How Inefficient Can An Electricity Market Be?

Marcel Solé Àvila[1,*], Razgar Ebrahimy[1], Georgios Tsaousoglou[1]

1 Introduction

Imperfectly competitive electricity markets are exposed to strategic bidding behaviors by big players and are thus threatened by significant inefficiency. The related literature has studied relevant game-theoretic models based on equilibrium problems with equilibrium constraints. However, the papers of this literature consider, each time, a given system (e.g. particular generators and cost functions) and assess the equilibrium inefficiency of that particular system. In this work, the goal is assessing the inefficiency of market equilibria, not for a single (arbitrary) set of participants, but *in the worst-case*.

2 Preliminaries & System Model

Consider a day-ahead electricity market for a horizon of discrete timeslots, $t \in \mathcal{T}$. A set of generators, $g \in \mathcal{G}$, submit price-quantity bids in the market, and the operator decides the dispatch towards satisfying a demand profile at the minimum possible cost, to maximize welfare. The operator's problem therefore reads as in Figure 1.

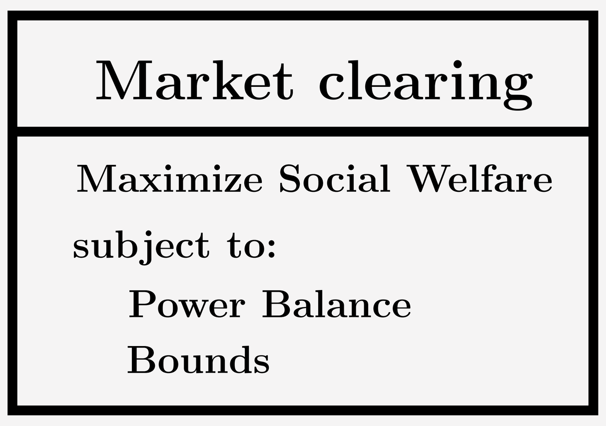

Figure 1: Market operator's problem

The cost of a generator is modeled by $C(x_{g,t}; \alpha_{g,t}, \beta_{g,t})$, where $\alpha_{g,t}, \beta_{g,t}$ parameterize the function. If the market operator knows the true values of $\alpha_{g,t}$ and $\beta_{g,t}$, then the Market Clearing problem leads to the *optimal* system cost, C^{opt}. Since each generator is a profit-maximizing player, it is incentivized to strategize over its bids $(\widehat{\alpha}_{g,t}, \widehat{\beta}_{g,t})_{t\in\mathcal{T}}$ so that it steers the market outcome towards solutions that maximize its own profit. Thereby, the generator's bidding optimization problem takes a bi-level form, as Figure 2 shows, reformulated into an MPEC.

Figure 2: Strategic generator's problem

When more (or all) generators bid strategically, there is a collection $\text{MPEC}_{g\in\mathcal{G}}$ of interdependent problems, known as EPEC, as in Figure 3. This models the electricity market as a game $\mathcal{E}$. A solution of the EPEC defines a Nash Equilibrium of the game $\mathcal{E}$, and it is denoted by C^{eq}.

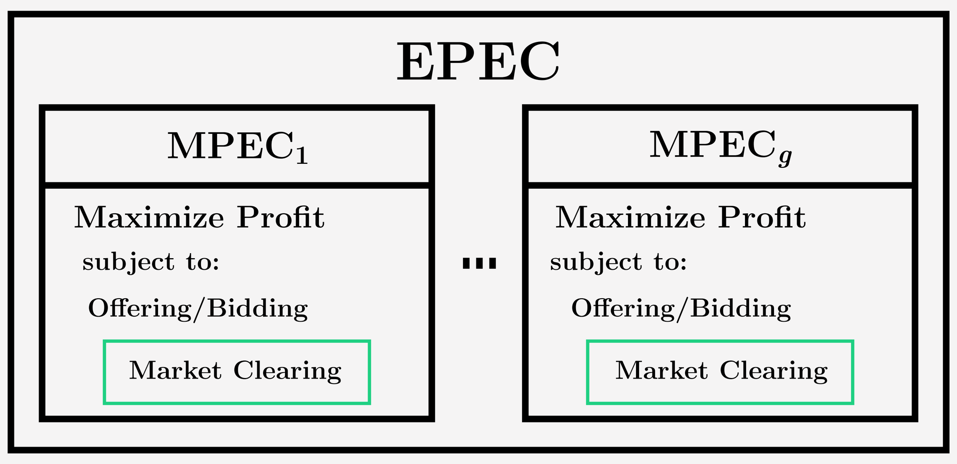

Figure 3: Market equilibirum problem

3 Problem formulation & Methodology

The inefficiency of a market is defined as the game's *Price of Anarchy* (PoA), i.e. the ratio between the system cost at equilibrium and the minimum system cost. Given a game $\mathcal{E}$, the PoA reflects market inefficiency from generators' strategic behavior and depends on their true costs $(\alpha_{g,t}, \beta_{g,t})_{g\in\mathcal{G}}$. The vector $\boldsymbol{\theta} = (\theta_g)_{g\in\mathcal{G}}$ contains the types of all generators, then a game's PoA reads as:

$$PoA(\boldsymbol{\theta}) = \frac{C^{\text{eq}}(\boldsymbol{\theta})}{C^{\text{opt}}(\boldsymbol{\theta})} \geq 1$$

The objective at hand is to identify the generators configuration that maximizes market inefficiency, thereby defining the Robust Price of Anarchy (RPoA) as a stress-test of the market mechanism.

$$RPoA(\mathscr{E}) = \max_{\boldsymbol{\theta}\in\Theta(\mathscr{E})} \{PoA(\boldsymbol{\theta})\}$$

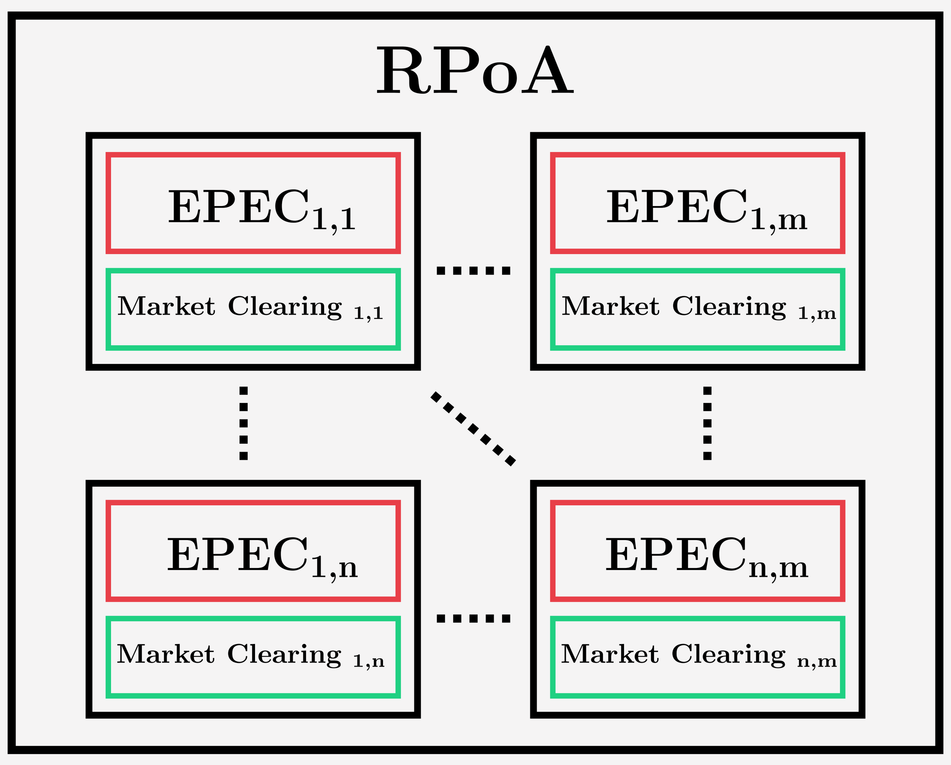

Figure 4: Robust Price of Anarchy problem

Solving The RPoA is computationally challenging. It is solved as illustrated in Figure 5.

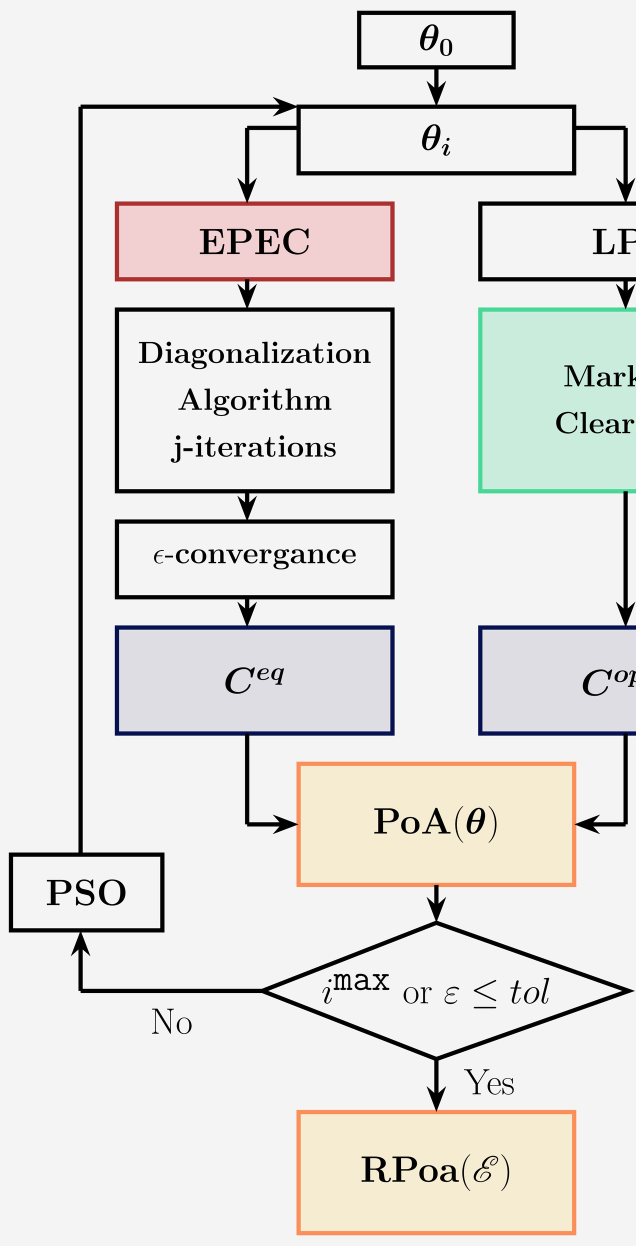

Figure 5: Robust Price of Anarchy problem

4 Results

Figure 6 shows the results compared to the theoretical upper bound given in the literature, showing that the market mechanism inefficiency is higher than anticipated.

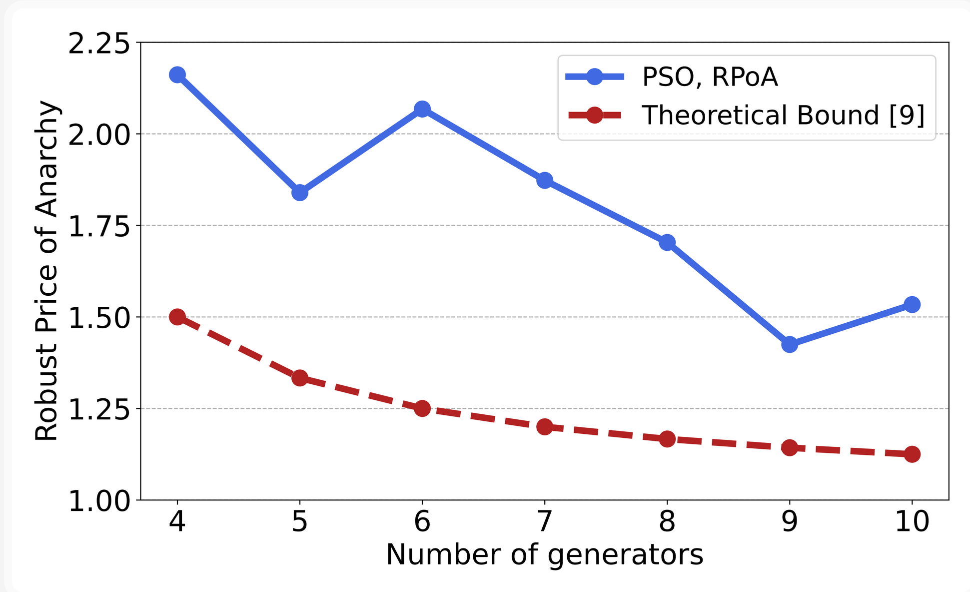

Figure 6: Robust price of anarchy as a function of the number of strategic market participants.

The frequency of PoA occurrences is assessed in Figure 7, which presents the empirical PoA distribution.

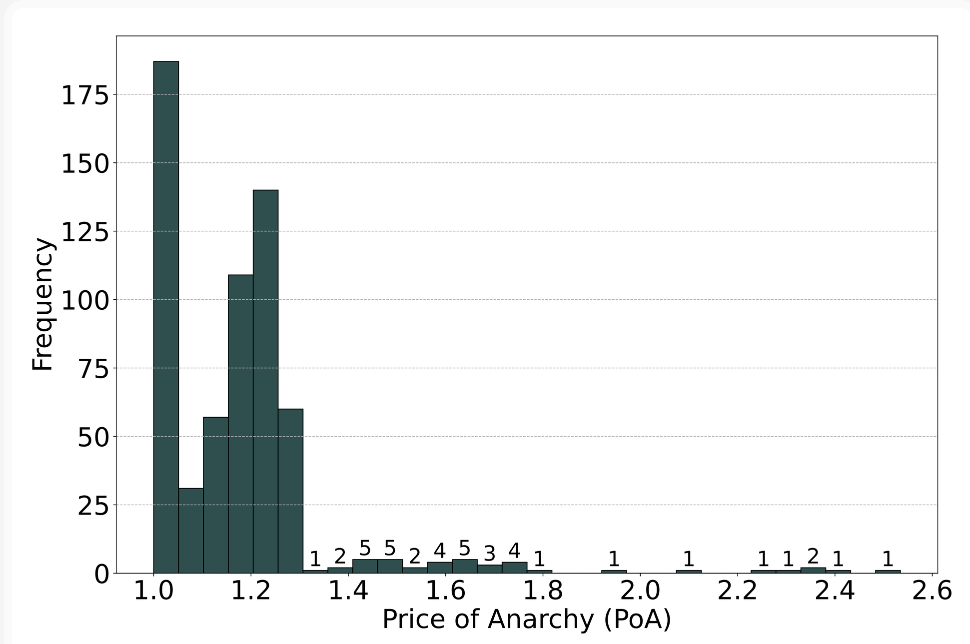

Figure 7: Empirical frequency of the PoA for three generators (discretized grid of cost function parameters).

Scan me to read the paper:

PowerTech KIEL 2025

[1] Technical University of Denmark, Department of Applied Mathematics and Computer Science
* Corresponding author: msoav@dtu.dk