# The Segmented Pay-as-Clear Approach for (Energy) Markets

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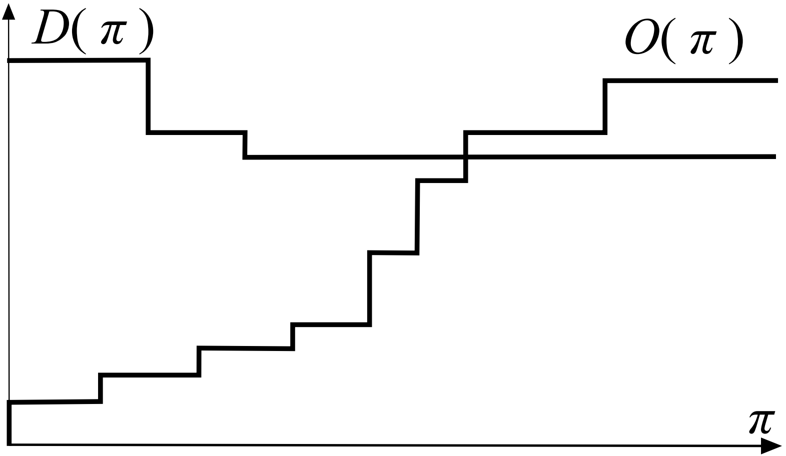
# Outline


1. A brief introduction to Pay-as-Clear (energy) markets
2. The Problem
3. Discussing the problem
4. Our solution, in details
5. Can it work?
6. Can it be applied to practical markets?
7. Conclusions

# The Pay-as-Clear market clearing mechanism

- Market $=$ sellers $+$ buyers of a fungible divisible commodity (energy)
  - set $S$ of sell offers $\langle\, sp_j\,,\, sq_j\,\rangle$: will sell $(\leq)$ $sq_j$ for a price $\geq sp_j$
  - set $B$ of purchase bids $\langle\, bp_i\,,\, bq_i\,\rangle$: will buy $(\leq)$ $bq_i$ for a price $\leq bp_i$
- Nondecreasing offer curve (not function) $O(\pi) = \sum_{j\,:\,sp_j \geq \pi} sq_j$
- Nonincreasing demand curve (not function) $D(\pi) = \sum_{j\,:\,bp_j \leq \pi} bq_j$
- Clearing price $\pi^* =$ "where $O(\pi)$ and $D(\pi)$ meet" $\Longrightarrow$ total amount $q^*$ (of energy) exchanged over the market
- Forget about market failures and degeneracy ...
- But why Pay-as-Clear?

# The Pay-as-Clear Model, graphically



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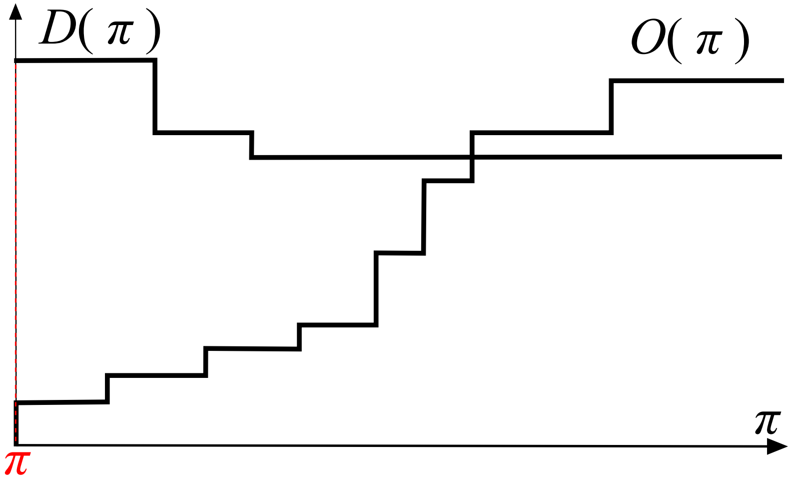

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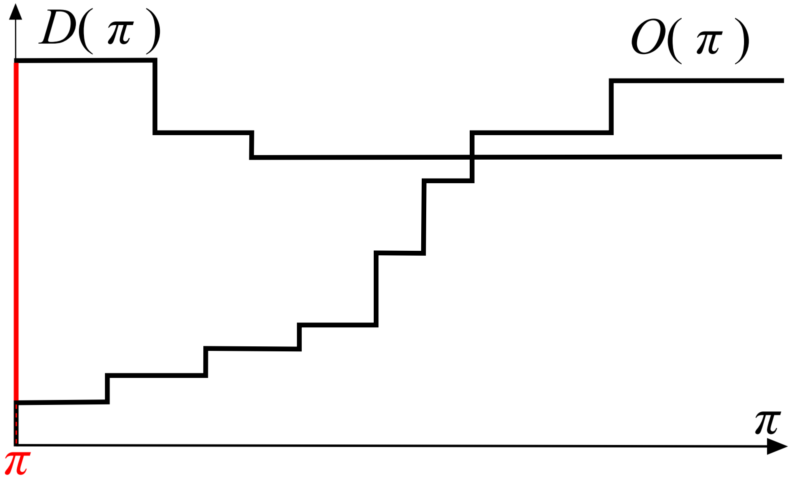

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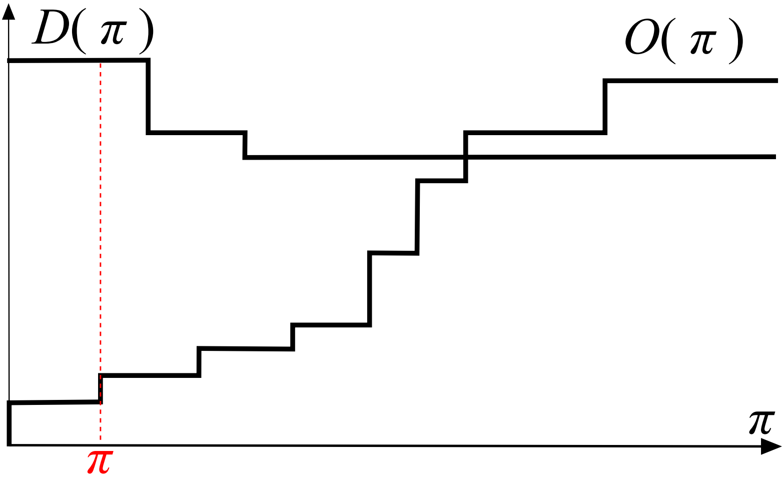

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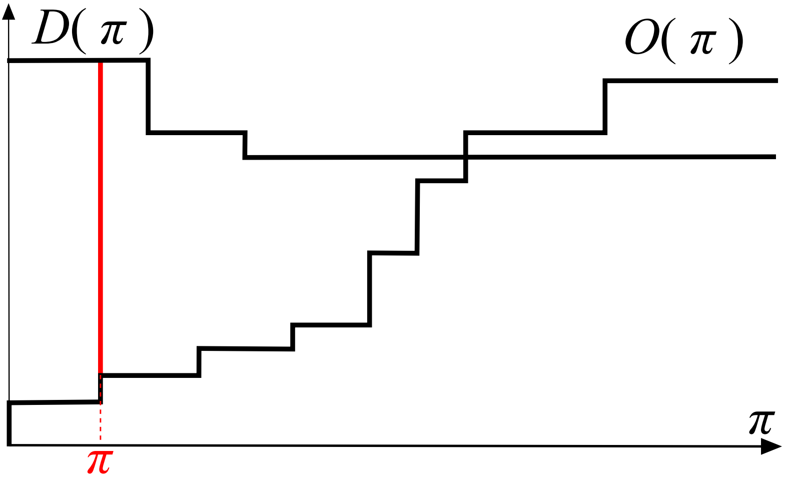

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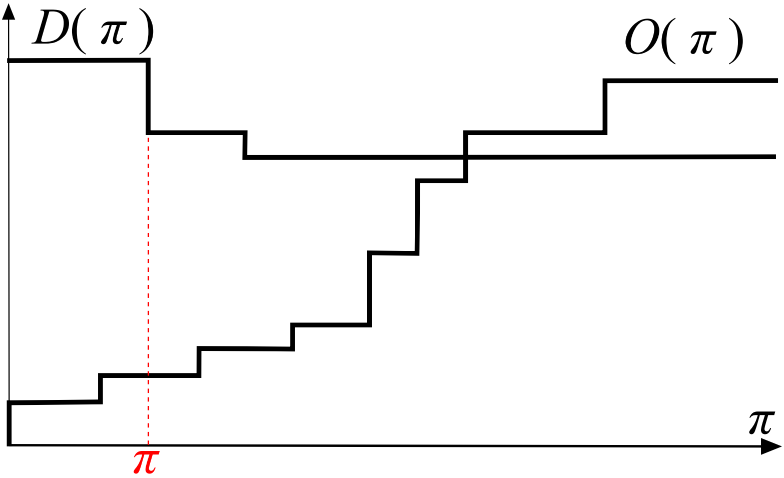

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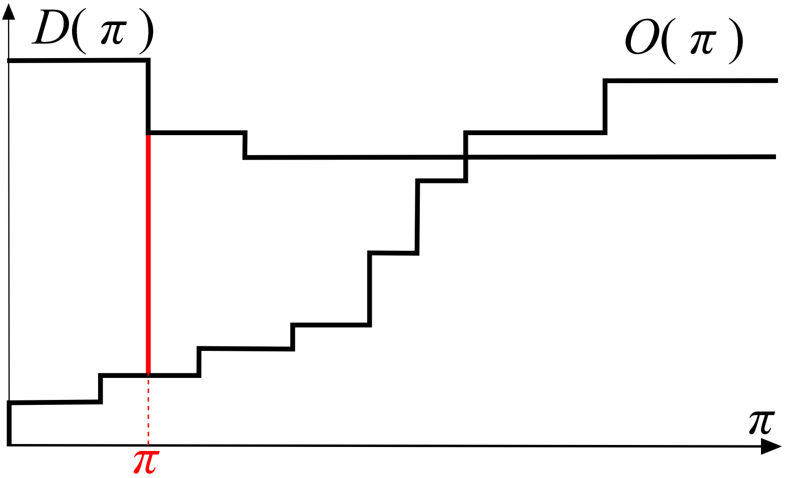

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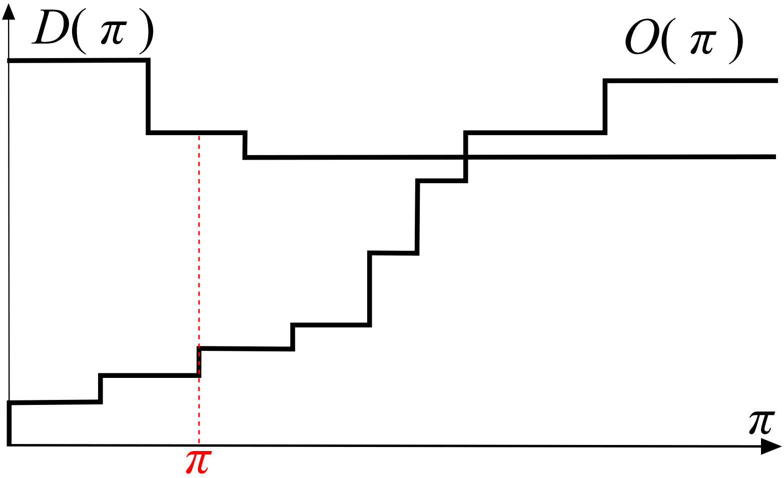

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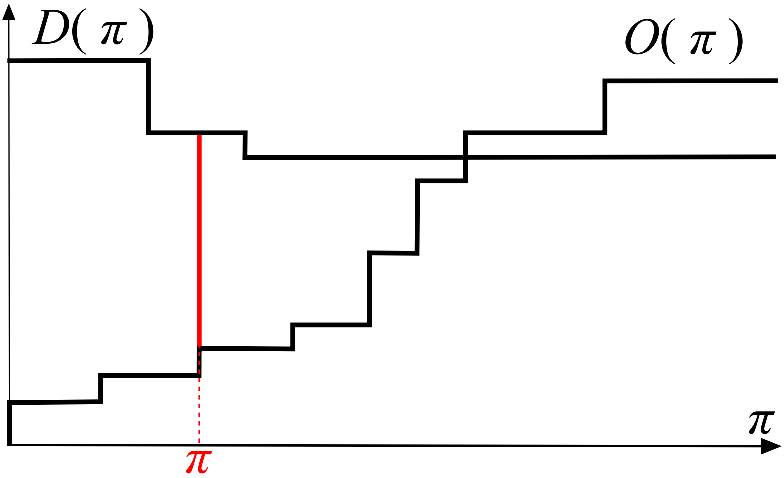

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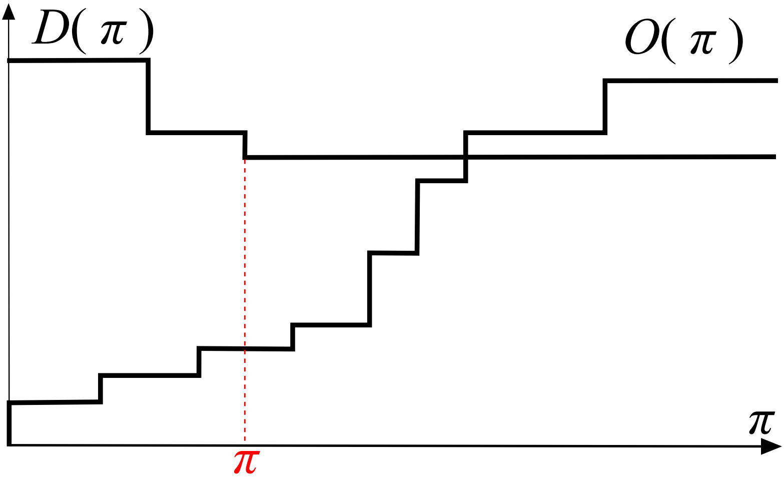

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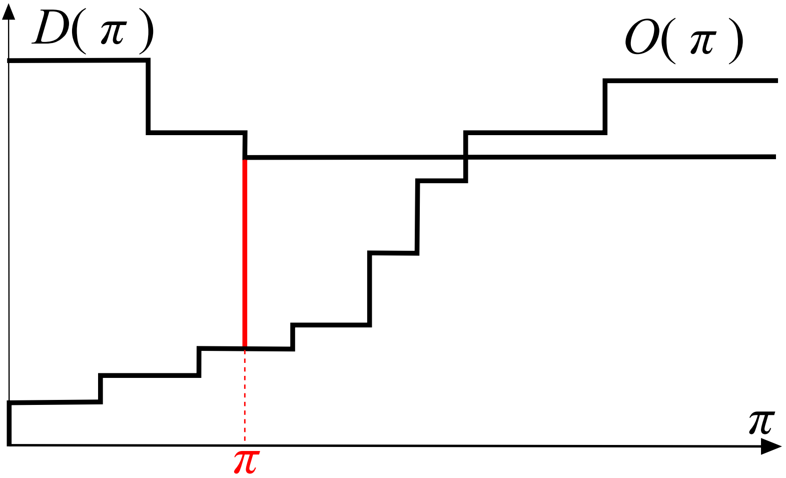

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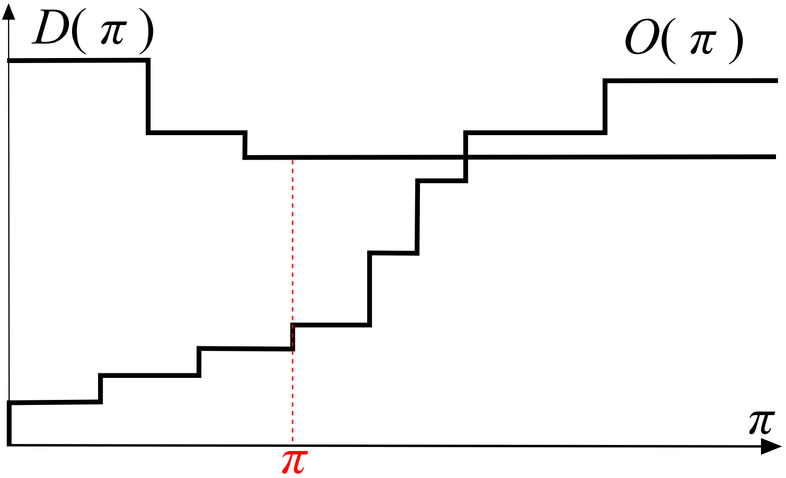

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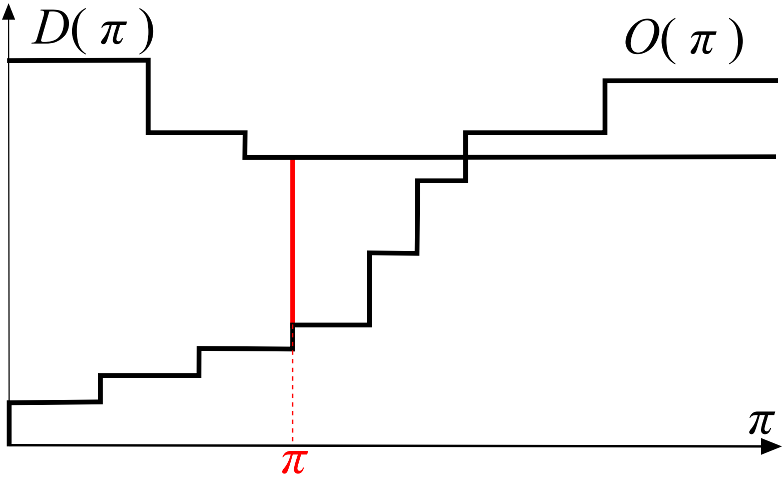

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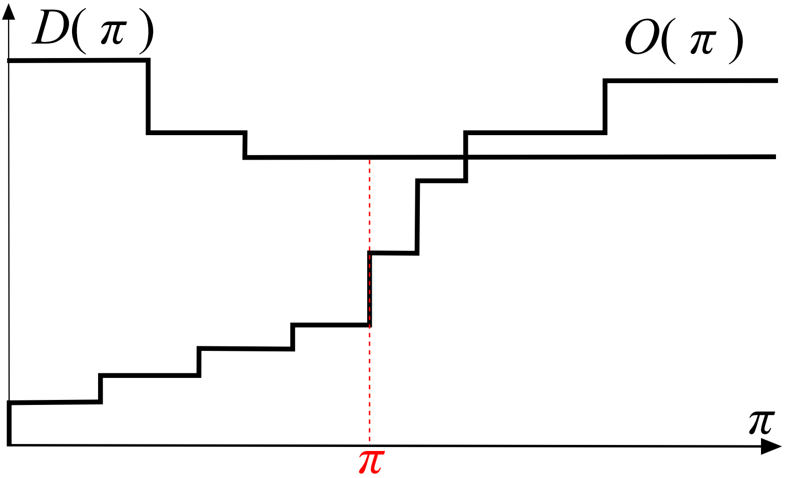

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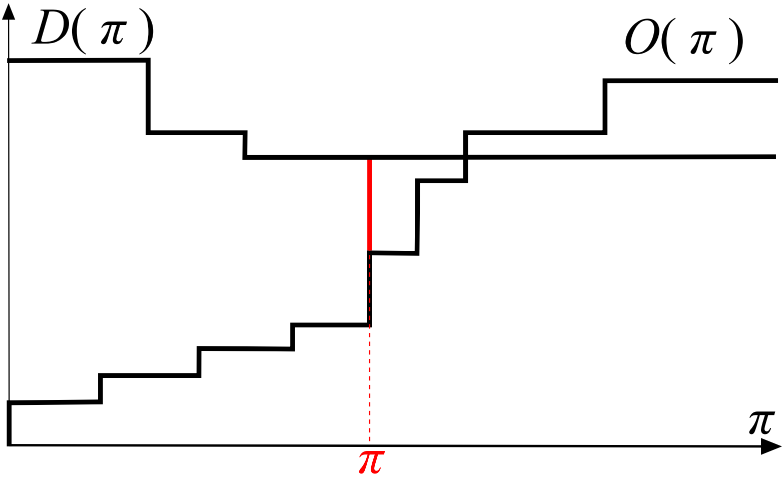

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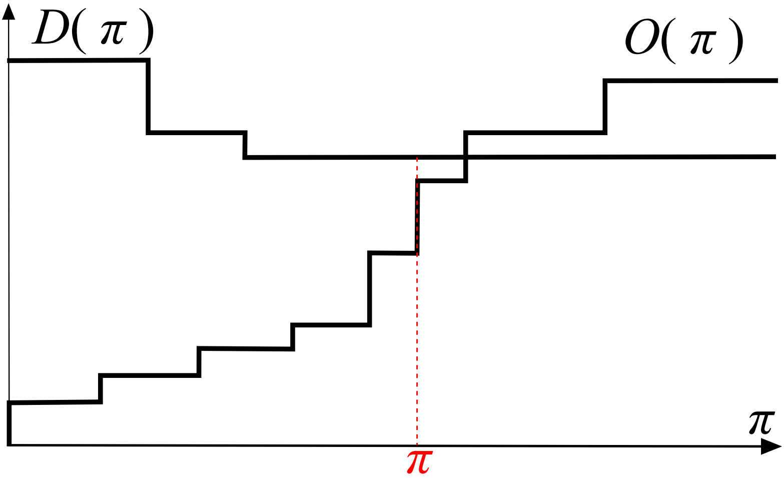

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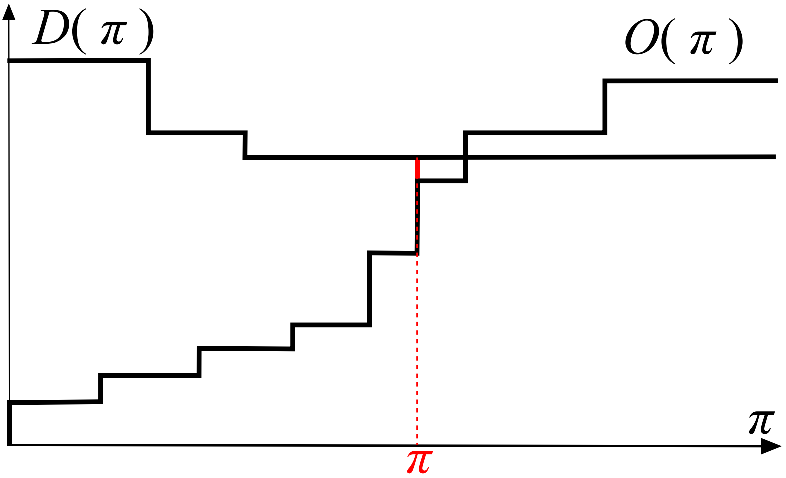

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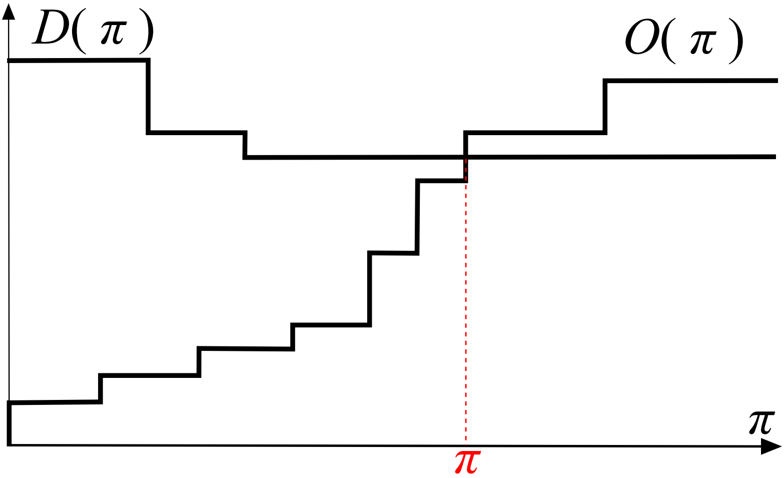

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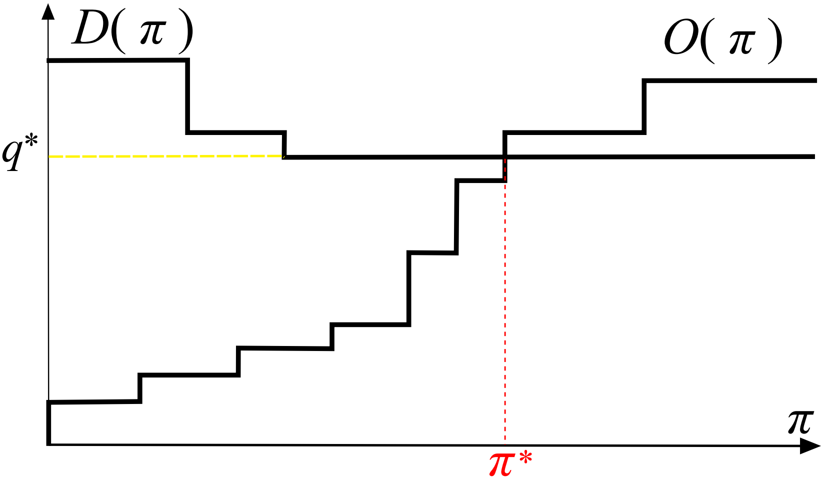

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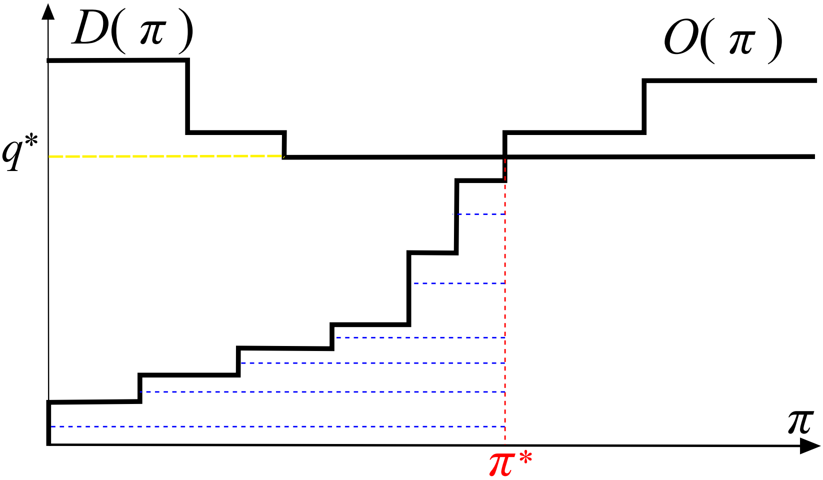
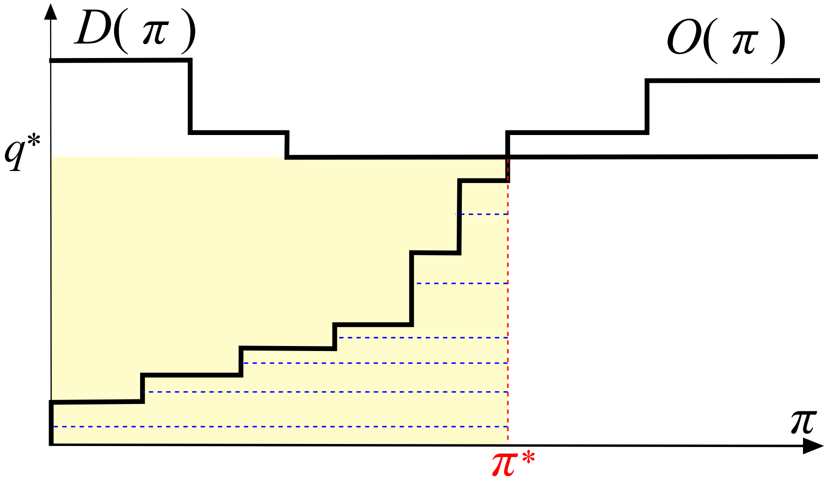



- Everyone paid at the clearing price $\pi^*$

# The Pay-as-Clear Model, graphically




- Everyone paid at the clearing price $\pi^*$ $\implies$ total system cost $= \pi^* q^*$

# Everyone loves it because it's an LP

- Let's simplify: fixed demand $\equiv$ only sell offers ($\approx$ true in electricity)

- Primal / dual market clearing problems:

$$\min \ \sum_{j \in S} sp_j s_j \tag{1}$$
$$0 \leq s_j \leq sq_j \quad j \in S \tag{2}$$
$$\sum_{j \in S} s_j = d \tag{3}$$

$$\max \ \sum_{j \in S} sq_j \eta_j \ + \ \pi d \tag{4}$$
$$\eta_j + \pi \leq sp_j \ , \ \eta_j \leq 0 \quad j \in S \tag{5}$$

- Primal feasibility + dual feasibility + complementary slackness

$$\eta_j (s_j - sq_j) = 0 \qquad j \in S \tag{6}$$
$$(sp_j - \eta_j - \pi) s_j = 0 \qquad j \in S \tag{7}$$

$\Longrightarrow$ optimal $\pi^*$ the market clearing price

- Easy to see with just a bit of logic, but I like it different

# I love it even more because it's a Lagrangian

- Lagrangian relaxation of (1)–(3) w.r.t. (3) (multiplier $\pi$):

$$\min \; \sum_{j \in S} sp_j s_j + \pi( d - \sum_{j \in S} s_j ) = \pi d + \sum_{j \in S} ( sp_j - \pi ) s_j \qquad (8)$$

$$0 \leq s_j \leq sq_j \qquad j \in S \qquad (2)$$

  clearly separable in $j$, (3) only linking constraint

- $\pi > sp_j \implies sp_j - \pi < 0 \implies s^*_j(\pi) = sq_j$, i.e., as soon as the price is $>$ than my asking price I sell everything

- $\phi(\pi)$ dual function, $g(\pi) = d - \sum_{j \in S} s^*_j(\pi)$ its (sub)gradient

- $\pi^*$ optimal $\iff g(\pi^*) = 0 \iff \sum_{j \in S} s^*_j(\pi) = d$

- Adjust $s^*_j$ for which $sp_j = \pi^*$ to make it work (nondifferentiable)

- Not too important, just faster than juggling complementary slackness

# It has many nice properties

- Day-Ahead Market solved every day for every hour of the next day (plus primary/secondary reserve markets, ancillary services, ...)
- Long-term average gives long-term price signal: how much is worth investing in new generation (5+y to build, 10+y amortization, ...)
- Hourly price gives short-term price signal: how much energy is worth in this specific hour, crucial for Unit Commitment (peak shaving ...)
- Pay-as-bid (apparently) not as good (don't ask ...)
- Can resist complications: variable demand, (DC) network constraints, strange market constructs (unique national price, complex bids, ...) because it's an LP or MPCC $\equiv \mathcal{NP}$-hard, but we are happy with that
- Everyone's happy then, so what's the problem?

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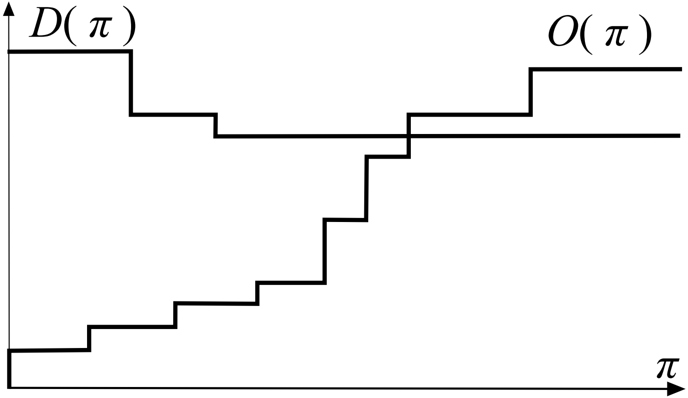
# The Problem

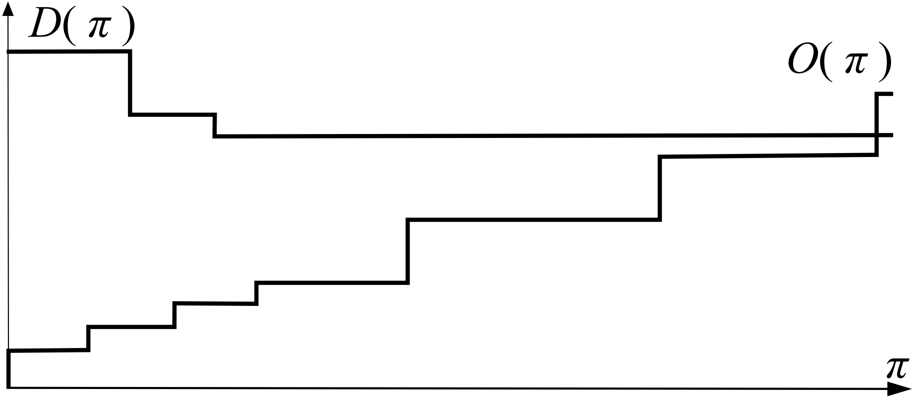
# The Problem – Root Cause

# The Problem – Technical – graphically




- W.r.t. "normal" times

# The Problem – Technical – graphically




- W.r.t. "normal" times gas prices shot up

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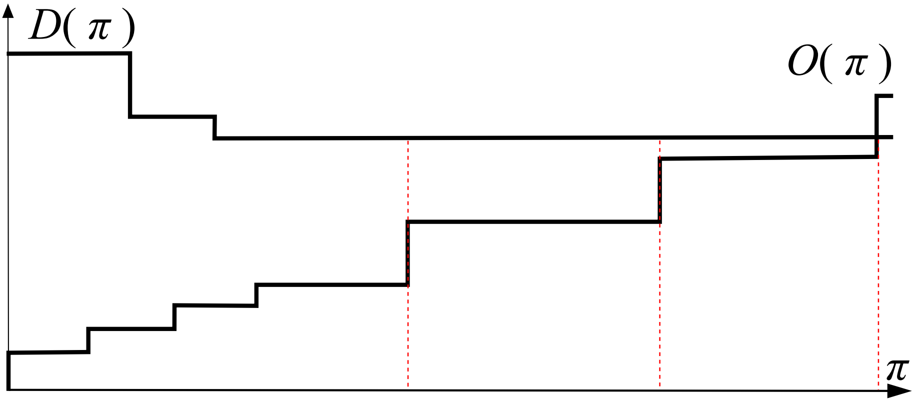


- W.r.t. "normal" times gas prices shot up $\Longrightarrow$ gas-fired units increased $sp_j$

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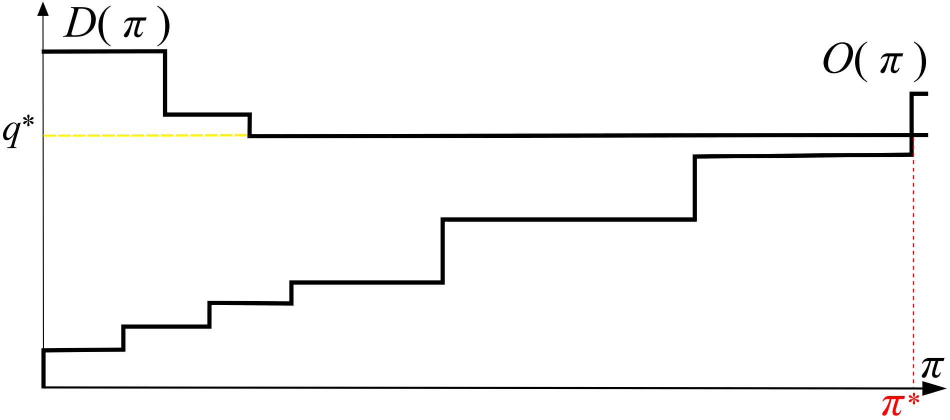


- W.r.t. “normal” times gas prices shot up $\Longrightarrow$ gas-fired units increased $sp_j$
- $\pi^*$ shot up,

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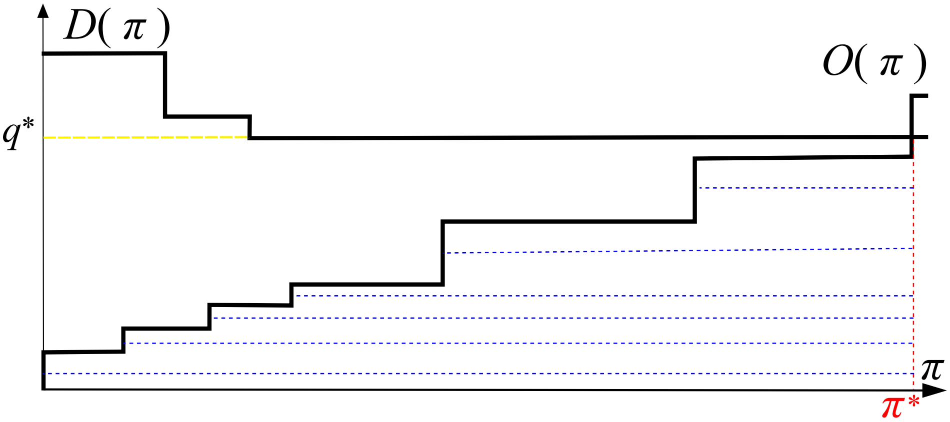


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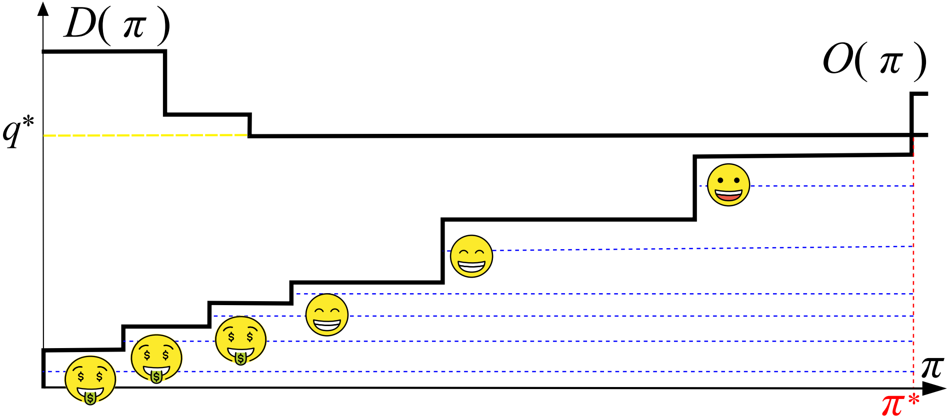


- W.r.t. "normal" times gas prices shot up $\Longrightarrow$ gas-fired units increased $sp_j$
- $\pi^*$ shot up, producers corked spumante,

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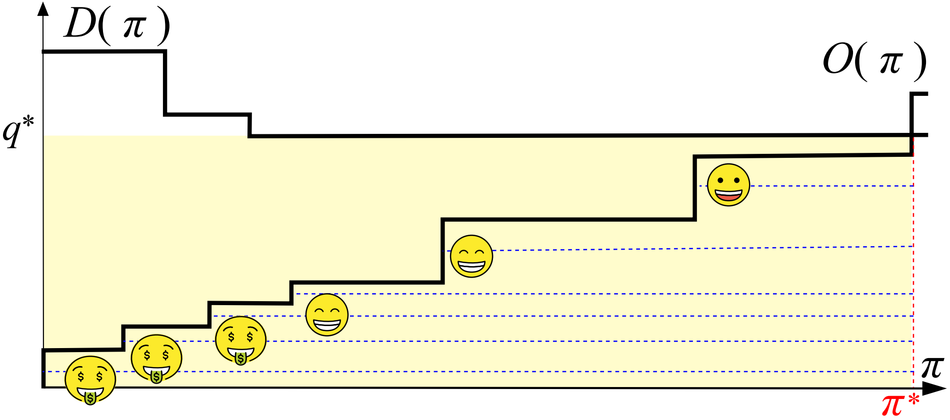


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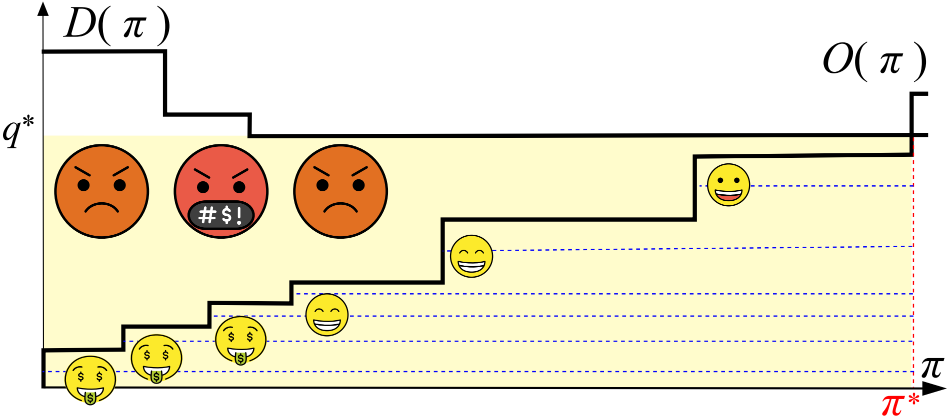


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- $\pi^*$ shot up, producers corked spumante, consumers went down in flames

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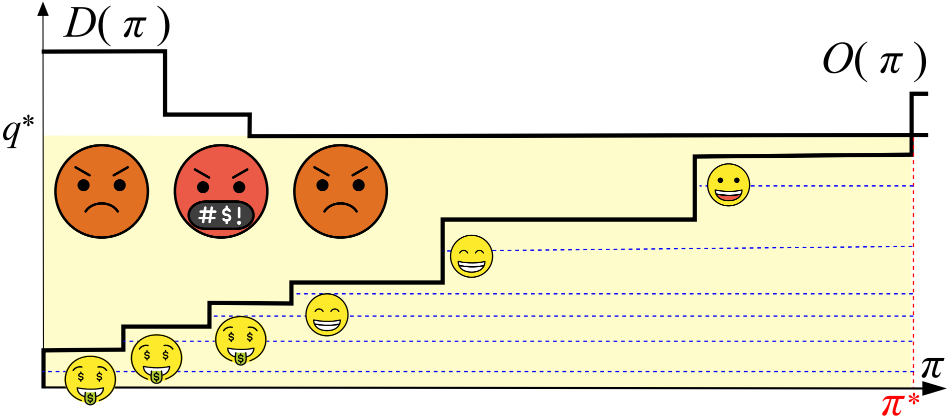


- W.r.t. "normal" times gas prices shot up $\Longrightarrow$ gas-fired units increased $sp_j$
- $\pi^*$ shot up, producers corked spumante, consumers went down in flames
- The real energy cost had increased way less than the clearing price

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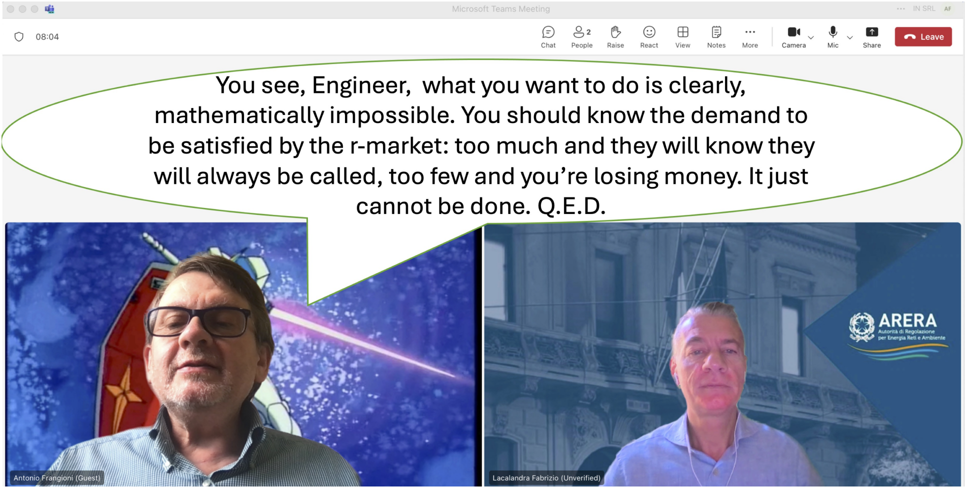
# Us discussing energy problems goes a loooooong way

# What Fabrizio wanted

- Partition $S = S^r \cup S^g$: $S^r$ = reserved (renewables) market, $S^g$ = general (gas-fired) market
- Have producers in each market only slog it out among themselves $\Longrightarrow$ different prices for the same commodity, reflecting fundamentally different cost structure of sets of producers
- Both markets must satisfy the same demand
- Economists were sharpening forks and lighting up pyres, but that was not what was bothering me
- How can you have two markets be separate, and then "magically" agree on the demand each will satisfy?
- Never believed in magic, and never were afraid to tell
- Some wishes just never come true, I'm not the fairy godmother!

# How the discussion went



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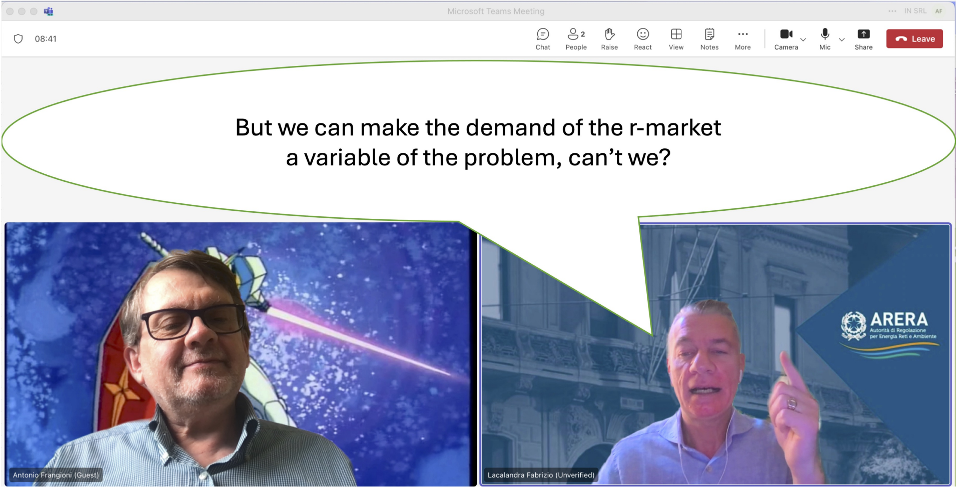

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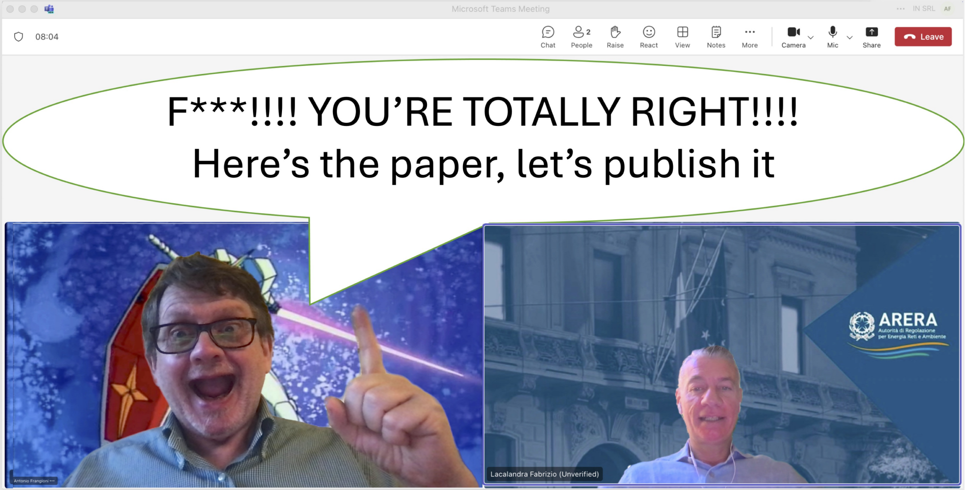

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# Segmented-Pay-as-Clear, version I: bilevel program

$$\min_{d^r, d^g} \; \pi^r d^r + \pi^g d^g$$

$$d^r + d^g = d \;\; , \;\; d^r \geq 0 \;\; , \;\; d^g \geq 0$$

$$\pi^r \in \left\{ \begin{array}{ll} \arg\max_{\pi^r, \eta} & \sum_{j \in S^r} sq_j \eta_j \; + \; \pi^r d^r \\ & \eta_j + \pi^r \leq sp_j \, , \, \eta_j \leq 0 \quad j \in S^r \end{array} \right.$$

$$\pi^g \in \left\{ \begin{array}{ll} \arg\max_{\pi^g, \eta} & \sum_{j \in S^g} sq_j \eta_j \; + \; \pi^g d^g \\ & \eta_j + \pi^g \leq sp_j \, , \, \eta_j \leq 0 \quad j \in S^g \end{array} \right.$$

- The two markets compete among them for the demand
- Producers in each market compete among them as usual
  but not directly with producers in the other market
- The objective is bilinear (nonconvex), but bilevels are hard anyway:
  throw it to `Gurobi` via `BilevelJump`, it'll eat it
- Cannot do worse than PaC (will be obvious shortly)

# Segmented-Pay-as-Clear, version II: MPCC

$$\min \pi^r d^r + \pi^g d^g \tag{9}$$

$$d^r + d^g = d \quad , \quad d^r \geq 0 \quad , \quad d^g \geq 0 \tag{10}$$

$$0 \leq s_j \leq sq_j \qquad j \in S \tag{2}$$

$$\textstyle\sum_{j \in S^r} s_j = d^r \tag{11}$$

$$\eta_j + \pi^r \leq sp_j \quad , \quad \eta_j \leq 0 \qquad j \in S^r \tag{12}$$

$$\textstyle\sum_{j \in S^g} s_j = d^g \tag{13}$$

$$\eta_j + \pi^g \leq sp_j \quad , \quad \eta_j \leq 0 \qquad j \in S^g \tag{14}$$

$$\eta_j ( s_j - sq_j ) = 0 \qquad j \in S \tag{15}$$

$$( sp_j - \eta_j - \pi^r ) s_j = 0 \qquad j \in S^r \tag{16}$$

$$( sp_j - \eta_j - \pi^g ) s_j = 0 \qquad j \in S^g \tag{17}$$

- Bilinear objective (9) and complementarity constraints (15)–(17)
- But one bilinearity can kill the other

# Hocus Pocus, nonlinearity vanish! Thanks Medhi Madani

- Actually, a well-known trick in this line of business
- Multiply (30) by $\pi^r$ to get

$$\pi^r \sum_{j \in S^r} s_j = \pi^r d^r$$

- Sum (16) over $j \in S^r$ and rearrange:

$$\sum_{j \in S^r} (sp_j - \eta_j) s_j = \pi^r \sum_{j \in S^r} s_j = \pi^r d^r$$

- Now (15) gives $\eta_j s_j = \eta_j sq_j$, thus

$$\pi^r d^r = \sum_{j \in S^r} (sp_j s_j - \eta_j sq_j) \tag{18}$$

- Repeat the arguments for $j \in S^g$ and $\pi^g$ to get

$$\pi^r d^r + \pi^g d^g = \sum_{j \in S} (sp_j s_j - \eta_j sq_j) \tag{19}$$

- One nonlinearity has vanished in thin air

# Segmented Prices-as-Clear, the Final Reformulation

- Only one market, but with a limit on the energy from $S^r$:

$$\min \ \sum_{j \in S} sp_j s_j \qquad (1)$$
$$0 \leq s_j \leq sq_j \quad j \in S \qquad (2)$$
$$\sum_{j \in S^r} s_j \leq d^r \qquad (20)$$
$$\sum_{j \in S} s_j = d \qquad (3)$$

$$\max \ \sum_{j \in S} sq_j \eta_j \ + \ \pi d \ + \ \pi^r d^r \qquad (21)$$
$$\eta_j + \pi \leq sp_j \quad j \in S^g \qquad (22)$$
$$\eta_j + \pi + \pi^r \leq sp_j \quad j \in S^r \qquad (23)$$
$$\eta_j \leq 0 \quad j \in S \qquad (24)$$
$$\pi^r \leq 0 \qquad (25)$$

- g-market clears at $\pi$, r-market clears at $\pi + \pi^r < \pi$ (cf. (25)) $\Longrightarrow$ cannot be worse than PaC, equal if $d^r$ "too large" $\Longrightarrow$ $\pi^r = 0$ $\Longrightarrow$
$(\pi + \pi^r) \sum_{j \in S^r} s_j + \pi(d - \sum_{j \in S^r} s_j) = \pi d + \pi^r \sum_{j \in S^r} s_j = \pi d + \pi^r d^r$

- Compact reformulation of SPaC, can be linearised using (18):

$$\min \left\{ \pi d + \pi^r d^r \ : \ (\pi, \pi^r) \in \operatorname{argmax} \{ (21)\text{–}(25) \} \right\}$$

- Easy to write as MPCC using (1)–(25) + their complementary slackness

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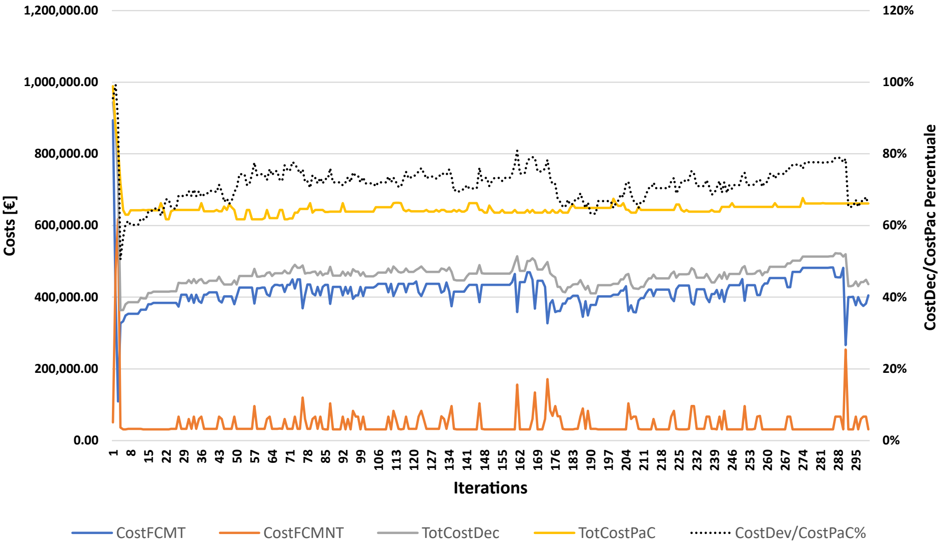
# Can it be gamed?

- Of course it can: everyone offers the same (collusion)
- Bad case: all bids on g-market same as PaC, all on the r-market $\pi^\star - \varepsilon$
  $\Longrightarrow\ \pi^g = \pi^*$, $\pi^r = -\varepsilon\ \equiv$ negligible decrease of total system cost
- However, this reeks of collusion three miles off
- A result is proven in the paper that roughly speaking says:
  if enough bids in the r-market are "fair" then
  strategic bidders in the r-market can only achieve a fraction of $\pi^*$-PaC
  that decreases as $d^r \to d$ (the size of the r-market increase)
- Complicated, but: if $d^r = 0.8d$ + enough bids in $S^r$ "low", then
  cost on r-market $\leq 33\%$ of $\pi^*$−PaC $\equiv$ large decrease of system cost
- Many ifs and buts, but it does seem to indicate:
  you need a rather serious collusion to neuter the effect

# Would it work in practice?

- Hard to say, can try to get clues by Agent-Based simulations
- Simple rules to emulate behaviour of (not-too-smart) rational players:
  - if my offer was only partly accepted I very likely stay put
  - if my offer was totally accepted I may (not too likely) increase it
  - if my offer was rejected I will likely decrease it
  - if my offer is rejected for $k$ consecutive rounds I will surely decrease it
  - anyway I will never offer below my baseline (CAPEX + OPEX) realistic cost (wind, solar, ROR hydro, hydro, coal, CGT, gas turbines, . . . )
- Tested with demand a varying fraction of $d^{\max}$ (high/low demand hours)
- Lots of parameters, set with common sense (Fabrizio knows) + minimal tuning (don't want to be cherry-picking your agents)
- Not a proof by all means, but an accepted way to get some clues

# AB simulations results I




- System costs for the 30-agents test case with $d = 60\% d^{\max}$

# AB simulations results II

| $d \;/\; d^{\max}$ | 40% | 45% | 50% | 55% | 60% | 65% | 70% | 75% | 80% | 85% |
|---|---|---|---|---|---|---|---|---|---|---|
| $\pi^r$ | 73.29 | 85.12 | 96.53 | 97.19 | 100.09 | 100.77 | 104.77 | 106.16 | 111.06 | 110.69 |
| $\pi^g$ | 122.57 | 123.43 | 132.05 | 139.85 | 145 | 147.66 | 150.83 | 153.19 | 158.14 | 164.31 |
| $\pi^{PaC}$ | 74.74 | 122.22 | 131.67 | 139.47 | 144.79 | 147.43 | 150.7 | 152.98 | 157.79 | 164.02 |
| $C(S^r)/C(S^g)$ | 97.487 | 31.25 | 6.044 | 3.01 | 2.03 | 1.508 | 1.238 | 1.026 | 0.899 | 0.753 |
| TC_SPaC/TC_PaC | 98.36% | 70.24% | 76.19% | 75.40% | 76.99% | 78.26% | 80.48% | 81.74% | 83.44% | 82.88% |
| Min | 74.0% | 66.4% | 71.0% | 70.8% | 72.7% | 74.9% | 77.0% | 78.2% | 79.0% | 78.2% |
| Max | 101.5% | 100.7% | 99.7% | 99.3% | 98.7% | 99.6% | 100.4% | 100.0% | 99.1% | 100.3% |
| Std | 3.7% | 3.3% | 2.7% | 2.7% | 2.6% | 2.3% | 2.9% | 2.9% | 2.9% | 3.3% |

- Sample results with 100 agents (other similar except with 6, too few)
- Variable $d \;/\; d^{\max}$ simulates demand fluctuation over day
- Short-term price signal still there ($\Longrightarrow$ long-term one)
- Consistent reduction in total cost save for very low demand
- Quite stable results (low std)

# AB simulations results takeaways

- System does reach some sort of (realistic?) equilibrium
- Agents correctly learn how to exploit different demand scenarios
- Long- and short-term price signals on $\pi^g$ conserved ($\approx$ PaC)
- $S^r$ producers still more than decently retributed (realistic prices), just not as much as $S^g$ producers (makes sense)
- Significant total system cost reductions (wish I could have 0.001% ...), yet not unrealistic one (historical bids gives $>$ 80%, had tell a referee)
- All in all, surprisingly (too?) reasonable results

# Outline


1. A brief introduction to Pay-as-Clear (energy) markets
2. The Problem
3. Discussing the problem
4. Our solution, in details
5. Can it work?
6. Can it be applied to practical markets?
7. Conclusions

# Case of elastic demand

$$\min \pi \sum_{i \in B} b_i - \pi^r d^r \tag{26}$$

$$0 \le s_j \le sq_j \qquad j \in S \tag{27}$$

$$0 \le b_i \le bq_i \qquad i \in B \tag{28}$$

$$\sum_{j \in S} s_j = \sum_{i \in B} b_i \tag{29}$$

$$\sum_{j \in S^r} s_j \le d^r \le \sum_{i \in B} sq_i \tag{30}$$

$$\mu_i + \pi \ge bp_i \quad , \quad \mu_i \ge 0 \qquad i \in B \tag{31}$$

$$\eta_j + \pi^r - \pi \ge -sp_j \quad , \quad \eta_j \ge 0 \qquad j \in S^r \tag{32}$$

$$\eta_j - \pi \ge -sp_j \quad , \quad \eta_j \ge 0 \qquad j \in S^g \tag{33}$$

$$\sum_{i \in B} (bp_i b_i - \mu_i bq_i) \ge \sum_{j \in S} (\eta_j sq_j + sp_j s_j) \tag{34}$$

$$\pi^r (d^r - \sum_{j \in S^r} s_j) = 0 \quad , \quad pi^r \ge 0 \tag{35}$$

$$\eta_j (sq_j - s_j) = 0 \qquad j \in S \tag{36}$$

$$\mu_i (bq_i - b_i) = 0 \qquad i \in B \tag{37}$$

$$(\eta_j + \pi^r - \pi + sp_j) s_j = 0 \qquad j \in S^r \tag{38}$$

$$(\eta_j - \pi + sp_j) s_j = 0 \qquad j \in S^g \tag{39}$$

# Important note: economic equilibrium of the system

- Objective (26) can be linearised via (18)
- Same linearization trick: (40) gives $\pi b_i = (bp_i - \mu_i) b_i$,
  (37) gives $\mu_i bq_i = \mu_i b_i \implies \pi b_i = bp_i b_i - \mu_i bq_i$
- Of course, same for selling bids (both in $S^r$ and in $S^g$)
- Thus (linear) economic equilibrium constraint (34) ensures
  buyers are paying no less than sellers are getting (enough money around)
- Difference can be positive, have to be given back to buyers as a
  discount on their bills $\implies$ actual energy price $<$ clearing price $\pi^*$
- Weird: some $i \in B$ not accepted even if the actual energy price $< bp_i$,
  to be well thought-of from the regulatory viewpoint (if ever ...)

# Case of elastic demand and (DC) network constraints

$$\min \ \pi \textstyle\sum_{i \in B} b_i - \pi^r d^r \tag{26}$$

$$(27), (30), (28), (29), (31), (35), (36), (37), (40) \tag{42}$$

$$m_l \leq \textstyle\sum_{k \in \mathcal{K}} S_l^k \big( \sum_{i \in I(k)} b_i - \sum_{j \in J(k)} s_j \big) \leq M_l \qquad l \in \mathcal{L} \tag{43}$$

$$\pi^k = \pi + \textstyle\sum_{l \in \mathcal{L}} S_l^k (\lambda_l^+ - \lambda_l^-) \qquad k \in \mathcal{K} \tag{44}$$

$$\eta_j + \pi^r - \pi^{k(j)} \geq -sp_j \ , \ \ \eta_j \geq 0 \qquad j \in S^r \tag{45}$$

$$\eta_j - \pi^{k(j)} \geq -sp_j \ , \ \ \eta_j \geq 0 \qquad j \in S^g \tag{46}$$

$$\textstyle\sum_{i \in B} (bp_i b_i - \mu_i bq_i) - \sum_{j \in S} (\eta_j sq_j + sp_j s_j) \geq \sum_{l \in \mathcal{L}} (M_l \lambda_l^+ - m_l \lambda_l^-) \tag{47}$$

$$(\eta_j + \pi^r - \pi^{k(j)} + sp_j) s_j = 0 \qquad j \in S^r \tag{48}$$

$$(\eta_j - \pi^{k(j)} + sp_j) s_j = 0 \qquad j \in S^g \tag{49}$$

$$\lambda_l^- \big( \textstyle\sum_{k \in \mathcal{K}} S_l^k \big( \sum_{i \in I(k)} b_i - \sum_{j \in J(k)} s_j \big) - m_l \big) = 0 \qquad l \in \mathcal{L} \tag{50}$$

$$\lambda_l^+ \big( M_l - \textstyle\sum_{k \in \mathcal{K}} S_l^k \big( \sum_{i \in I(k)} b_i - \sum_{j \in J(k)} s_j \big) \big) = 0 \qquad l \in \mathcal{L} \tag{51}$$

$$\lambda_l^+ \geq 0 \ , \ \ \lambda_l^- \geq 0 \qquad l \in \mathcal{L} \tag{52}$$

# Adding the Italian Prezzo Unico Nazionale (PUN)

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- No, you don't really want to see it, just boring (check the paper)
- Take away: if you can do it with PaC, you can do it with SPaC
- MPCC is "lingua franca" of market models, SPaC very natural in MPCC: just add the bound constraint on $S^r$ and the corresponding dual variable
- A few not-entirely-trivial issues (economic equilibrium), but very doable
- Almost obvious multiple segmentation of seller market: just add multiple copies of the constraint and of the dual variable
- Multiple segmentation of buyer market possible too in the same way (could it ever make sense? who knows?)
- All in all a simple yet flexible modification of PaC, but MPCC = hard: how about solving it?

# The algorithmic aspects

- MPCC in general $\mathcal{NP}$-hard, market clearing has to be "quick"
- Routinely done already in practice: Italian PUN, complex offers, ...
- SPaC not fundamentally more difficult than most practical EU markets, MIP-ing complementarity OK because variables nicely bounded
- Besides, when $d^r$ is fixed it $\approx$ boils down to the original clearing problem (an LP if that was, $\approx$ whatever is currently being solved otherwise)
- Trivial approach: (cleverly) finitely sample $d^r$, return best solution found embarrassingly parallel (MOs can surely buy some large enough server)
- Possibly Benders' style approach (but subproblem may not be convex)
- Typical problem our community loves to deal with,
  I'd be rather optimistic we can crack it if the interest is there
- But is the interest there? Will it ever be used?

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  should different producers of the same fungible good be paid differently?
- My humble take: in a real market probably not, but
  the energy market is not a real market, so why not?
- Maybe I'm completely wrong (only a humble optimizer), time will tell

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- Pity because the general idea looks nice and easily applicable
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