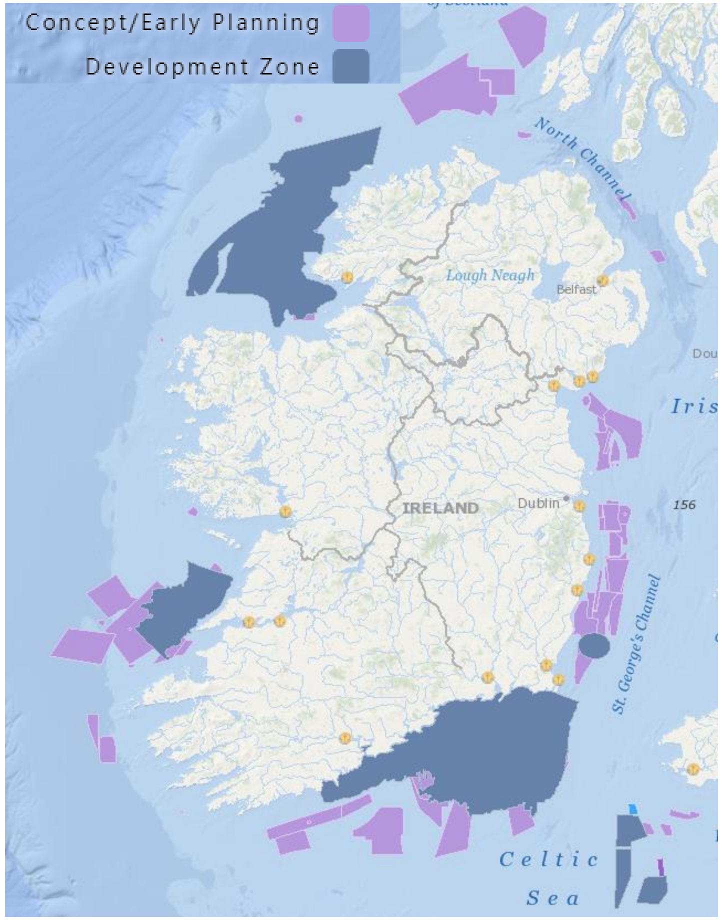
- **3074 MW** were auctioned by ORESS (supporting scheme), two more auctions to be organized.

2030

- **5GW** offshore wind connected to the grid
- **2GW** of floating offshore wind for non-grid use

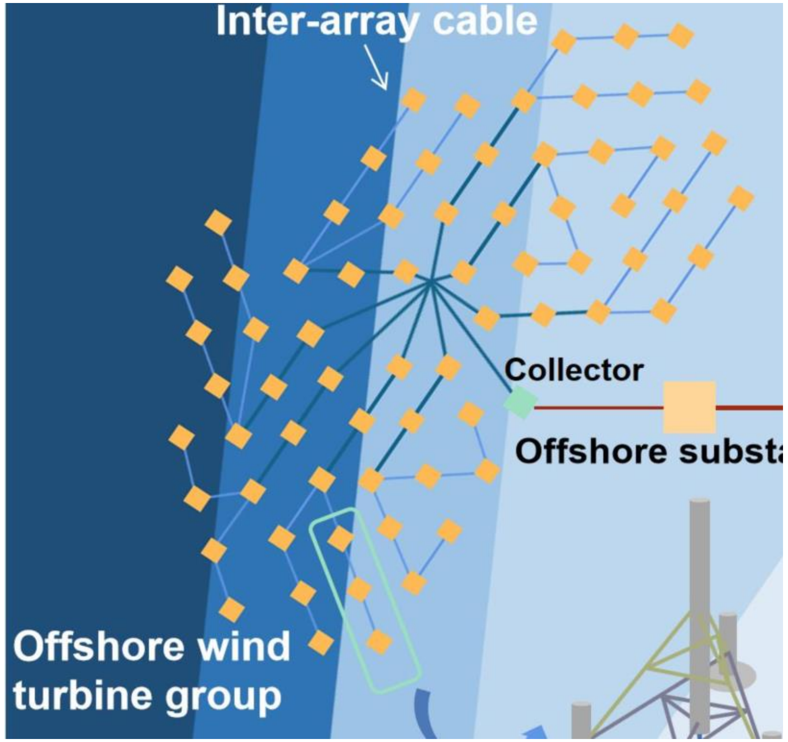
2040 … … **20GW**

2050 … … **37GW**



* Global Offshore Renewable Map | 4C Offshore, https://map.4coffshore.com/offshorewind/

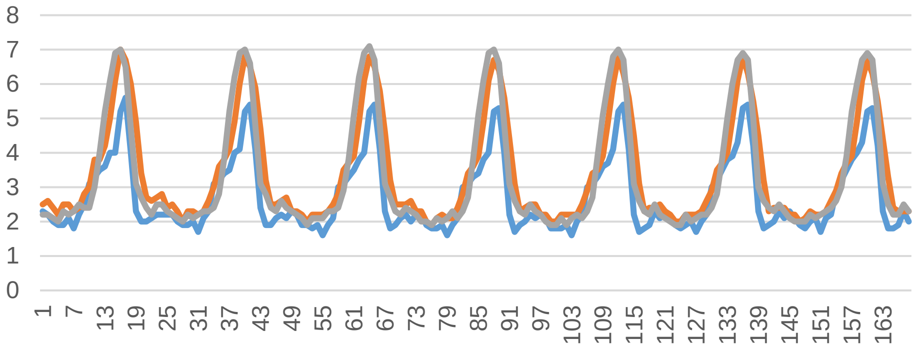
1.2 Challenges in offshore wind integration



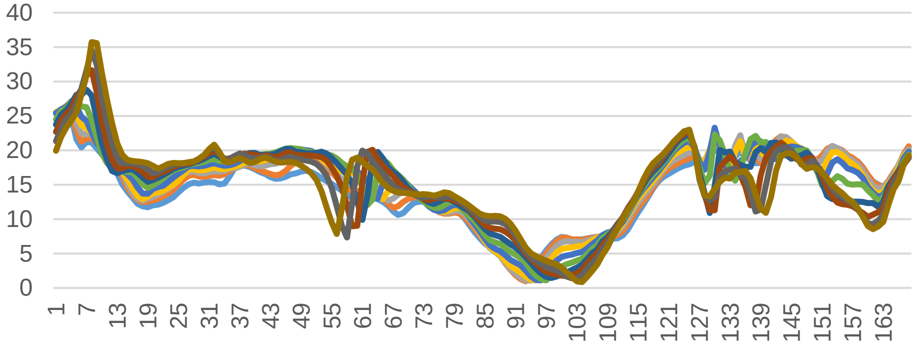
Large volume:

- Increase the burden on the onshore grid interconnection point

Onshore wind:



Offshore wind:



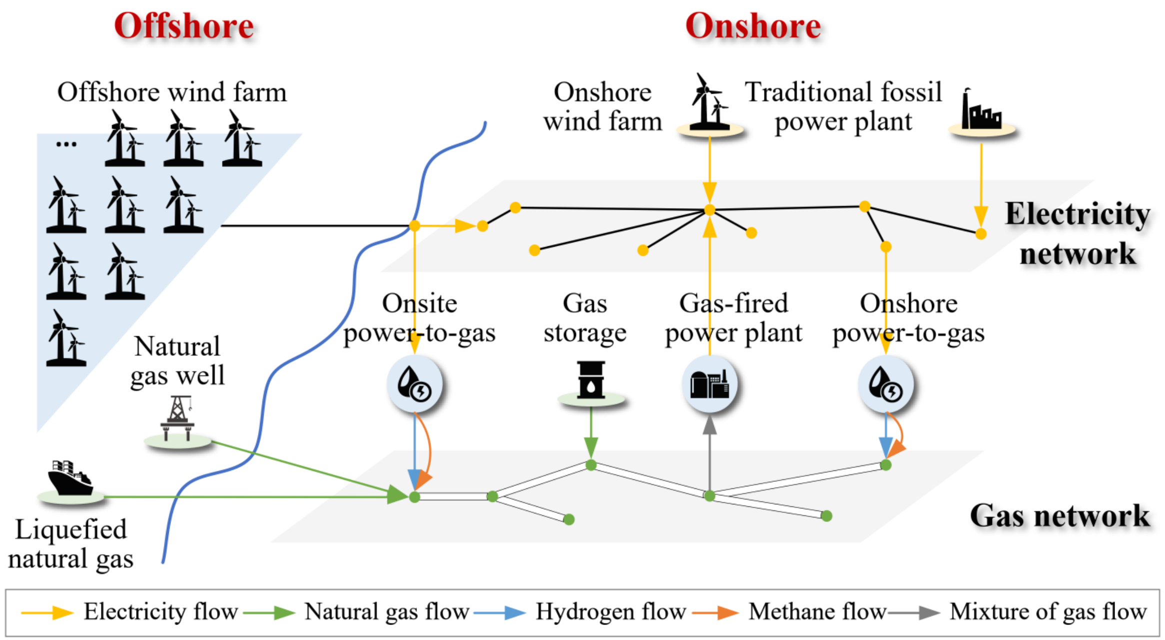
Highly stochastic:

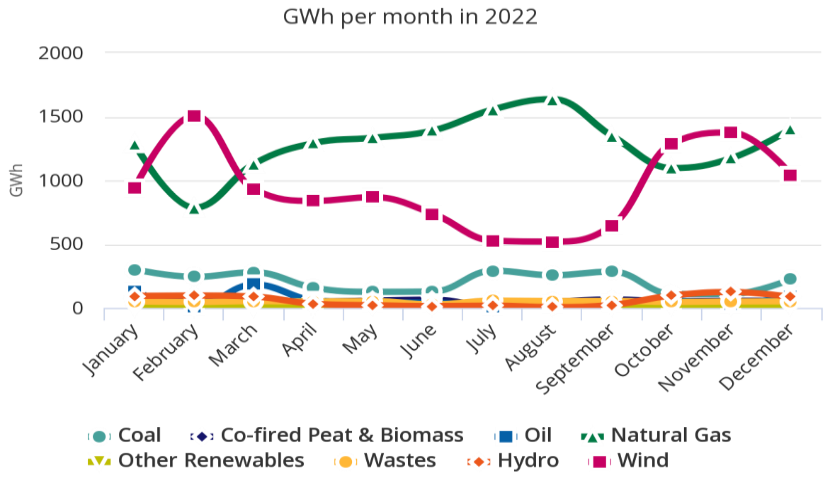
- Require more flexibility from the grid.

** Guo X, Chen X, Chen X, et al. Grid integration feasibility and investment planning of offshore wind power under carbon-neutral transition in China[J]. Nature Communications, 2023, 14(1): 2447.*

1.3 Integration by H-IEGS

Hydrogen-blended integrated electricity and gas systems





- Electricity and gas systems are coupled by gas-fired power plants and power to gas (PTG).
- Hydrogen is injected into the gas network by PTG
- Offshore wind farms are integrated both directly into electricity systems by HVDC/HVAC or indirectly into gas systems by hydrogen

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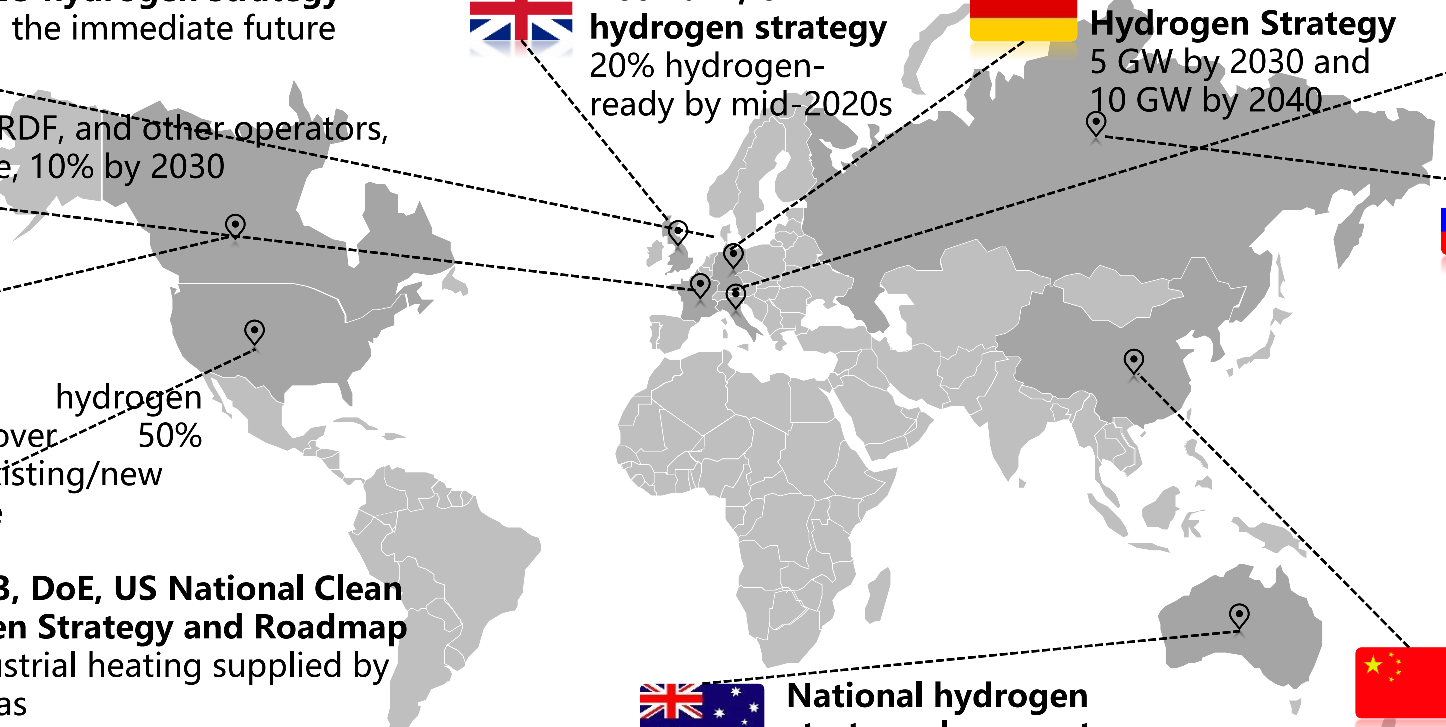
1.3 Integration by H-IEGS



Jul 2020, EU hydrogen strategy
5%-10% in the immediate future

GRTgaz, GRDF, and other operators,
6% feasible, 10% by 2030

2×10^7 t/year hydrogen production, over 50% transported by existing/new Gas infrastructure

Jun 2023, DoE, US National Clean Hydrogen Strategy and Roadmap
- 20-50% of industrial heating supplied by clean natural gas
- 2022-2025, assessing the compatibility
- 2026-2029, develop national guidance for hydrogen blending limits

Dec 2022, UK hydrogen strategy
20% hydrogen-ready by mid-2020s

German National Hydrogen Strategy
5 GW by 2030 and 10 GW by 2040

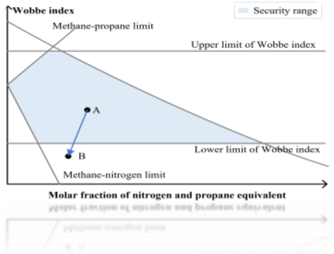
Italian gas group SNAM, 10%

National Hydrogen Energy Strategy
- using hydrogen blending or pure hydrogen to exported to European countries

National hydrogen strategy document
- Regards the blending of hydrogen as a strategic focus area

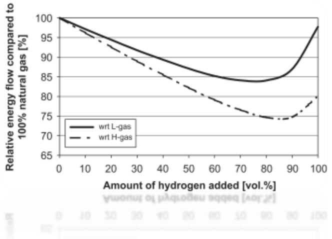
2021-2022, Medium and long-term plan for the development of hydrogen energy industry (2021-2035) …
- Under testing, early stage

1.4 Additional challenges by hydrogen blending



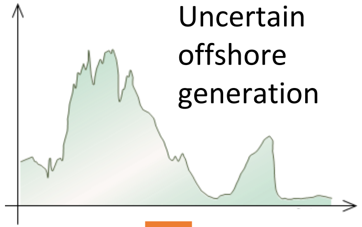
Gas quality

- Low heat value
- unideal combustion



Change in Gas flow pattern

- Change in gas flow pattern
- Linepack swing



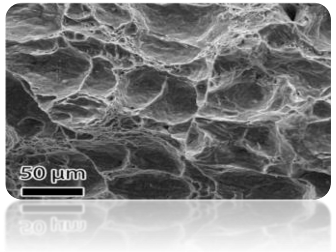
Uncertain offshore generation

Heterogenous and variant gas compositions across the network

Combustion dynamics

- Flashbacks, overheating issues
- potential corrosion of materials

…

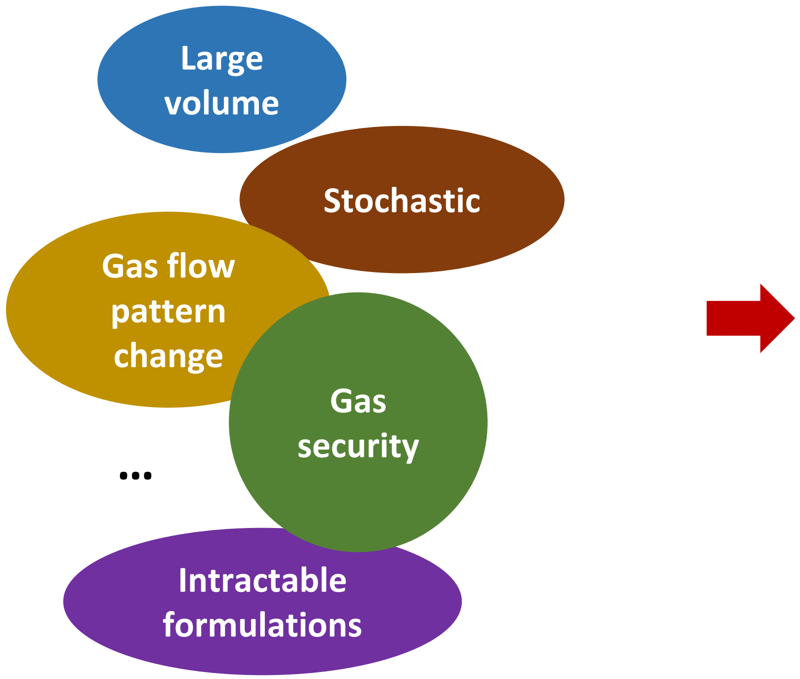


Hydrogen embrittlement

- Corrosion of pipelines, valves, etc.

1.5 Contributions

Proposes a novel offshore wind accommodation scheme by using the flexibility of both electricity/gas systems and hydrogen-blending techniques.



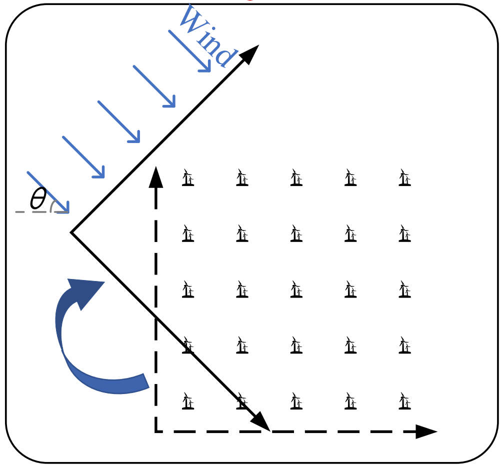
- A distributionally robust chance-constrained (DRCC) operation framework.
- A sequential convex programming embedded DRCC (SCP-DRCC) solution method.
- A moment-based ambiguity set characterization of offshore wind farm uncertainties with wake effect.
- A large-scale and comprehensive energy system case study with practical suggestions.

Contents

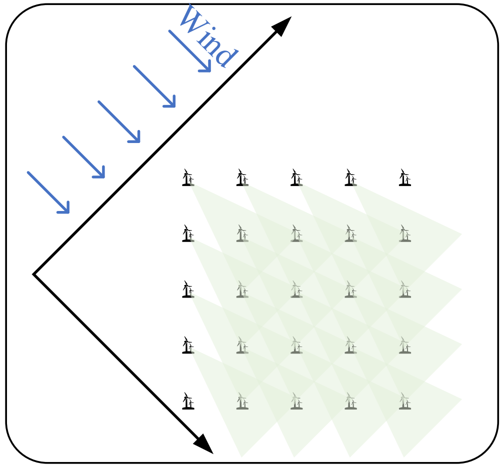
2 General procedures

Offshore wind – Uncertainty set – wake effect

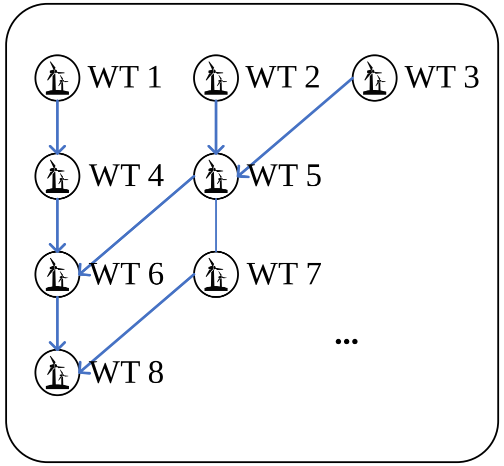
Step 1: Model vectorized stochastic wind velocity



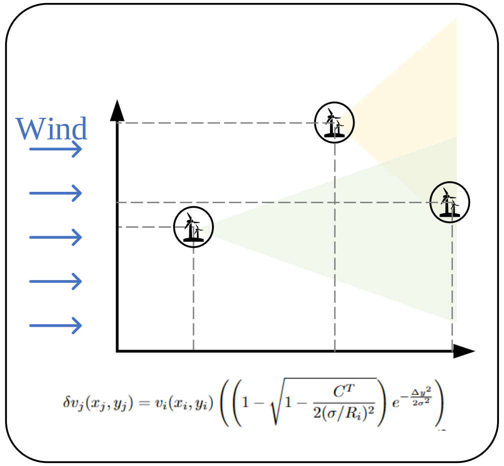
Step 2: Establish time-varying coordinate axes



Step 3: Outline wake effect regions of wind turbines



Step 4: Build recursive tree of cumulative wake effects

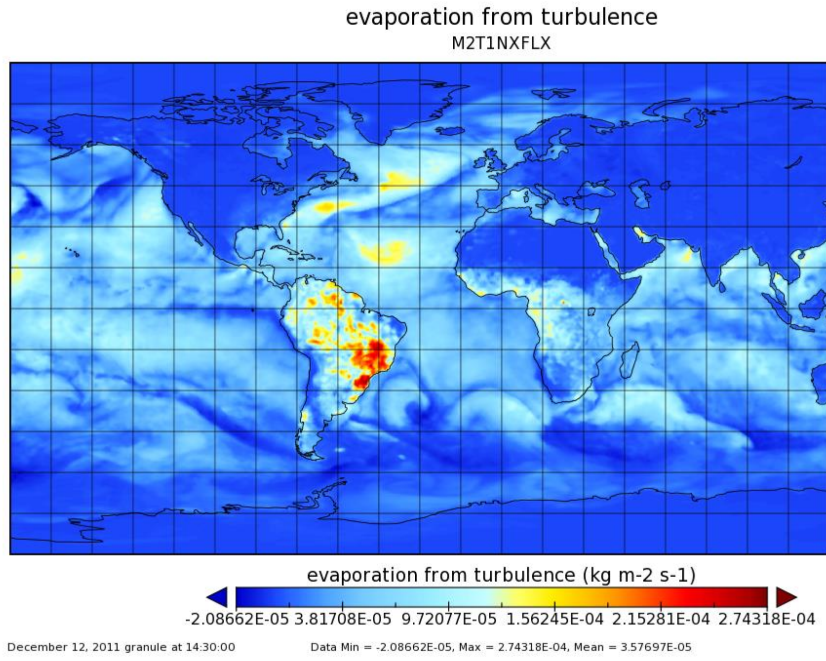


Step 5: Calculate wind speed with cumulative wake effects

Step 6: Formulate the uncertainty set of offshore wind generations

2 General procedures

Step 1: Model vectorized stochastic wind velocity



MERRA-2

Data are collected from MERRA-2 tavg1_2d_flx_Nx: 2d,1-Hourly,Time-Averaged,Single-Level,Assimilation,Surface Flux Diagnostics V5.12.4 (M2T1NXFLX)

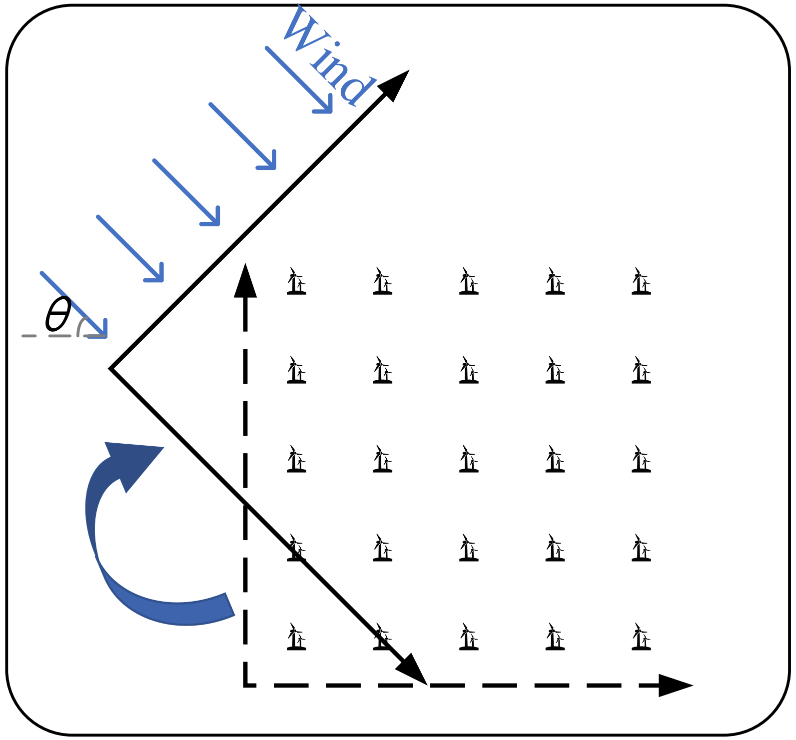
- Spatial resolution: 0.5 ° lon x 0.625 ° lat
- Temporal resolution: 1 hour

Obtain the forecast deviation for wind speed and direction:

$$\dot{v}_{m,k} = \{v_{m,k} = \overline{v}_{m,k} + \Delta v_{m,k}, \theta_{m,k} = \overline{\theta}_{m,k} + \Delta\theta_{m,k}\}$$

2 General procedures

Step 2: Establish time-varying coordinate axes according to the wind direction.

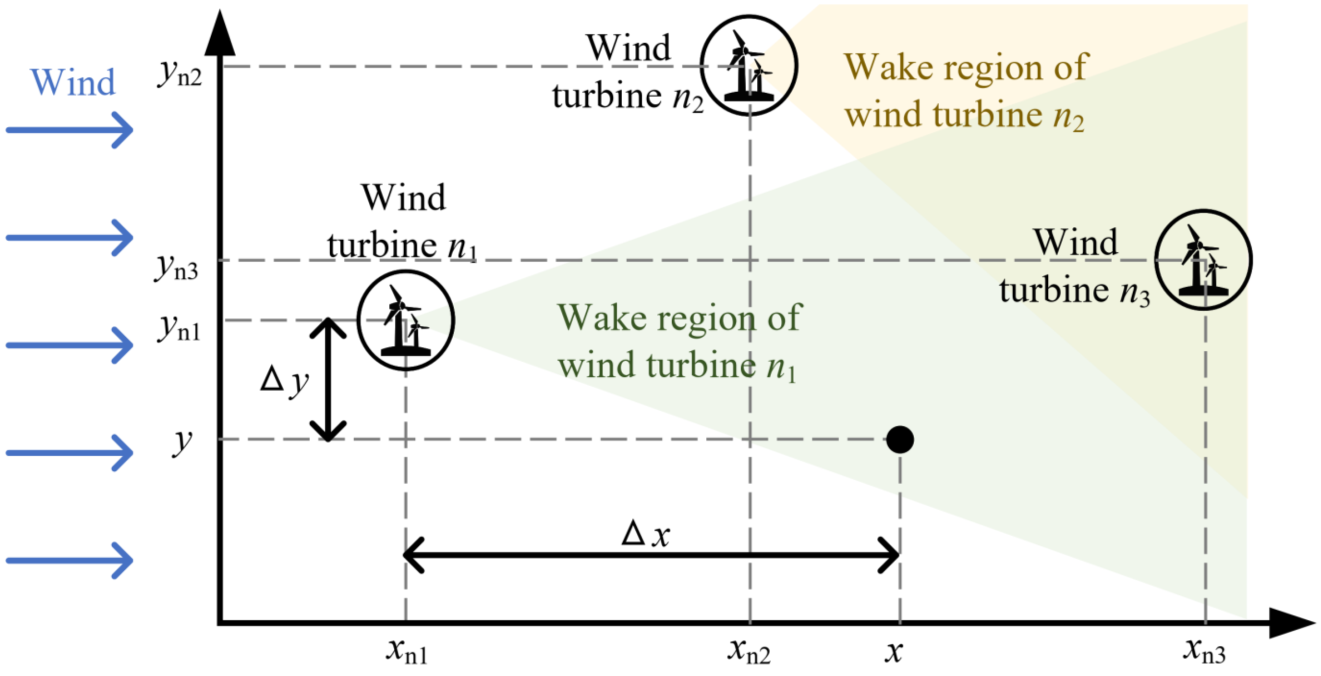


$$\begin{bmatrix} x_n \\ y_n \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{n,0} \\ y_{n,0} \end{bmatrix}$$

New coordinates Original coordinates

2 General procedures

Step 3: Outline the wake effect regions of WTs.



Decrease in wind speed (Frandsen–Gaussian model):

$$\delta v_{n_1} = v_{n_1}\left(\left(1-\sqrt{1-\frac{C^T}{2\left(\omega/R_{n_1}\right)^2}}\right)e^{-\frac{\Delta y^2}{2\omega^2}}\right)$$

where

$$\omega = \left(\mathrm{R}_{\mathrm{n}_1} + 0.56/\left(\ln \mathrm{z}^{\mathrm{h}} - \ln \mathrm{z}_0\right)\Delta\mathrm{x}\right)/2$$

(thrust coefficient, rotor diameter, distance, …)

Then solve

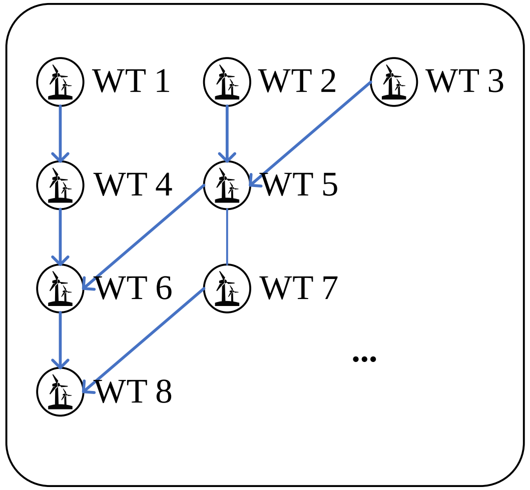
$$\delta \mathrm{v}_{\mathrm{n}_1} > \epsilon^{\mathrm{w}}$$

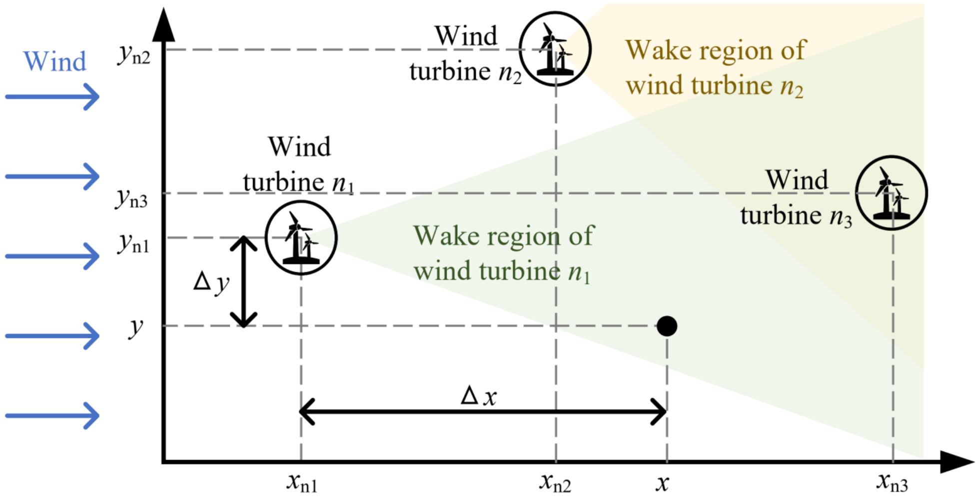
To outline the wake effect region

2 General procedures

Step 4: Build the recursive tree of cumulative wake effects.

Step 5: Calculate wind speed considering cumulative wake effects.



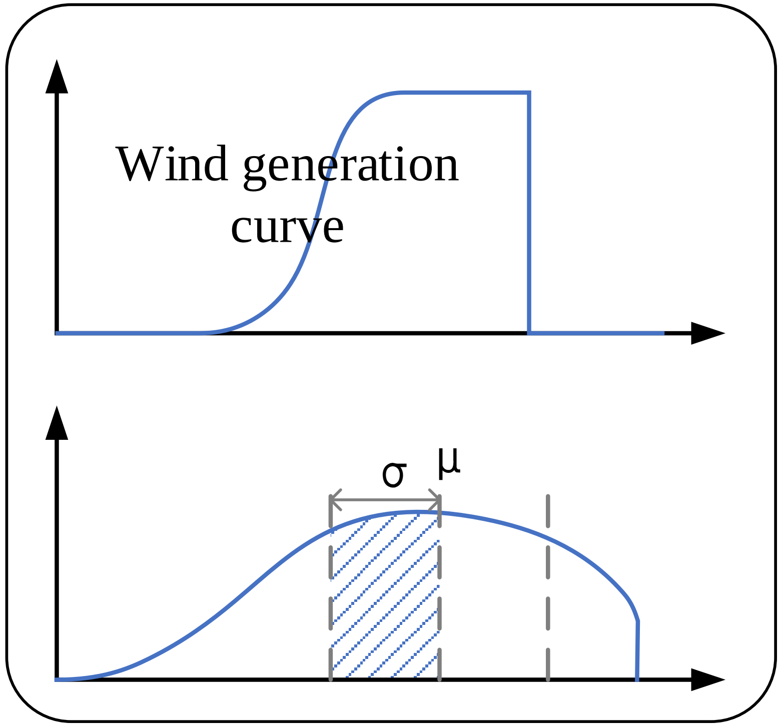


Updated wind speed:

$$v_n = v_m - \left(\sum_{n' \in \mathcal{N}_n} \delta v_{n'} \right)^{\frac{1}{2}}$$

2 General procedures

Step 6: uncertainty set



Electricity generation of wind farm

$$P_{i,k}^{max,owf} = \sum_{m\in\mathcal{M}_i}\sum_{n\in\mathcal{N}_{i,m}} f^{wt}(v_{n,k})$$

moment-based ambiguity set of available generating capacity

Prediction error

$$\Xi_i = \left\{ \Pr(\boldsymbol{\xi}) \middle| \mathbb{E}(\boldsymbol{\xi}) = \boldsymbol{\mu}, \mathbb{E}\left(\boldsymbol{\xi}\boldsymbol{\xi}^T\right) = \boldsymbol{\sigma} \right\}$$

Mean value

Varia
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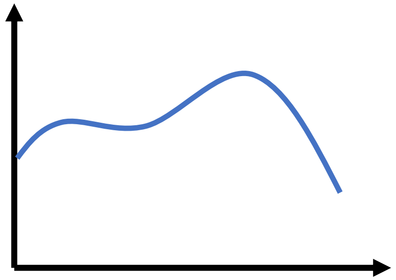
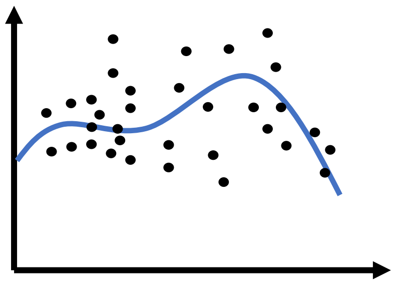
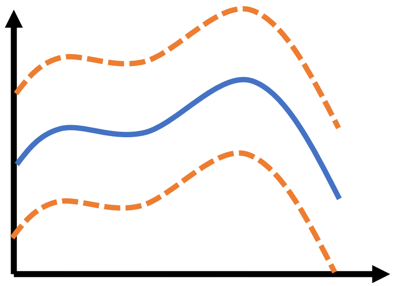
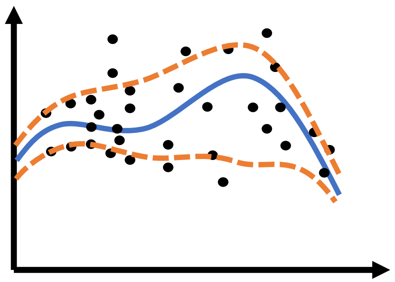
3.1 Idea of DRCC

	Deterministic optimization	Stochastic optimization	Robust optimization	Distributionally robust optimization
				
Fea tures	Assume we can accurately know the uncertain variable in advance	Calculate the optimization results in different scenarios	Consider the worst scenario within a certain "budget"	Partially reflect the probability distribution
Pros	Fast calculation	Can consider the probability distribution	Relatively fast	Balance the computation speed and optimality
Cons	Can not withstand the risk of uncertainty	Slow	Too conservative (high operating cost)	A bit slower than RO, a bit more conservative than SO

3.2 Gas security

Gas Safety (Management) Regulations 1996

REQUIREMENTS UNDER NORMAL CONDITIONS

1. The content and characteristics of the gas shall be in accordance with the values specified in the following table.

Content or characteristic	Value
hydrogen sulphide content	≤5 mg/m³;
total sulphur content (including H_2S)	≤50 mg/m³;
hydrogen content	≤0.1% (molar);
oxygen content	≤0.2% (molar);
impurities	shall not contain solid or liquid material which may interfere with the integrity or operation of pipes or any gas appliance (within the meaning of regulation 2(1) of the 1994 Regulations) which a consumer could reasonably be expected to operate;
hydrocarbon dewpoint and water dewpoint	shall be at such levels that they do not interfere with the integrity or operation of pipes or any gas appliance (within the meaning of regulation 2(1) of the 1994 Regulations) which a consumer could reasonably be expected to operate;
WN	(i) ≤51.41 MJ/m³, and (ii) ≥47.20 MJ/m³;
ICF	≤0.48
SI	≤0.60

- hydrogen content: ≤0.1% (molar)
- Wobbe index (WI): (i) ≤51.41 MJ/m3, and (ii) ≥47.20 MJ/m3
- incomplete combustion factor (ICF): ≤0.48
- soot index (SI): ≤0.60

The Gas Safety (Management) (Amendment) Regulations 2023

Came into force on 6 April 2023:

- Relative density of ≤0.700
- Removed ICF and SI requirement
- oxygen content of ≤1% (molar) so long as it is conveyed at pressures ≤38 barg

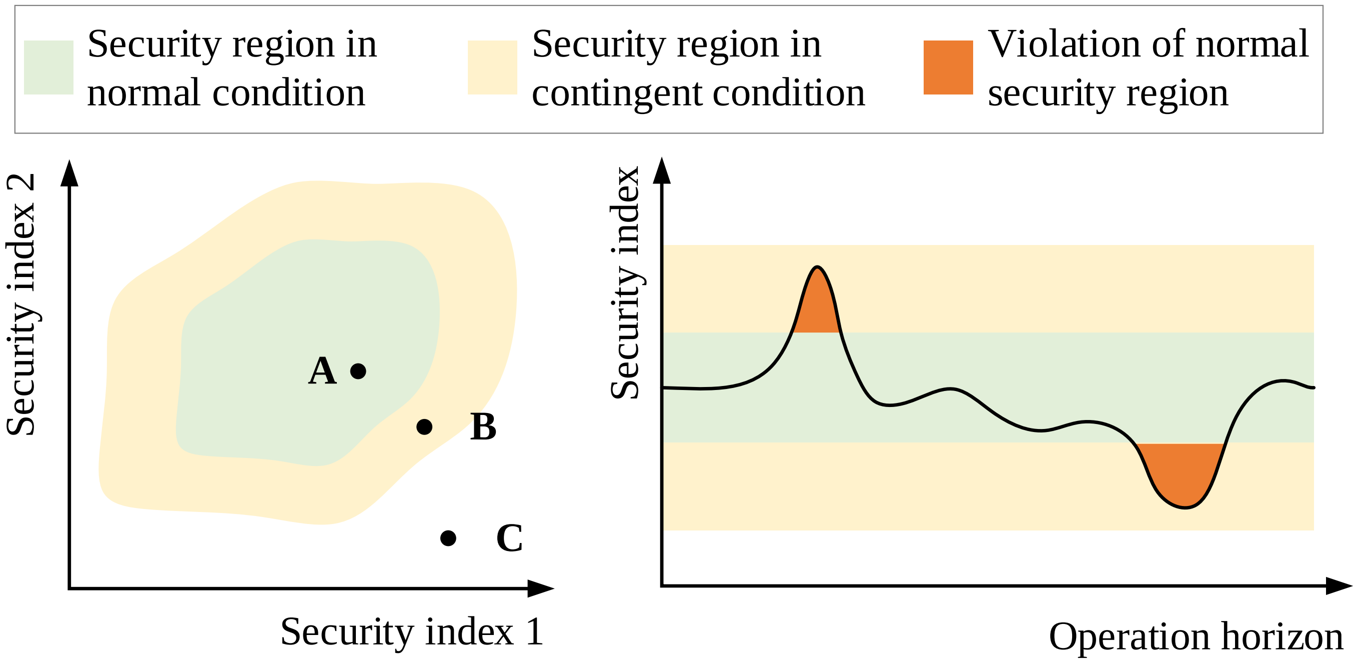
On 6 April 2025:

Change the lower limit of WI to ≥46.5MJ/m3

(Policy decision on the role of hydrogen blending at distribution level by the end of 2023)

https://www.legislation.gov.uk/uksi/1996/551/contents/made
https://www.legislation.gov.uk/uksi/2023/284/made
https://www.hse.gov.uk/gas/gas-safety-management-regulation-changes.htm

3.2 Gas security



- Wobbe index

$$WI_{i,k} = \sum_{g \in \mathcal{G}} \chi_{i,k,g} GCV_g \left(RD_{i,k}\right)^{-\frac{1}{2}}$$

- Relative density

$$RD_{i,k} = \sum_{g \in \mathcal{G}} \chi_{i,k,g} M_g / M^{air}$$

- Flame speed factor

$$FS_{i,k} = \frac{\sum_{g \in \mathcal{G}} \chi_{i,k,g} fs_g}{AF + 5\chi_{i,k}^{ni} - 18.8\chi_{i,k}^{ox} + 1}$$

- Gas security chance constraints:

$$\inf_{\Xi} \Pr\left\{WI^{min,N} \le \widetilde{WI}_{i,k} \le WI^{max,N}, \widetilde{RD}_{i,k} \le RD^{max,N}, FS^{min,N} \le \widetilde{FS}_{i,k} \le FS^{max,N}\right\} \ge 1 - \epsilon^N$$

3.3 Optimization model

Objective function

- Minimize the expected operating cost:

$$f = \min \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{I}} E_{\Xi} \left(\sum_{i \in \mathcal{L}^{tpp}} c_{i,l}^{E} \widetilde{P_{i,l,k}} + \sum_{l \in \mathcal{L}^{gs}} c_{i,l}^{G} \widetilde{q_{i,l,k}} \right)$$

By controlling the generators, PTGs, gas sources, …

And keep all the constraints:

Power system:

- Generator constraints
- DC power flow
- Transmission line capacity

…

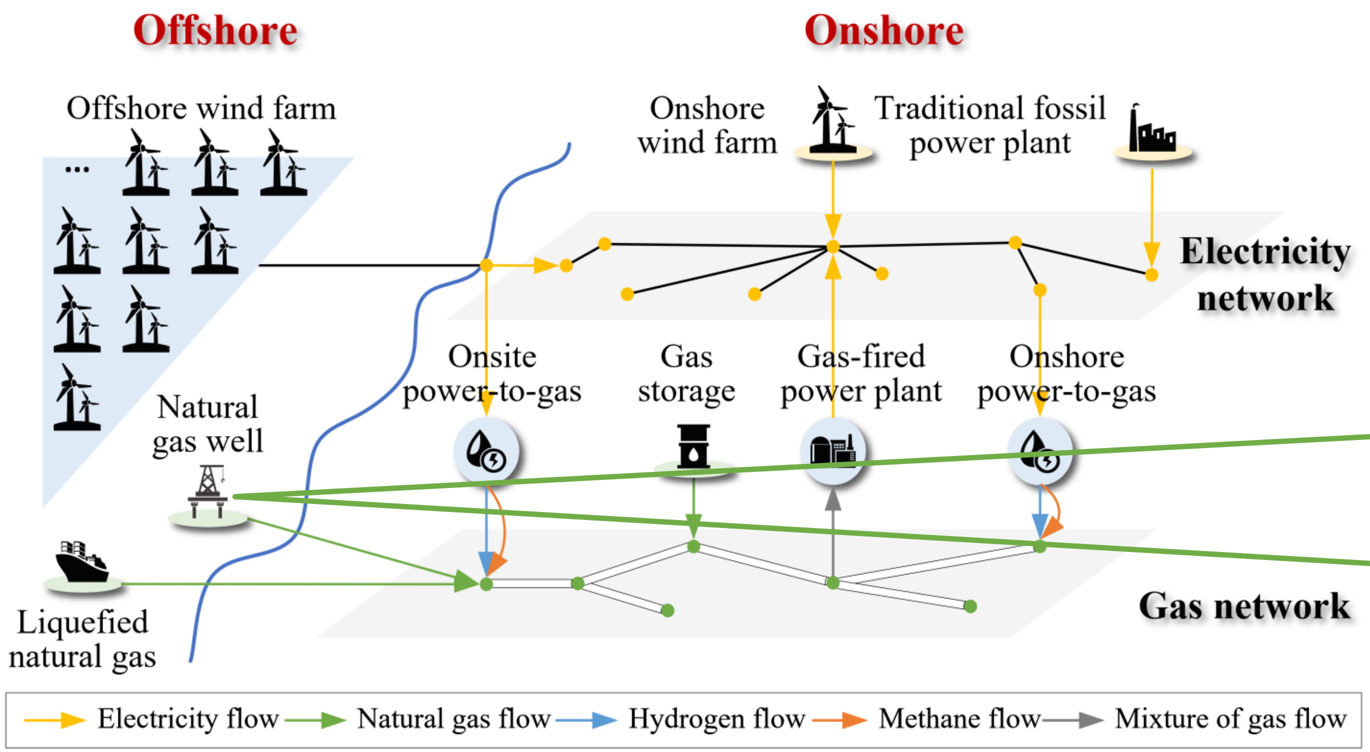
Gas system:

- Gas security constraints
- Gas source constraints
- PTG constraints
- Weymouth equation
- Gas mixing
- Nodal energy balance

…

Different from the traditional gas system models with uniform gas composition

3.4 Modeling of gas system



Modeling of gas source:

- Gas composition:

$$\widetilde{q_{i,l,k,g}^{s}} = \chi_{i,l,g}^{s}\widetilde{q_{i,l,k}^{s}}, \quad \sum_{g \in \mathcal{G}} \chi_{i,l,g}^{s} = 1$$

- Upper and lower bounds:

$$\inf_{\Xi} \Pr\{q_{i,l}^{s,min} \leq \widetilde{q_{i,l,k}^{s}} \leq q_{i,l}^{s,max}\} \geq 1 - \epsilon^{G}$$

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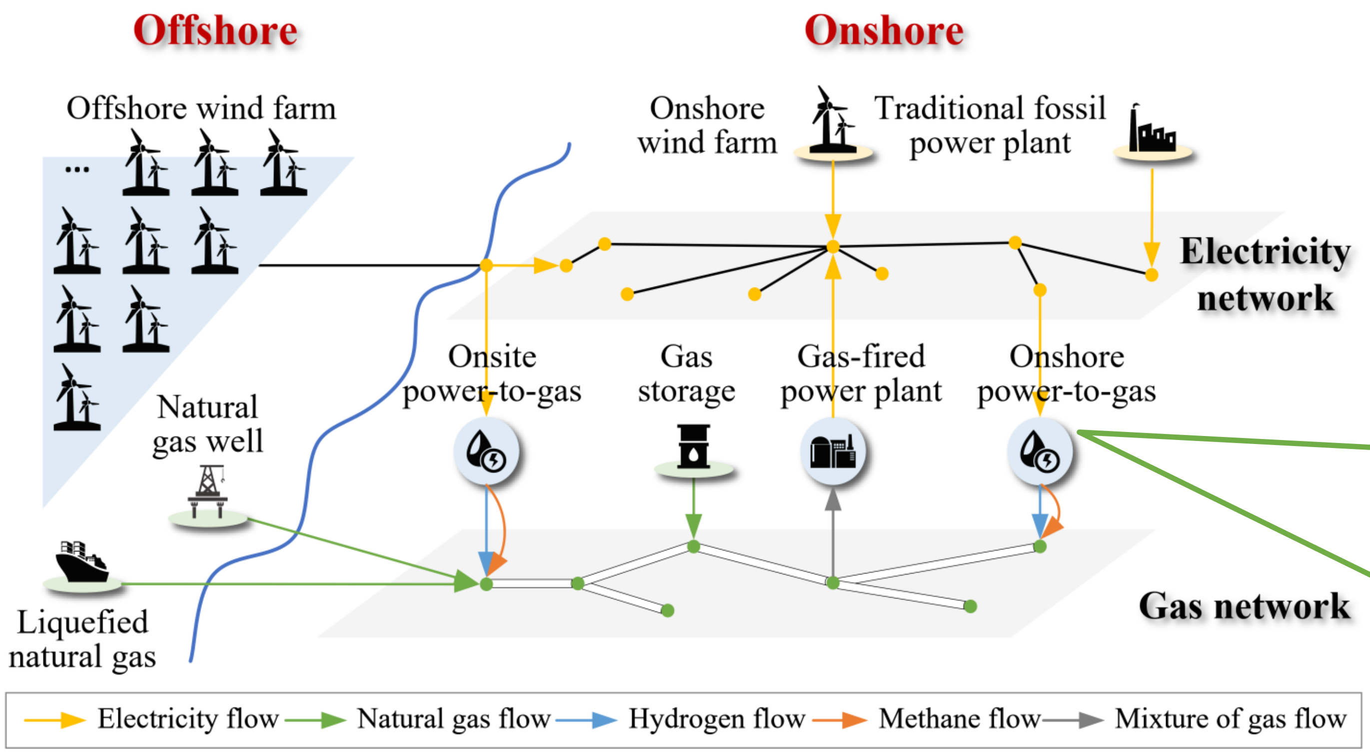
3.4 Modeling of gas system



Modeling of PTG:

- Energy conversion:

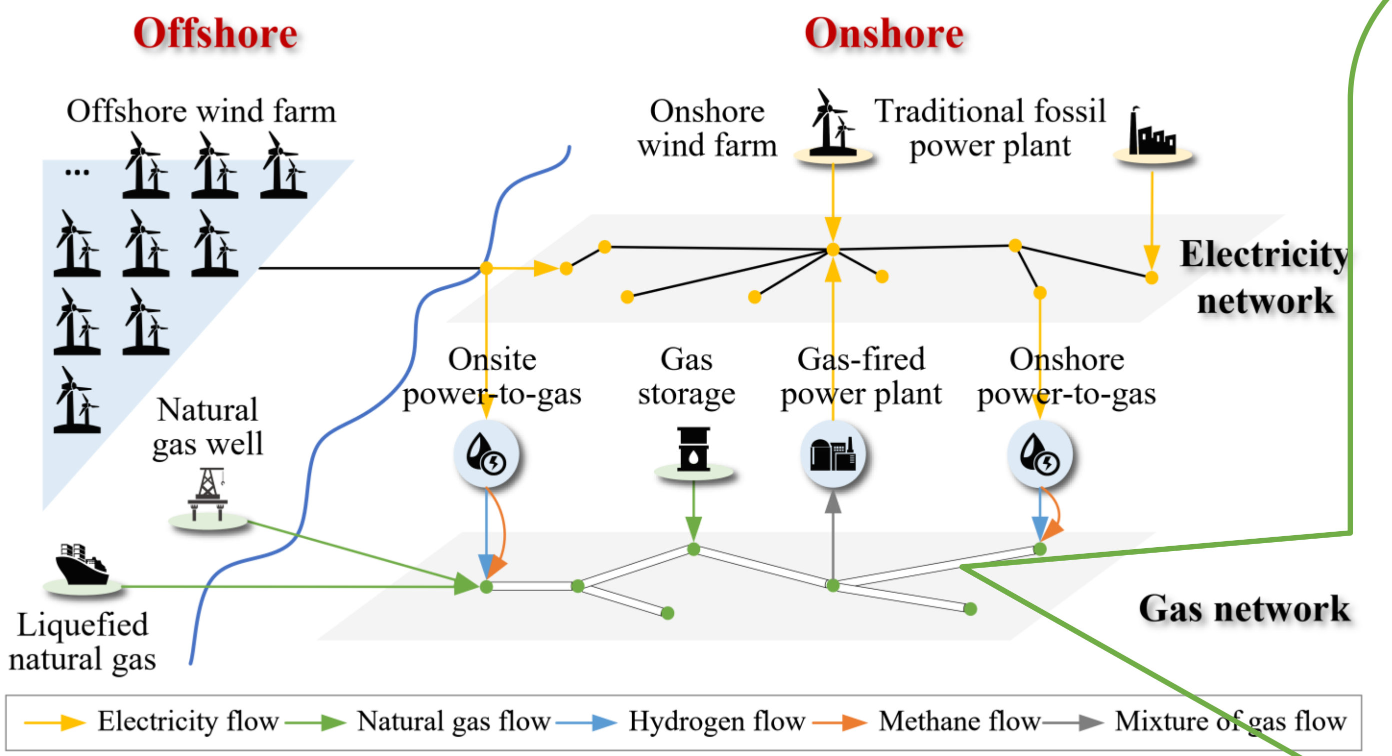
$$\widetilde{q_{i,l,k}^{hy}} GCV^{hy} + \widetilde{q_{i,l,k}^{me}} GCV^{me} \eta_{i,l}^{me} = \widetilde{P_{i,l,k}^{ptg}} \eta_{i,l}^{el}$$

- Capacity limits:

$$\inf_{\Xi} \Pr\{ P_{i,l,k}^{ptg,min} \le \widetilde{P_{i,l,k}^{ptg}} \le P_{i,l,k}^{ptg,max} \} \ge 1 - \epsilon^{G}$$

$$\inf_{\Xi} \Pr\{ \widetilde{q_{i,l,k}^{me}}, \widetilde{q_{i,l,k}^{hy}} \ge 0 \} \ge 1 - \epsilon^{G}$$

3.4 Modeling of gas system



Modeling of gas flow in pipelines:

- Weymouth equation:

$$\widetilde{p_{i,k}^2} - \widetilde{p_{j,k}^2} = \gamma_{ij,k} \frac{16 f_{ij} (\rho^{ng})^2 T^{ng} L_{ij} z^{ng}}{\pi^2 D_{ij}^5} \widetilde{r_{ij,k} q_{ij,k}^2}$$

- Gas flow sum and gas constant:

$$\widetilde{q_{ij,k}} = \sum_{g \in \mathcal{G}} \widetilde{q_{ij,k,g}}, \quad \widetilde{r_{ij,k}} = \sum_{g \in \mathcal{G}} R_g \widetilde{\chi_{ij,k,g}}$$

- Pipeline capacity:

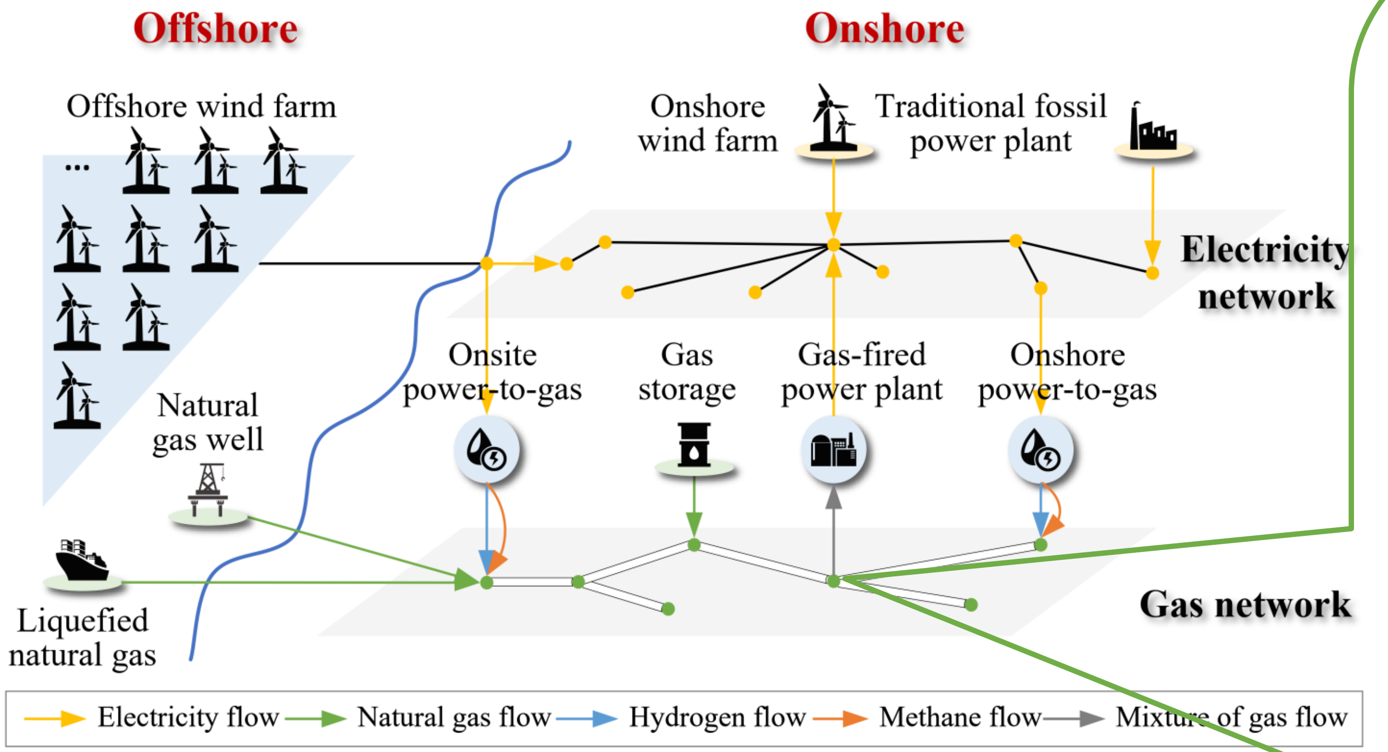
$$\inf_{\Xi} \Pr\{ (1 - \gamma_{ij}) q_{ij}^{max}/2 \le [\widetilde{q_{ij,k}}, \widetilde{q_{ij,k,g}}] \le (1 + \gamma_{ij}) q_{ij}^{max}/2 \} \ge 1 - \epsilon^G$$

$$\inf_{\Xi} \Pr\{ (1 - \gamma_{ij}) q_{ij}^{max}/2 \le [\widetilde{q_{ij,k}}, \widetilde{q_{ij,k,g}}] \le (1 + \gamma_{ij}) q_{ij}^{max}/2 \} \ge 1 - \epsilon^G$$

- Gas pressure limit

$$\inf_{\Xi} \Pr\{ p_i^{min} \le \widetilde{p_{i,k}} \le p_i^{max} \} \ge 1 - \epsilon^G$$

3.4 Modeling of gas system



Modeling of nodal gas mixing:

- Gas component mixing

$$\widetilde{\chi_{i,k,g}} = \left(\sum_{l \in \mathcal{L}_i^{s}} \widetilde{q_{i,l,k,g}^{s}} + \sum_{l \in \mathcal{L}_i^{ptg}} \widetilde{q_{i,l,k,g}^{ptg}} + \sum_{j \in \mathcal{J}_i} \frac{1-\gamma_{ij}}{2} \widetilde{q_{ij,k,g}} \right) / \left(\sum_{l \in \mathcal{L}_i^{s}} \widetilde{q_{i,l,k}^{s}} + \sum_{l \in \mathcal{L}_i^{ptg}} \widetilde{q_{i,l,k}^{ptg}} + \sum_{j \in \mathcal{J}_i} \frac{1-\gamma_{ij}}{2} \widetilde{q_{ij,k}} \right)$$

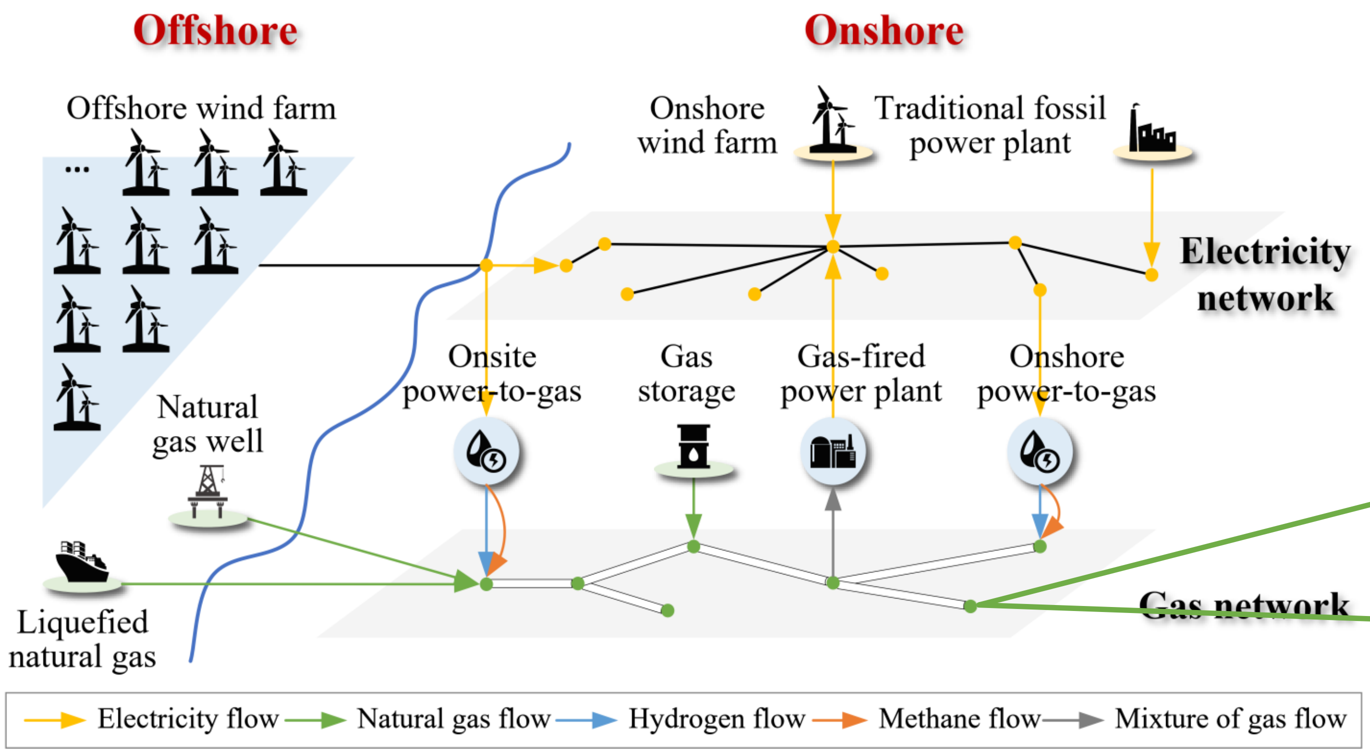
- Gas composition in pipeline:

$$\widetilde{q_{ij,k,g}} / \widetilde{q_{ij,k}} = \left((1+\gamma_{ij}) \widetilde{\chi_{i,k,g}} + (1-\gamma_{ij}) \widetilde{\chi_{j,k,g}} \right) / 2$$

- Nodal gas balance:

$$\sum_{l \in \mathcal{L}_i^{s}} \widetilde{q_{i,l,k,g}^{s}} + \sum_{l \in \mathcal{L}_i^{ptg}} \widetilde{q_{i,l,k,g}^{ptg}} + \sum_{j \in \mathcal{J}_i} \frac{1-\gamma_{ij}}{2} \widetilde{q_{ij,k,g}} = \sum_{j \in \mathcal{J}_i} \frac{1+\gamma_{ij}}{2} \widetilde{q_{ij,k,g}} + \sum_{l \in \mathcal{L}_i^{gpp}} \widetilde{q_{i,l,k,g}^{gpp}} + \widetilde{q_{i,k,g}^{d}}$$

3.4 Modeling of gas system



Modeling of gas demand:

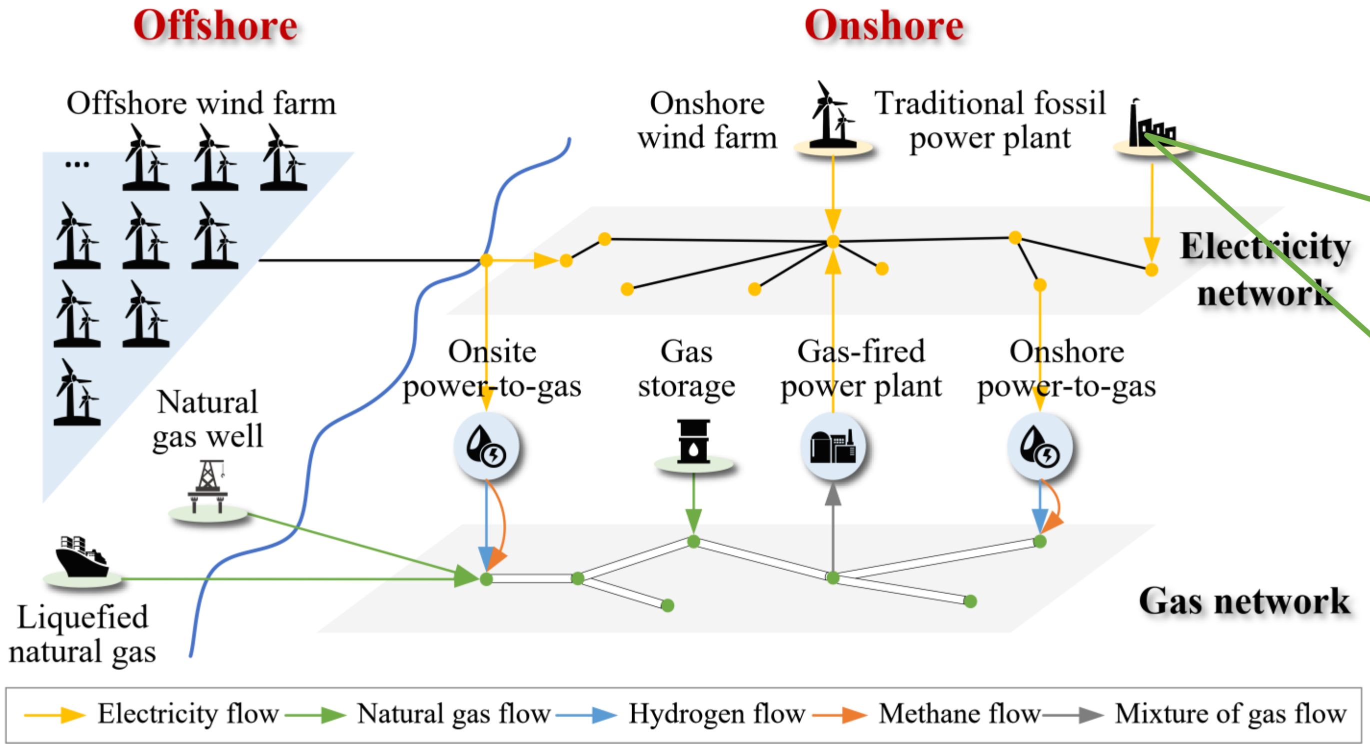
- Gas demand energy:

$$\sum_{g \in \mathcal{G}} GCV_g \widetilde{q_{i,k,g}^{d}} = GCV^{ng} q_{i,k}^{d}$$

- Gas demand composition:

$$\widetilde{q_{i,k,g}^{d}} / \sum_{g \in \mathcal{G}} \widetilde{q_{i,k,g}^{d}} = \widetilde{\chi_{i,k,g}}$$

3.5 Modeling of electricity system



Modeling of generators:

For non-gas-fired power plants:

- Capacity constraints:

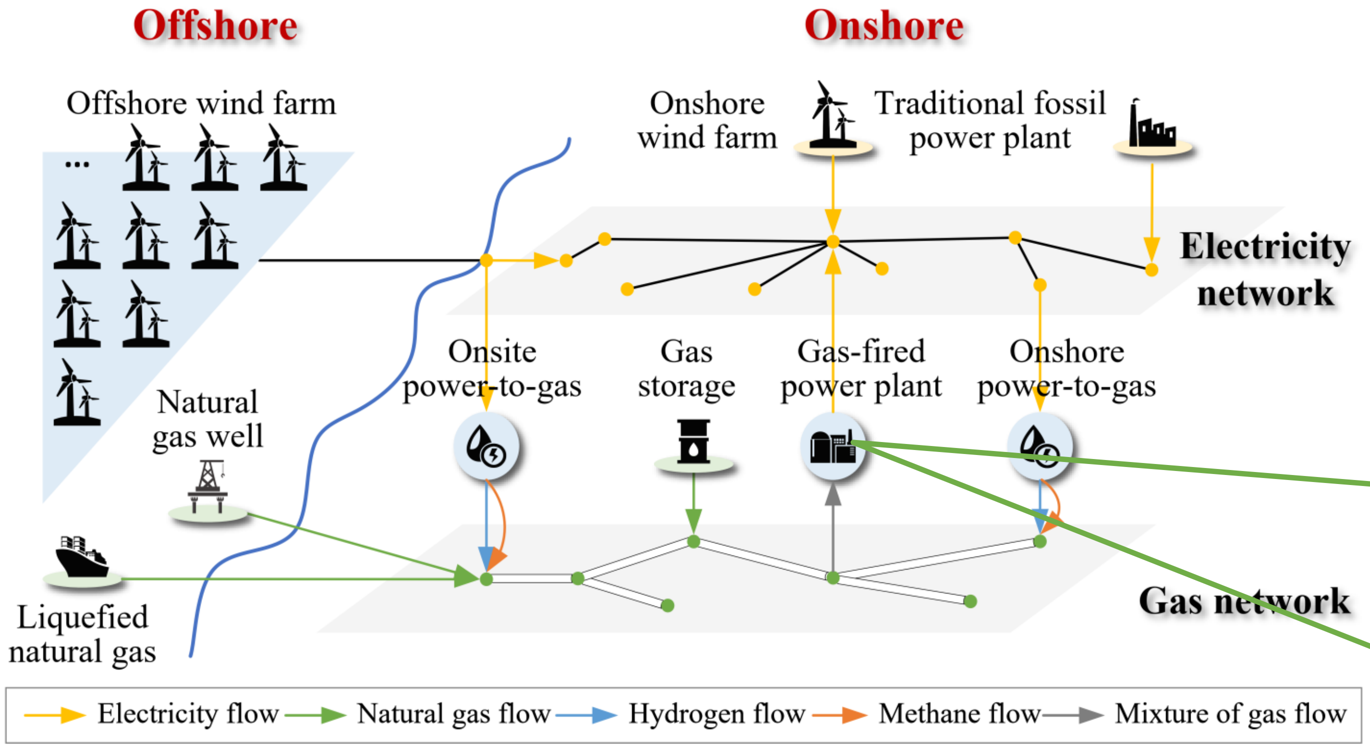
$$\inf_{\Xi} \Pr\{ P_{i,l}^{min} \leq \widetilde{P_{i,l,k}} \leq P_{i,l}^{max} \} \geq 1 - \epsilon^E$$

For offshore wind:

- Energy conversion:

$$\inf_{\Xi} \Pr\{ P_{i,l}^{min} \leq \widetilde{P_{i,l,k}} \leq \widetilde{P_{i,l}^{max}} \} \geq 1 - \epsilon^E$$

3.5 Modeling of electricity system



Modeling of generators:

For gas-fired power plants:

- Energy conversion:

$$\widetilde{P_{i,l,k}} = \eta_{i,l}^{gpp} \sum_{g\in\mathcal{G}} \widetilde{q_{i,l,k,g}}\, GCV_g$$

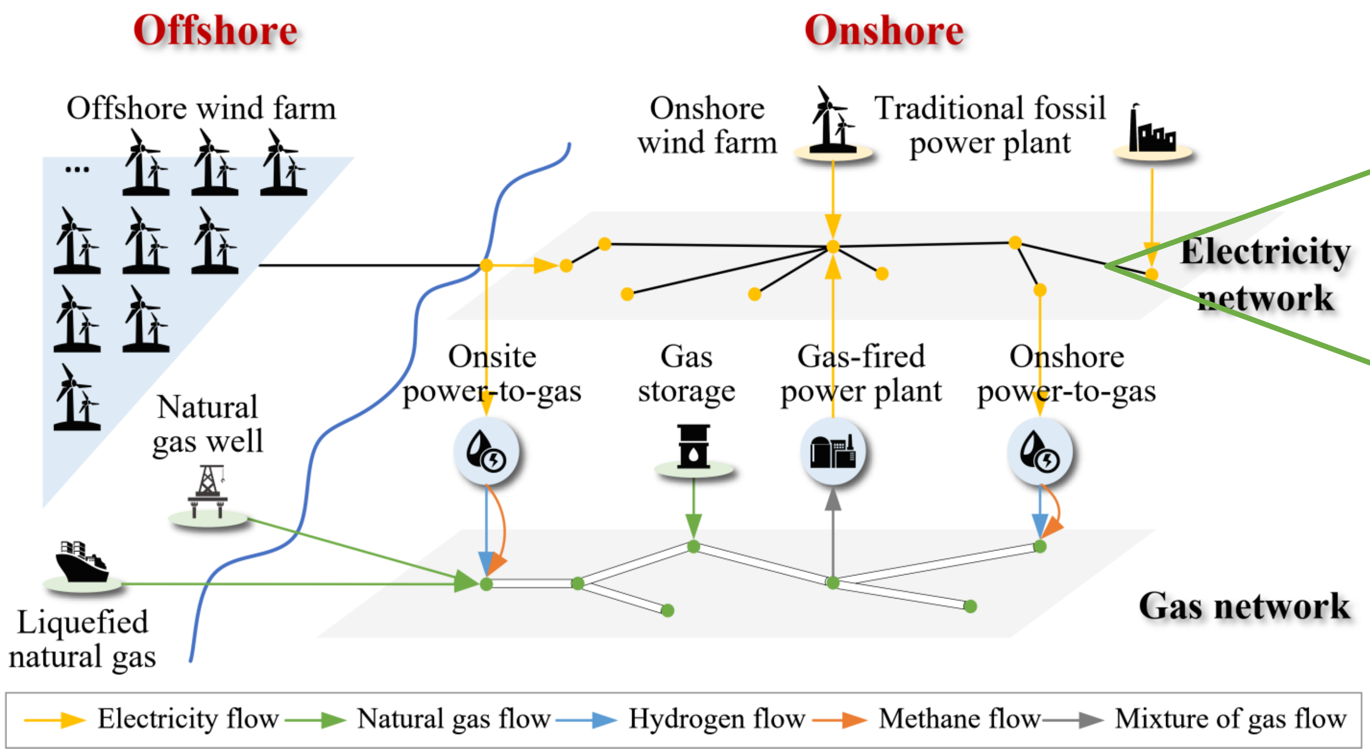
- Gas composition:

$$\widetilde{q_{i,l,k,g}^{gpp}} / \sum_{g\in\mathcal{G}} \widetilde{q_{i,l,k,g}} = \widetilde{\chi_{i,k,g}}$$

- Capacity:

$$\inf_{\Xi} \Pr\{P_{i,l}^{min} \le GCV^{ng}\, \widetilde{q_{i,l,k}^{gpp}} \le P_{i,l}^{max}\} \ge 1 - \epsilon^{E}$$

3.5 Modeling of electricity system



Modeling of transmission lines:

- Power balance:

$$\sum_{\substack{l\in\mathcal{L}_i^{tpp}\cup\mathcal{L}_i^{gpp}\\ \cup\mathcal{L}_i^{owf}\cup\mathcal{L}_i^{rng}}} \widetilde{P_{i,l,k}} - \sum_{l\in\mathcal{L}_i^{ptg}} \widetilde{P_{i,l,k}^{ptg}} - P_{i,k}^{d} - \sum_{j\in\mathcal{J}_i} \widetilde{P_{ij,k}} = 0$$

- DC power flow:

$$\widetilde{\theta_{i,k}} - \widetilde{\theta_{j,k}} = X_{ij}\widetilde{P_{ij,k}}$$

- Capacity:

$$\inf_{\Xi} \Pr\{-P_{ij}^{max} \le \widetilde{P_{ij.k}} \le P_{ij}^{max}\} \ge 1 - \epsilon^{E}$$

Contents

4.1 Challenges in solving this problem

Complicated nonconvexities

- Chance constraints:

$$\inf_{\Xi} \Pr\{-P_{ij}^{max} \leq \widetilde{P_{ij.k}} \leq P_{ij}^{max}\} \geq 1 - \epsilon^{E}$$

Introduced by offshore wind uncertainties

- Joint chance constraints:

$$\inf_{\Xi} \Pr\{WI^{min,N} \leq \widetilde{WI_{i,k}} \leq WI^{max,N}, \widetilde{RD_{i,k}} \leq RD^{max,N}, FS^{min,N} \leq \widetilde{FS_{i,k}} \leq FS^{max,N}\} \geq 1 - \epsilon^{N}$$

Introduced by complex gas security constraints

- Square-root term:

$$WI_{i,k} = \sum_{g \in \mathcal{G}} \chi_{i,k,g} GCV_g \left(RD_{i,k}\right)^{-\frac{1}{2}}$$

- Bilinear term:

$$\widetilde{q_{i,k,g}^{d}} / \sum_{g \in \mathcal{G}} \widetilde{q_{i,k,g}^{d}} = \widetilde{\chi_{i,k,g}}$$

Introduced mainly by gas mixing equations

- Special form of cubic terms

$$\widetilde{p_{i,k}^{2}} - \widetilde{p_{j,k}^{2}} = \gamma_{ij,k} \frac{16 f_{ij} (\rho^{ng})^2 T^{ng} L_{ij} z^{ng}}{\pi^2 D_{ij}^{5}} \widetilde{r_{ij,k} \widetilde{q_{ij,k}^{2}}}$$

Introduced by variant gas compositions

And the combination of them

4.2 Reformulation of nonlinearities

- Linearize the square-root term in gas security constraints and split the joint chance constraints by Bonferroni approximation theory

$$WI_{i,k} = 2GCV_{i,k}\left(\sqrt{RD^{ng}} + RD_{i,k}/\sqrt{RD^{ng}}\right)^{-1}$$

$$\inf_{\Xi} \Pr\{2\sqrt{RD^{ng}} \sum_{g\in\mathcal{G}} \widetilde{\chi_{i,k,g}}\, GCV_g - WI^{min,N} \sum_{g\in\mathcal{G}} \widetilde{\chi_{i,k,g}}\, RD_g \geq WI^{min,N} RD^{ng}\} \geq 1 - \epsilon^G / N^{jc}$$

- Linearize bilinear terms using Taylor approximation, and further drive the relaxation tight in following solution procedures:

$$\widehat{x^T J x} + \nabla\left(x^T J x\right)\left(x - \hat{x}\right) + K^T x + L = 0$$

4.3 Reformulation of chance constraints

- Single side chance constraints

$$\inf_{\Xi} \Pr\{\boldsymbol{A}^{\boldsymbol{T}}(\boldsymbol{x})\boldsymbol{\xi} + \boldsymbol{B}(\boldsymbol{x}) \leq \boldsymbol{C}\} \geq 1 - \epsilon$$

$$A^T(x)\mu + B(x) + \left((1-\epsilon)/\epsilon\right)^{\frac{1}{2}} \left\| \sigma^{\frac{1}{2}} A(x) \right\|_2 \leq C$$

Deterministic second-order cone constraints

- Double side chance constraints:

$$\inf_{\Xi} \Pr\{\left|\boldsymbol{A}^{\boldsymbol{T}}(\boldsymbol{x})\boldsymbol{\xi} + \boldsymbol{B}(\boldsymbol{x})\right| \leq \boldsymbol{C}\} \geq 1 - \epsilon$$

Introducing two ancillary variables

$$u^2 + \left(\left\| \sigma^{\frac{1}{2}} A(x) \right\|_2\right)^2 \leq (C - v)^2 \epsilon$$
$$|B(x)| \leq u + v,\ u \geq 0,\ 0 \leq v \leq C$$

Deterministic second-order cone constraints

4.4 Unified affine mapping

Generally, uncertain variables can be written as adjustments based on forecast errors of offshore wind farm

$$\tilde{x} = x_{i,k} + \varphi^{x}(1^{T}\xi)$$

Substituting it into original linear/nonlinear constraints will produce additional constraints:

- For linear constraints:

$$D^{T}x = E,\ D^{T}\varphi = 0$$

- For bilinear constraints:

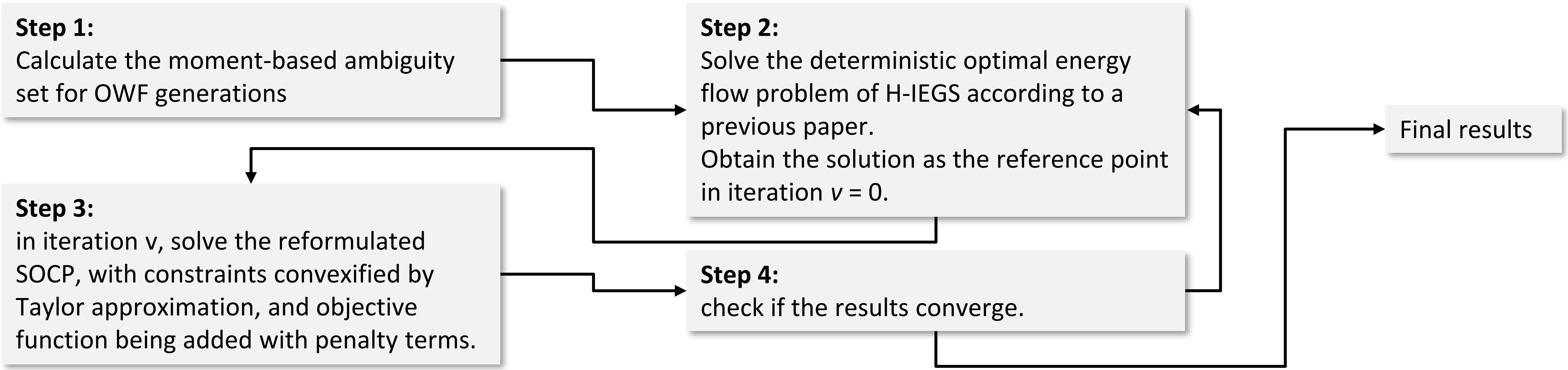
$$x^{T}Fx + G^{T}x + H = 0$$
$$2x^{T}F\varphi + G^{T}\varphi = 0,\ \varphi^{T}F\varphi = 0$$

- For cubic terms in Weymouth equation:

$$\widetilde{p_i^2} - \widetilde{p_j^2} \geq \Theta_{ij}\left(\widehat{r_{ij}\widetilde{q_{ij}^2}} + \widetilde{r_{ij}\widehat{q_{ij}^2}} - \widehat{r_{ij}\widehat{q_{ij}^2}}\right)$$
$$\widetilde{p_i^2} - \widetilde{p_j^2} \leq \Theta_{ij}\left(\widetilde{r_{ij}\widehat{q_{ij}^2}} + 2r_{ij}\widehat{\widehat{q_{ij}\widetilde{q_{ij}}}} - 2\widehat{r_{ij}\widehat{q_{ij}^2}}\right) + \varepsilon_{ij}, \varepsilon_{ij} \geq 0$$

4.5 DRCC-SCP procedures

- After reformulation, a second-order cone programming problem
- Sequential convex programming is used to gradually drive the relaxation tight and converge to the optimum of the DRCC problem



Contents

5.1 Case information

Ireland offshore wind

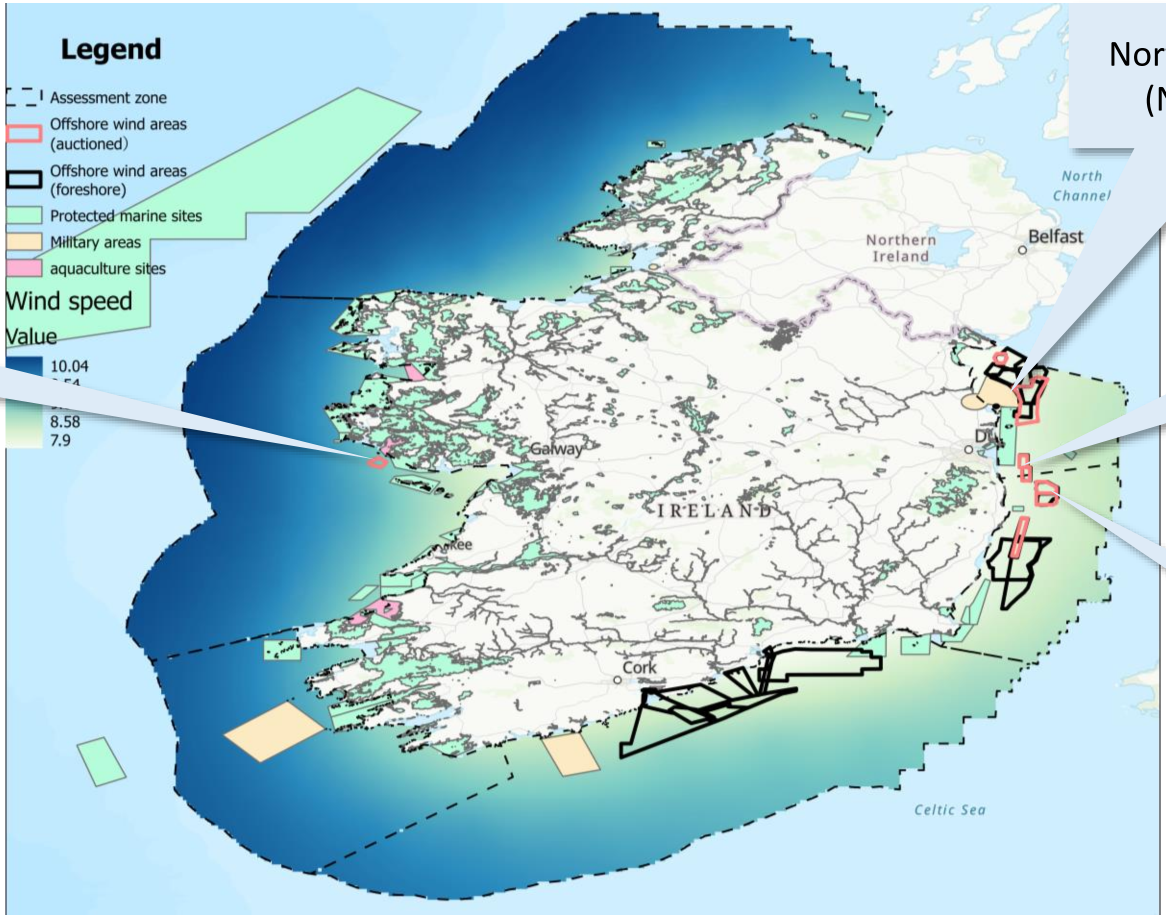
ORESS1 auction:

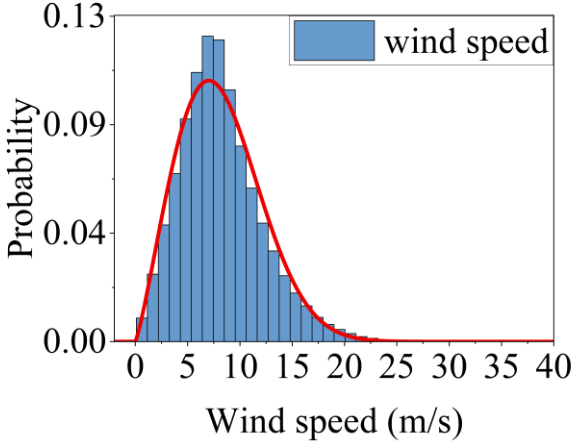
Sceirde Rocks Offshore Wind Farm 450 MW

North Irish Sea Array (NISA): 500 MW

Dublin Array 824 MW

Codling Wind Park: 1300MW





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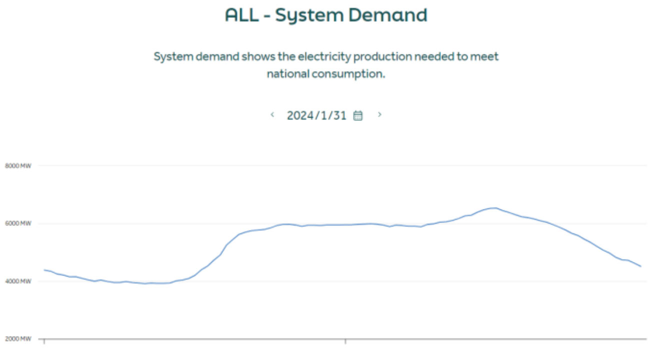
5.1 Case information

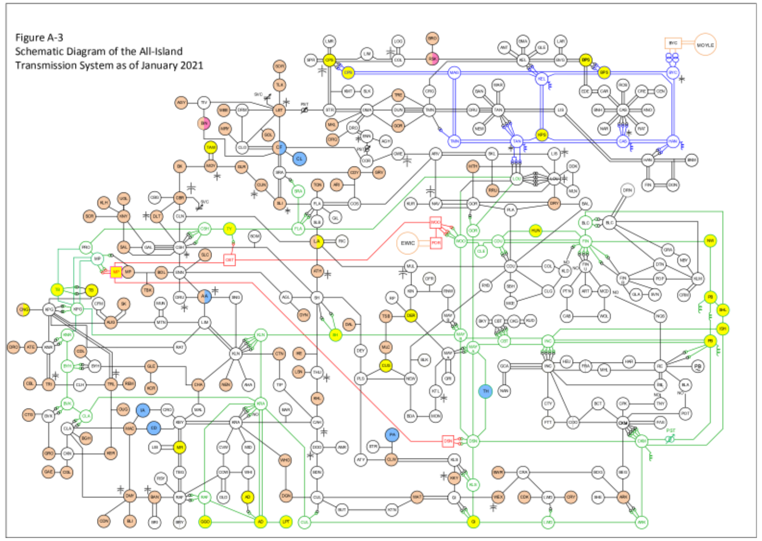
Ireland electricity system

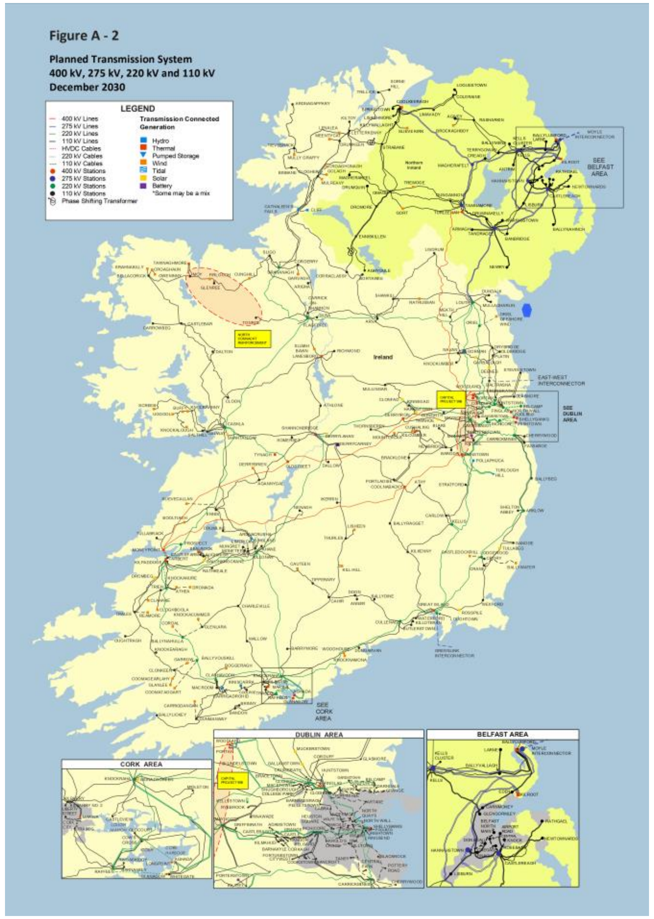
- 1192 buses,
- 1369 branches,
- 140 generators, 19.55 GW
- Max load around 6.5 GW

Load curve



Schematic Diagram of the All-Island



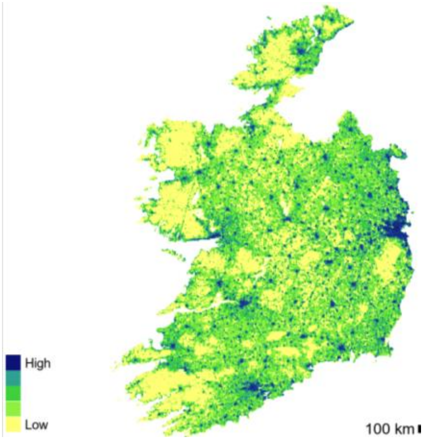


* *All-Island Ten-Year Transmission Forecast Statement 2021*

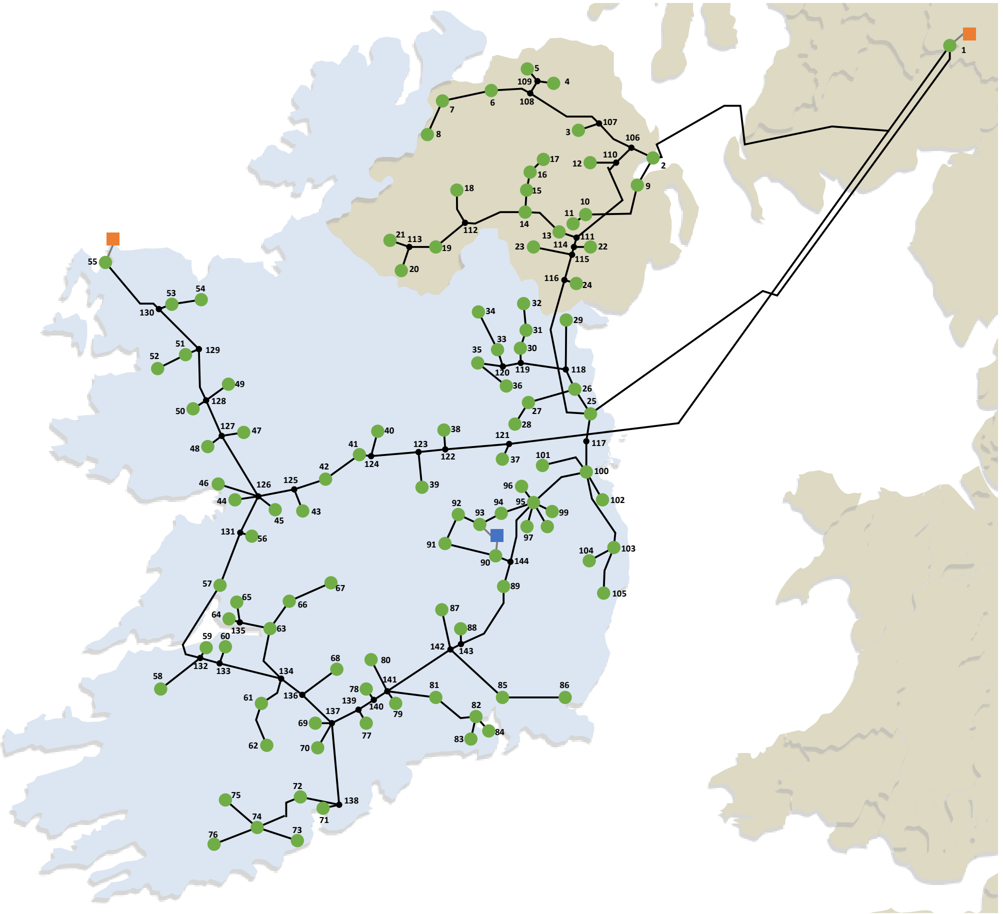
5 Case information

Ireland's gas system

- 144 buses
- 144 pipelines
- with a total gas supply capacity of 41.21 Mm^3/day



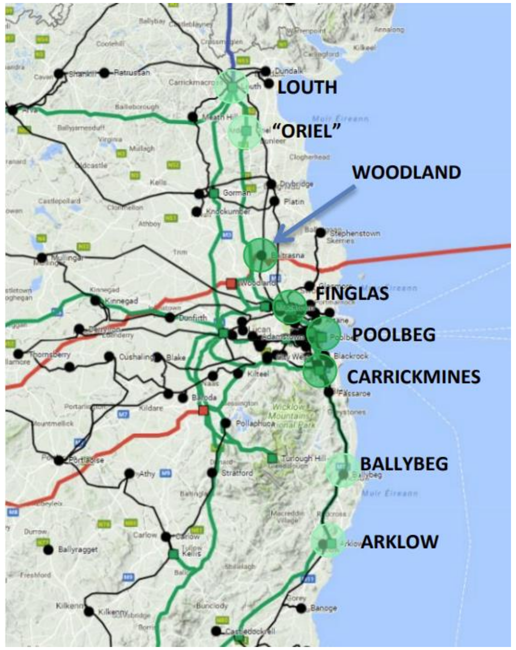
Estimate the nodal gas demand by population density



* https://www.gasnetworks.ie/docs/corporate/gas-regulation/GNI-2020-Network-Development-Plan.pdf

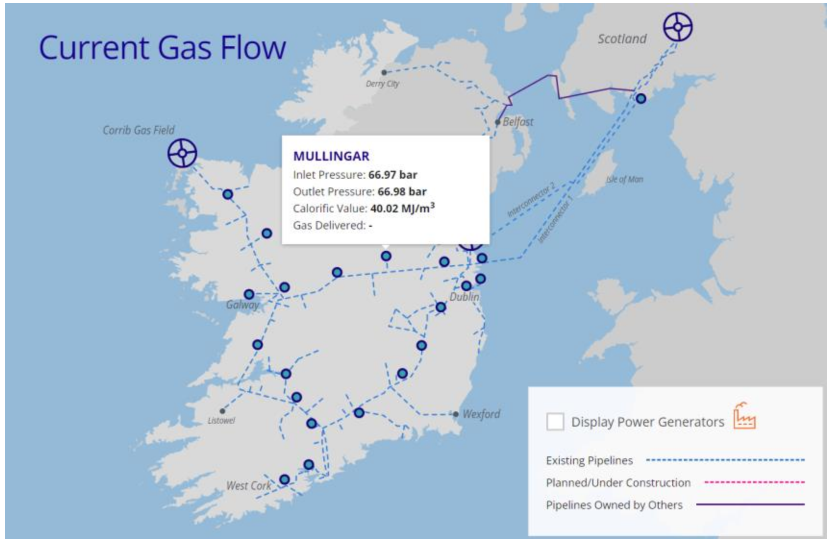
5 Case information

Offshore wind interconnection to electricity system



Offshore wind and gas-fired power plant interconnection to gas system

- Find the locations
- Find the nearest gas bus
- Use the map from GNI as the reference



* https://www.eirgridgroup.com/site-files/library/EirGrid/East-Coast-Generation-Opportunity-Assessment.pdf

5.1 Validation of proposed SCP-DRCC

Convergence and computation speed of SCP

Method 1: our method (SCP)

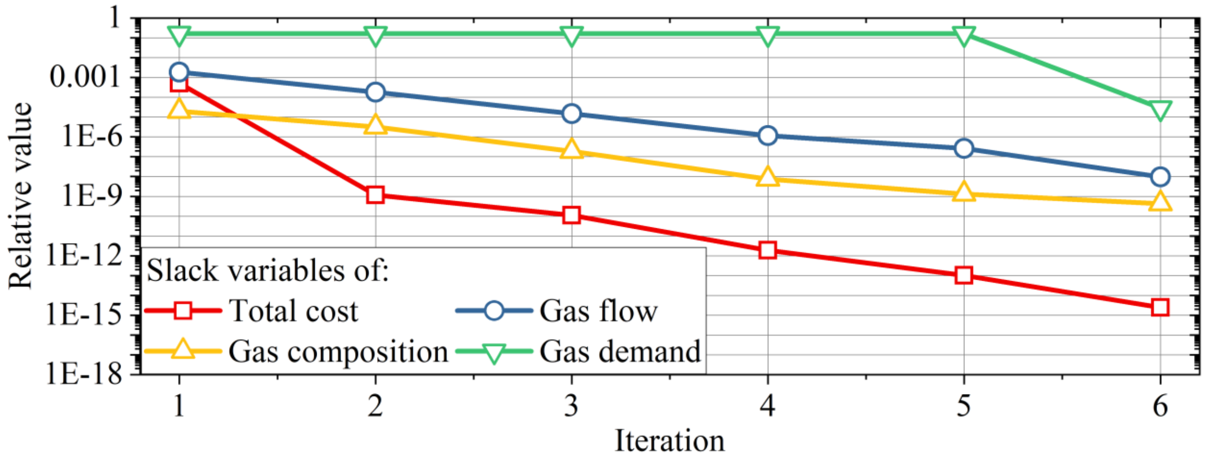
Method 2: dynamic outer approximation used in the latest Gurobi

Method 3: IPOPT

- computation time saved by 76.14% and 99.85%
- Accuracies are similar

Comparisons of different solution methods

Method	Method 1	Method 2	Method 3
Computation time (s)	0.9024	3.782	620.4
Objective function (€)	233527.87	233527.98	233527.86
Max relative differences	2.97×10^{-3}	1.49×10^{-3}	/



Convergence of SCP-DRCC

5.1 Validation of proposed SCP-DRCC

Uncertainty handling of DRCC

Method 4: our method (DRCC)
Method 5: perfect information, deterministic solution
Method 6: Robust optimization with ±σ uncertainty budget

Comparison of different uncertainty handling methods

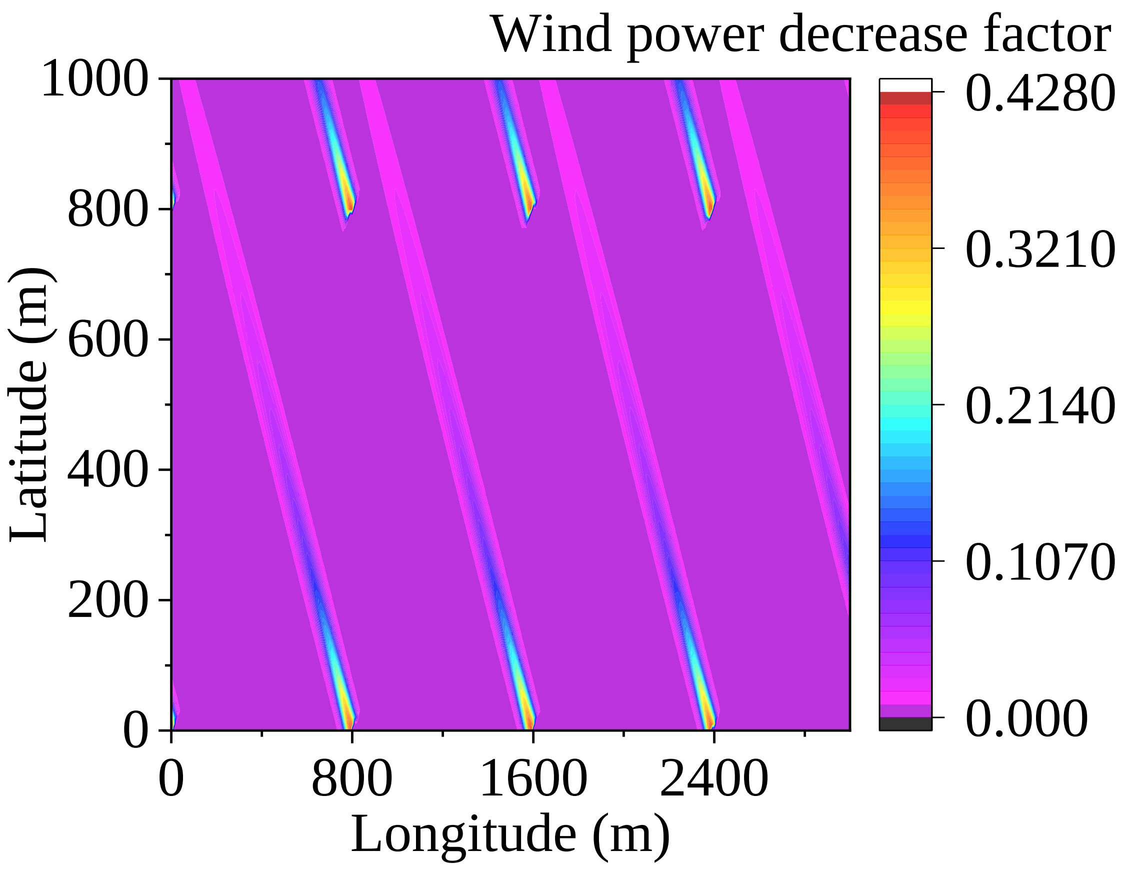
Method	Method 4	Method 5	Method 6
Total cost (€)	285791	281338	295053
Electricity system cost (€)	51917	56356	41287
Gas system cost (€)	233873	224982	253766
Electricity consumption of PTG (MW)	71.60	413.83	0
Hydrogen production of PTGs (Mm^3/day)	0.4896	2.3588	0
Gas production of gas sources (Mm^3/day)	26.88	25.87	29.14

- our method achieves the best balance between cost and conservativeness.
- Compared to the lowest cost in Method 5, the cost in Method 4 increases slightly by 1.58%
- Method 6 is more conservative. Its cost is 5.93% higher than in method 5, and the hydrogen production is zero. Therefore, it is not an appropriate operating strategy for energy system decarbonization.

5.2 Integration of offshore wind

Wake effect

- When the distance between wind turbines is 800m, the wake effect is around 5% when the wind is at certain angles.
- the impact is sparse.
- Our recursive-tree-based method can save the scenario required for the calculation from 1.5×10^8 to 2524.

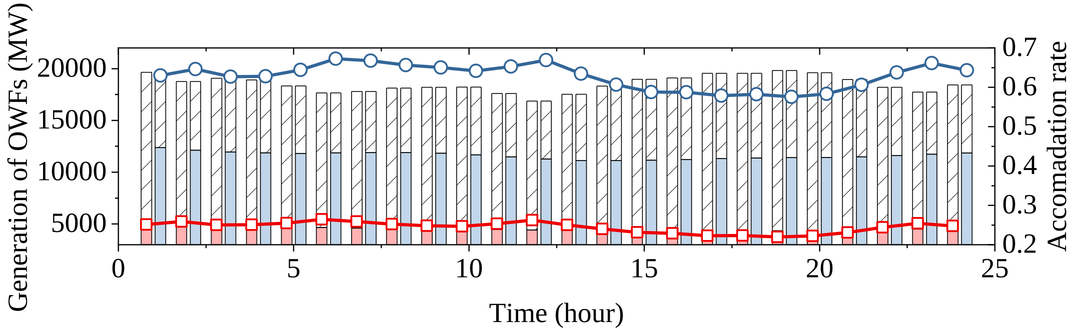


5.2 Integration of offshore wind

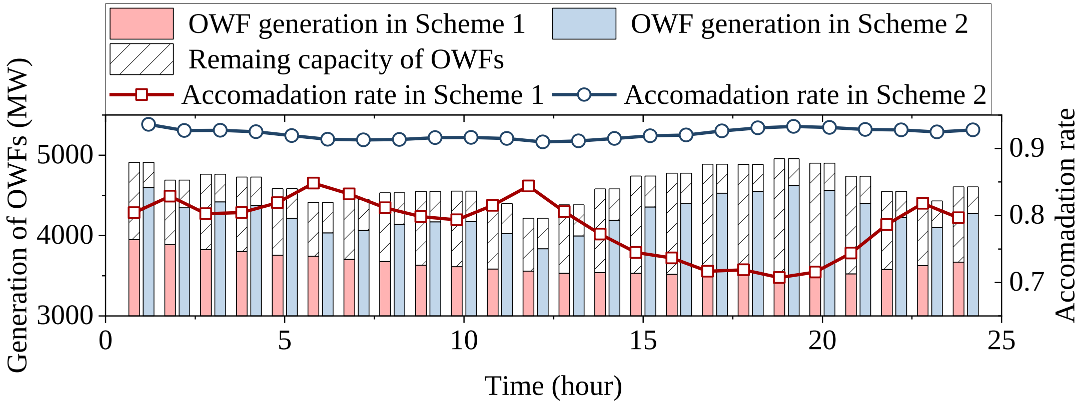
Typical daily operation and offshore accommodation

Three offshore wind scenarios:
Scenario 1: 2030, 5GW
Scenario 2: 2040, 20 GW
Scenario 3: 2050, 37 GW

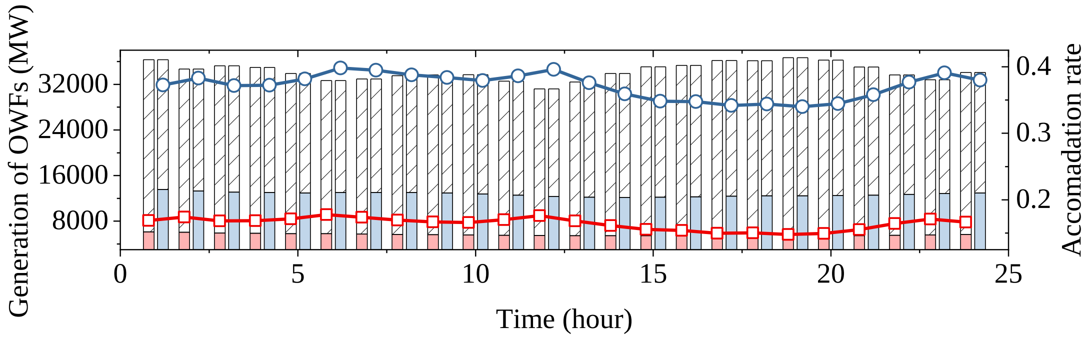
Two integration schemes:
Scheme 1: electricity system flexibility only
Scheme 2: hydrogen blending flexibility



2040 (b)



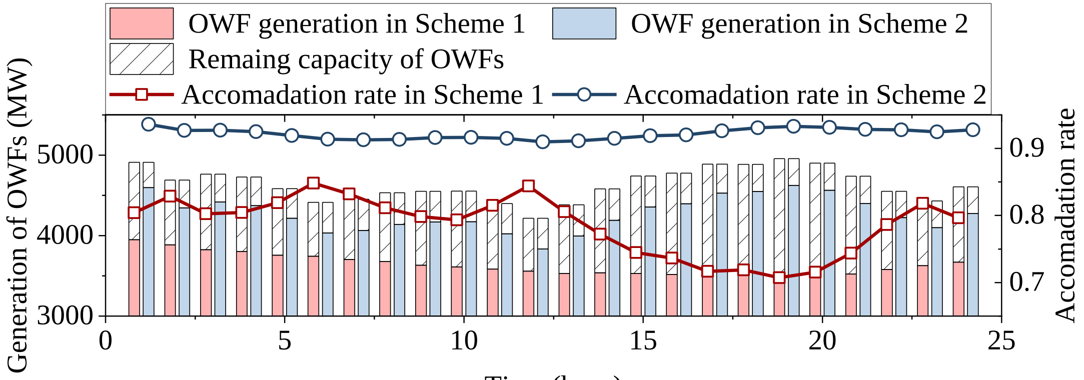
2030 (a)



2050 (c)

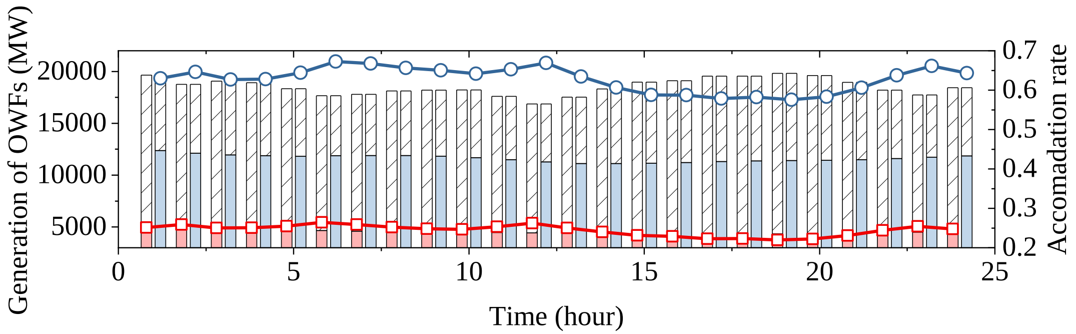
5.2 Integration of offshore wind

- Scheme 2 can significantly promote the accommodation rate.
- In 2040 and 2050, this trend becomes more obvious.
- the electricity system flexibility can be considered sufficient in accommodating the offshore goal of Ireland in 2030, but when the OWF capacity continues to grow in the long term, new technologies (such as hydrogen blending) are required.

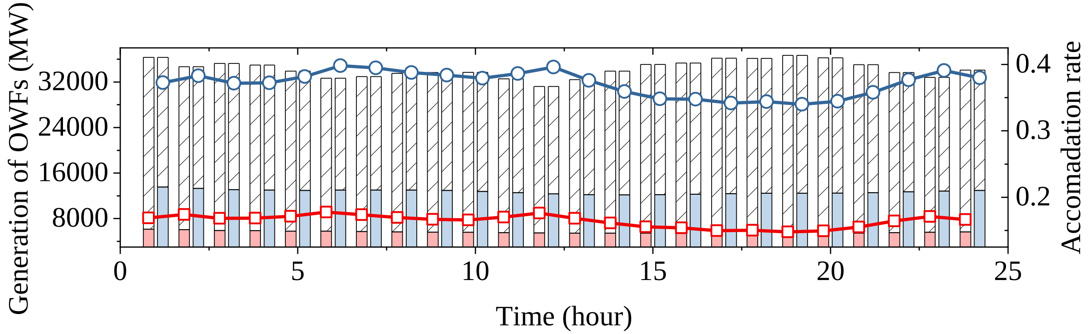


2030 (a)

- accommodation rates in Scheme 2 are also decreasing in 2050. require new integration methods.



2040 (b)

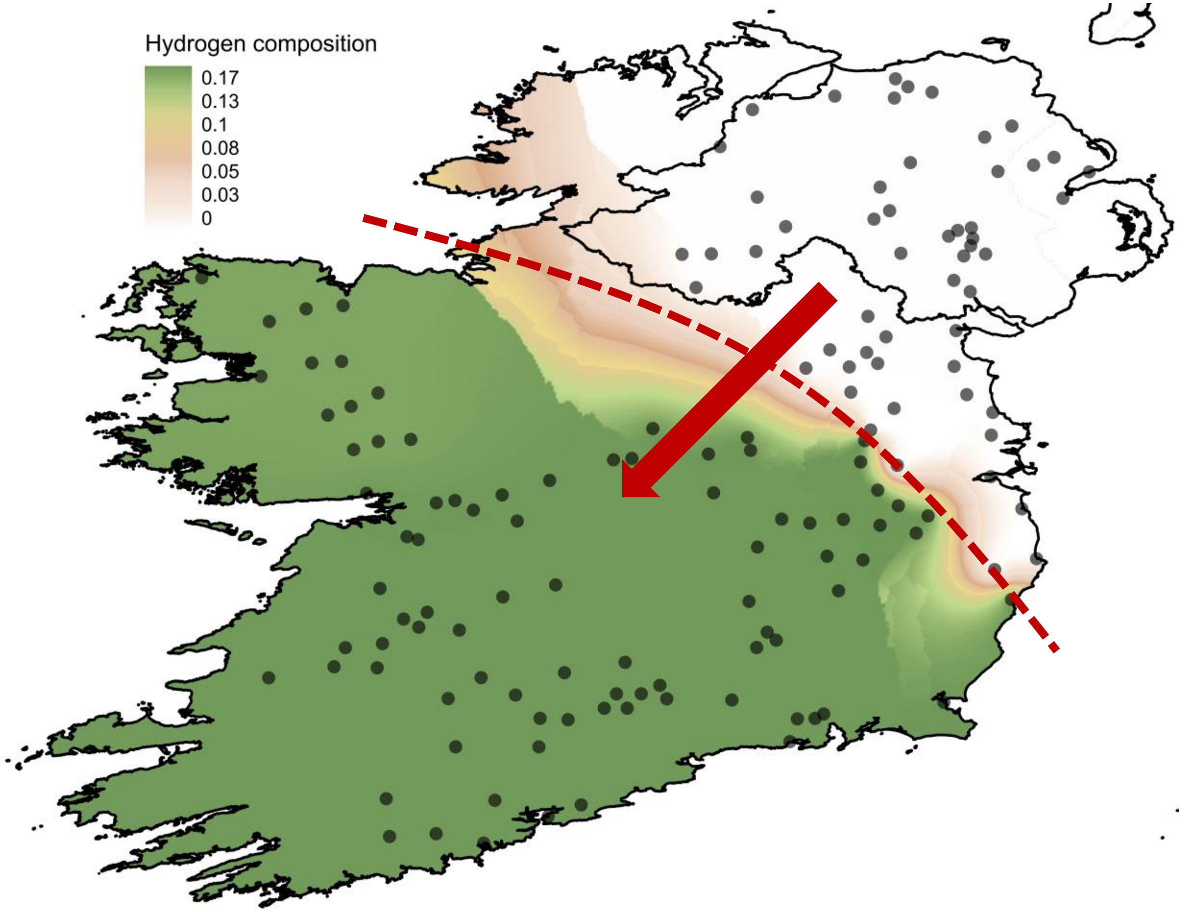


2050 (c)

5.2 Integration of offshore wind

Molar fraction of hydrogen

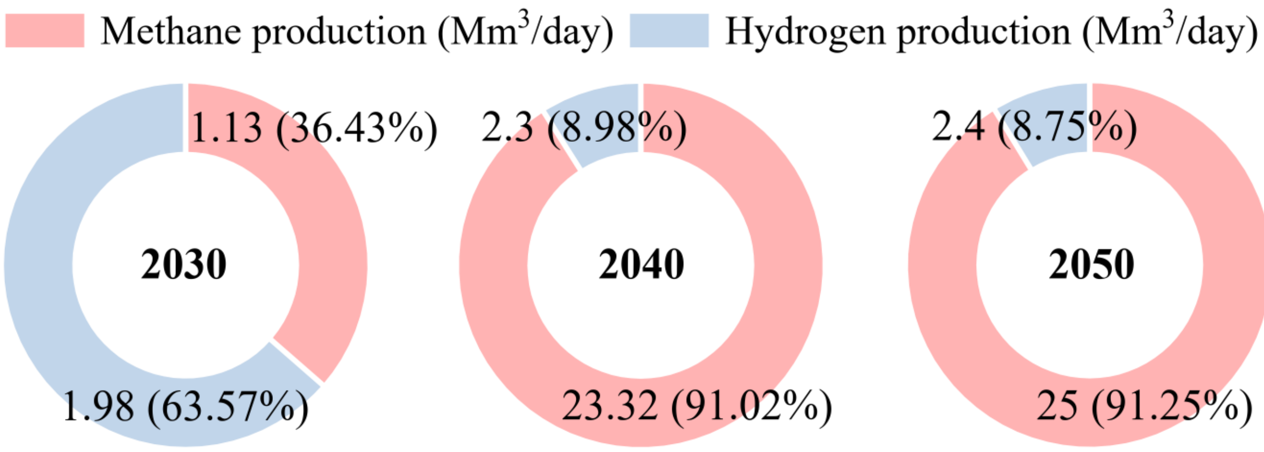
- a clear line that separates the high and low hydrogen concentration areas.
- In the northeast areas is upstream of the gas network with no offshore wind, and therefore the hydrogen is not blended.
- Since the hydrogen is blended in west Ireland from the Atlantic Ocean, east Dublin Bay, and South coastal areas, the hydrogen concentrations in southwest Ireland are relatively higher and reach their maximum possible value of 15.84% (constrained by gas security limits).
- although OWFs are interconnected to the Dublin area, due to the high load density, their electricity generations are consumed directly by electricity demand rather than converting into hydrogen, so the hydrogen concentration in the Dublin area is still low.



5.2 Integration of offshore wind

PTG gas production

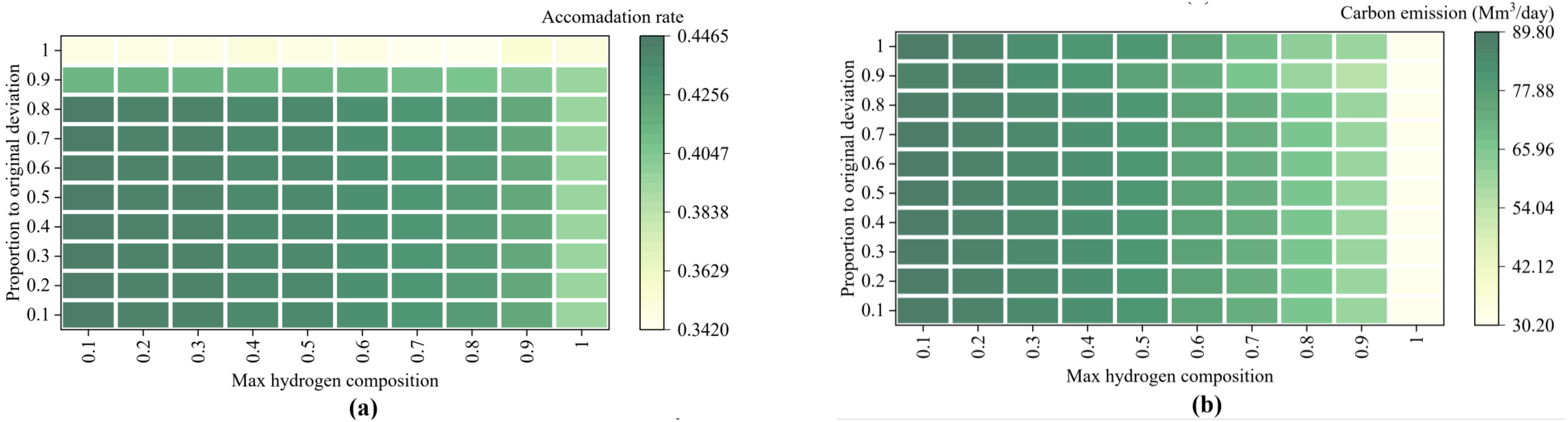
- in 2030, most of the surplus offshore wind generation is used to produce hydrogen.
- in 2040 and 2050 with the further increase in OWF capacity, the proportions of hydrogen production are reduced significantly to only 9%. This is mainly because due to the gas security limits, the gas network is **no longer able to absorb more hydrogen**.
- This kind of decrease in hydrogen injection will lead to extra energy loss during the methanation process and higher carbon content in the gas network, and therefore is not beneficial for overall energy efficiency and decarbonization.



5.3 Sensitivity analysis

If the accommodation rate can be higher in the long term?

Two technical advancement pathways:
Pathway 1: more accurate wind forecast
Pathway 2: higher tolerance for hydrogen

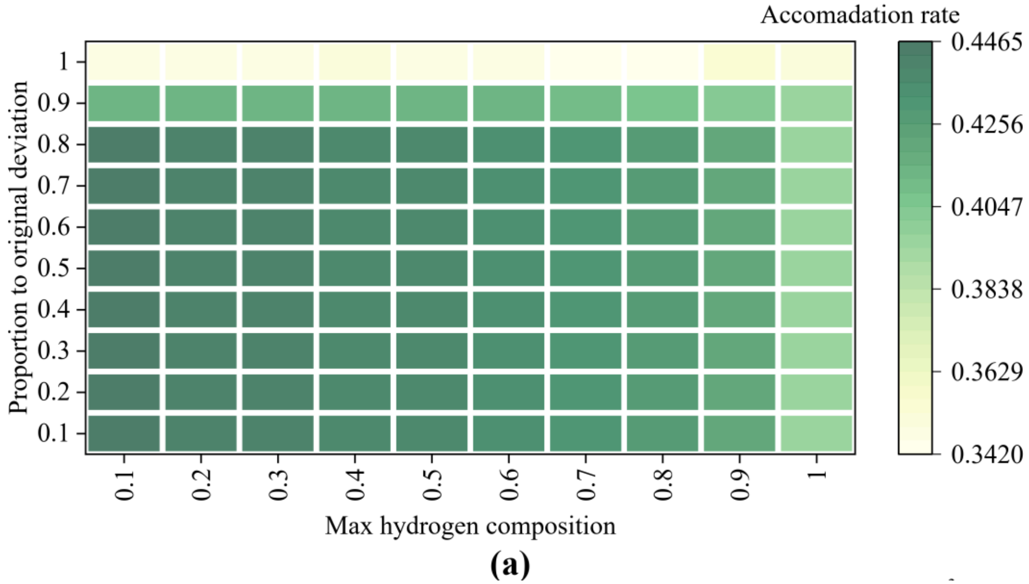


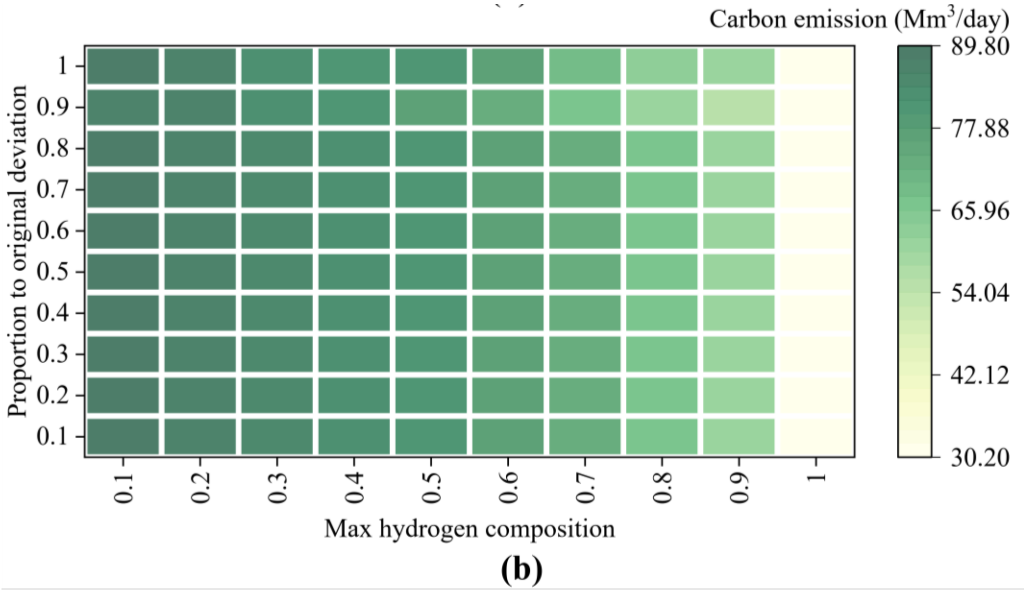
Sensitivity analysis: (a) accommodation rate; (b) carbon emission.

5.3 Sensitivity analysis

- The accommodation rate increases with the increase in wind prediction precision.
- The positive impact of Pathway 1 has an upper limit even if the prediction precision increases to 100%.

- the advancement in Pathway 1 does not have significant impacts on reducing the system's carbon dioxide emissions.



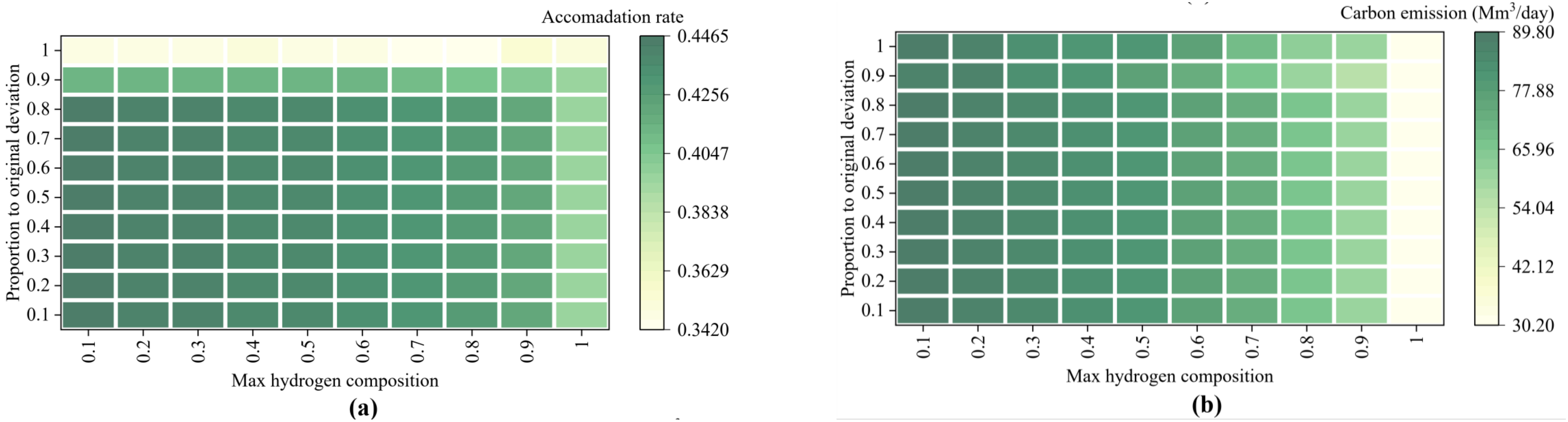


Sensitivity analysis: (a) accommodation rate; (b) carbon emission.

5.3 Sensitivity analysis

- interestingly, the offshore wind accommodation rate will decrease slightly with the advancement in Pathway 2
- Because the bottleneck lies in the gas network capacity (and total gas demand)

- Nonetheless, the system operating cost has been reduced from 269441 to 247376 €/hour
- the carbon dioxide emission has also reduced significantly by 64.44%.



Sensitivity analysis: (a) accommodation rate; (b) carbon emission.

Contents

6.1 Conclusions

- Power system flexibility is enough for short-term (5GW), but not enough for mid/long term.
- New sources of flexibility (including gas network, and hydrogen blending) are critical in the mid/long term.
- With technical advancement in the future, the carbon emission and accommodation rate can be significantly improved, but have limits.
- To break this bottleneck, alternative measures, such as enhancing power/gas system transmission capacities, cross-border renewable electricity/gas trading (more recommended)… are essential.

6.2 Further discussions

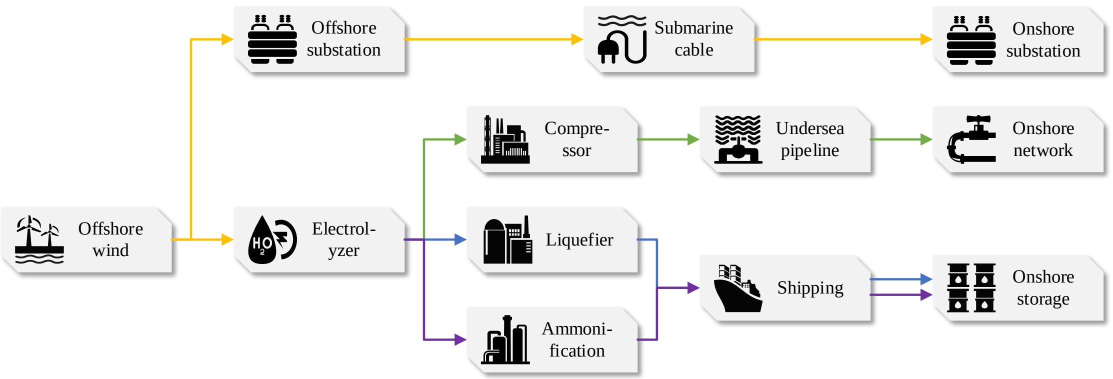
Limitations of this work:

- Implemented in the operation stage (one stage), while only considering the constraints by network structure, not other factors the generator flexibility (ramping), frequency regulation requirements, etc.
- Limited to pipeline hydrogen transportation only, while neglecting shipping, tube trailer, direct use, and other options.
- Limited to domestic energy consumption only.

6.3 Next step work

Reshaping energy structure in Europe: Carbon mitigation potential of hydrogen production export from offshore wind in Ireland

- Map the levelized cost of offshore wind electricity/hydrogen/ammonia by HVDC, pipeline, and shipping
- Evaluate the domestic consumption potential of these electricity/chemical products
- Calculate the receiving potential of the wider sector (power, industry, marine…) in nearby countries (the UK, and mainland Europe)
- Evaluate the carbon mitigation potential in Ireland and its wider impacts on Europe



Thank you!

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