Locational Signals in Capacity Markets

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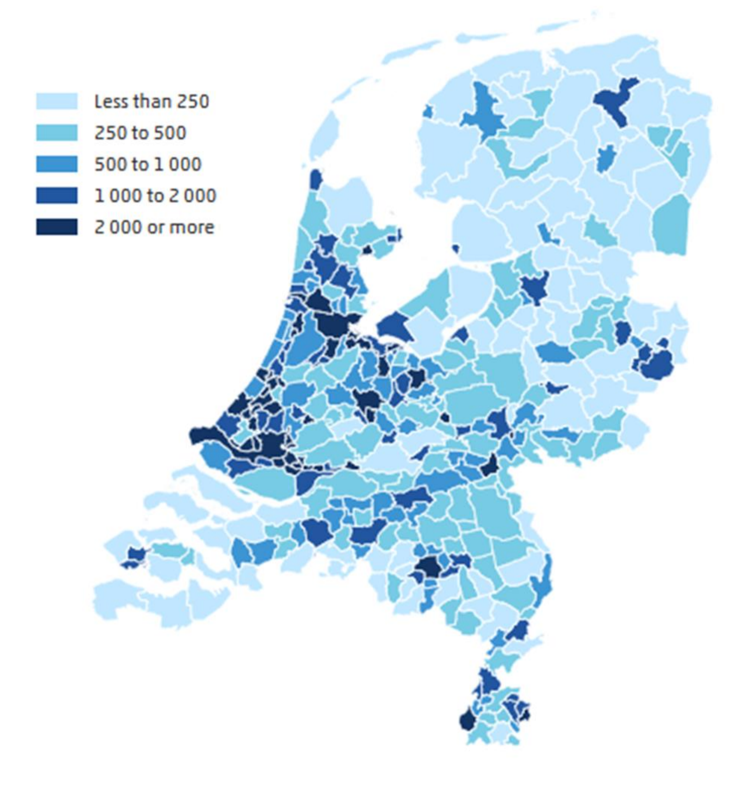
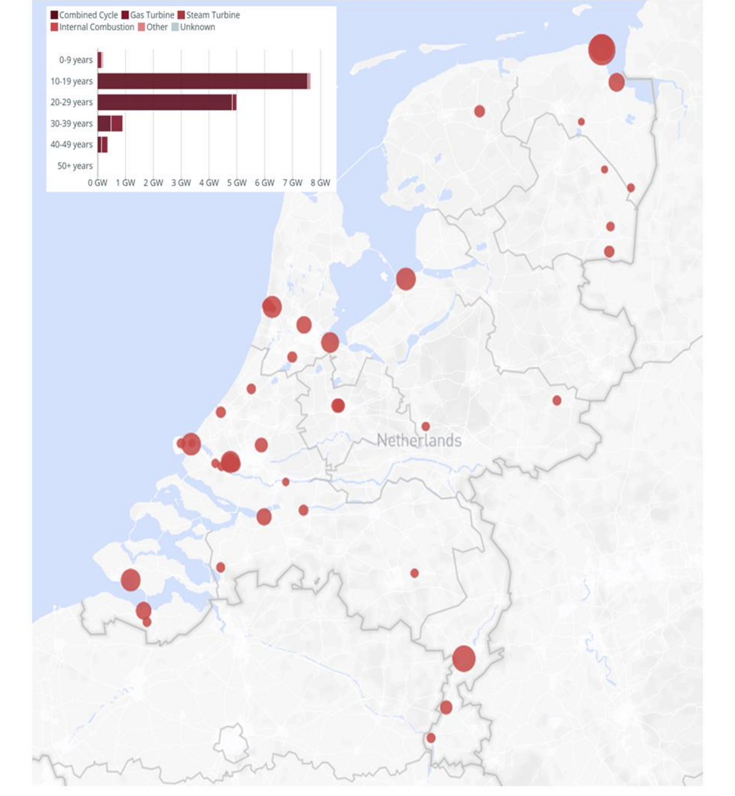
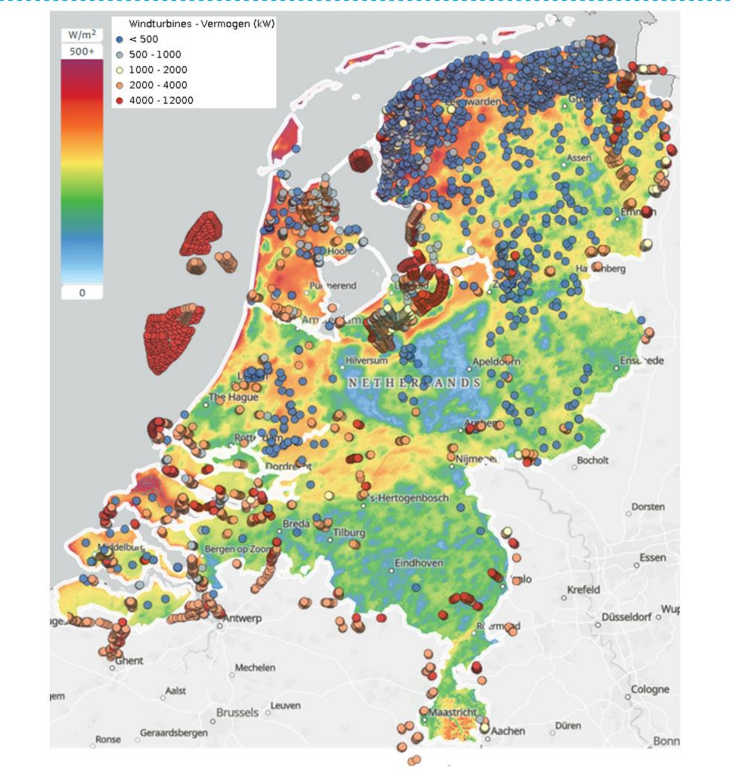


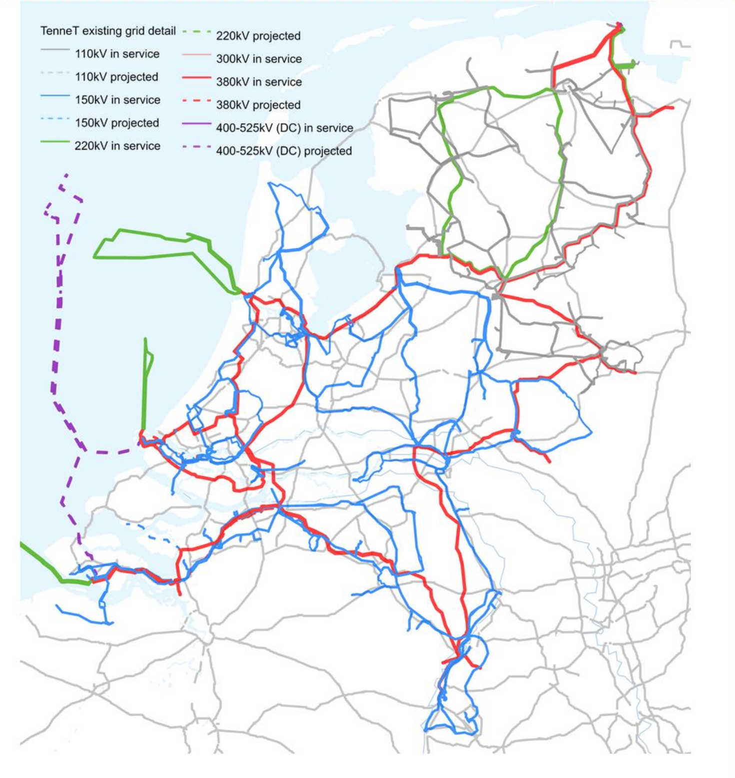
i) Population density of The Netherlands, residents per km² [3]



ii) Operational oil and gas power plants in The Netherlands [4]



iii) Operational wind power turbines in The Netherlands, overlaid on a map of wind power potential [5,6]



iv) Existing and planned high voltage transmission network of The Netherlands [7]

Capacity Market Design

Liberalised electricity markets have been identified as providing insufficient generation investment incentives. Market actors reliant on scarcity pricing alone struggle to guarantee long-term cost reimbursement [1,2]. Capacity markets are increasingly accepted as the key mechanism for ensuring long-term revenue stability, while also enabling risk sharing between generators and consumers. This PhD will examine remaining capacity market design questions such as locational signals, consumer integration, and energy-limited resources. The goal is to improve system resource adequacy and consumer affordability.

Locational Investment Needs

Prior to market liberalization, thermal generation resources were often constructed near high demand locations (*figs. i, ii*). In current EOM designs in Europe, there are no market-based incentives to locate in optimal sites. Most recent investments have been in peak renewable potential zones far from demand (*fig. iii*), resulting in growing grid congestion for many countries. If investors were guided towards locations with better network access (*fig. iv*) through locational investment signals in capacity markets, this problem could potentially be avoided. Additionally, if investments are incentivised towards areas with greater network availability during scarcity periods, system resource adequacy could be improved [8]. One drawback identified for capacity market designs with locational signals is the potential for market power exertion [9]. Large firms with greatest ability to exert this power often own resources in multiple areas, enabling internal spatial risk hedging. Literature examining how locational signals in capacity markets impact these portfolio companies is narrow.

Research Questions

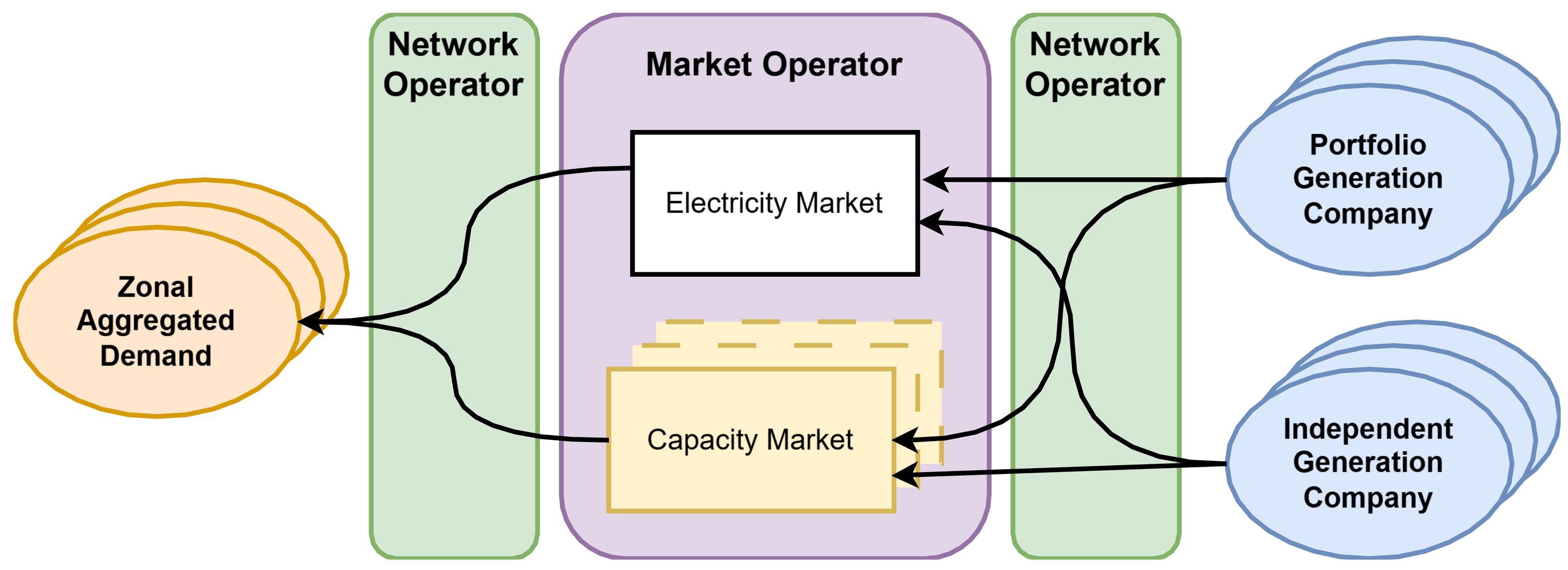
1. What are the system impacts of different locational signals? *(Resource adequacy, social welfare, investment levels, redispatch requirements, CO2 emissions, …)*
2. How do these signals impact the investment decisions of portfolio generation companies, in comparison to independent generators?
3. To what extend do market power opportunities increase for different signal types?

Methodology

An abstract system model is created to examine the impacts of each of the following capacity market locational signals independently:

Single Capacity Zone	Multiple Capacity Zones	Conditional Capacity Zones	Locational Bid Adjustments
Belgium, Portugal	*Italy*	*PJM (USA)*	*Ireland, Mexico*

Within each model, an individual optimisation problem is created for each market actor in the system, consisting of their feasibility constraints and objective function (if appropriate).



v) Overview of electricity system & market setup

The following problem is derived for a generation company which owns and operates resource *r* at node *n.* The objective function is to maximise a weighted sum of expected profit and conditional value at risk (CVaR). Constraints include limits on total amount of investment possible, generation per timestep, and amount of capacity contracts sold.

$$\max_{\substack{q,\Delta y,\\ u,\alpha,y}} \left(\gamma_g \cdot \left(\sum_s P_s \Pi_{g,s}\right) + (1-\gamma_g)\cdot\left(\alpha_g - \frac{1}{\beta_g}\sum_s P_s u_{g,s}\right)\right) \quad \forall g \in G \qquad (1a)$$

Primal Feasibility Constraints

$$\Delta y_{g,n,r} - \Delta y^{MAX}_{g,n,r} \le 0 \quad \forall g,n,r \quad (\delta^+_{g,n,r}) \qquad (1b)$$

$$q_{g,n,r,t,s} - A_{n,r,t,s}\cdot(y^0_{g,n,r} + \Delta y_{g,n,r}) \le 0 \quad \forall n,r,t,s \quad (\theta^+_{g,n,r,t,s}) \qquad (1c)$$

$$y_{g,n,r} - \kappa_{n,r}\cdot(y^0_{g,n,r} + \Delta y_{g,n,r}) \le 0 \quad \forall n,r \quad (\mu^+_{g,n,r}) \qquad (1d)$$

$$\alpha_g - \Pi_{g,s} - u_{g,s} \le 0 \quad \forall g,s \quad (\phi^+_{g,s}) \qquad (1e)$$

$$-u_{g,s} \le 0 \quad \forall g,s \quad (\phi^-_{g,s}) \qquad (1f)$$

$$-y_{g,n,r} \le 0 \quad \forall g,n,r \quad (\mu^-_{g,n,r}) \qquad (1g)$$

$$-\Delta y_{g,n,r} \le 0 \quad \forall g,n,r \quad (\delta^-_{g,n,r}) \qquad (1h)$$

$$u_{g,s}, \Delta y_{g,n,r}, q_{g,n,r,t,s} \le 0 \quad \forall g,n,r,t,s \quad (\theta^-_{g,n,r,t,s}) \qquad (1i)$$

$$\alpha_g \in \mathbb{R} \quad \forall g \qquad (1j)$$

$$\Pi_{g,s} = \sum_{n\in N}\sum_{r\in R}\left[\sum_{t\in T}\left(W_t\cdot\left(q_{g,n,r,t,s}\cdot(\lambda^{EOM}_{n,t,s} - C^{O\&M}_{n,r}) - y_{g,n,r}\cdot\Delta t\cdot h_{nts}\right)\right) + \left(y_{g,n,r}\cdot(\lambda^{CM}_n)\right) - \left(\Delta y_{g,n,r}\cdot C^{Inv}_{n,r}\right)\right] \qquad (1k)$$

$$h_{nts} = \max(\lambda^{EOM}_{nts} - \lambda^{RO}, 0) \qquad (1l)$$

This problem is then be converted into an equivalent <u>dual</u> problem:

$$\min_{\theta,\phi,\mu,\delta}\left(\sum_n\sum_r\left(\mu^+_{nr}\kappa_{nr}y^0_{nr} + \delta^+_{nr}\Delta y^{MAX}_{gnr} + \sum_t\sum_s(\theta^+_{nrts}A_{nrts}y^0_{nr})\right)\right) \quad \forall g \in G \qquad (2a)$$

Dual Feasibility Constraints

$$(\gamma_g P_s + \phi^+_s)\cdot W_t\cdot(\lambda^{EOM}_{n,r,t,s} - C^{O\&M}_{n,r}) - \theta^+_{nrts} \le 0 \quad \forall g,n,r,t,s \quad (q_{g,n,r,t,s}) \qquad (2b)$$

$$\sum_s(\gamma_g P_s + \phi^+_s)\cdot(\lambda^{CM}_n - \sum_t W_t\cdot\Delta t\cdot h_{nts}) - \mu^+_{nr} \le 0 \quad \forall g,n,r \quad (y_{g,n,r}) \qquad (2c)$$

$$\sum_{t,s}(\theta^+_{nrts}A_{nrts}) - \sum_s C^{Inv}_{nr}(\gamma_g P_s + \phi^+_s) + \mu^+_{nr}\kappa_{nr} - \delta^+_{nr} \le 0 \quad \forall g,n,r \quad (\Delta y_{g,n,r}) \qquad (2d)$$

$$\frac{-P_s(1-\gamma_k)}{\beta_k} + \phi^+_s \le 0 \quad \forall g,s \quad (u_{g,s}) \qquad (2e)$$

$$(1-\gamma_g) - \sum_s \phi^+_s - = 0 \quad \forall g \quad (\alpha_g) \qquad (2f)$$

$$-\phi^+_{g,s} \le 0 \quad \forall g,s \quad (u_{g,s}) \qquad (2g)$$

$$-\mu^+_{g,n,r} \le 0 \quad \forall g,n,r \quad (y_{g,n,r}) \qquad (2h)$$

$$-\delta^+_{g,n,r} \le 0 \quad \forall g,n,r \quad (\Delta y_{g,n,r}) \qquad (2i)$$

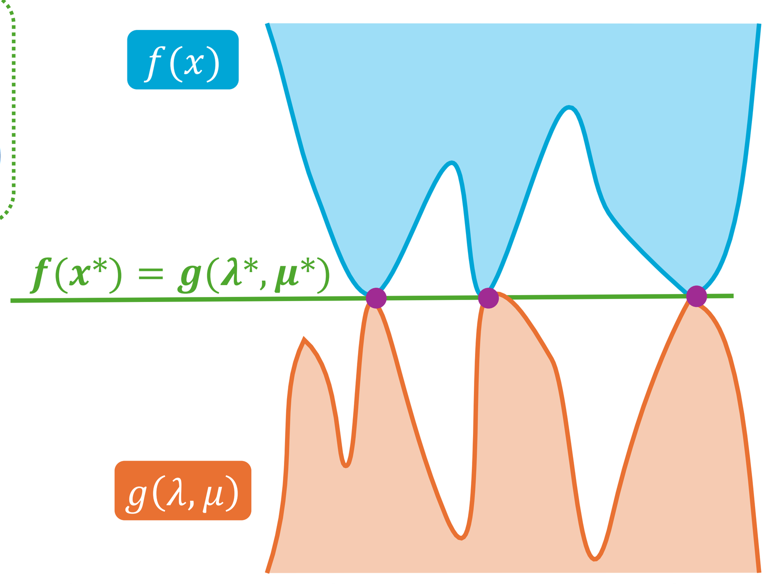
$$-\theta^+_{g,n,r,t,s} \le 0 \quad \forall g,n,r,t,s \quad (q_{g,n,r,t,s}) \qquad (2j)$$

In order to combine all agents into a single system model, these two problems are combined into a single set of feasibility constraints using following the methodology described by [10, 11]. Strong duality is assumed, and the primal objective function is set equal to the dual objective function:

Strong Duality

$$\gamma_g\cdot\left(\sum_s P_s\Pi_{g,s}\right) + (1-\gamma_g)\cdot\left(\alpha_g - \frac{1}{\beta_g}\sum_s P_s u_{g,s}\right) = \mu^+_{nr}\kappa_{nr}y^0_{nr} + \delta^+_{nr}\Delta y^{MAX}_{gnr} + \sum_t\sum_s(\theta^+_{nrts}A_{nrts}y^0_{nr})$$

This strong duality condition is combined with the primal and dual feasibility conditions (1b-1j, 2b-2j) to form a single feasibility problem for the generation company. This narrows the feasibility space to a set of equally optimal points.



vi) Abstract illustration of equilibrium points produced for each market actor using primal dual reformulation methodology

This process is repeated for all market actors. The resulting sets of feasibility constraints of each actor are collected into a single set of conditions for the entire system. This ensures that the decision space is restricted to solutions which are optimal and acceptable for every market actor.

This Primal-Dual reformulation methodology converts the separate optimisation problems into a single MPEC, allowing for exploration of multiple equilibria using secondary objective functions. The model can thus be used to assess the impact of each locational signal design from multiple points of view, depending on which upper level objective function is chosen. These objectives can include energy not served (ENS), social welfare, and carbon emissions.

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