# Flow-based nodal cost-allocation in a heterogeneous highly renewable European electricity network

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# Network- and infrastructure-modelling

| General modelling | |
|---|---|
| Renewable generation makeup | $G_n^R(t) = G_n^W(t) + G_n^S(t)$ |
| Renewable penetration | $\langle G_n^R \rangle = \gamma_n \langle L_n \rangle$ |
| Wind-solar mix | $\langle G_n^W \rangle = \alpha_n \langle G_n^R \rangle$<br>$\langle G_n^S \rangle = (1-\alpha_n) \langle G_n^R \rangle$ |
| Renewable mismatch | $\Delta_n(t) = G_n^R(t) - L_n(t)$ |
| Nodal balancing | $G_n^R(t) - L_n(t) = B_n(t) + P_n(t)$ |
| Synchronized balancing | $B_n(t) = \frac{\langle L_n \rangle}{\Sigma_K \langle L_k \rangle} \sum_m \Delta_m(t)$ |
| Flows on links | $F_l = \sum_n H_{ln} P_n(t)$ |

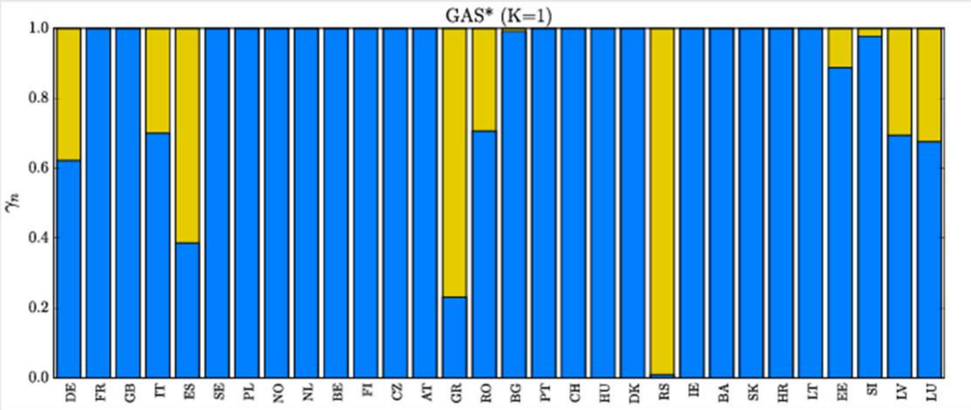
| Infrastructure modelling | |
|---|---|
| Nodal backup energy | $E_n^B = \langle G_n^B \rangle$ |
| Backup capacity | $0{,}99 = \int_0^{\varkappa_n^B} dG_n^B p_n(G_n^B)$ |
| Transmission capacity | $0{,}99 = \int_{-\varkappa_l^T}^{\varkappa_l^T} dF_l p_l(F_l)$ |
| Total transmission capacity | $\varkappa^T = \sum_l d_l \varkappa_l^T$ |
| Wind capacity | $\varkappa_n^W = \frac{\alpha_n \gamma_n \langle L_n \rangle}{CF_n^W}$ |
| Solar capacity | $\varkappa_n^S = \frac{(1-\alpha_n)\gamma_n \langle L_n \rangle}{CF_n^S}$ |

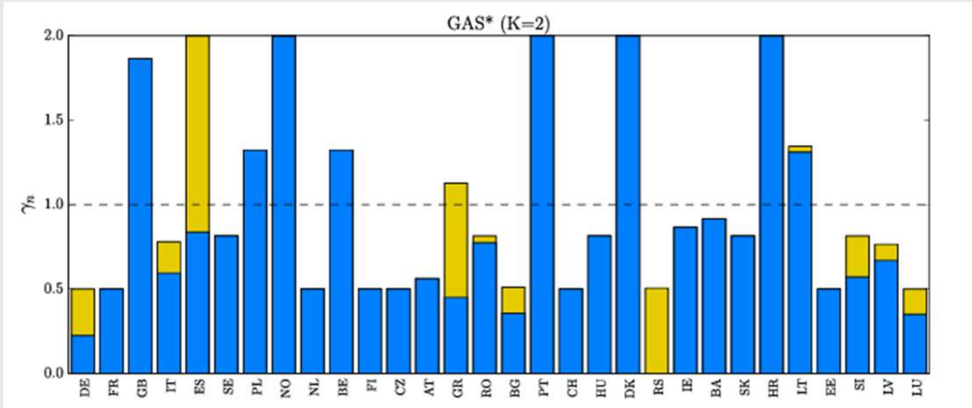
# Cost modelling

| Cost modelling | |
|---|---|
| Present value of investment, Generation capacity | $V = \text{CapEx} + \sum_{t=1}^{T_{life}} \frac{\text{OpEx}_\text{t}}{(1+r)^t}$ |
| Present value of investment, Transmission | $V_l^T = \varkappa_l^T d_l c_l$ |
| Total present value of transmission system | $V^T = \sum_l V_l^T + N_{HVDC} \cdot 150.000€$ |
| System costs | $LCOE_V = \frac{V}{\sum_{t=1}^{T_{life}} \frac{L_{EU,t}}{(1+r)^t}}$ <br> $LCOE_{EU} = \sum_V LCOE_V$ |

# Heterogenity and flow tracing

$$\frac{1}{K} \leq \gamma_n \leq K$$




Flow tracing algorithm:

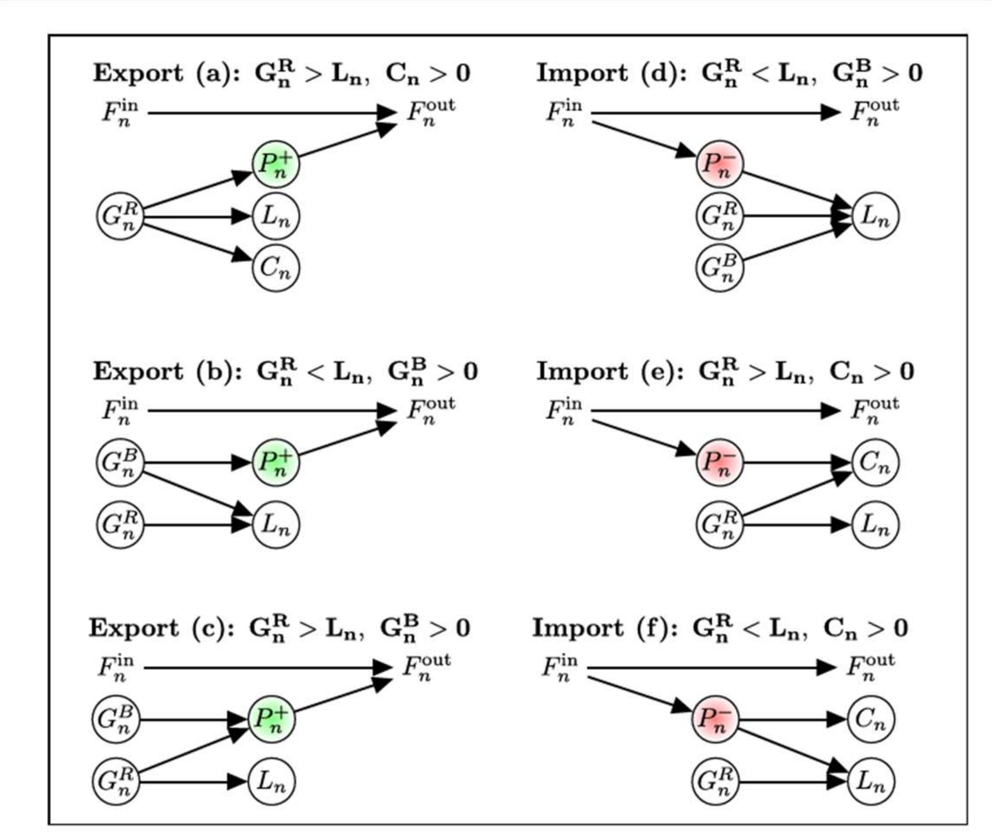
$$\delta_{n,m} \cdot q^{in}_{(n,\mu)} P^+_n + \sum_k q_{k\to n(m,\mu)} \cdot F_{k\to n} = \boldsymbol{q^{out}_{n,(m,\mu)} P^-_n} + \sum_k q_{n\to k(m,\mu)} \cdot F_{n\to k} \qquad ; \mu = \{W, S, B, T\}$$

The **average export transfer function** is found from the resulting out-partitions when applying the alorithm to every injection pattern:

$$\mathcal{E}^{\mu}_{m\to n} = \left\langle\, \boldsymbol{q^{out}_{n,(m,\mu)} P^-_n} \,\right\rangle$$

# Flow tracing continued

Six nodal electricity partition cases are used:




**A node will prefer to use its own renewable energy generation to cover its own load** and then to export the more expensive backup energy power generation to the network. Curtailment and and backup power is distributed relative to the average load.

A measure that describes the generation capacity of a type $\mu \in \{W, S, B\}$ located at $m$ used b $n$ is defined:

$$\varkappa_{m\to n}^{\mu} = \begin{cases} \left[\dfrac{\mathcal{E}_{m\to n}^{\mu}}{\langle G_m^{\mu}\rangle - \langle C_m^{\mu}\rangle}\right] \kappa_m^{\mu} & \text{if } m \neq n \\ \kappa_m^{\mu} - \displaystyle\sum_{s\neq m} \kappa_{m\to s}^{\mu} & \text{if } m = n \end{cases}$$

# Nodal cost allocation

| **Nodal cost modelling** | |
|---|---|
| Nodal LCOE | $$LCOE_{EU} = \sum_n \frac{\langle L_n \rangle}{\langle L_{EU} \rangle} LCOE_n$$ |
| Nodal present values of investment | $\{V_W, V_S, V_B, V_T\} \Longrightarrow \{V_{W,n}, V_{S,n}, V_{B,n}, V_{T,n}\}$ |
| Installked capacity at node including exports | $$\kappa_n^\mu = \kappa_{n\to n}^\mu + \sum_{m\neq n} \kappa_{n\to m}^\mu$$ |
| Total capacity used by node including imports | $$\tilde{\kappa}_n^\mu = \kappa_{n\to n}^\mu + \sum_{m\neq n} \kappa_{m\to n}^\mu$$ |

Allocation of transmission capacity costs $V_n^T$ can be allocated by two different schemes.

**Average load of country:**

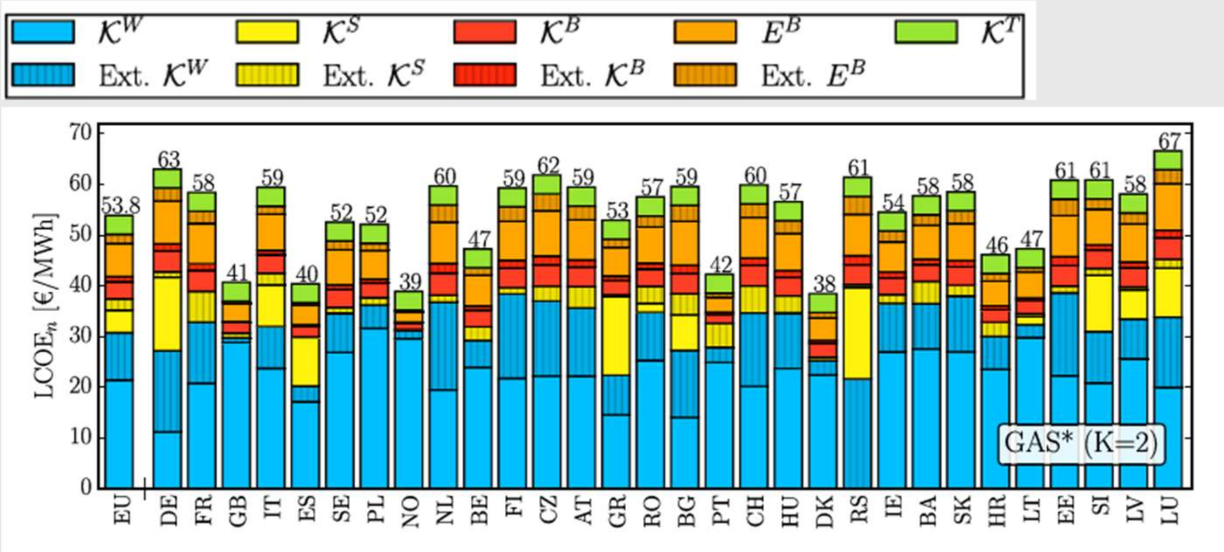
$$V_n^T = \frac{\langle L_n \rangle}{\langle L_{EU} \rangle} V^T$$

**Flow based transmisson infrastructure cost allocation:**

$$V_n^T = \sum_l \kappa_{l,n}^T \; d_l c_l$$

Based on capacity usage measure that indicates how much of a transmission-line's capacity is allocated to node $n$

# Results



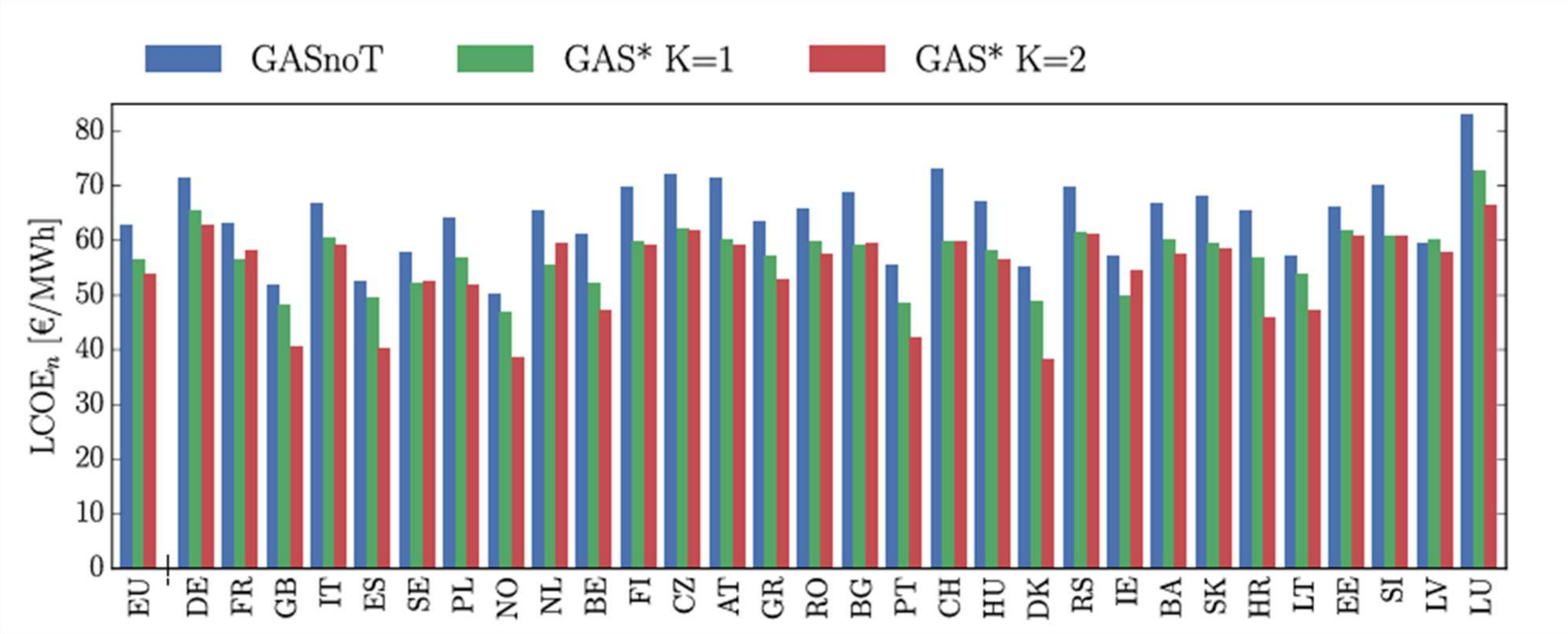

As $\frac{1}{K} \leq \gamma_n \leq K$ increases the savings grow **dispproporionately favouring net exporters**. It is therefore of interest to allocate transmission capacity costs based on capacity usage.

| Heterogeneity constraint | $LCOE_{EU}$ | WSD | WSD for import/export: | | |
|---|---|---|---|---|---|
| | | | 100/0 | 50/50 | 0/100 |
| $K = 1$ (no trans.) | 63.0 | 7.27 | | | |
| $K = 1$ | 56.6 | 5.38 | 5.28 | 5.22 | 5.17 |
| $K = 2$ | 53.8 | 8.54 | 10.22 | 6.72 | 3.83 |

**Weighted standard deviation (WSD):**

$$WSD = \sqrt{\sum_{n=1}^{N} \frac{\langle L_n \rangle}{\langle L_{EU} \rangle} (LCOE_n - LCOE_{EU})^2}$$

# Results continued




For **almost** all nodes: $LCOE_n^{K=1,noT} > LCOE_n^{K=1,T} > LCOE_n^{K=2,T}$

*Even when transmission infrastruce capacity costs are distributed mainly to net exporters these remain the primary benificiaries!*