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Masters's Dissertation

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ABSTRACT

Abstract goes here.

1 METHODOLOGY

Three different archetypes for auctions were identified as the common procurement methods for energy and ancillary services within liberalised electricity markets: sequential, simultaneous, and co-optimised.

1.1 Cooptimised Auctions

Cooptimised auctions are those in which there is a single auction for electricity and ancillary service, all products are procured at the same time.

1.1.1 *Mathematical Formulation*

Objective function

If loads are considered price takers, the objective function can be expressed as a cost minimisation as follows

$$\min \mathrm{C}^{\mathrm{op}}_{\mathrm{G}} + \mathrm{C}^{\mathrm{op}}_{\mathrm{W}} + \mathrm{C}^{\mathrm{op}}_{\mathrm{PV}} + \mathrm{C}^{\mathrm{op}}_{\mathrm{S}} \tag{1}$$

where $\mathrm{C}^{\mathrm{op}}_{\mathrm{G}}$ represents the operating cost of a conventional generating power plant. $\mathrm{C}^{\mathrm{op}}_{\mathrm{W}}$ and $\mathrm{C}^{\mathrm{op}}_{\mathrm{PV}}$ represent the cost of wind and solar power plants, respectively. And $\mathrm{C}^{\mathrm{op}}_{\mathrm{S}}$ represents the cost of operating storage.

$$\mathrm{C}^{\mathrm{op}}_{\mathrm{G}} = \mathrm{c}^{\mathrm{op}}_{\mathrm{g}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}_{\mathrm{g,t}} + \mathrm{c}^{\mathrm{fr}}_{\mathrm{g}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}^{\mathrm{fr}}_{\mathrm{g,t}} + \mathrm{c}^{\mathrm{sr}}_{\mathrm{g}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}^{\mathrm{sr}}_{\mathrm{g,t}}$$

$$\mathrm{C}^{\mathrm{op}}_{\mathrm{W}} = \mathrm{c}^{\mathrm{op}}_{\mathrm{w}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}_{\mathrm{w,t}} \approx 0$$

$$\mathrm{C}^{\mathrm{op}}_{\mathrm{PV}} = \mathrm{c}^{\mathrm{op}}_{\mathrm{pv}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}_{\mathrm{pv,t}} \approx 0$$

$$\mathrm{C}^{\mathrm{op}}_{\mathrm{S}} = \mathrm{c}^{\mathrm{dis}}_{\mathrm{s}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}^{\mathrm{dis}}_{\mathrm{s,t}} - \mathrm{c}^{\mathrm{ch}}_{\mathrm{s}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}^{\mathrm{ch}}_{\mathrm{s,t}} + \mathrm{c}^{\mathrm{fr}}_{\mathrm{s}} \sum_{\mathrm{t=0}}^{\mathrm{T}} \mathrm{P}^{\mathrm{fr}}_{\mathrm{s,t}}$$

The terms $\mathrm{c}^{\mathrm{ch}}_{\mathrm{s}}$ and $\mathrm{c}^{\mathrm{dis}}_{\mathrm{s}}$ are the price at which the storage operator is willing to charge and discharge to the grid, respectively, in $/MWh, paid for each MWh extracted or injected into the network. Wind and solar PV cost are zero or near zero, but the terms are included in the equation.

Constraints

Power balance constraint:

$$\sum_{\mathrm{g=1}}^{\mathrm{G}} \mathrm{P}_{\mathrm{g,t}} + \sum_{\mathrm{w=1}}^{\mathrm{W}} \mathrm{P}_{\mathrm{w,t}} + \sum_{\mathrm{pv=1}}^{\mathrm{PV}} \mathrm{P}_{\mathrm{pv,t}} + \sum_{\mathrm{s=1}}^{\mathrm{S}} (\mathrm{P}^{\mathrm{dis}}_{\mathrm{s,t}} - \mathrm{P}^{\mathrm{ch}}_{\mathrm{s,t}}) = \mathrm{P}^{\mathrm{D}}_{\mathrm{t}} \quad \forall \mathrm{t} \tag{2}$$

Reserves constraints:

$$\sum_{\mathrm{g=1}}^{\mathrm{G}} \mathrm{P}^{\mathrm{fr}}_{\mathrm{g,t}} + \sum_{\mathrm{s=1}}^{\mathrm{S}} \mathrm{P}^{\mathrm{fr}}_{\mathrm{s,t}} \geq \mathrm{P}^{\mathrm{fr}}_{\mathrm{t}} \quad \forall \mathrm{t} \tag{3}$$

$$\sum_{\mathrm{t=1}}^{\mathrm{G}} \mathrm{P}^{\mathrm{sr}}_{\mathrm{g,t}} \geq \mathrm{P}^{\mathrm{sr}}_{\mathrm{t}} \quad \forall \mathrm{t} \tag{4}$$

Fast reserve can be provided by conventional power plants and storage technologies, while slow reserve will only be provided by conventional power plants. Wind and solar PV technologies are not qualified to deliver these reserves.

Conventional power plants:

$$\mathrm{P}^{\mathrm{min}}_{\mathrm{g}} \mathrm{u}_{\mathrm{g,t}} \leq \mathrm{P}_{\mathrm{g,t}} \leq \mathrm{P}^{\mathrm{max}}_{\mathrm{g}} \mathrm{u}_{\mathrm{g,t}} \quad \forall \mathrm{g,t} \tag{5}$$

$$\mathrm{P}_{\mathrm{g,t}} - \mathrm{P}_{\mathrm{g,t-1}} \leq \Delta \mathrm{P}^{\mathrm{up}}_{\mathrm{g}} \quad \forall \mathrm{g,t} > 1 \tag{6}$$

$$\mathrm{P}_{\mathrm{g,t-1}} - \mathrm{P}_{\mathrm{g,t}} \leq \Delta \mathrm{P}^{\mathrm{dn}}_{\mathrm{g}} \quad \forall \mathrm{g,t} > 1 \tag{7}$$

$$\mathrm{P}^{\mathrm{fr}}_{\mathrm{g,t}} \leq \mathrm{P}^{\mathrm{maxfr}}_{\mathrm{g}} \quad \forall \mathrm{g,t} \tag{8}$$

$$\mathrm{P}^{\mathrm{fr}}_{\mathrm{g,t}} + \mathrm{P}^{\mathrm{sr}}_{\mathrm{g,t}} \leq \mathrm{P}^{\mathrm{maxsr}}_{\mathrm{g}} \quad \forall \mathrm{g,t} \tag{9}$$

$$\mathrm{P}_{\mathrm{g,t}} + \mathrm{P}^{\mathrm{fr}}_{\mathrm{g,t}} + \mathrm{P}^{\mathrm{sr}}_{\mathrm{g,t}} \leq \mathrm{P}^{\mathrm{max}}_{\mathrm{g}} \mathrm{u}_{\mathrm{g,t}} \quad \forall \mathrm{g,t} \tag{10}$$

where $\mathrm{u}_{\mathrm{g,t}}$ is 1 when the unit is dispatching, otherwise its value is zero.

Wind and solar PV power plants:

$$\mathrm{P}_{\mathrm{w,t}} = \mathrm{P}^{\mathrm{max}}_{\mathrm{w}} \mathrm{x}_{\mathrm{w,t}} \quad \forall \mathrm{w,t} \tag{11}$$

$$\mathrm{P}_{\mathrm{pv,t}} = \mathrm{P}^{\mathrm{max}}_{\mathrm{pv}} \mathrm{x}_{\mathrm{pv,t}} \quad \forall \mathrm{pv,t} \tag{12}$$

where $\mathrm{P}^{\mathrm{max}}$ represents the maximum power output of the unit given the current environmental conditions, while $\mathrm{x}_{\mathrm{w,t}}$ and $\mathrm{x}_{\mathrm{pv,t}}$ are numbers between 0 and 1 representing the curtailment of the unit in case there is excess generation in the grid.

Storage constraints:

$$P^{ch}_{s,t} \leq P^{max}_{s}(1 - v_{g,t}) \qquad \forall s,t \qquad (13)$$
$$P^{dis}_{s,t} \leq P^{max}_{s} v_{g,t} \qquad \forall s,t \qquad (14)$$
$$E_{s,t} = E_{s,t-1} + P^{ch}_{s,t}\eta^{ch}_{s} - P^{dis}_{s,t}/\eta^{dis}_{s} \qquad \forall s,t \qquad (15)$$
$$E_{s,t} \leq E^{max}_{s} \qquad \forall s,t \qquad (16)$$
$$E_{s,t} \geq E^{min}_{s} \qquad \forall s,t \qquad (17)$$
$$E_{s,t=last} = E^{end}_{s} \qquad \forall s \qquad (18)$$
$$E_{s,t=1} = E^{start}_{s} \qquad \forall s \qquad (19)$$
$$P^{dis}_{s,t} - P^{ch}_{s,t} + P^{fr}_{s,t} \leq P^{max}_{s} \qquad \forall s,t \qquad (20)$$

$$E^{min}_{s} \leq E_{s,t-1} + P^{ch}_{s,t}\eta^{ch}_{s} - (P^{dis}_{s,t} + P^{fr}_{s,t})/\eta^{dis}_{s} \qquad \forall s,t$$

where $v_{g,t}$ is 1 when the storage is discharging into the grid, otherwise it is zero. P^{max}_{s} represents the maximum power output and input of the storage technology, it is assumed symmetrical. η_s is the efficiency of charging or discharging of the battery. E^{max}_{s} and E^{min}_{s} represent the maximum and minimum charge the battery should have at any given moment. E^{start}_{s} and E^{end}_{s} force the storage to start and end the day with a given level of charge.

1.2 Simultaneous Auctions

Sequential auctions are those in which there is a separate auction for electricity procurement and for each ancillary service. Each individual auction can be expressed as an optimisation problem where maximising social welfare at each individual auction is the goal.

1.2.1 *Mathematical Formulation - Electricity*

Objective function

If loads are considered price takers, the objective function can be expressed as a cost minimisation as follows

$$\min C^{op}_{G} + C^{op}_{W} + C^{op}_{PV} + C^{op}_{S} \qquad (21)$$

where C^{op}_{G} represents the operating cost of a conventional generating power plant. C^{op}_{W} and C^{op}_{PV} represent the cost of wind and solar power plants, respectively. And C^{op}_{S} represents the cost of operating storage.

$$C^{op}_{G} = c^{op}_{g,i}\sum_{t=0}^{T} P_{g,i,t} \qquad (22)$$

$$C^{op}_{W} = c^{op}_{w}\sum_{t=0}^{T} P_{w,t} \approx 0 \qquad (23)$$

$$C^{op}_{PV} = c^{op}_{pv}\sum_{t=0}^{T} P_{pv,t} \approx 0 \qquad (24)$$

$$C^{op}_{S} = c^{dis}_{s}\sum_{t=0}^{T} P^{dis}_{s,t} - c^{ch}_{s}\sum_{t=0}^{T} P^{ch}_{s,t} \qquad (25)$$

The terms c^{ch}_{s} and c^{dis}_{s} are the price at which the storage operator is willing to charge and discharge to the grid, respectively, in $/MWh, paid for each MWh extracted or injected into the network. Wind and solar PV cost are zero or near zero, but the terms are included in the equation. The offered cost of electricity for each generator, equation 22, is divided into capacity blocks i see explanation in the next section.

Opportunity Cost

For conventional generation power plans, the opportunity cost is not calculated by the algorithm. In reality, each generator decides the price with which their capacity is offered into the market. In order to replicate this, a special calculation is made to simulate the offered price of generators to the system operator. The process follows these steps:

1. Obtain reserve price from the co-optimised auction result.
2. Add forecast uncertainty.
3. Calculate potential profit for each period.
4. If profitable, increase capacity price accordingly.

The initial forecast is extracted from the marginal price obtained in the co-optimised auction result, this is a good approximation and idealisation that generators could have. Because all forecasts can't be equal, a forecasting error is added to each one in all periods, this error can go from -20% to 20% of the initial average daily forecasted price. After this, each generator calculates their potential profit, if assigned reserves, with the forecasted price. If the generator does not expect to be profitable, it does not increase the offered cost of electricity. On the other hand, if profit is expected to be made, the generator increases the offered price for a share of its total capacity, assuming that in case they are called to dispatch electricity in full, it will earn as much as they were expecting to earn in the reserves market. Finally, when calculating the final offered price, each generator makes a separate calculation for both fast and slow reserves, and allocates more capacity, in terms of pricing, to the most profitable product.
INSERT CHART EXPLAINING PROCESS.

Constraints
Power balance constraint:

$$\sum_{g=1}^{G} \mathrm{P_{g,t}} + \sum_{w=1}^{W} \mathrm{P_{w,t}} + \sum_{pv=1}^{PV} \mathrm{P_{pv,t}} + \sum_{s=1}^{S} (\mathrm{P_{s,t}^{dis}} - \mathrm{P_{s,t}^{ch}}) = \mathrm{P_t^D} \tag{26}$$

To avoid a lack of available capacity for the next auctions, a constraint forcing some spinning reserve is introduced. Minimum no-load spinning capacity constraint:

$$\mathrm{P_t^{spin}} \geq \mathrm{P^{spinmin}} \qquad \forall t \tag{27}$$

$$\mathrm{P_t^{spin}} = \sum_{g=1}^{G} (\mathrm{P_g^{max} u_{g,t}} - \mathrm{P_{g,t}}) \qquad \forall t \tag{28}$$

where $\mathrm{P^{spinmin}}$ represents an estimation of the required spinning capacity for the procurement of reserves in MW. **I think it makes sense, it only considers already spinning power plants, discuss with Thomas and Mostafa**.

Conventional power plants (Same as co-optimised but without reserves):

$$\mathrm{P_g^{min} u_{g,t}} \leq \mathrm{P_{g,t}} \leq \mathrm{P_g^{max} u_{g,t}} \qquad \forall g, t \tag{29}$$

$$\mathrm{P_{g,t}} - \mathrm{P_{g,t-1}} \leq \Delta \mathrm{P_g^{up}} \qquad \forall g, t > 1 \tag{30}$$

$$\mathrm{P_{g,t}} = \sum_{i}^{I} \mathrm{P_{g,i,t}} \qquad \forall g, t \tag{31}$$

$$\mathrm{P_{g,i,t}} \leq \mathrm{P_{g,i,t}^{max}} \qquad \forall g, i, t \tag{32}$$

where $\mathrm{P_{g,i,t}}$ is the power used in each offered block, and $\mathrm{P_{g,i,t}^{max}}$ is the maximum capacity of each capacity block.

Wind and solar PV power plants:

$$\mathrm{P_{w,t}} = \mathrm{P_w^{max} x_{w,t}} \qquad \forall w, t \tag{33}$$

$$\mathrm{P_{pv,t}} = \mathrm{P_{pv}^{max} x_{pv,t}} \qquad \forall pv, t \tag{34}$$

where $\mathrm{P^{max}}$ represents the maximum power output of the unit given the current environmental conditions, while $\mathrm{x_{w,t}}$ and $\mathrm{x_{pv,t}}$ are numbers between 0 and 1 representing the curtailment of the unit in case there is excess generation in the grid.

Storage constraints without reserves:

$$\forall t \, \mathrm{P_{s,t}^{ch}} \leq \mathrm{P_s^{max}} (1 - \mathrm{v_{g,t}}) \qquad \forall s, t \tag{35}$$

$$\mathrm{P_{s,t}^{dis}} \leq \mathrm{P_s^{max} v_{g,t}} \qquad \forall s, t \tag{36}$$

$$\mathrm{E_{s,t}} = \mathrm{E_{s,t-1}} + \mathrm{P_{s,t}^{ch}} \eta_s^{ch} - \mathrm{P_{s,t}^{dis}} / \eta_s^{dis} \qquad \forall s, t \tag{37}$$

$$\mathrm{E_{s,t}} \leq \mathrm{E_s^{max}} \qquad \forall s, t \tag{38}$$

$$\mathrm{E_{s,t}} \geq \mathrm{E_s^{min}} \qquad \forall s, t \tag{39}$$

$$\mathrm{E_{s,t=last}} = \mathrm{E_s^{end}} \qquad \forall s \tag{40}$$

$$\mathrm{E_{s,t=1}} = \mathrm{E_s^{start}} \qquad \forall s \tag{41}$$

1.2.2 *Fast and Slow Reserves*

After clearing the electricity auction, the reserves are auctioned. Reserves can only be provided by storage (fast) and power plants already operating (fast and slow). Wind and Solar technologies can't provide any kind of reserve.

Objective function

$$\min \mathrm{C}_{\mathrm{G}}^{\mathrm{op}} + \mathrm{C}_{\mathrm{S}}^{\mathrm{op}} \tag{42}$$

where

$$\begin{aligned}
\mathrm{C}_{\mathrm{G}}^{\mathrm{op}} &= \mathrm{c}_{\mathrm{g}}^{\mathrm{fr}} \sum_{\mathrm{t}=0}^{\mathrm{T}} \mathrm{P}_{\mathrm{g,t}}^{\mathrm{fr}} + \mathrm{c}_{\mathrm{g}}^{\mathrm{sr}} \sum_{\mathrm{t}=0}^{\mathrm{T}} \mathrm{P}_{\mathrm{g,t}}^{\mathrm{sr}} \\
\mathrm{C}_{\mathrm{S}}^{\mathrm{op}} &= \mathrm{c}_{\mathrm{s}}^{\mathrm{fr}} \sum_{\mathrm{t}=0}^{\mathrm{T}} \mathrm{P}_{\mathrm{s,t}}^{\mathrm{fr}}
\end{aligned}$$

Balance constraints:

$$\sum_{\mathrm{g}=1}^{\mathrm{G}} \mathrm{P}_{\mathrm{g,t}}^{\mathrm{fr}} + \sum_{\mathrm{s}=1}^{\mathrm{S}} \mathrm{P}_{\mathrm{s,t}}^{\mathrm{fr}} \geq \mathrm{P}_{\mathrm{t}}^{\mathrm{fr}} \qquad \forall \mathrm{t} \tag{43}$$

$$\sum_{\mathrm{t}=1}^{\mathrm{G}} \mathrm{P}_{\mathrm{g,t}}^{\mathrm{sr}} \geq \mathrm{P}_{\mathrm{t}}^{\mathrm{sr}} \qquad \forall \mathrm{t} \tag{44}$$

Conventional power plants:

$$\begin{aligned}
\mathrm{P}_{\mathrm{g,t}}^{\mathrm{fr}} &\leq \mathrm{P}_{\mathrm{g}}^{\mathrm{maxfr}} && \forall \mathrm{g}, \mathrm{t} \\
\mathrm{P}_{\mathrm{g,t}}^{\mathrm{fr}} + \mathrm{P}_{\mathrm{g,t}}^{\mathrm{sr}} &\leq \mathrm{P}_{\mathrm{g}}^{\mathrm{maxsr}} && \forall \mathrm{g}, \mathrm{t} \\
\mathrm{P}_{\mathrm{g,t}} + \mathrm{P}_{\mathrm{g,t}}^{\mathrm{fr}} + \mathrm{P}_{\mathrm{g,t}}^{\mathrm{sr}} &\leq \mathrm{P}_{\mathrm{g}}^{\mathrm{max}} \mathrm{u}_{\mathrm{g,t}} && \forall \mathrm{g}, \mathrm{t}
\end{aligned}$$

Storage constraints:

$$\mathrm{P}_{\mathrm{s,t}}^{\mathrm{dis}} - \mathrm{P}_{\mathrm{s,t}}^{\mathrm{ch}} + \mathrm{P}_{\mathrm{s,t}}^{\mathrm{fr}} \leq \mathrm{P}_{\mathrm{s}}^{\mathrm{max}} \quad \forall \mathrm{s}, \mathrm{t}$$

$$\mathrm{E}_{\mathrm{s}}^{\mathrm{min}} \leq \mathrm{E}_{\mathrm{s,t-1}} + \mathrm{P}_{\mathrm{s,t}}^{\mathrm{ch}} \eta_{\mathrm{s}}^{\mathrm{ch}} - (\mathrm{P}_{\mathrm{s,t}}^{\mathrm{dis}} + \mathrm{P}_{\mathrm{s,t}}^{\mathrm{fr}}) / \eta_{\mathrm{s}}^{\mathrm{dis}} \quad \forall \mathrm{s}, \mathrm{t}$$

1.3 Sequential Auctions

Sequential auctions are those in which there is a separate auction for electricity procurement and for each ancillary service. Each individual auction can be expressed as an optimisation problem where maximising social welfare at each individual auction is the objective.