Revisiting minimum profit conditions in uniform price day-ahead electricity auctions

Energy Day Workshop, 16th April 2018

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CORE and LSM
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Content

- **I – Context and key issues at stake**
  - Context
  - Non-convex bids: which non-convexities ?
  - Market equilibrium supported by uniform prices (MESUP)
  - Key issues with non-convexities and non-existence of a MESUP

- **II – EU rules and minimum profit conditions in uniform price auctions**
  - A closer look at **current PCR bidding products**
  - Start up costs recovery conditions in practice and academic literature
  - A new "EU-like" approach to minimum profit (resp. maximum payment) conditions

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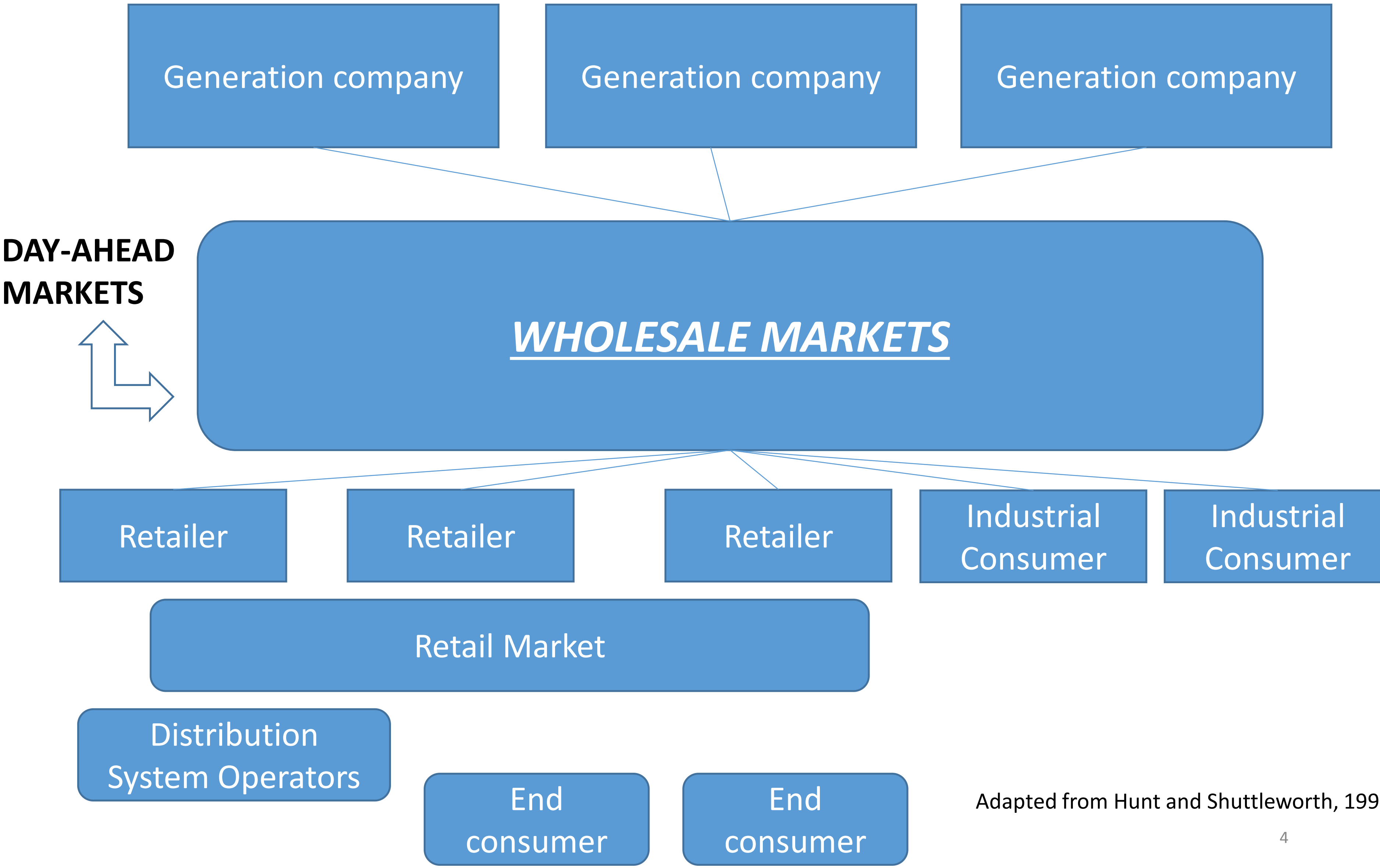
European day-ahead auctions



Adapted from Hunt and Shuttleworth, 1996

European day-ahead auctions

NEMOs ? → EPEX SPOT, Nord Pool, etc

1. Supply orders
2. Demand orders
3. Network transmission constraints

Computations by

“Nominated Electricity Market Operators”

(NEMO) in the European Legislation

(CACM Guidelines)

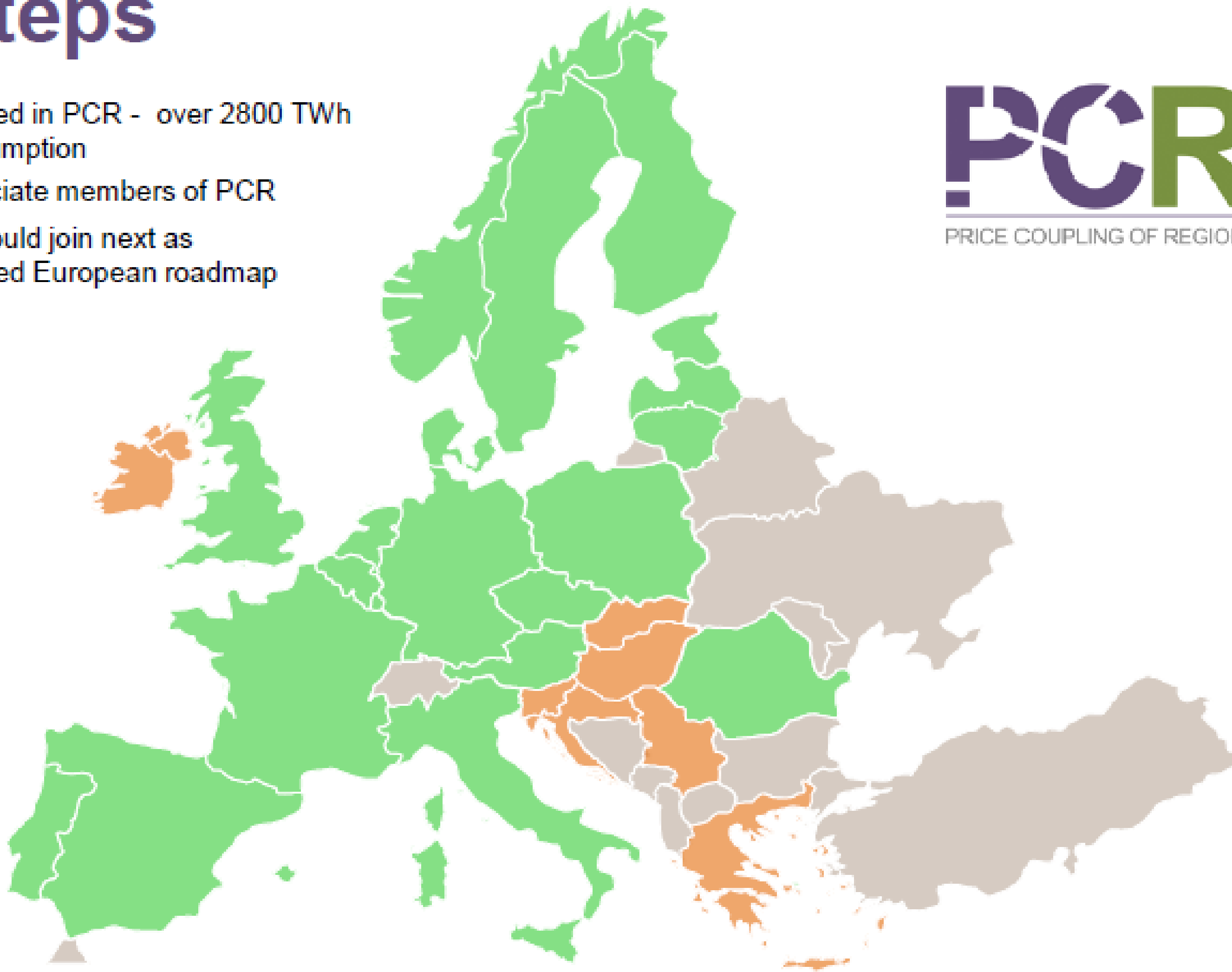
1. Market prices
2. Exchanged quantities and payments
3. Network flows

Day “D-1”

Day “D”: *actual delivery*

Towards Single European Market: Next Steps

- Markets included in PCR - over 2800 TWh of yearly consumption
- Markets associate members of PCR
- Markets that could join next as part of an agreed European roadmap



PRICE COUPLING OF REGIONS

(PCR official documentation)

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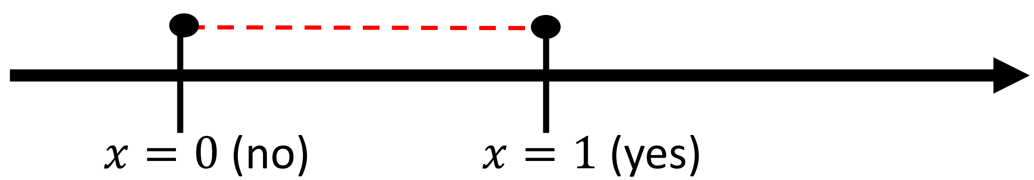
Which non-convexities ?

A *binary variable* for a « yes/no decision » yields a non-convex setting ... and ***classical strong duality results do not hold anymore***



1. Technical constraints
   - Minimum power output levels
   - Minimum up and down times
2. Costs structure
   - Start up costs / shut down costs

Yes / no
“unit commitment decisions”
(starting the plant or not)

…

Introducing non-convexities

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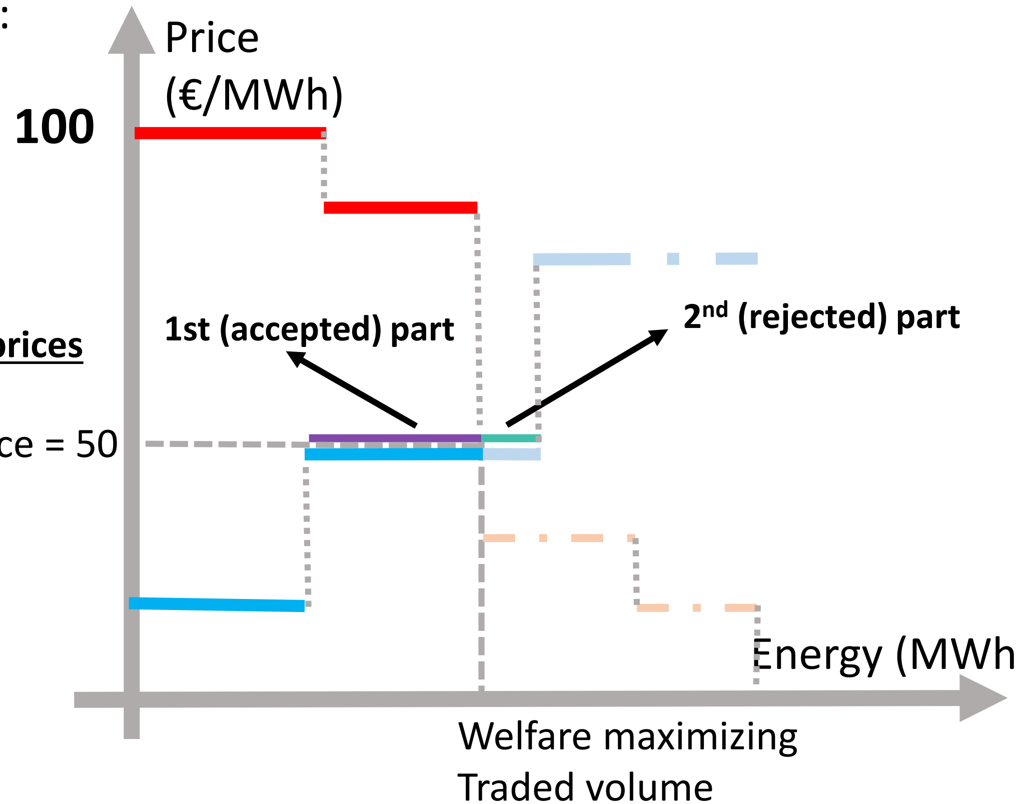
Market equilibrium supported by uniform prices

Given the computed market price "MCP":



"Everyone is perfectly happy" :

<u>"accepted volume decisions"</u>

<u>are optimal decisions of particip. facing market prices</u>

KEY:

« **fractionally accepted bids set the price** »

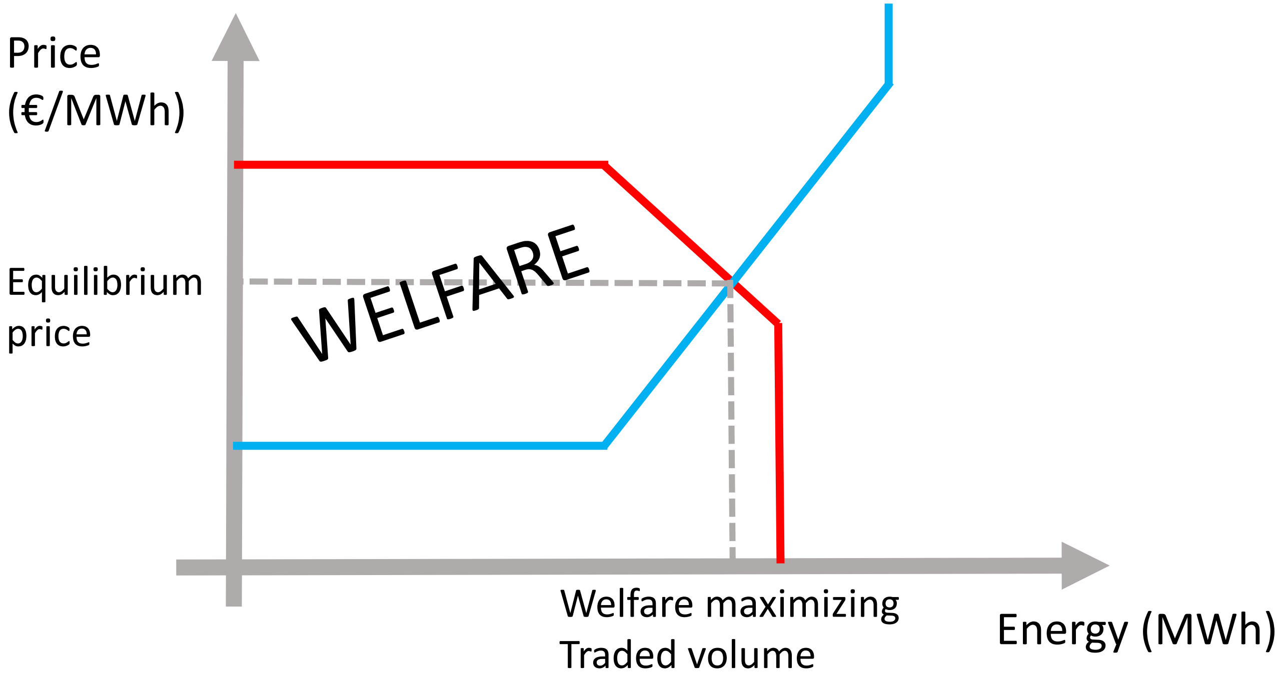
« Marginal units set the price »:

marginal pricing makes sense in a convex market as it corresponds to a market equilibrium

Market equilibrium supported by uniform prices

<u>Paul Samuelson's Principle [1]</u> - *in a well-behaved convex context:*

<u>a welfare maximizing solution corresponds to a market equilibrium and vice-versa</u> (duality/optimality conditions in convex optimization)



Paul Samuelson

Nobel prize in economics in 1970

Samuelson's principle
-> also for spatially separated markets …

pp. 283-284:

"The *first explicit statement that competitive market price is determined by the intersection of supply and demand functions* seems to have been

given by A. A. Cournot in 1838 in connection, curiously enough, with the more complicated problem of price relations between two spatially separate markets-such as Liverpool and New York. The latter problem, that of "communication of markets," has itself a long history, involving many of the great names of theoretical economics. [...]"

« Marginal units set the price »:
marginal pricing makes sense in a convex market as it corresponds to a market equilibrium

But may give odd/unintuitive results in the *non-convex* case !

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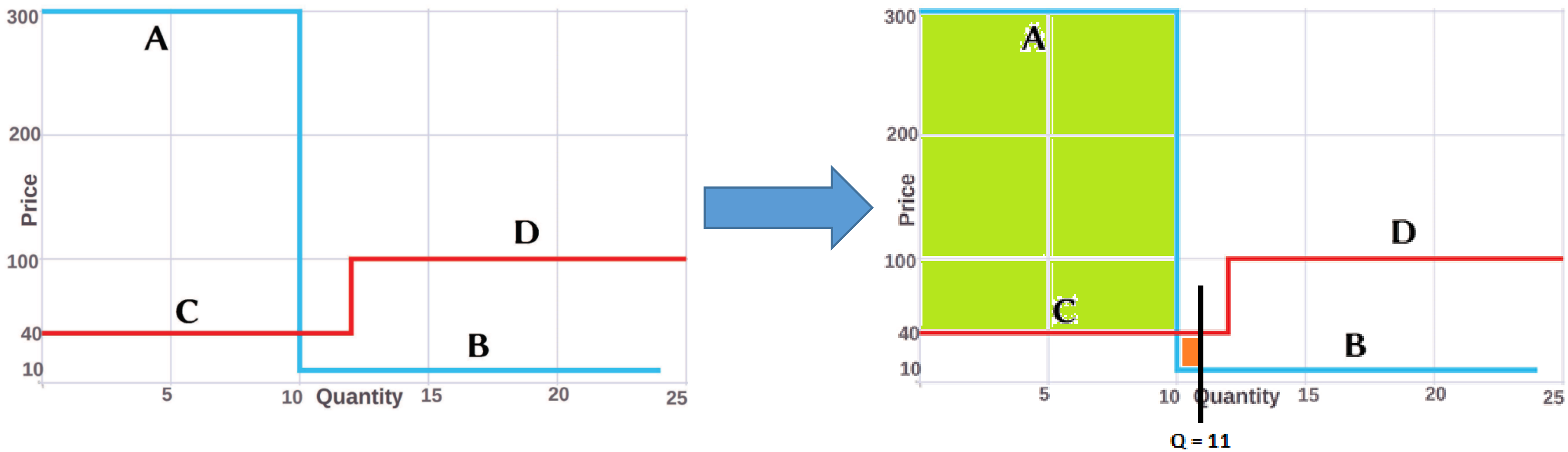
Key issues with non-convexities

Case A - Indivisibilities

Welfare Maximizing Solution:
Fully accept A + 11MW from C
+ 1 MW from B



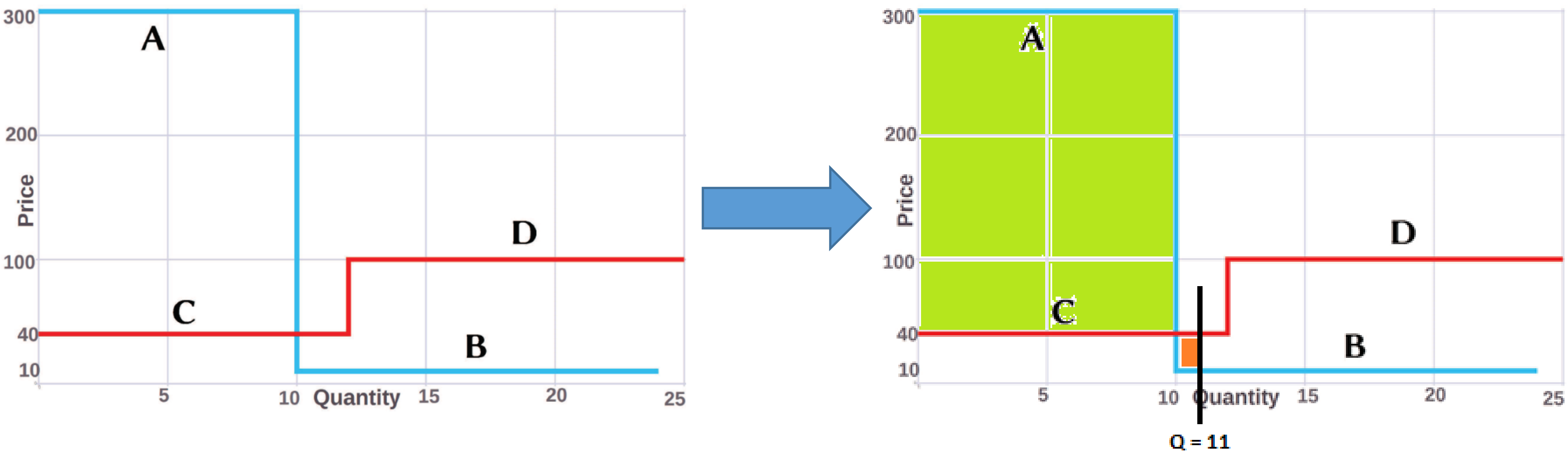
« Welfare = [green] - [orange] »

Bids	Quantity (MW)	Limit Price (€/MW)	Min. Acceptance Ratio
A (buy)	10	300	-
B (buy)	14	10	-
C (sell)	12	40	11/12 of 12 = 11 MW
D (sell)	13	100	-

Key issues with non-convexities

Case A - Indivisibilities

Welfare Maximizing Solution:
Fully accept A + 11MW from C
+ 1 MW from B



- Market equilibrium supported by a uniform price ?
  market price = 10 € /MW (B is fractionally accepted and sets the price)

- C would prefer to be fully rejected … (is out-of-the-money)

- <u>Hence: no market equilibrium supported by a uniform price exists here</u>

Notation: maximizing welfare ?

$$\max_{x,u}\ (300)10x_a + (10)14x_b - (40)12x_c - (100)13x_d$$

$$10x_a + 14x_b - 12x_c - 13x_d = 0$$
$$x_a \leq 1$$
$$x_b \leq 1$$
$$x_d \leq 1$$
$$x_c \leq u_c$$
$$x_c \geq (11/12)u_c$$
$$u \leq 1$$
$$x, u \geq 0$$
$$u_c \in \{0, 1\}$$

Optimal solution → $x_a = 1, x_b = \frac{1}{10}, x_c = \frac{11}{12}, x_d = 0$

$$\max_{(u,x)} \sum_c \Big(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic} \Big)$$

$$\sum_c \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

$$
\begin{aligned}
x_{ic} &\leq u_c && \forall ic \in I_c, c \in C \ [s_{ic}^{max}] \\
x_{ic} &\geq r_{ic} u_c && \forall ic \in I_c, c \in C \ [s_{ic}^{min}] \\
u_c &\leq 1 && \forall c \in C [s_c] \\
u &\geq 0 && \\
u_c &\in \mathbb{Z} &&
\end{aligned}
$$

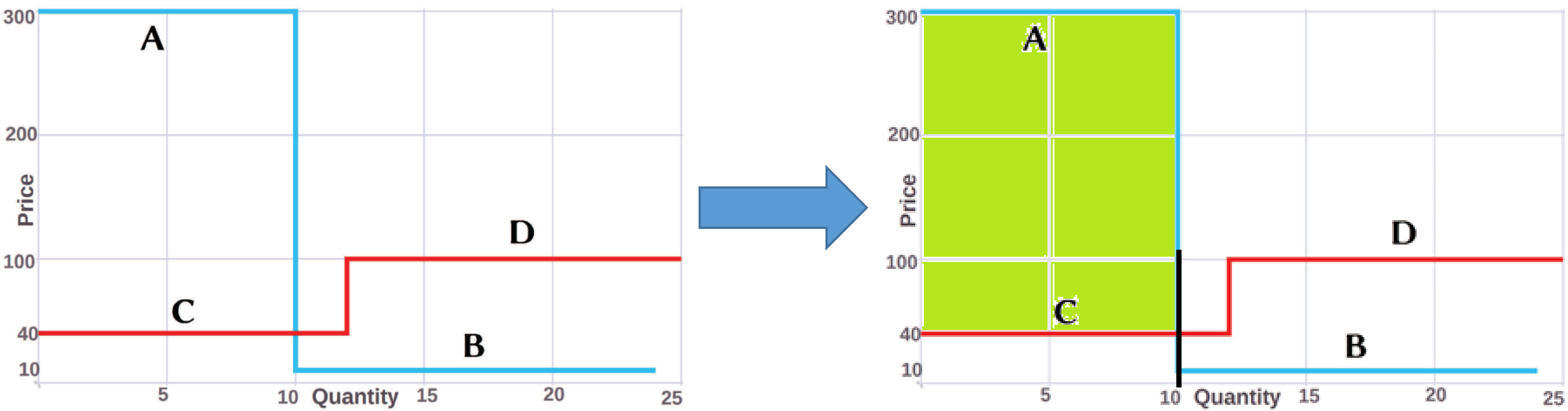
$Q < 0$ for sell orders, $Q > 0$ for buy orders,

$r_{ic} \in [0;1]$ min. acceptance ratio

Key issues with non-convexities

Case B – start up costs

Welfare Maximizing Solution:
Fully accept A + 10MW from C



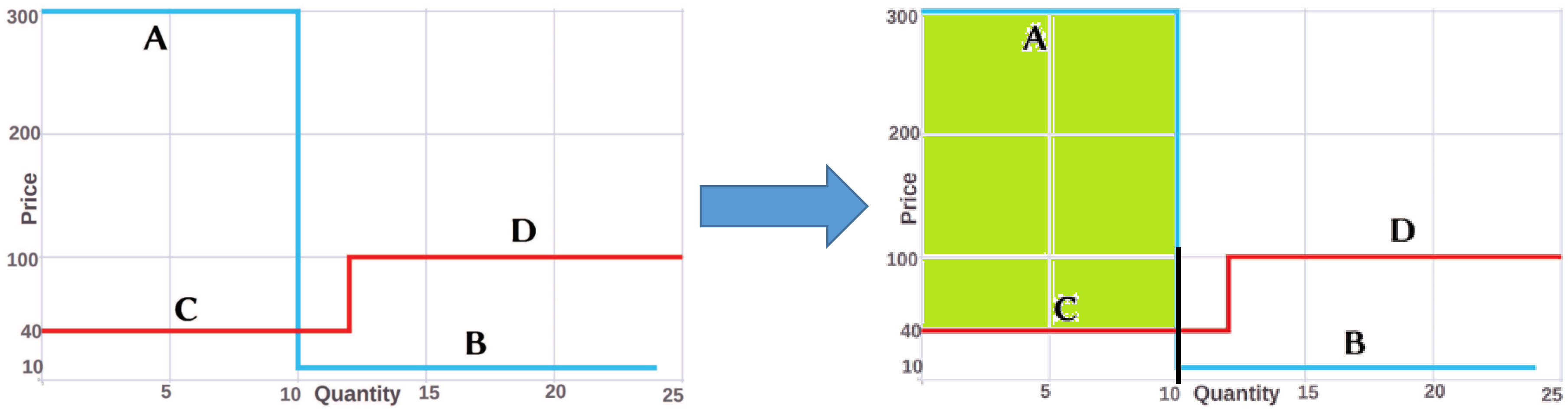
« Welfare = - 200 € »

Bids	Quantity (MW)	Limit Price (€/MW)	Start up costs
A (buy)	10	300	-
B (buy)	14	10	-
C (sell)	12	40	200 €
D (sell)	13	100	-

Key issues with non-convexities

Case B – start up costs

Welfare Maximizing Solution:
Fully accept A + 10MW from C



- Market equilibrium supported by a uniform price ?
  market price = 40 € /MW (C is fractionally accepted and sets the price)

- C not recovering its start up costs of 200 €
  would prefer to be fully rejected …

- <u>Hence: no market equilibrium supported by a uniform price exists here</u>

Maximizing welfare ?

Example 1.2:

$$\max_{x,u}\ (300)10x_a + (10)14x_b - (40)12x_c - (100)13x_d - 200u_c$$

$$10x_a + 14x_b - 12x_c - 13x_d = 0 \tag{17}$$
$$x_a \leq 1 \tag{18}$$
$$x_b \leq 1 \tag{19}$$
$$x_d \leq 1 \tag{20}$$
$$x_c \leq u_c \tag{21}$$
$$u \leq 1 \tag{22}$$
$$x, u \geq 0 \tag{23}$$
$$u \in \{0, 1\} \tag{24}$$

Optimal solution → $x_a = 1, x_b = 0, x_c = \frac{10}{12}, x_d = 0$

$$\max_{(u,x)} \sum_c \left(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic}\right) - F_c u_c$$

$$\sum_c \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

$$x_{ic} \leq u_c \qquad \forall ic \in I_c, c \in C \; [s_{ic}^{max}]$$

$$x_{ic} \geq r_{ic} u_c \qquad \forall ic \in I_c, c \in C \; [s_{ic}^{min}]$$

$$u_c \leq 1 \qquad \forall c \in C [s_c]$$

$$u \geq 0, u_c \in \mathbb{Z}$$

$Q < 0$ for sell orders, $Q > 0$ for buy orders,

$r_{ic} \in [0; 1]$ min. acceptance ratio

More Generally, one could consider as well … (for the key issues here, “story is the same”)

- ***Several locations*** connected with linear transmission network models

- ***Multiperiod models with ramp constraints on generation***

The math. optimization view on the inexistence of a market equilibrium …

$$\max_{(u,x)} \sum_{c} \Big(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic} \Big) - F_c u_c$$

$$\sum_{c} \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

$$x_{ic} \leq u_c \qquad \forall ic \in I_c, c \in C \; [s_{ic}^{max}]$$

$$x_{ic} \geq r_{ic} u_c \qquad \forall ic \in I_c, c \in C \; [s_{ic}^{min}]$$

$$u_c \leq 1 \qquad \forall c \in C [s_c]$$

$$u \geq 0, u_c \in \mathbb{Z}$$

Primal constraints (feasible dispatch)

$$s_{ic}^{max} - s_{ic}^{min} + Q_{ic}\pi = P^{ic} Q_{ic} \qquad [x_{ic}]$$

$$s_c \geq \sum_{ic \in I_c} (s_{ic}^{max} - r_{ic} s_{ic}^{min}) - F_c \qquad [u_c]$$

$$s_c, s^{max}, s^{min} \geq 0$$

Dual constraints (prices)

$$s_{ic}^{max}(u_c - x_{ic}) = 0 \qquad \forall c, i \in I_c$$

$$s_{ic}^{min}(x_{ic} - r_{ic} u_c) = 0 \qquad \forall c, i \in I_c$$

$$s_c(1 - u_c) = 0 \qquad \forall c \in C$$

$$u_c(s_c - \sum_{i \in I_c} (s_{ic}^{max} - r_{ic} s_{ic}^{min}) + F_c) = 0 \qquad \forall c \in C$$

Compl. constraints (equilibrium)

Market equilibrium
with uniform prices
=
Optimality conditions
For the *continuous relax.*
of a welfare maximization

Most of the time,
incompatible with $u_c \in Z$

Key issues in non-convex markets

1. **Market equilibrium with uniform prices in non convex markets is a mathematical impossibility** (proof: cf. previous toy examples)

2. **Which bid quantities to match ? At which market price(s) ?**

3. **<u>Market Models/Pricing rules</u> specification:**

   1. **Bid types used to describe technical constraints and costs**
   2. **Admissible pairs of matched bids and market prices**
   3. **Settlement rules: how much someone is paying/is paid**
   4. **Objective: maximizing welfare, etc**

4. ***Given a market design*, in order to find (ideally) optimal solution(s):**
   1. **mathematical formulations**
   2. **Algorithms working with these formulations**

Some market models are much easier to handle than others from a computational point of view !

They can also make more sense from an economic point of view !

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Bidding Products and rules in EUPHEMIA/PCR

- **Classical bid curves** (“hourly bids”)
  - Users: all PXs in Europe
  - Describe marginal costs/utility without additional restrictions
  - Should be ‘at equilibrium’ (***e.g. fractionally accepted bids set the price***)
- **Block orders** (regular, linked, exclusive)
  - Users: EPEX and Nord Pool (France, Germany, Belgium, Norway, The Netherlands, etc)
  - In essence, they model ***indivisibilities <-> minimum power output levels over several hours***
  - Could be paradoxically rejected (and ***for those with min. ac. ratios, set price if marginal***)
- **MIC orders** (MIC for minimum income condition)
  - Users: OMIE (Spain and Portugal)
  - In essence, they model that ***start up costs should be recovered***
  - Ramping constraints of units could also be specified (in the “complex orders” …)
  - Could be paradoxically rejected (*with all dependent sub-bid curves which are otherwise cleared as classical bid curves if the bid MIC order is accepted*)
- **PUN orders**
  - Users: GME (Italy)
  - ***Demand*** in different bidding zones ***cleared at one unique price*** (Prezzo Unico Nazionale, weighted average of zonal prices + tolerance)
  - Acceptance according to PUN price + should be ‘in order of merit’ w.r.t. to bid price (if a PUN is rejected, all PUNs with a lower price will be rejected)

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Complex orders with a minimum income condition (MICs) in Spain

Input DATA for a complex order with a MIC

1. **Marginal cost bid curves** for each hour of the day
2. **Start up cost**
3. **Ad hoc variable costs** … (?) (no clear meaning, seems intended to model a "block-like condition" / indivisibilities)
4. Load gradient (ramping constraints) could be specified

IF a bid is accepted, the following Minimum Income Condition should be satisfied:

(Sold quantities)x(market prices) $\geq$ start up cost + (sold quantities) x (ad hoc variable cost)

Minimum income condition: basic formulation

$$(u_c = 1) \Longrightarrow \sum_{h \in H_c} (-Q_{hc} x_{hc}) p_m \geq F_c + \sum_{h \in H_c} (-Q_{hc} x_{hc}) V_c, \qquad (11)$$

With, F_c fixed costs, V_c variable cost, $(-Q_{hc} x_{hc})$ exec. quant.

Non-convex quadratic constraint but … **exact linearization without any aux. var.** in Madani & VV, A MIP framework for non-convex uniform price day-ahead electricity auctions, EURO Journal on Computational Optimization, 2017

Other options (academic literature):

As it is impossible ('most of the time') to enforce a full market equilibrium, i.e.: primal, dual and complementarity constraints.

Most previous other propositions:

- enforce primal and dual conditions
- Minimize complementarity constraints violations, i.e. sum of deviations from market equilibrium
- write ad hoc non-convex quadratic constraints to ensure minimum profit conditions which are approximated by linear constraints.

Drawbacks:

- *no control over which deviations are allowed*: optimality conditions e.g. for the TSOs not enforced (no spatial equilibrium) +losses could be incurred to the demand side in the 'basic version'
- Could be computationally challenging to solve large-scale instances
- Not possible to give an exact linearization of min. income conditions because missing some essential compl. constraints not enforced

Academic papers

Essentially this idea, with some interesting variants, in :

- Raquel Garcia-Bertrand, Antonio J. Conejo, and Steven Gabriel. Electricity market near-equilibrium under locational marginal pricing and minimum profit conditions, European Journal of Operational Research, 174(1):457-479, 2006
- Raquel Garcia-Bertrand, Antonio J. Conejo, and Steven A. Gabriel. Multi-period near-equilibrium in a pool-based electricity market including on/off decisions. Networks and Spatial Economics, 5(4):371-393, 2005.
- C. Ruiz, A.J. Conejo, and S.A. Gabriel. Pricing non-convexities in an electricity pool. Power Systems, IEEE Transactions on, 27(3):1334-1342, 2012
- Steven A. Gabriel, Antonio J. Conejo, Carlos Ruiz, and Sauleh Siddiqui. Solving discretely constrained, mixed linear complementarity problems with applications in energy. Computers and Operations Research, 40(5):1339 - 1350, 2013

General idea for previous approaches to minimum profit conditions in uniform price auctions …

$$\min_{\alpha,\beta,\gamma,\epsilon} \sum_{ic} \alpha_{ic} + \sum_{ic} \beta_{ic} + \sum_{c} \gamma_c + \sum_{c} \epsilon_c$$

$$\sum_{c} \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

$$x_{ic} \leq u_c \qquad \forall ic \in I_c, c \in C \ [s_{ic}^{max}]$$

$$x_{ic} \geq r_{ic} u_c \qquad \forall ic \in I_c, c \in C \ [s_{ic}^{min}]$$

$$u_c \leq 1 \qquad \forall c \in C [s_c]$$

$$u \geq 0, u_c \in \mathbb{Z}$$

Primal constraints (feasible dispatch)

$$s_{ic}^{max} - s_{ic}^{min} + Q_{ic}\pi = P^{ic} Q_{ic} \qquad [x_{ic}]$$

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$$\alpha_{ic} \geq s_{ic}^{max}(u_c - x_{ic}) \qquad \forall c, i \in I_c$$

$$\beta_{ic} \geq s_{ic}^{min}(x_{ic} - r_{ic} u_c) \qquad \forall c, i \in I_c$$

$$\gamma_c \geq s_c(1 - u_c) \qquad \forall c \in C$$

$$\epsilon_c \geq u_c(s_c - \sum_{i \in I_c} (s_{ic}^{max} - r_{ic} s_{ic}^{min}) + F_c \qquad \forall c \in C$$

Compl. constraints (equilibrium)

+ ad hoc
non-convex quadratic constraints
to ensure minimum profit
conditions
(then linear **approx**.)

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- Steven A. Gabriel, Antonio J. Conejo, Carlos Ruiz, and Sauleh Siddiqui. Solving discretely constrained, mixed linear complementarity problems with applications in energy. Computers and Operations Research, 40(5):1339 - 1350, 2013

General previous approach for minimum profit conditions in uniform price auctions …

$$\min \sum_c s_c - \sum_c \left(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic}\right) - F_c u_c$$

$$\sum_c \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

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$$s_c, s^{max}, s^{min} \geq 0$$

Dual constraints (prices)

+ ad hoc
non-convex quadratic constraints
to ensure minimum profit
conditions
(then linear **approx.**)

N.B.
min (dual objective – primal objective)
→ Minimizing sum of complementarity slacks

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“EU-*like*” market rules

- Bids with **start up costs**, **ramp constraints** and **minimum power output levels**
- **Demand side analogue !**
- Precise the idea of “EU-*like*” rules as a “*VARIANT*” OF IP PRICING (O’Neill et al.)
- ***Computationally-efficient MILP (exact) formulation without any auxiliary variables***! … meaningful complementarity conditions are implied via duality
- ***Benders decomposition with locally strengthened cuts*** derived from the MILP
- Open-source code in Julia/JuMP is online (updated version soon as well)
- Results used for comparison with IP Pricing and Convex Hull Pricing in a forthcoming WP

$$\sum_{c} \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

$$x_{ic} \leq u_c \qquad \forall ic \in I_c, c \in C \; [s_{ic}^{max}]$$

$$x_{ic} \geq r_{ic} u_c \qquad \forall ic \in I_c, c \in C \; [s_{ic}^{min}]$$

$$u_c \leq 1 \qquad \forall c \in C [s_c]$$

$$u \geq 0$$

$$u \in \mathbb{Z}$$

$$s_{ic}^{max} - s_{ic}^{min} + Q_{ic} \pi = P^{ic} Q_{ic} \qquad [x_{ic}]$$

$$s_c + \delta_c^r - \cancel{\delta_c^a} \geq \sum_{ic \in I_c} (s_{ic}^{max} - r_{ic} s_{ic}^{min}) - F_c \qquad [u_c]$$

$$\cancel{\delta_c^a \leq M_c u_c}$$ **δ_c^a *upper bound* on losses of c** $\forall c \in C$

$$\delta_c^r \leq M_c(1 - u_c)$$ **δ_c^r *upper bound* on opport. costs of c** $\forall c \in C$

$$s_c, s^{max}, s^{min}, \delta_c^a, \delta_c^r \geq 0$$

Duality used to imply appropriate complementarity conditions instead of using an MPEC

$$\sum_{c} s_c - \cancel{\sum_{c \in C} \delta_c^a} \leq^{\cdots=} \sum_{c} \Big(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic} \Big) - F_c u_c$$

$$\max_{(u,x)} \sum_c \left(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic}\right) - F_c u_c$$

$$\sum_c \sum_{ic \in I_c} Q_{ic} x_{ic} = 0 \qquad [\pi]$$

$$x_{ic} \leq u_c \qquad \forall ic \in I_c, c \in C \ [s_{ic}^{max}]$$

$$x_{ic} \geq r_{ic} u_c \qquad \forall ic \in I_c, c \in C \ [s_{ic}^{min}]$$

$$u_c \leq 1 \qquad \forall c \in C [s_c]$$

$$u \geq 0$$

$$u \in \mathbb{Z}$$

$$s_{ic}^{max} - s_{ic}^{min} + Q_{ic}\pi = P^{ic} Q_{ic} \qquad [x_{ic}]$$

$$s_c + M_c(1 - u_c) \geq \sum_{ic \in I_c} (s_{ic}^{max} - r_{ic} s_{ic}^{min}) - F_c \qquad [u_c]$$

$$s_c, s^{max}, s^{min} \geq 0$$

$$\sum_c s_c \leq^{\ldots=} \sum_c \left(\sum_{ic \in I_c} P^{ic} Q_{ic} x_{ic}\right) - F_c u_c$$

This is a generalization of bock bids

A block bid is just such an order

- With only one leg for the bid curve in each hour (the volume of the block for that hour)
- That must be entirely accepted or rejected (r_{ic}=1),
- Without fixed cost (F_c=0)

This is a modification of MIC bids

Similarities: for both bids

- A fixed cost is specified,
- The order can only be accepted if the order is profitable at market prices, taking into account the fixed cost
- There can be a full bid curve at each hour
- There can be ramping constraints

Differences:

- There is only one variable cost (for MICs, the variable cost specified in the bid curve can be different from the variable cost specified in the minimum income condition)
- With MICs, we have to treat the MIC condition explicitly/separately (here this is handled globally through the "dual welfare ≤ primal welfare" constraint)
- The objective function is consistent with the "dual welfare ≤ primal welfare" constraint)

→ This is the right way to handle startup cost in a "EU-like" approach

Benders decomposition derived from the MILP formulation

- globally valid "no-good" cuts (also by Martin, Muller and Pokutta in a related context):

$$\sum_{c \mid u_c^*=1} (1 - u_c) + \sum_{c \mid u_c^*=0} u_c \geq 1$$

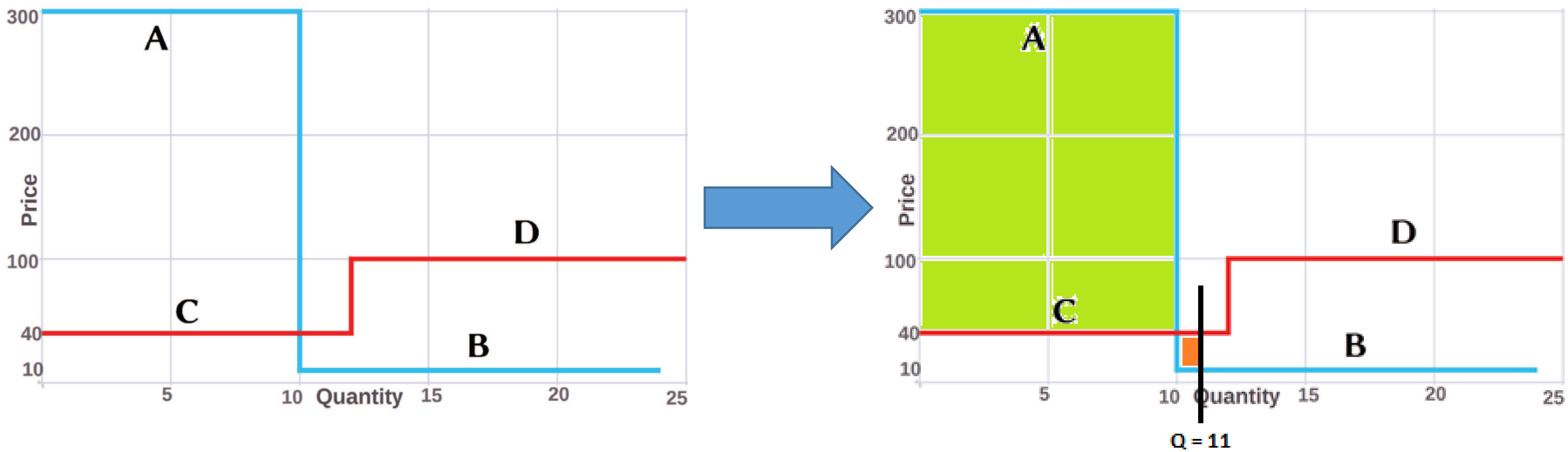
- *locally* valid (strengthened) Benders cuts:

$$\sum_{c \mid u_c^*=1} (1 - u_c) \geq 1$$

Back to the toy examples … (block order case)

Case A - Indivisibilities

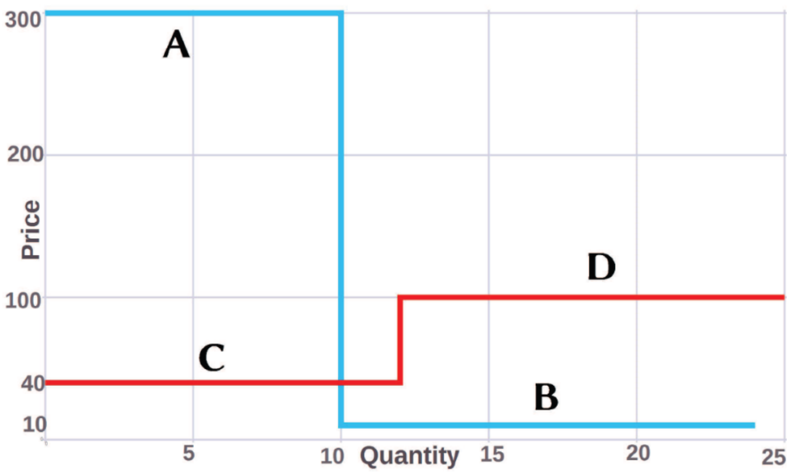
Welfare Maximizing Solution:
Fully accept A + 11MW from C
+ 1 MW from B

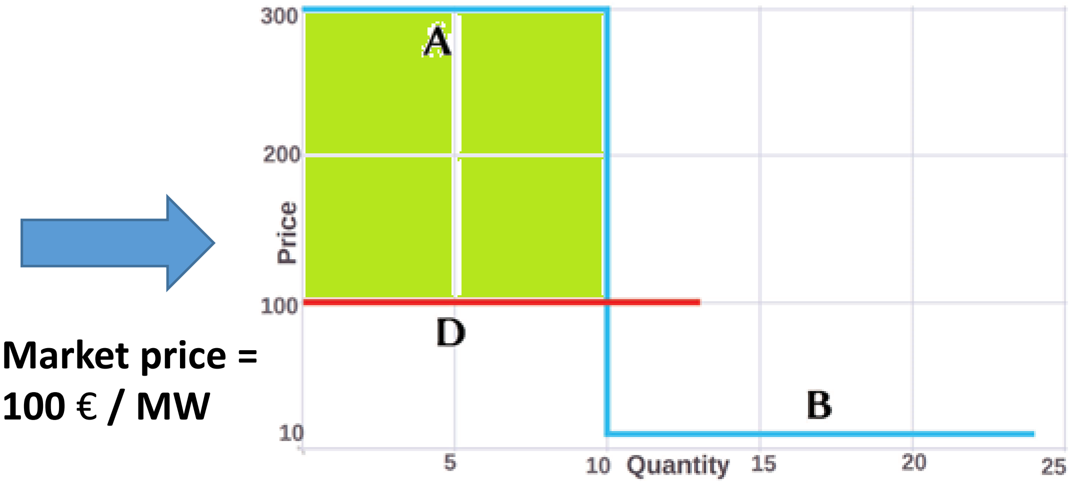


« Welfare = - »

Bids	Quantity (MW)	Limit Price (€/MW)	Min. Acceptance Ratio
A (buy)	10	300	-
B (buy)	14	10	-
C (sell)	12	40	11/12 of 12 = 11 MW
D (sell)	13	100	-

Uniform pricing rules in Euphemia (*block order case*)





Market price = 100 € / MW

(a) <u>Less Welfare</u>

(b) no losses incurred !

(No "make-whole payments" required)

(c) **<u>C is now paradoxically rejected</u>**

<u>Paradoxical rejection only allowed for non-convex bids</u>

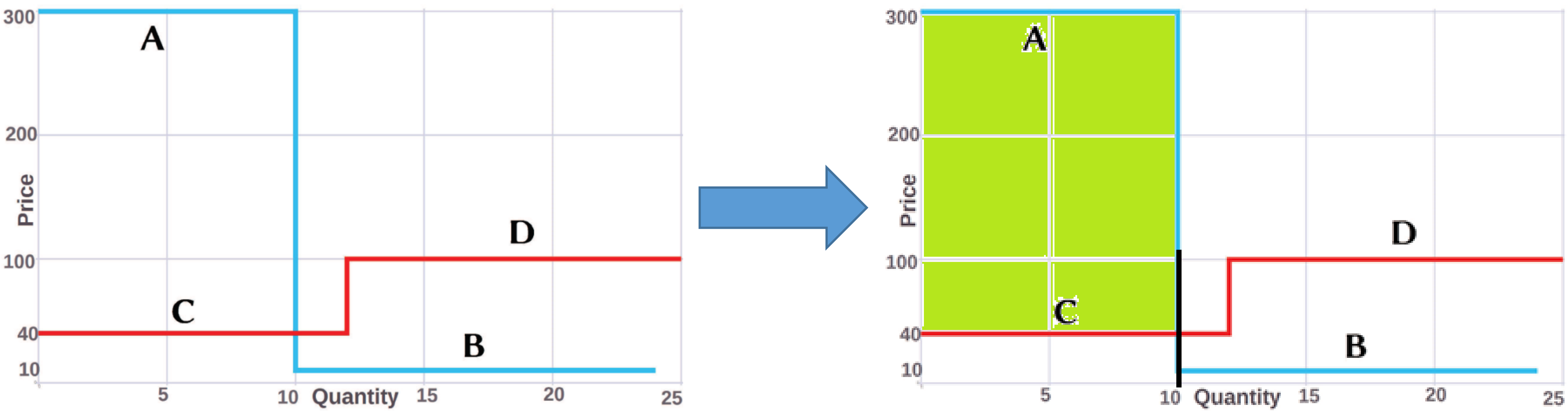
only deviation from equilibrium allowed

Bids	Quantity (MW)	Limit Price (€/MW)	Min. Acceptance Ratio
A (buy)	10	300	-
B (buy)	14	10	-
C (sell)	12	40	<u>11/12 of 12 = 11 MW</u>
D (sell)	13	100	-

Back to the toy examples … (start up costs case)

Case B – start up costs

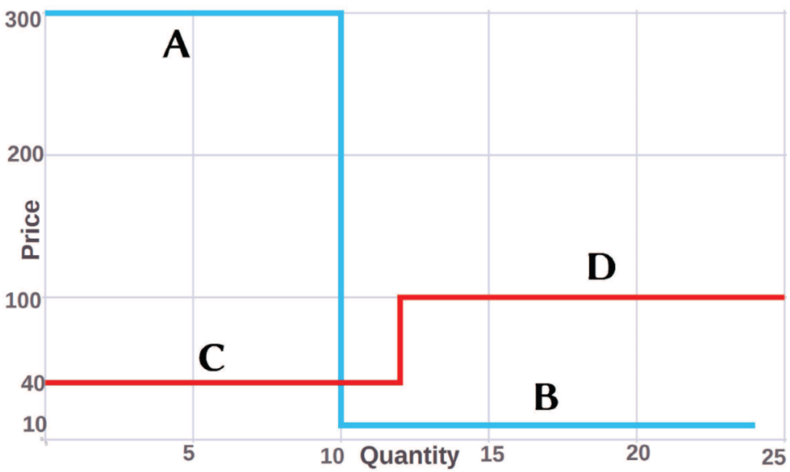
Welfare Maximizing Solution:
Fully accept A + 10MW from C



« Welfare = - 200 € »

Bids	Quantity (MW)	Limit Price (€/MW)	Start up costs
A (buy)	10	300	-
B (buy)	14	10	-
C (sell)	12	40	200 €
D (sell)	13	100	-

Uniform pricing rules in Euphemia (*start up costs case*)



Market price =
100 € / MW

(a) Less Welfare

(b) no losses incurred !

(No "make-whole payments" required)

(c) **C is now paradoxically rejected**

Paradoxical rejection only allowed for non-convex bids

only deviation from equilibrium allowed

Bids	Quantity (MW)	Limit Price (€/MW)	Start up costs
A (buy)	10	300	-
B (buy)	14	10	-
C (sell)	12	40	200 €
D (sell)	13	100	-

OMIE market rules vs new approach: numerical insight

Inst.	Welfare	Abs. gap	Solver's cuts	Nodes	Runtime	# MP Bids	# Curve Steps
1	151218658.27	0.00	24	388	72.63	92	14494
2	115365156.34	0.00	15	181	38.08	90	14309
3	112999837.94	1644425.79	21	4085	600.17	91	14329
4	107060355.83	0.00	16	0	7.63	89	14370
5	100118316.52	0.00	15	347	96.06	89	15091
6	97572068.18	0.00	18	1116	143.65	86	14677
7	87937471.32	1091700.74	27	4958	600.11	87	14979
8	89866979.23	0.00	87	1707	296.41	87	16044
9	86060320.81	0.00	97	361	57.27	81	15177
10	90800596.61	3755055.95	59	2430	600.02	90	16475

Table 4: Instances with 'MIC Orders' as in OMIE-PCR

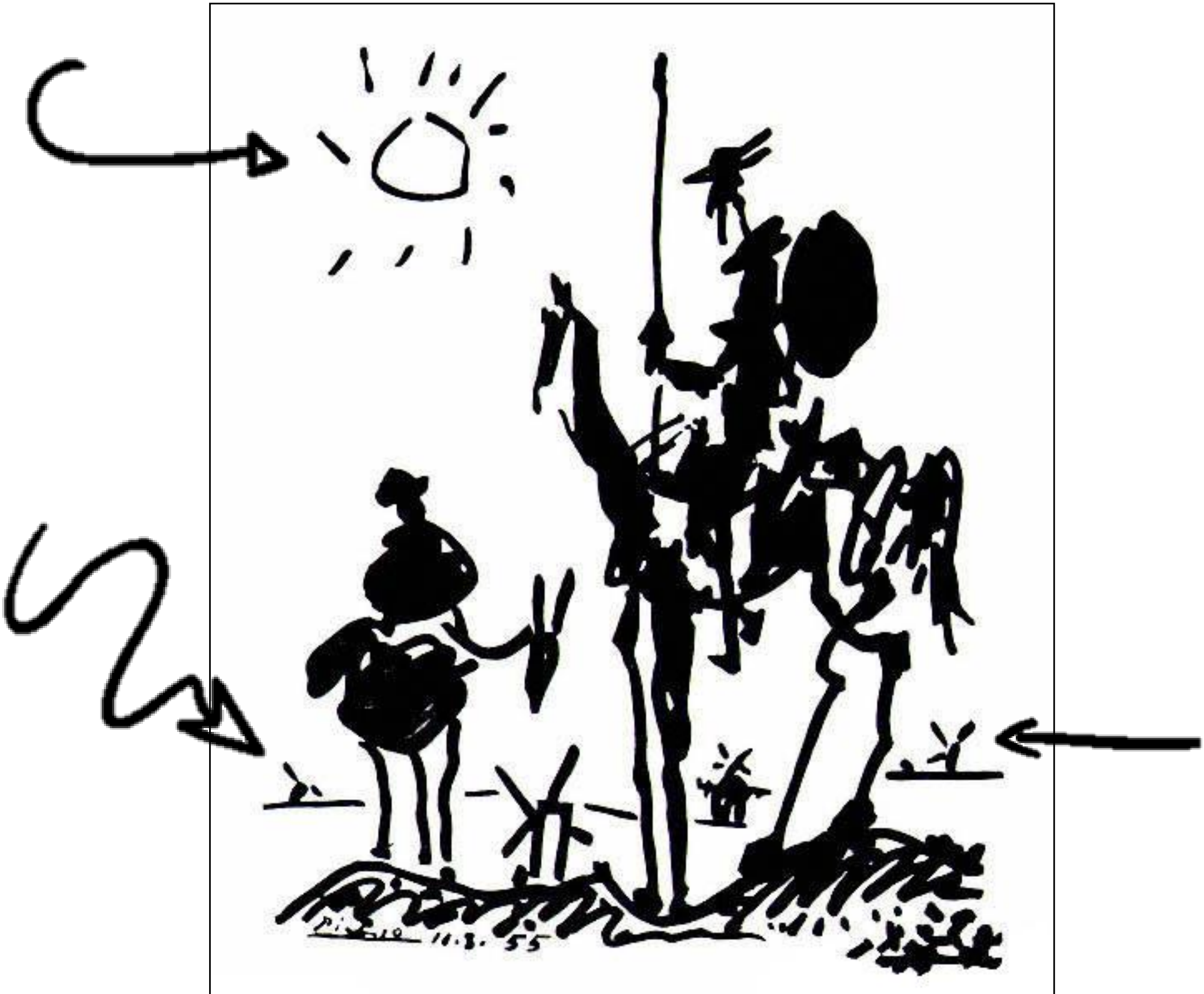
N.B. 'MIC Orders' as in OMIE-PCR do not include here 'ad hoc variables costs' but the same marginal costs as those used for the presented alternative, plus an estimated 'minimum power output level' parameter.

Source code (in Julia / JuMP) and datasets :
https://github.com/madanim/revisiting_mp_conditions/

Inst.	Welfare	Lazy cuts	Solver's cuts	Nodes	Runtime	# MP Bids	# Curve Steps
1	151487156.16	2	0	5	2.66	92	14494
2	115475592.36	1	18	5	1.38	90	14309
3	114220400.20	1	28	3	1.81	91	14329
4	107219935.90	2	14	11	1.78	89	14370
5	100743738.16	1	12	3	1.36	89	15091
6	98359291.45	1	3	3	1.36	86	14677
7	89251699.16	1	29	8	1.54	87	14979
8	90797407.15	1	11	3	1.66	87	16044
9	86403721.22	2	1	13	2.24	81	15177
10	94034444.59	1	40	4	1.54	90	16475

Table 6: Instances with MP bids - Benders decomposition of Theorem 7

As a matter of conclusion … uncertainty, reserve, etc



Day-ahead markets in the US / EU: a bit different

ISOs (US)

- Independent, non-profit organizations (CAISO, ISO-NE)
- Load forecasts (e.g. CAISO)
- Bids to match forecasts
- Detailed technical constraints (minimum up/down times, ramp constraints, etc)

Power exchanges (EU)

- *Privately owned commercial companies e.g. main shareholders of EPEX SPOT: Deutsche Börse (51%) and (Public) European TSOs (49%)*
- <u>***Two sided*** **auctions**</u>
- <u>**Demand bids representing elastic demand, some with non-convexities!**</u>
- Less detailed technical constraints (minimum power output levels but e.g. no minimum up/down times, etc)