On Some Advantages of Convex Hull Pricing

for the European Electricity Auction (and Beyond)

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Join work with Anthony Papavasiliou & Yves Smeers

October 2024

LIDS Seminar

UCLouvain

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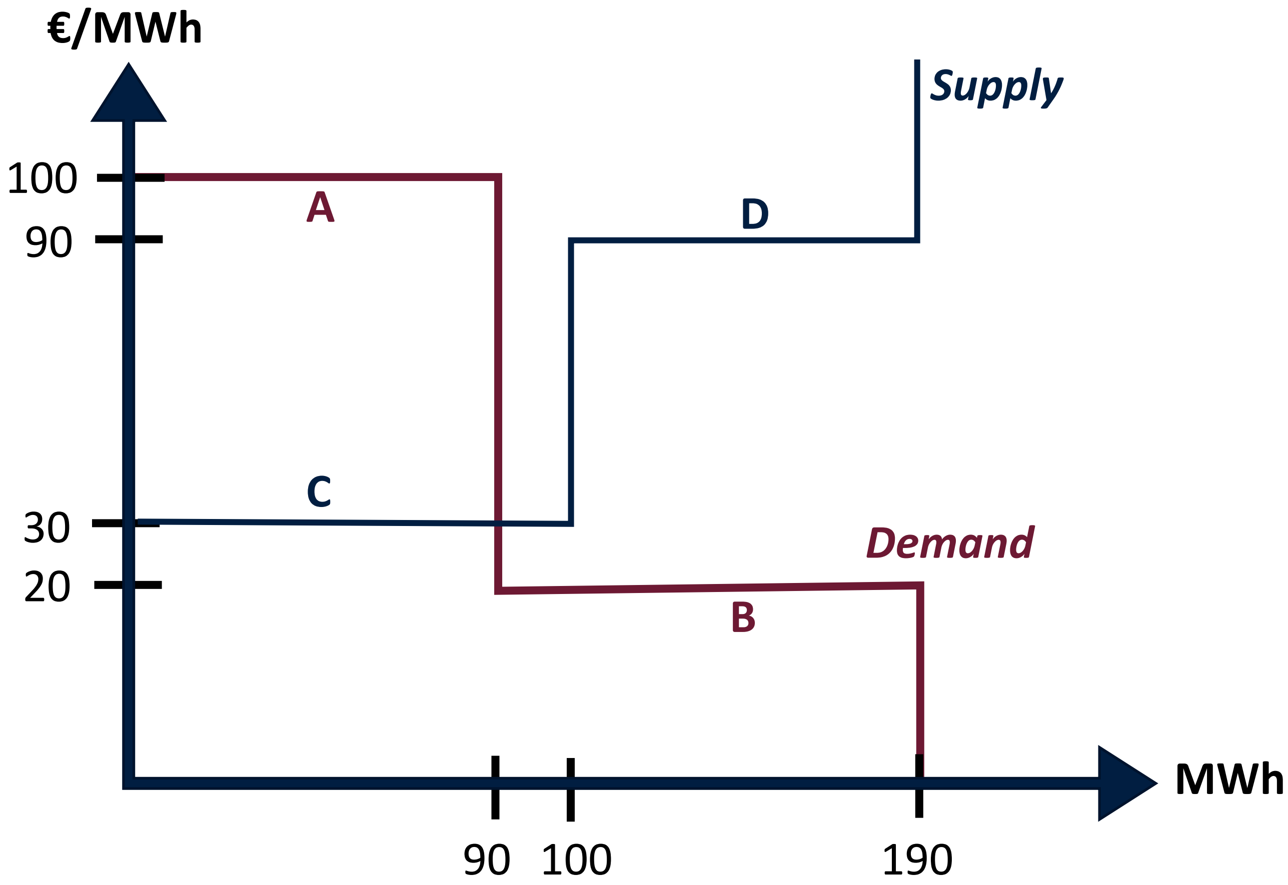
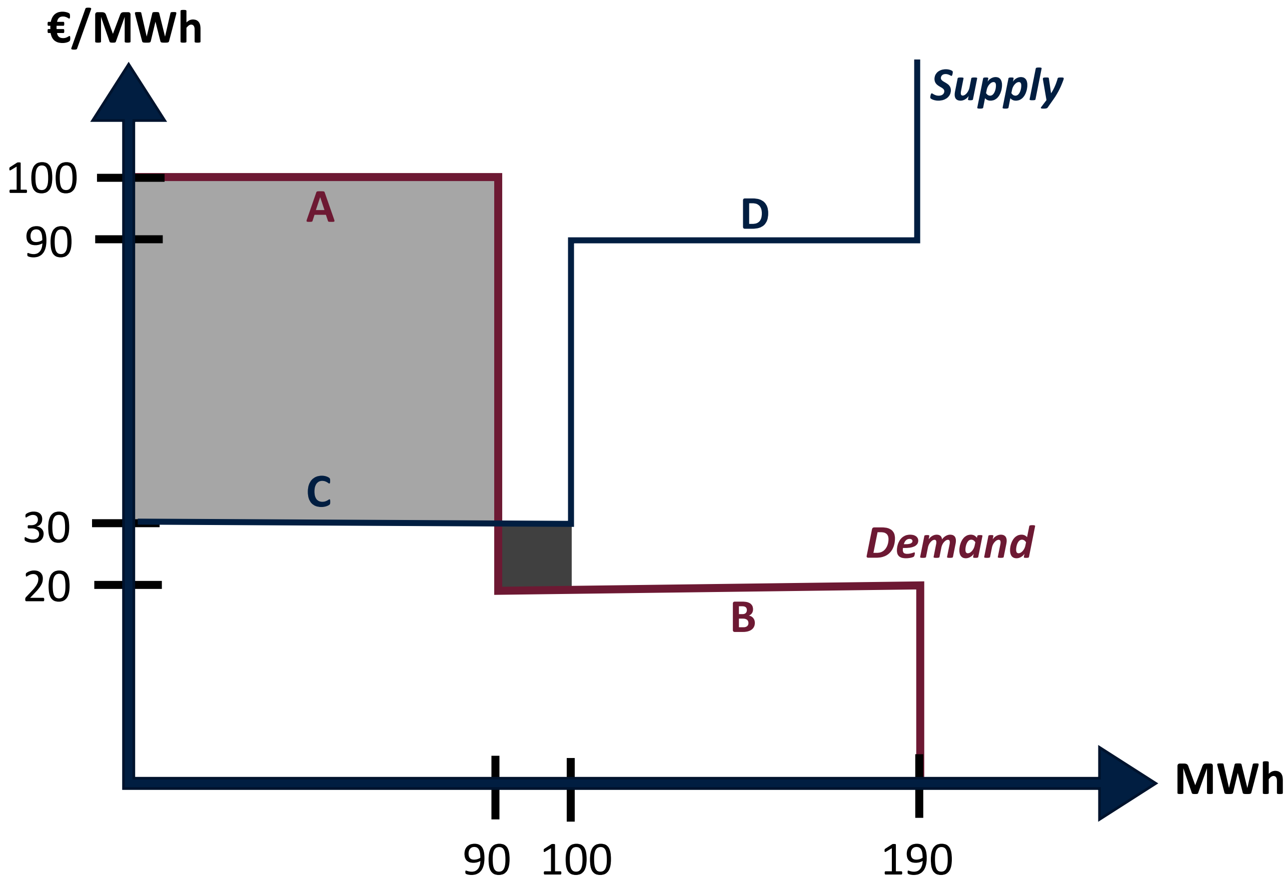
Pricing with indivisibilities



- **C** is *indivisible* (all-or-nothing)
- Welfare optimum solution is to clear **A, C** and a fraction of **B**
- What is the right price?
  - At 20€/MWh C is not willing to produce
  - At 30€/MWh, B is not willing to consume

Pricing with indivisibilities



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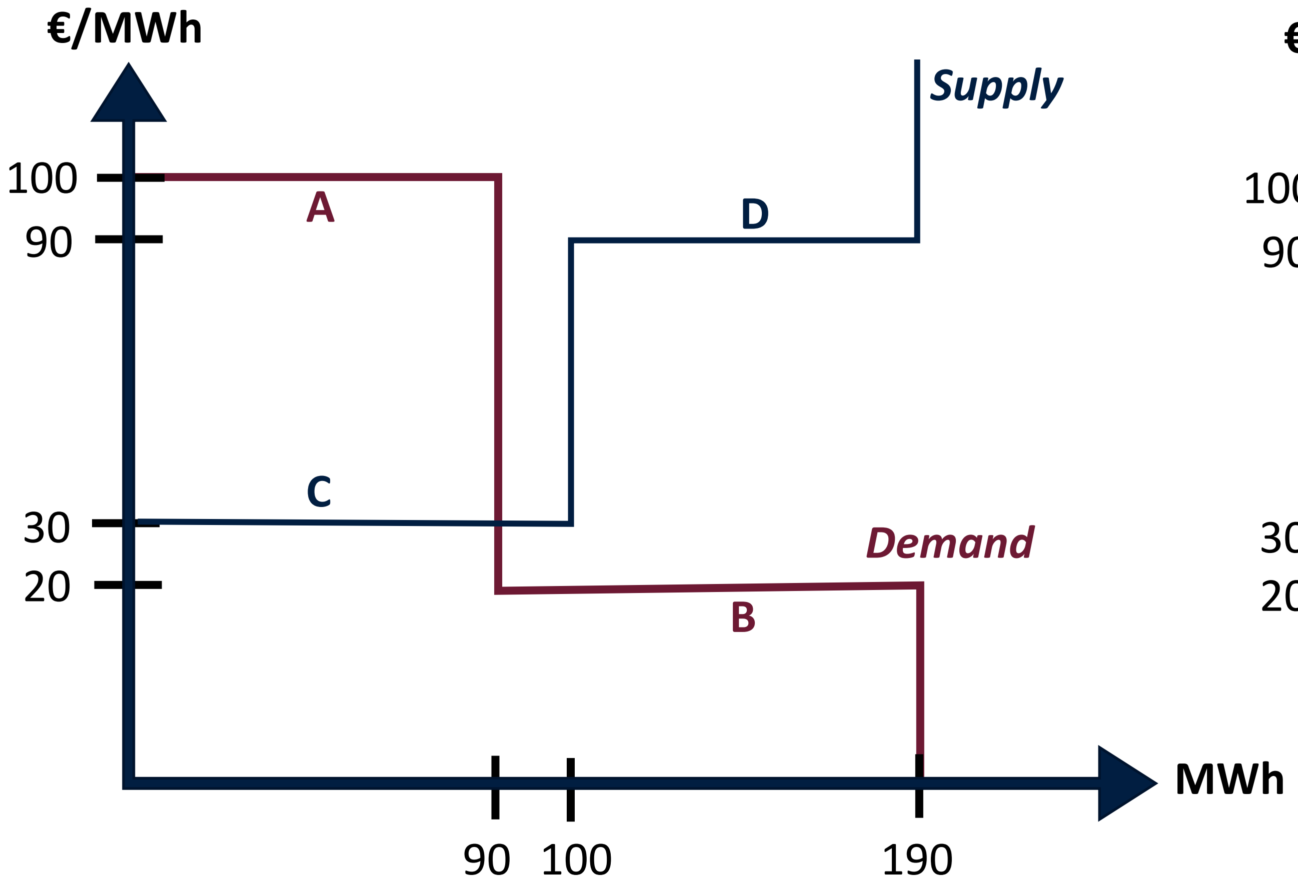

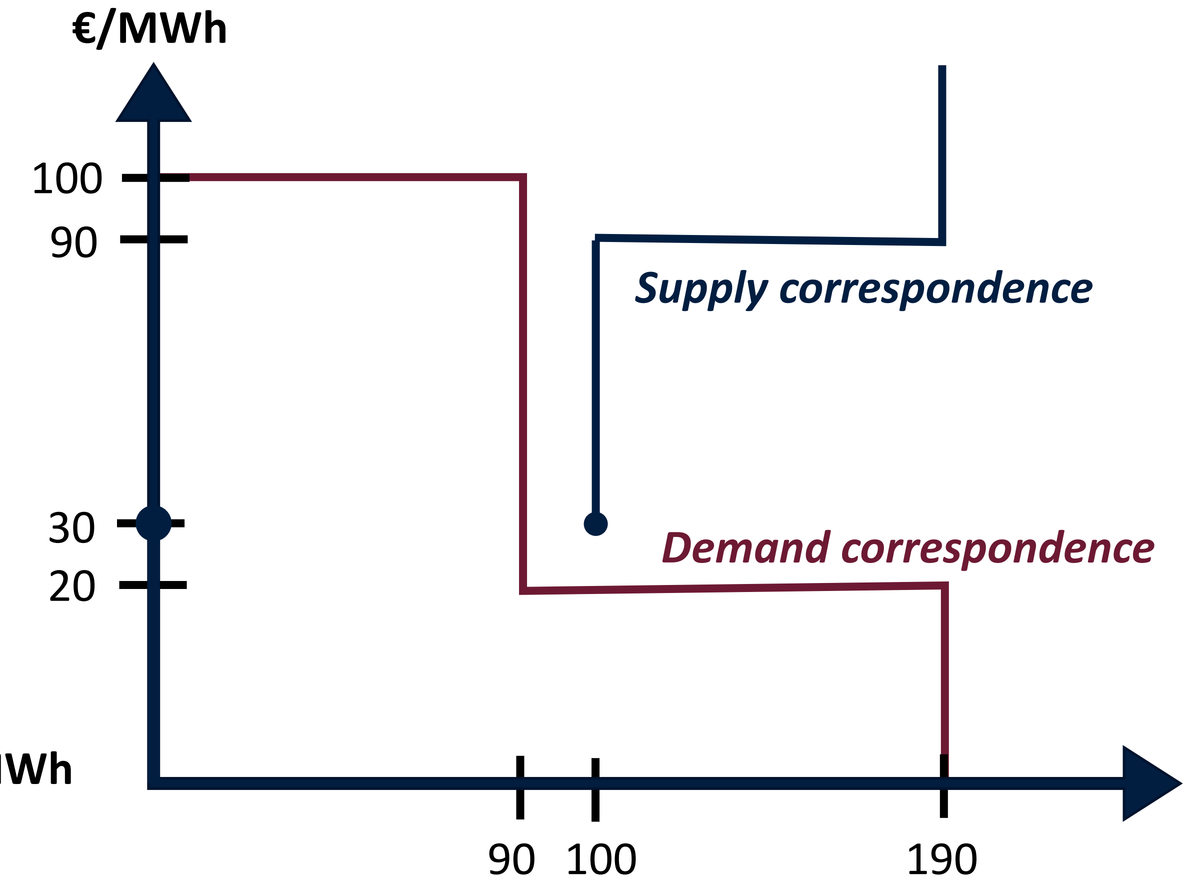

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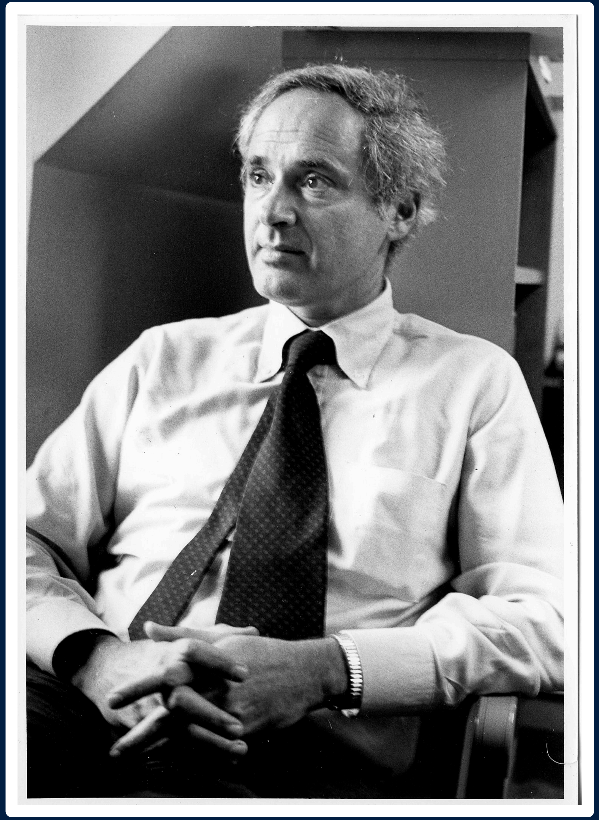
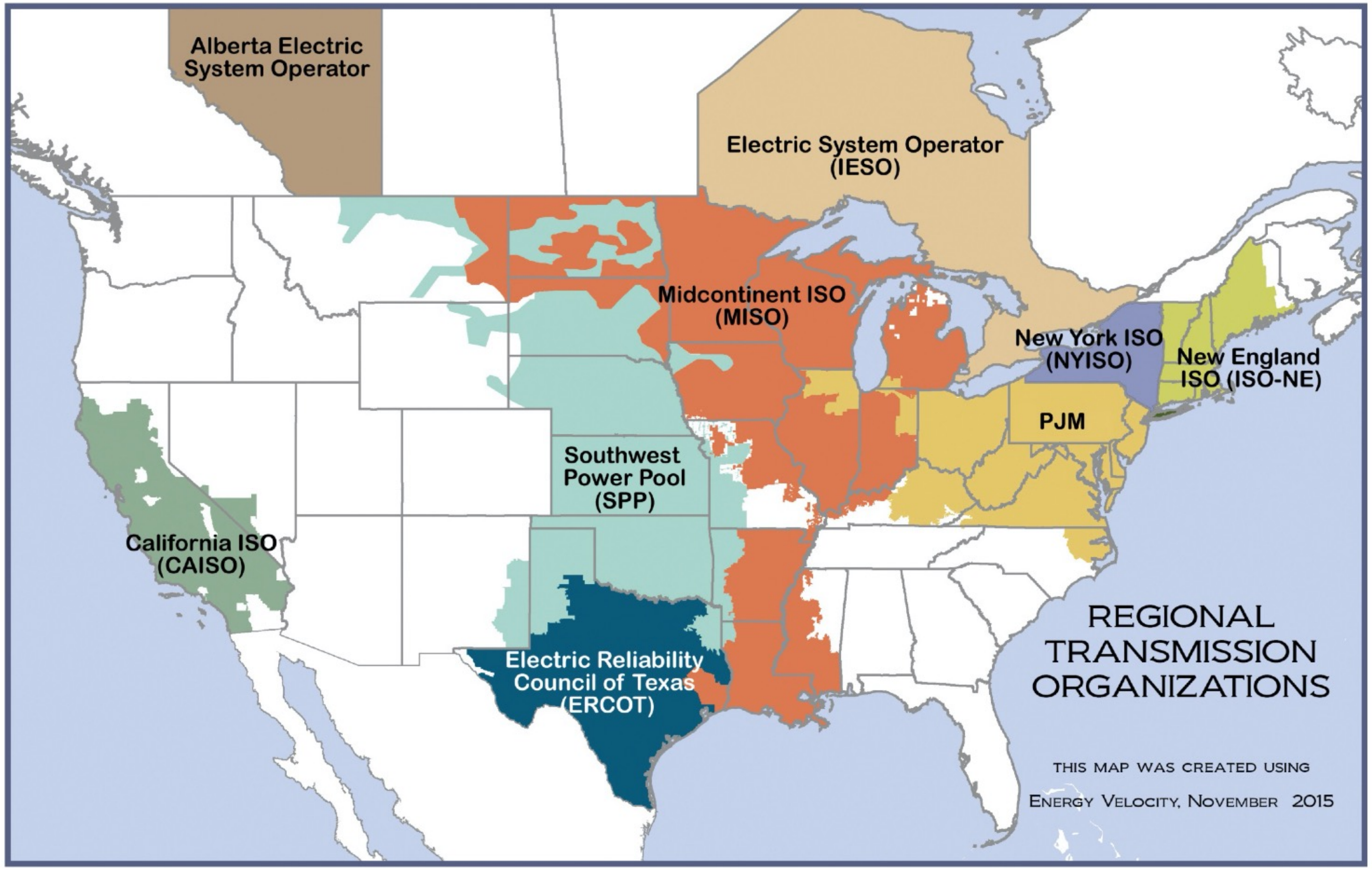
"in the presence of indivisibilities in production, prices simply don't do the jobs that they were meant to do"

(Scarf, 1994)



Electricity markets in the US



1992 : Energy Policy Act

creation of ISOs that operate the market

Early 2000': NYISO "hybrid pricing"

Marginal pricing traditionally adopted by many ISOs to clear the market + side payments

2014: FERC launches consultation about price formation

2015 : MISO implements ELMP

2017 : PJM made similar proposal

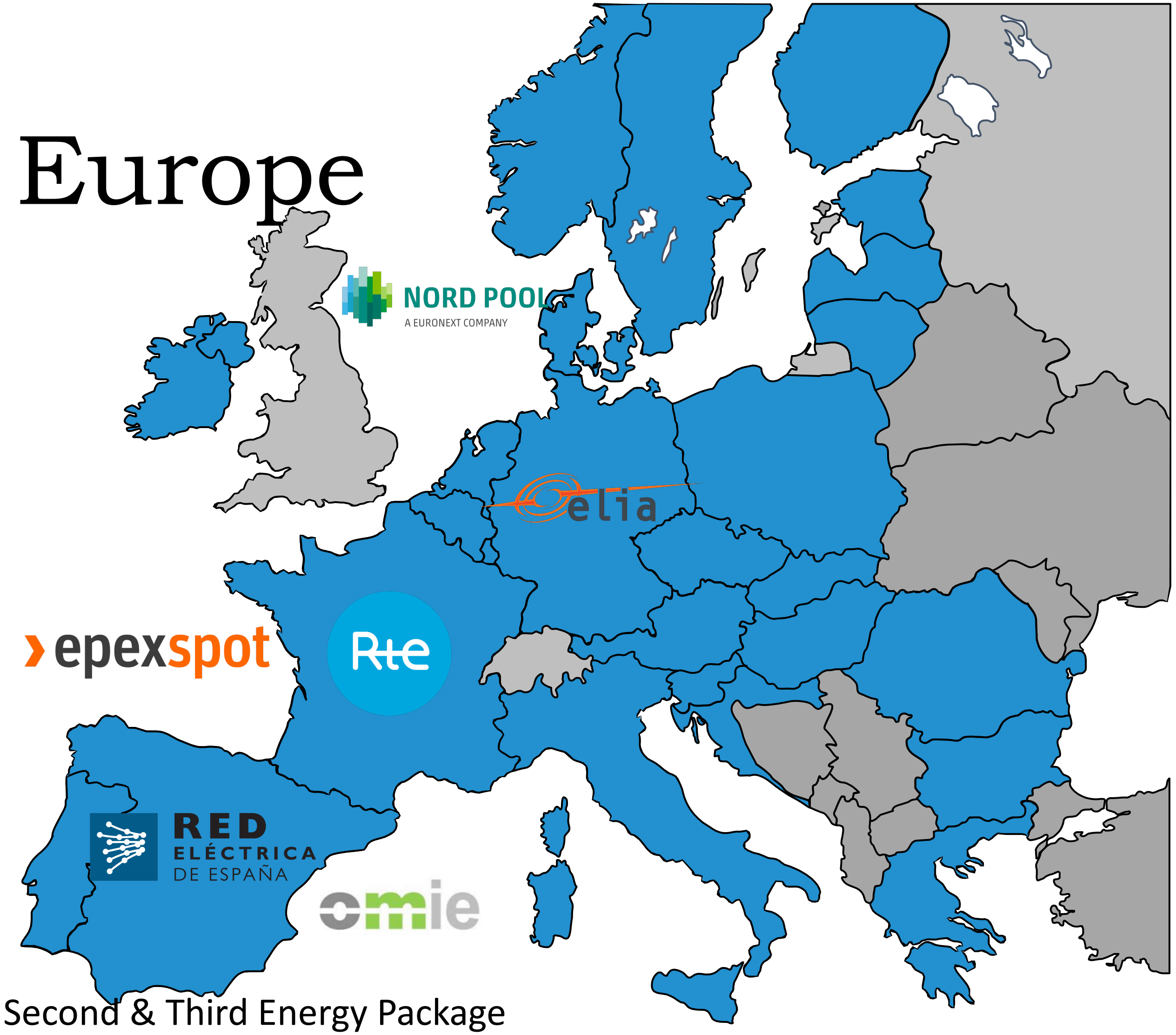
1990

2000

2010

2020

Electricity markets in Europe



❑ **Institutional framework**:

- **TSOs** operate the grid
- "**Nominated Electricity Market Operators**" (NEMOs) operate the market

1993 : European Single Market

1996 : First Energy Package (kickoff the liberalization of the power sector)

2003 – 2009 : Second & Third Energy Package (unbundling of competitive and regulated segments)

1990

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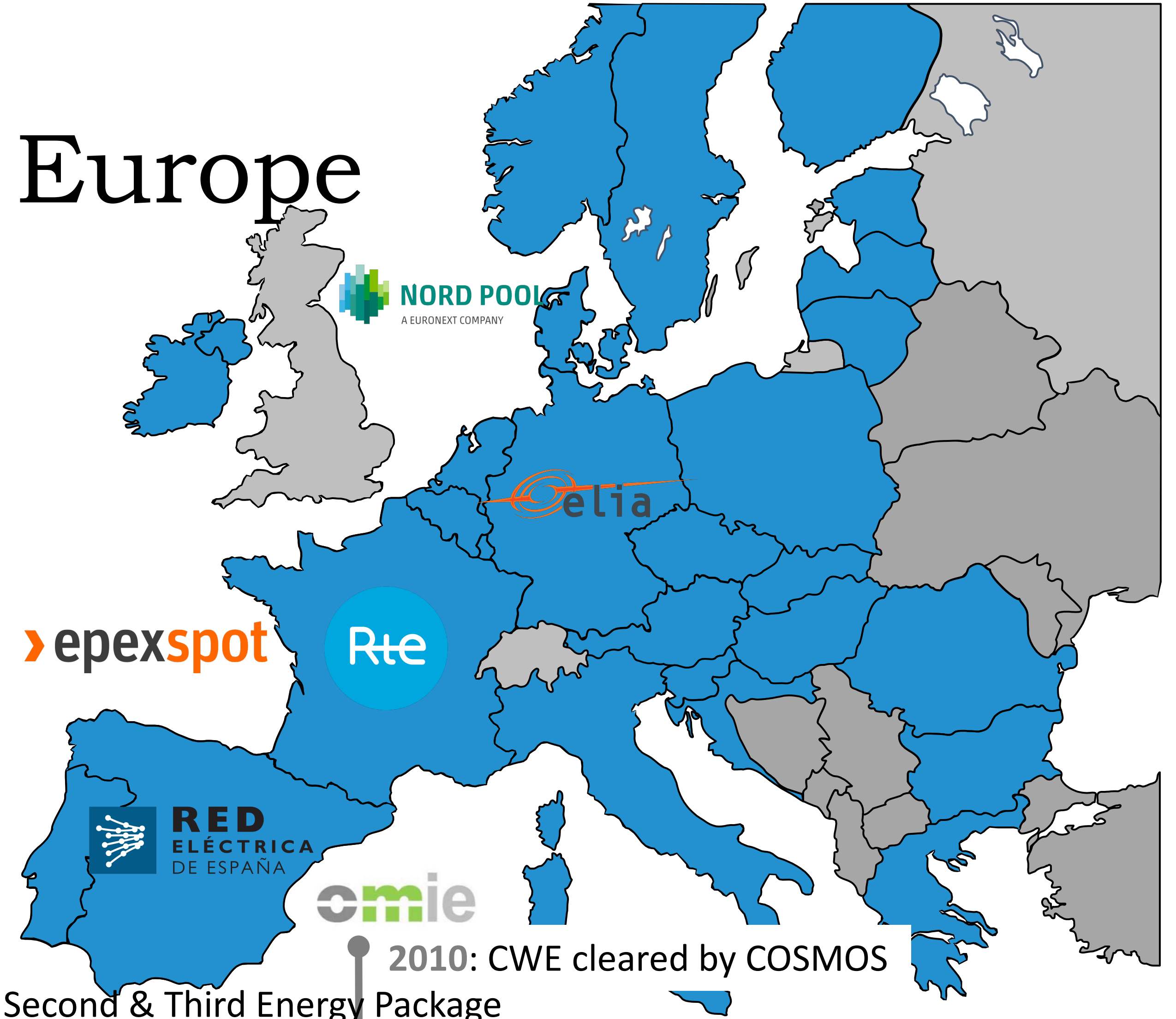
Electricity markets in Europe



- **Institutional framework**:
  - **TSOs** operate the grid
  - "**Nominated Electricity Market Operators**" (NEMOs) operate the market
- **EU Electricity market — "Price Coupling of Regions"**:
  - 27 countries
  - 30 TSOs
  - 16 NEMOs
  - 4.66 TWh daily trade

1993 : European Single Market

1996 : First Energy Package (kickoff the liberalization of the power sector)

2003 – 2009 : Second & Third Energy Package (unbundling of competitive and regulated segments)

2006: Trilateral Market Coupling

2010: CWE cleared by COSMOS

2014: Single Day-Ahead Coupling (SDAC), Price Coupling of Regions

1990

2000

2010

2020

Objectives of the work

- Ongoing **discussions among European stakeholders** & research undertaken by NEMOs to **reform the current EU pricing rule** (NEMO Committee, 2020a ; MCSC, 2022 ; SDAC, 2023)
- How to price the indivisibilities has also been a **vivid subject of debate in the US** for the past 20 years: heterogeneous and changing policies
- **Objective of the paper** : contribute to these discussions, in particular the reform of the European pricing rules
  - Formalize the problem
  - Theoretical cross-comparison of several pricing approaches
  - Numerical simulations on auction dataset

- SDAC, 2023, Non-uniform pricing: Explanatory note, https://www.nemo- committee.eu/assets/files/ sdac- non- uniform- pricing- explanatory- note.pdf.
- NEMO Committee, 2020a. CACM annual report 2019. URL: http: //www.nemo- committee.eu/assets/files/cacm- annual- report- 2019.pdf.
- MCSC, 2022. Market Coupling Steering Committee: Market Coupling Consultative Group meeting, 1st of December. https: //eepublicdownloads.blob.core.windows.net/public- cdn- container/ clean- documents/events/2022/MCCG- presentation- 01122022final.pdf.

Plan

Motivations

- Theoretical motivation
- Policy relevance: both in US and EU markets

Theoretical framework

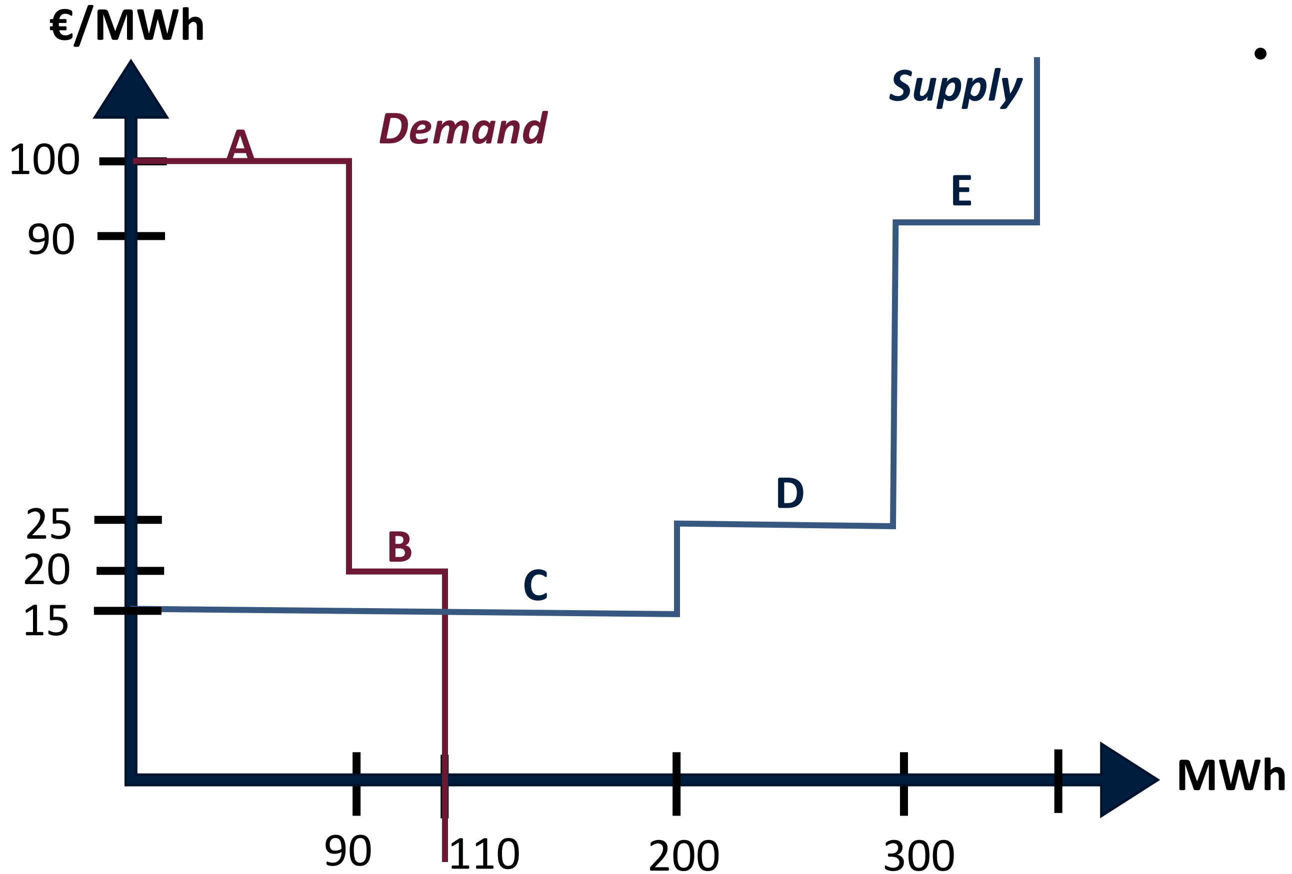
- Formalize the problem
- Solution to the problem — pricing schemes: marginal pricing, convex hull pricing…

Numerical simulations

- Numerical analysis on auction datasets
- Cross comparison of different pricing schemes
- Some advantages of convex hull pricing

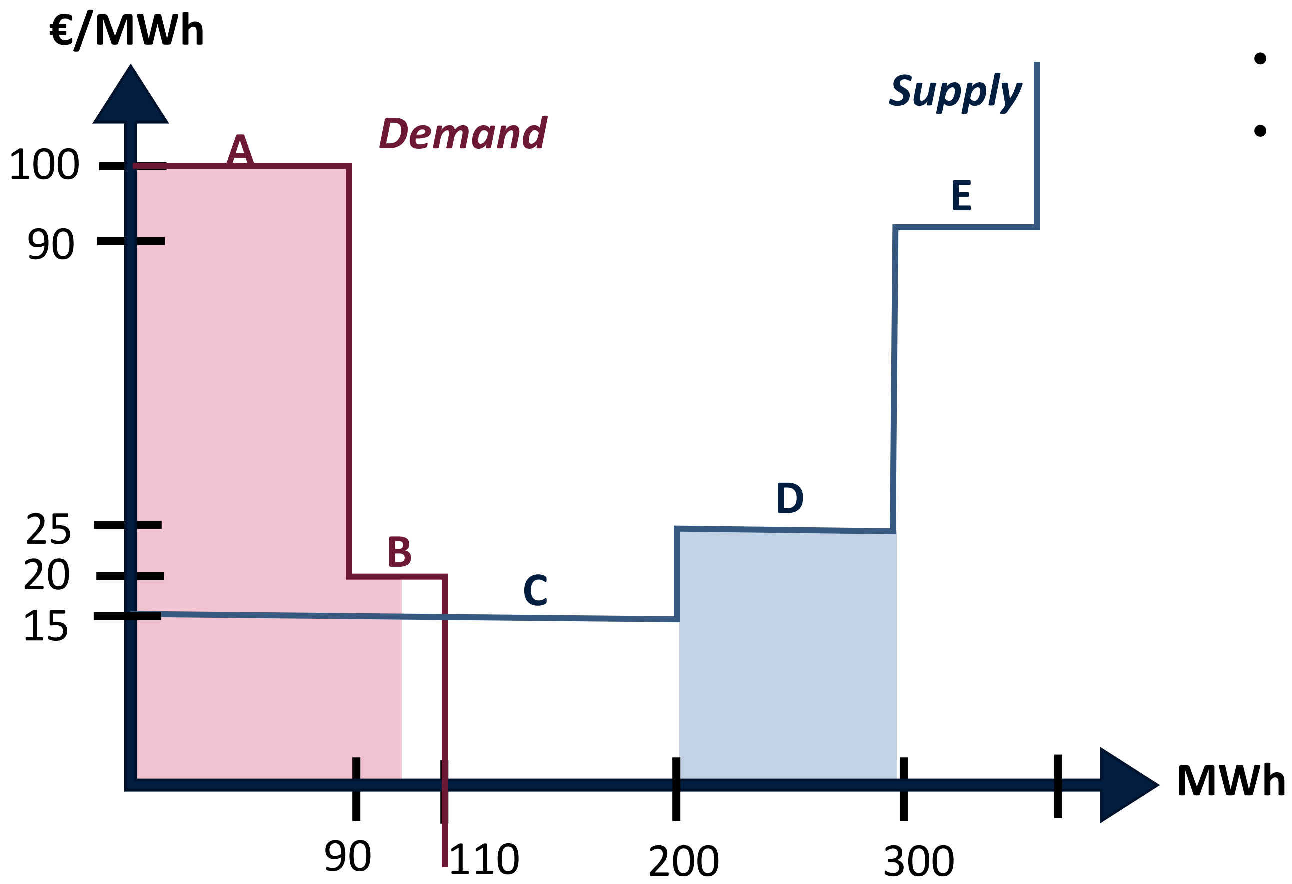
Conclusion

How to measure the consistency between price & cleared allocation



- **C** & **D** are *indivisible* (all-or-nothing)

How to measure the consistency between price & cleared allocation



- **C** & **D** are *indivisible* (all-or-nothing)
- Welfare optimum : clear **A**, **D** and 10MW of **B**

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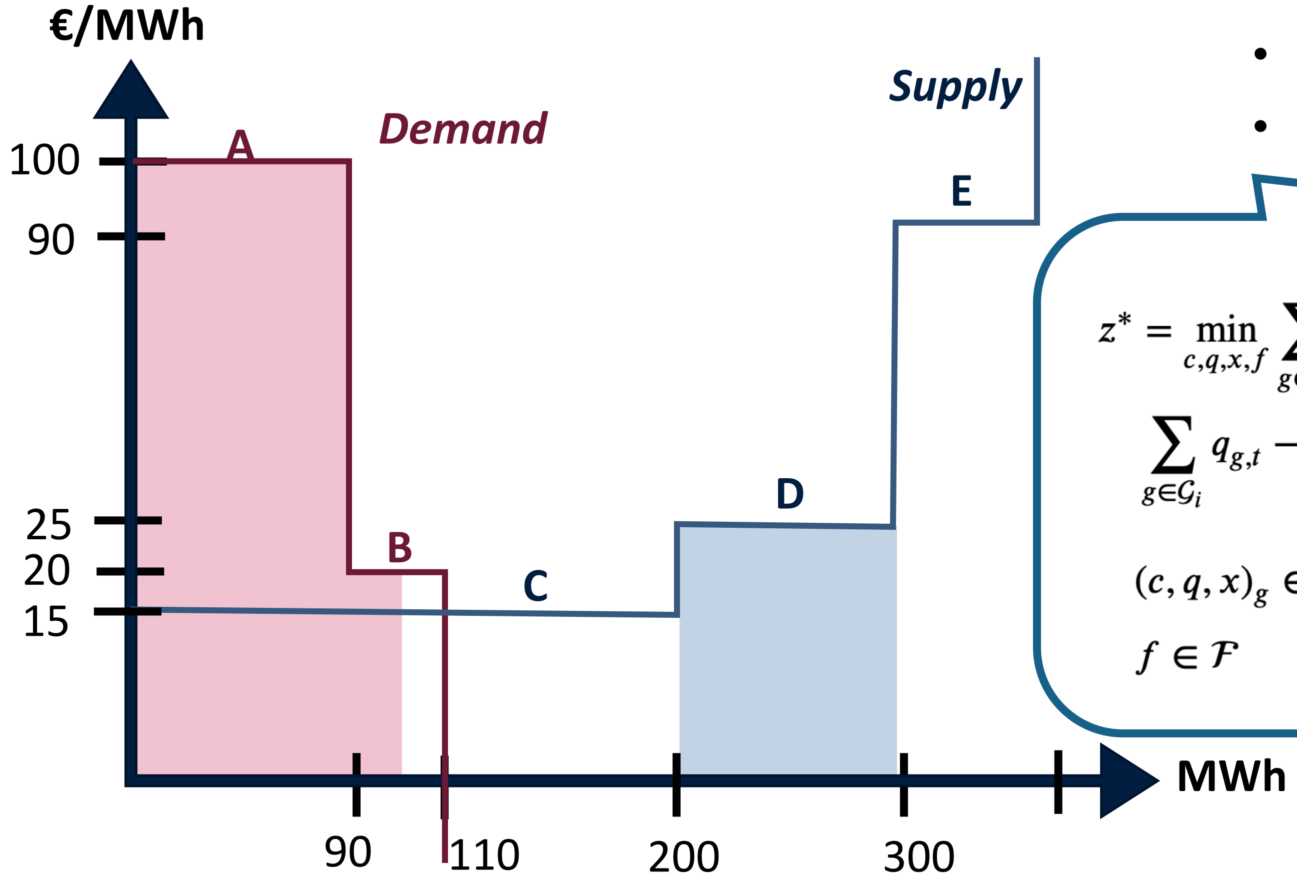


- **C** & **D** are *indivisible* (all-or-nothing)
- Welfare optimum : clear **A**, **D** and 10MW of **B**

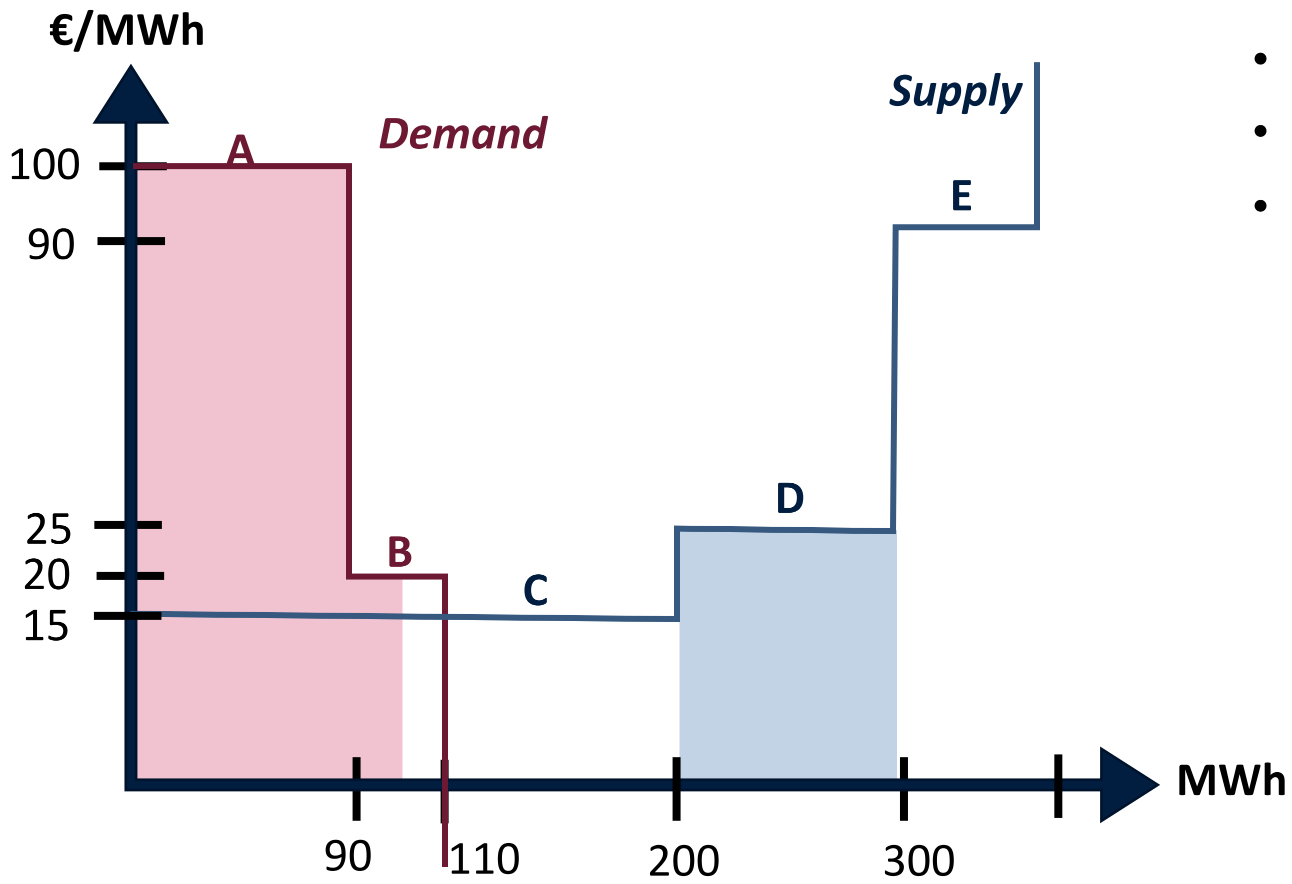
$$z^* = \min_{c,q,x,f} \sum_{g \in \mathcal{G}} c_g \tag{1a}$$

$$\sum_{g \in \mathcal{G}_i} q_{g,t} - D_t^i = \sum_{\substack{l \in \\ from(i)}} f_{l,t} - \sum_{\substack{l \in \\ to(i)}} f_{l,t} \quad \forall i \in \mathcal{N}, t \in \mathcal{T} \tag{1b}$$

$$(c, q, x)_g \in \mathcal{X}_g \quad \forall g \in \mathcal{G} \tag{1c}$$

$$f \in \mathcal{F} \tag{1d}$$

How to measure the consistency between price & cleared allocation



- **C** & **D** are *indivisible* (all-or-nothing)
- Welfare optimum : clear **A**, **D** and 10MW of **B**
- What is the right price?
  - **15€/MWh**
    - B has a lost opportunity of 50€
    - C is ok
    - D has a revenue shortfall of 1,000€
  - **20€/MWh**
    - B is ok
    - C has a lost opportunity of 1,000€
    - D has a revenue shortfall of 500€
  - **25€/MWh**
    - B has a revenue shortfall of 50€
    - C has a lost opportunity of 2,000€
    - D is ok

Two metrics to compare the candidate pricing approaches

- ***Lost opportunity costs (LOC)***

$$LOC = \max(profit\ under\ price\ p^*) - cleared\ profit$$

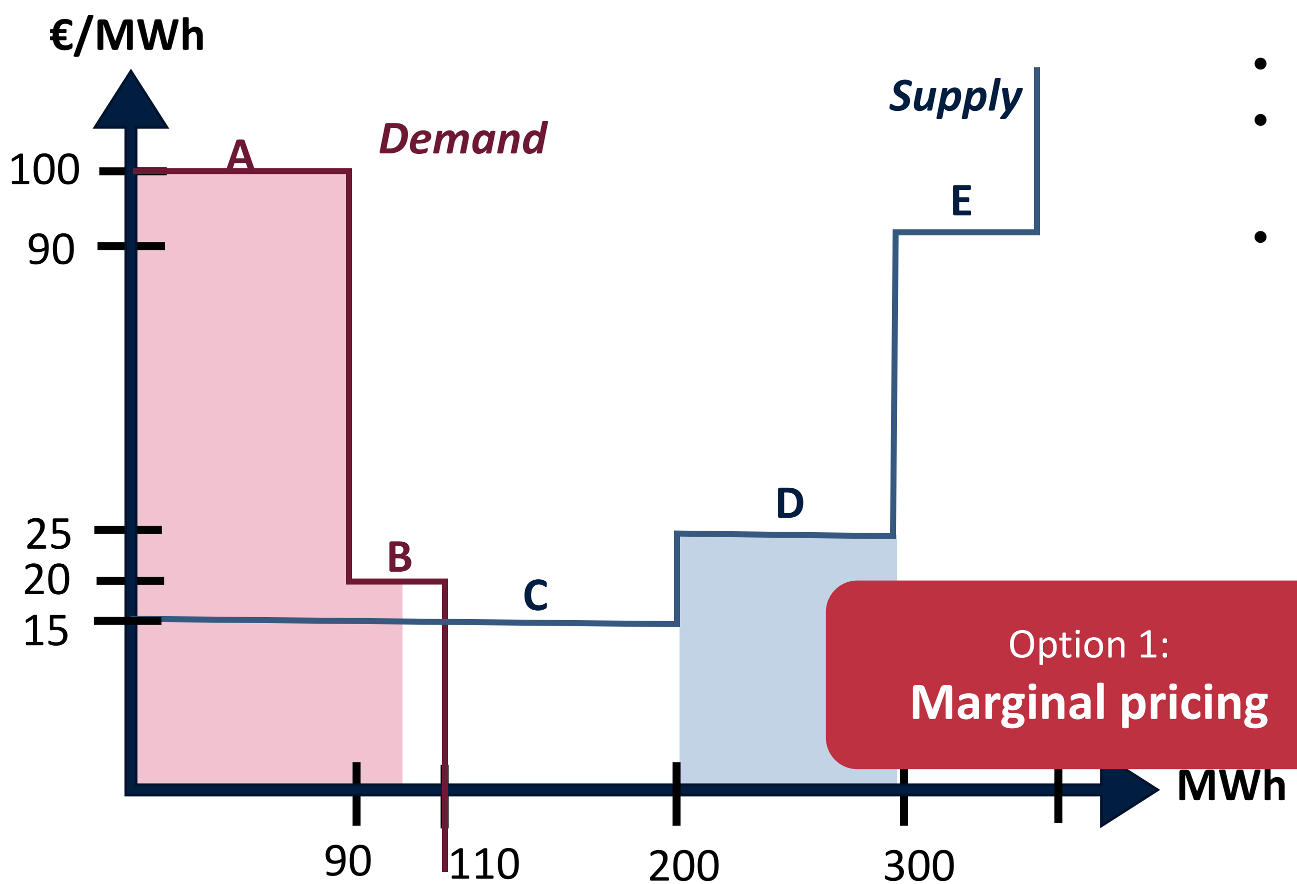
  - It measure the **incentive-compatibility** of prices and dispatch instructions
  - **Does the price *support* the cleared allocation?** If not, the dispatch could unravel as suppliers "self-schedule"

- ***Revenue shortfall (RS)*** (or "make-whole payments")

$$RS = -\min(0\ ;\ cleared\ profit)$$

  - It measure the **revenue-adequacy** of prices and dispatch instructions
  - **Does the uniform price enable the market participants to break even?**

Three candidate pricing schemes



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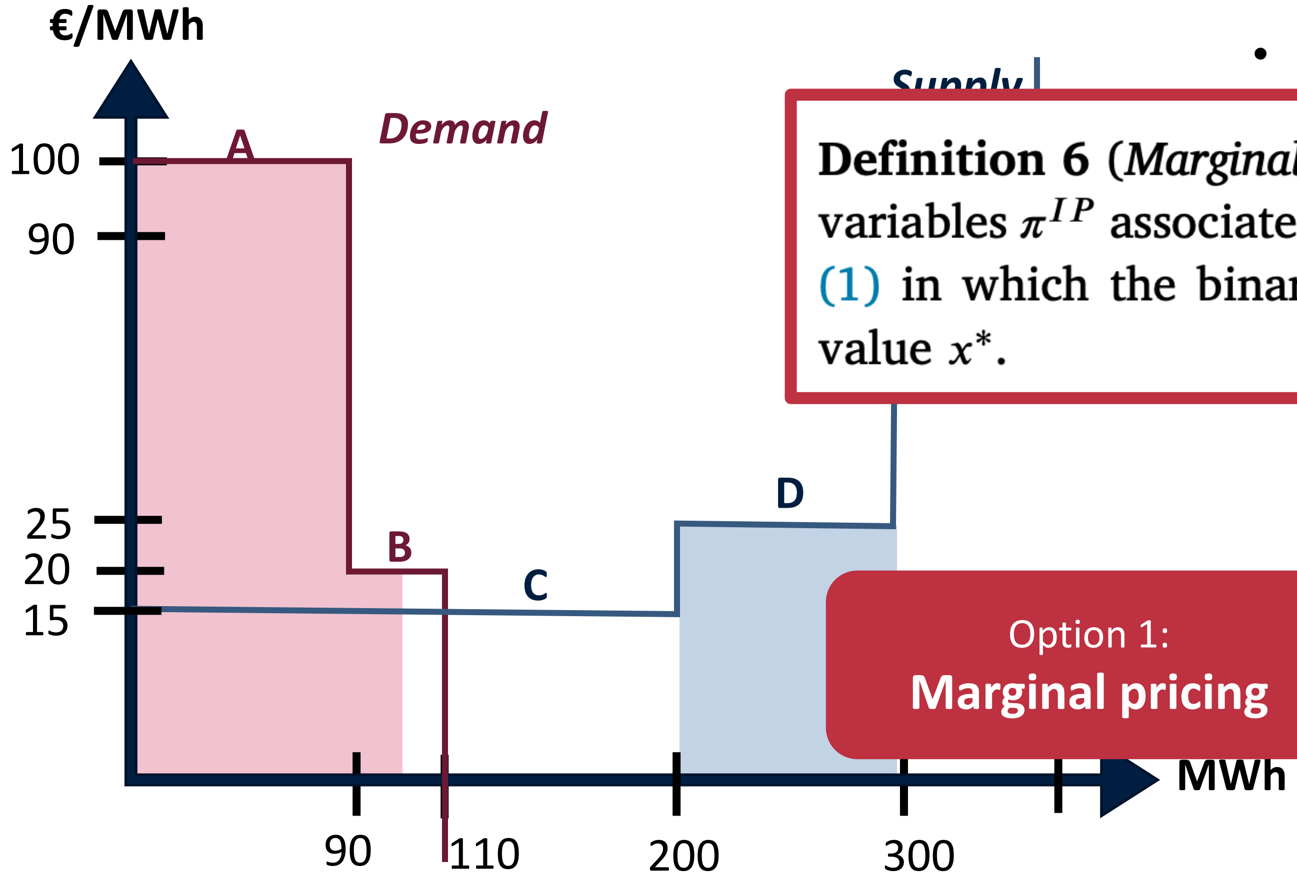
Option 1:
Marginal pricing

Three candidate pricing schemes



- **C & D** are *indivisible* (all-or-nothing)

Definition 6 (*Marginal Pricing*). The marginal (IP) prices are the dual variables π^{IP} associated with the market clearing constraint in problem (1) in which the binary variables x have been fixed to their optimal value x^*.

Option 1:
Marginal pricing

- C is ok
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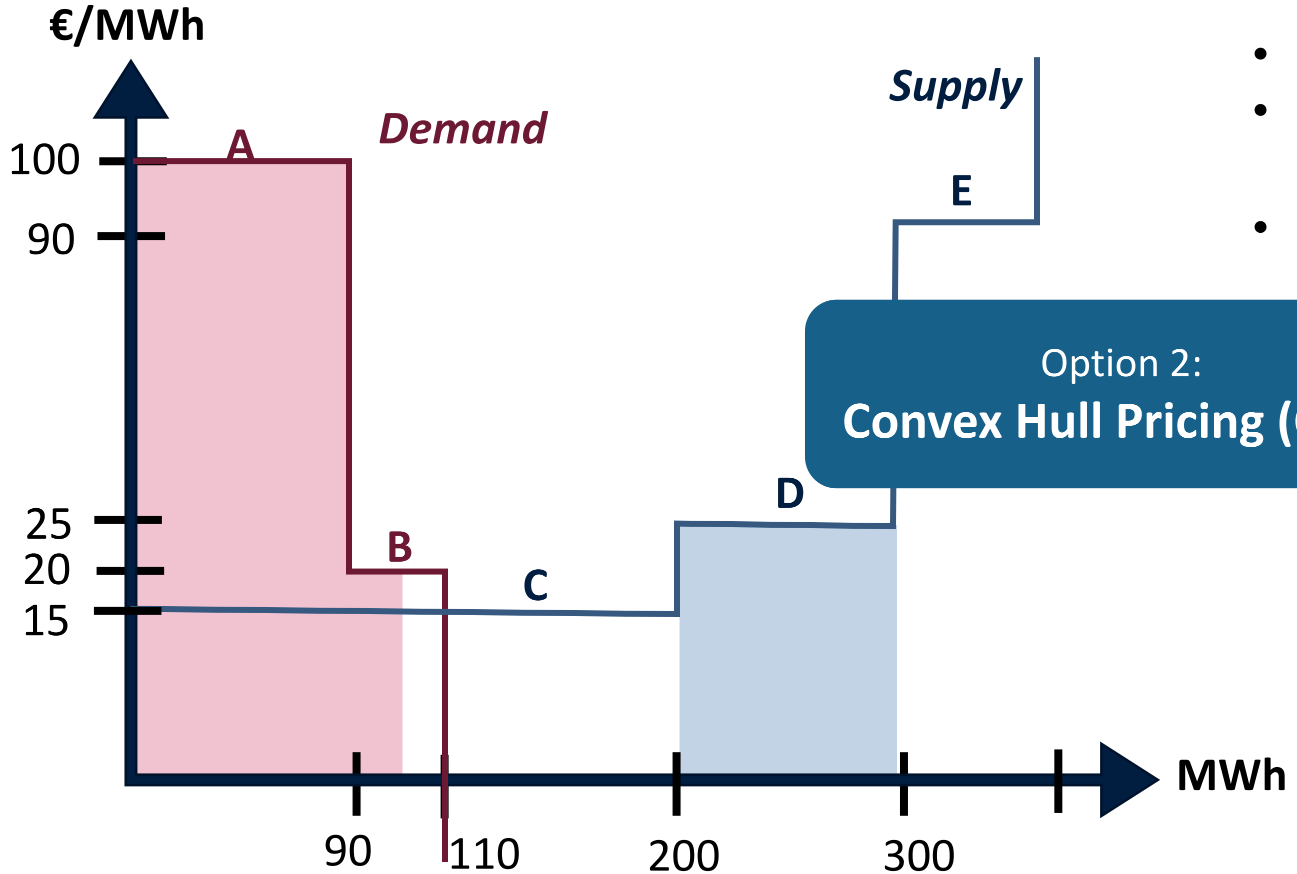
Three candidate pricing schemes



Option 2:
Convex Hull Pricing (CHP)

- **C** & **D** are *indivisible* (all-or-nothing)
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  - **15€/MWh**
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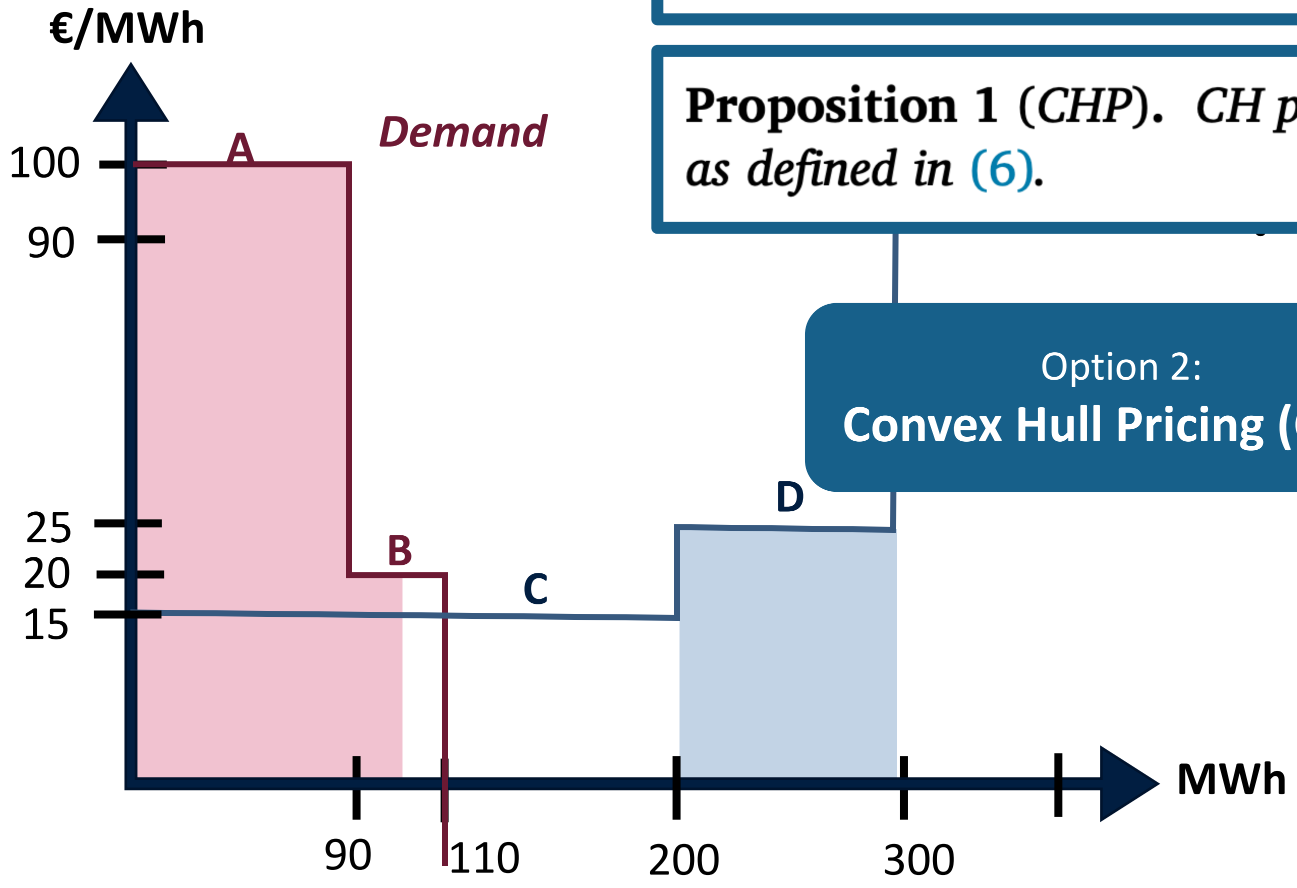
Three candi

Definition 7 (*Convex Hull Pricing*). The convex hull prices are the dual variables π^{CH} that are associated to the market clearing constraints in problem (1), in which the sets $\mathcal{X}_g$ are replaced by $\text{conv}(\mathcal{X}_g)$.

Proposition 1 (*CHP*). *CH prices minimize the total lost opportunity costs, as defined in* (6).



Option 2:
Convex Hull Pricing (CHP)

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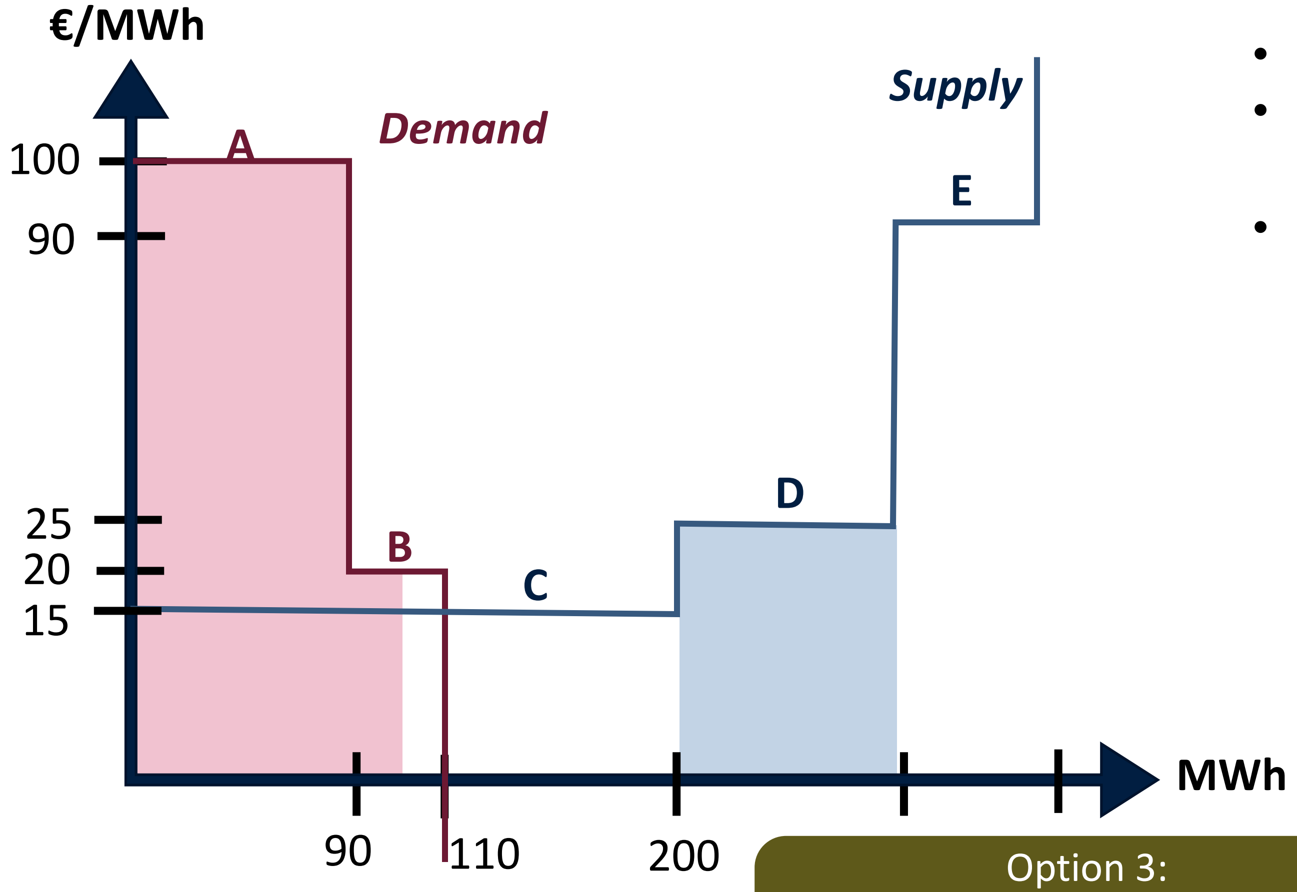

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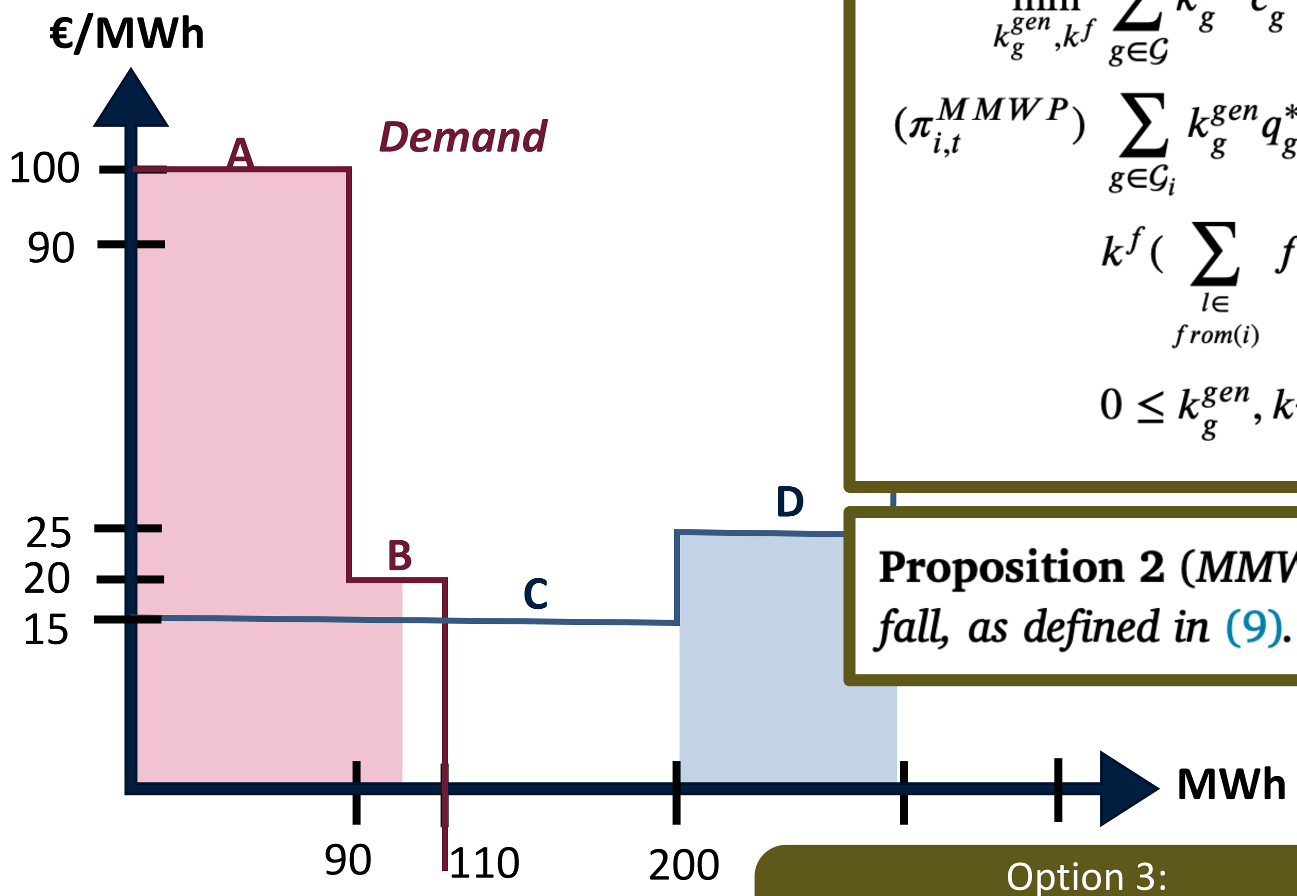
Option 3:
Minimal Make-whole Payment Pricing (MMWP)

Three candidat



Definition 9 (*Minimal Make-Whole Payments Pricing*). The minimal make-whole payments prices are the dual variables π^{MMWP} associated to the market clearing constraints in the following problem:

$$\min_{k_g^{gen},k^f} \sum_{g\in\mathcal{G}} k_g^{gen} c_g^* \tag{10a}$$

$$(\pi_{i,t}^{MMWP}) \quad \sum_{g\in\mathcal{G}_i} k_g^{gen} q_{g,t}^* - D_t^i = \tag{10b}$$

$$k^f\Big(\sum_{\substack{l\in\\ from(i)}} f_{l,t}^* - \sum_{\substack{l\in\\ to(i)}} f_{l,t}^*\Big) \quad \forall i\in\mathcal{N}, t\in\mathcal{T} \tag{10c}$$

$$0\le k_g^{gen}, k^f \le 1 \tag{10d}$$

Proposition 2 (MMWP). *MMWP prices minimize the total revenue shortfall, as defined in* (9).

- D has a revenue shortfall of 500€

- **25€/MWh**
  - B has a revenue shortfall of 50€
  - C has a lost opportunity of 2,000€
  - D is ok

Option 3:
Minimal Make-whole Payment Pricing (MMWP)

Three candidate pricing schemes

Pricing scheme	Objective	Computation	Math. Formulation	References
Marginal Pricing **(MP)**		Easy	Fix binary variables (primal-dependent)	O'Neill et al. (2005)
Convex Hull Pricing **(CHP)**	Minimize LOC	***Difficult*** but can be solved: (Stevens and Papavasiliou, 2022)	Convex hull of prod. & cons. sets (primal-dual separated)	Hogan and Ring (2003) and Gribik et al. (2007)
Minimal Make-Whole Payment pricing **(MMWP)**	Minimize RS	Easy	Solve ad-hoc problem	Madani and Papavasiliou (2022), Bichler et al. (2022)

- O'Neill, R.P., Sotkiewicz, P.M., Hobbs, B.F., Rothkopf, M.H., Stewart Jr, W.R., 2005. Efficient market-clearing prices in markets with nonconvexities. European journal of operational research 164, 269–285.
- Gribik, P.R., Hogan, W.W., Pope, S.L., et al., 2007. Market-clearing electricity prices and energy uplift. Cambridge, MA .
- Bichler, M., Knörr, J., Maldonado, F., 2022. Pricing in nonconvex markets:How to price electricity in the presence of demand response. Information Systems Research 34, 652–675.
- Madani, M., Papavasiliou, A., 2022. A note on a revenue adequate pric- ing scheme that minimizes make-whole payments. 18th International Conference on the European Energy Market (EEM) , 1–6.
- PJM, 2017. Proposed enhancements to energy price formation.
- Stevens, N., Papavasiliou, A., 2022. Application of the level method for computing locational convex hull prices. IEEE Transactions on Power Systems 37, 3958–3968.

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Two auction datasets used to compare the pricing schemes

FERC Dataset*	CWE dataset
~1000 power units	**~70 power units**
Sophisticated unit commitment model	Simpler unit commitment model
Convex & non-convex power units	Only non-convex power units
Possibility of inaction holds	Possibility of inaction does not hold
No network	**Network of 30 bidding zones**
11 load scenarios, 24 periods	**12 load scenarios** of 24 and 96 periods
Public data	Private data

* Knueven, B., Ostrowski, J., Watson, J.P., 2020. On mixed-integer programming formulations for the unit commitment problem. INFORMS J. Comput. 32, 857–876.
Krall, E., Higgins, M., O'Neill, R.P., 2012. Rto Unit Commitment Test System. Federal Energy Regulatory Commission, p. 98.

Some advantages of convex hull pricing

1 Marginal pricing leads to poor incentives for market participants

Table 2
Incentives of market agents on the CWE dataset depending on the price (average over 12 scenarios).

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost		5,489,000					
Av. Price [€/MWh]		42.8	43.4	47.3	27.7	23.8	52.6
Num. Suppl. with LOC		33.2%	35.9%	45.3%	83.6%	63.4%	64.3%
Av. LOC per Suppl.		3,528	278	1,285	141,834	29,326	27,066
LOC	Tot.	83,543	8,093	42,948	98,681,795	41,808,171	20,789,079
	Suppl.	83,543	6,810	39,006	8,746,513	1,350,259	1,250,017
	Net.	0	1,282	3,942	89,935,282	40,457,912	19,539,062
RS	Tot.	10,550	1,987	8,508	0	0	0
	Suppl.	10,550	1,987	8,508	0	0	0
	Net.	0	0	0	0	0	0

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RS	Tot.	10,550	1,987	8,508	0	0	0
	Suppl.	10,550	1,987	8,508	0	0	0
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Intuition: fixed “indivisible” costs (start-up, etc.) are not reflected the price signal

Some advantages of convex hull pricing

2 CHP significantly improves the incentives of the market participants

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Significant improvement of **total** incentives (LOC) for the participants under CH

Some advantages of convex hull pricing

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Table 2
Incentives of market agents on the CWE da ios).

Distribution of the LOC across participants: CHP improves significantly the average LOC born by individual agents

		MP	CHP	MMWP	MMWP*	MMWP**
Dispatch Cost				5 489 000		
Av. Price [€/MWh]		42.8	43.4			
Num. Suppl. with LOC		33.2%	35.9%			
Av. LOC per Suppl.		3,528	278			
LOC	Tot.	83,543	8,093			
	Suppl.	83,543	6,810			
	Net.	0	1,282			
RS	Tot.	10,550	1,987			
	Suppl.	10,550	1,987			
	Net.	0	0			

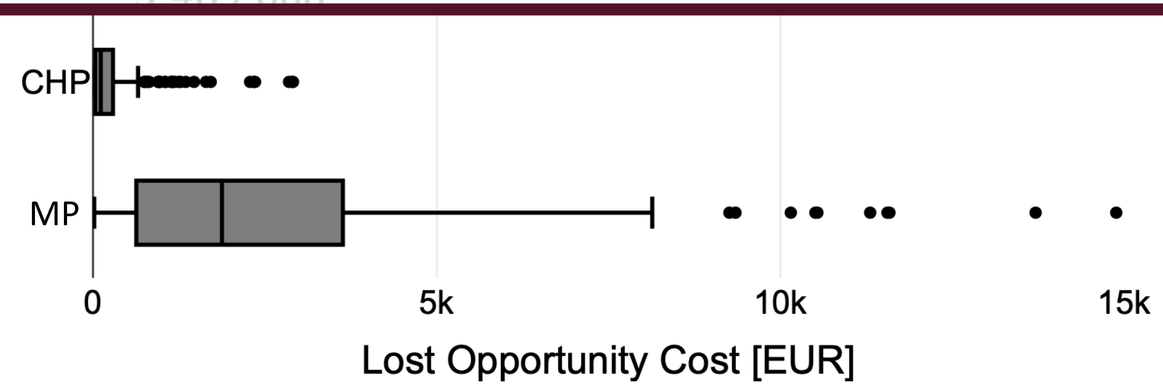

Figure 1: Distribution of the LOC accross suppliers for IP, CHP and ELMP (aggregate of all the CWE cases).

Some advantages of convex hull pricing

2 CHP significantly improves the incentives of the market participants

Proposition 3 (*LOC of Convex Agents in IP*). *Under IP pricing, all the convex market participants (the convex suppliers $g \in \mathcal{G}^C$ and the network) have a zero LOC.*

Table 2
Incentives of market agents on the CWE

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost							
Av. Price [€/MWh]		42.8					
Num. Suppl. with LOC		33.2%					
Av. LOC per Suppl.		3,528					
LOC	Tot.	83,543	8,093	42,948	98,681,795	41,808,171	20,789,079
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RS	Tot.	10,550	1,987	8,508	0	0	0
	Suppl.		1,987	8,508	0	0	0
				0	0	0	0

Proposition 5 (*Non-Zero LOC of Convex Agents*). *Under CHP, ELMP or MMWP, the convex market participants (both the convex suppliers and the network) may have a positive LOC.*

Although it does not mean that the LOC improves for each market participant

Some advantages of convex hull pricing

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2 CHP significantly improves the incentives of the market participants

Table 1
Incentives of market agents on the FERC dataset depending on the price (average over 11 scenarios).

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost					29,780,000		
Av. Price [$/MWh]		28.8	28.7	28.8	56.3	26.8	28.9
Num. Suppl. with LOC		3.4%	1.8%	7.5%	79.2%	24.7%	9.5%
Av. LOC per Suppl.		628	19	37	148,232	4,577	94
LOC	Tot.	37,576	323	2,801	130,147,114	1,176,050	14,217
	Conv.	0	67	94	1,978,501	5,268	79
	Non-Conv.	37,576	257	2,707	128,168,613	1,170,782	14,137
RS	Tot.	669	19	206	0	0	0
	Conv.	0	0	3	0	0	0
	Non-Conv.	669	19	203	0	0	0

Some advantages of convex hull pricing

2 CHP significantly improves the incentives of the market participants

Table 1
Incentives of market agents on the FERC dataset depending on the price (average over 11 scenarios).

		MP	CHP	EL[illegible]	[illegible]	[illegible]	[illegible]
Dispatch Cost							
Av. Price [$/MWh]		28.8	28.7	2[illegible]	[illegible]	[illegible]	[illegible]
Num. Suppl. with LOC		3.4%	1.8%	7.[illegible]	[illegible]	[illegible]	[illegible]
Av. LOC per Suppl.		628	19	37	[illegible]48,232	4,577	94
LOC	Tot.	37,576	323	[illegible],801	130,147,114	1,176,050	14,217
	Conv.	0	67	94	1,978,501	5,268	79
	Non-Conv.	37,576	257	2,707	128,168,613	1,170,782	14,137
RS	Tot.	669	19	206	0	0	0
	Conv.	0	0	3	0	0	0
	Non-Conv.	669	19	203	0	0	0

Significant improvement of **total** incentives (LOC) for the participants under CH

Some advantages of convex hull pricing

3 With CHP, the LOC are bounded : they do not grow with market size

Table 6
Results of CHP and IP pricing on FERC datasets (load profile `2015-08-01_lw`) depending on the market size. The initial 50-unit market is multiplied by a factor ranging from 2 to 20.

Market Size			Convex Hull Pricing		Marginal Pricing	
Number of Plants	Av. Hourly Load (MW)	Tot. Cost ($)	LOC ($)	LOC (% Tot. Cost)	LOC ($)	LOC (% Tot. Cost)
50	4,900	1,820,308	11,222	0.62%	276,383	15.18%
100	9,800	3,631,286	13,114	0.36%	538,713	14.84%
150	14,700	5,444,099	16,841	0.31%	805,370	14.79%
200	19,600	7,245,546	9,202	0.13%	1,060,574	14.64%
250	24,500	9,052,185	6,756	0.07%	1,320,763	14.59%
300	29,400	10,857,007	2,492	0.02%	1,579,297	14.55%
350	34,300	12,666,418	2,817	0.02%	1,842,613	14.55%
400	39,200	14,475,824	3,136	0.02%	2,105,629	14.55%
450	44,100	16,290,191	8,417	0.05%	2,373,870	14.57%
500	49,000	18,099,571	8,711	0.05%	2,636,708	14.57%
1000	98,000	36,183,999	2,280	0.01%	5,258,840	14.53%

Some advantages

3 With CHP, the LOC are bounded : the

Proposition 11 (*LOC Bound 1*). *Under CHP or ELMP, the total LOC is bounded. The bound depends on the shape of $\mathcal{X}_g$, but is independent of $|\mathcal{G}|$: $\lim_{|\mathcal{G}|\to\infty} LOC(\pi) < \Gamma$.*

Proposition 12 (*LOC Bound 2*). *Under IP or MMWP pricing, the total LOC is not necessarily bounded: it could be that $\lim_{|\mathcal{G}|\to\infty} LOC(\pi) \to \infty$.*

Table 6
Results of CHP and IP pricing on FERC dataset
market size. The initial 50-unit market is multipli

Market Size			Convex Hull Pricing		Marginal Pricing	
Number of Plants	Av. Hourly Load (MW)	Tot. Cost ($)	LOC ($)	LOC (% Tot. Cost)	LOC ($)	LOC (% Tot. Cost)
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1000	98,000	36,183,999	2,280	0.01%	5,258,840	14.53%

- With marginal pricing, the LOC grows with the market size
- With CHP not

Some advantages of convex hull pricing

4 Minimizing the LOC also leads to moderate RS

Table 2
Incentives of market agents on the CWE dataset depending on the price (average over 12 scenarios).

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Av. Price [€/MWh]		42.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Num. Suppl. with LOC		33.2%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Av. LOC per Suppl.		3,528	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
LOC	Tot.	83,543	8,093	[illegible]	[illegible]	[illegible]	[illegible]
	Suppl.	83,543	6,810	[illegible]	[illegible]	[illegible]	[illegible]
	Net.	0	1,282	[illegible]	[illegible]	[illegible]	[illegible]
RS	Tot.	10,550	1,987	[illegible]	0	0	0
	Suppl.	10,550	1,987	8,508	0	0	0
	Net.	0	0	0	0	0	0

Proposition 7 (*Relationship between RS and LOC*). *If all the market agents have the possibility of inaction* ($\mathbf{0} \in \mathcal{X}_g\ \forall g \in \mathcal{G}$, $\mathbf{0} \in \mathcal{F}$), *then* $RS_g^{gen}(\pi) \leq LOC_g^{gen}(\pi)\ \forall g$ *and* $RS^{net}(\pi) \leq LOC^{net}(\pi)$.

→ RS = incentive to self-schedule at 0

Some advantages of convex hull pricing

5 Minimizing the RS, on the other hand, exacerbates the LOC significantly

Important asymmetry ! :

- Minimizing the LOC leads to low RS
- Minimizing RS leads to very high LOC

Table 1
Incentives of market agents on the FERC dataset deper

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost					29,780,000		
Av. Price [$/MWh]		28.8	28.7	28.8	56.3	26.8	28.9
Num. Suppl. with LOC		3.4%	1.8%	7.5%	79.2%	24.7%	9.5%
Av. LOC per Suppl.		628	19	37	148,232	4,577	94
LOC	Tot.	37,576	323	2,801	130,147,114	1,176,050	14,217
	Conv.	0	67	94	1,978,501	5,268	79
	Non-Conv.	37,576	257	2,707	128,168,613	1,170,782	14,137
RS	Tot.	669	19	206	0	0	0
	Conv.	0	0	3	0	0	0
	Non-Conv.	669	19	203	0	0	0

Some advantages of convex hull pricing

5 Minimizing the RS, on the other hand, exacerbates the LOC significantly

Table 1
Incentives of market agents on the FERC dataset depending on the price (average over 11 scenarios).

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost					29,780,0[illegible]		
Av. Price [$/MWh]		28.8	28.7	28.8	[illegible]	[illegible]	[illegible]
Num. Suppl. with LOC		3.4%	1.8%	7.5%	[illegible]	[illegible]	[illegible]
Av. LOC per Suppl.		628	19	37	1[illegible]	[illegible]	[illegible]
LOC	Tot.	37,576	323	2,801	130[illegible]	[illegible]	[illegible]
	Conv.	0	67	94	1,[illegible]	[illegible]	[illegible]
	Non-Conv.	37,576	257	2,707	128,[illegible]	[illegible]	[illegible]
RS	Tot.	669	19	206	0	0	0
	Conv.	0	0	3	0	0	0
	Non-Conv.	669	19	203	0	0	0

Minimizing RS:
- Mild requirement
- Many ways to do it (not one single unambiguous pricing outcome)

Some advantages of convex hull pricing

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Incentives of market agents on the FERC dataset depending on the price (average over 11 scenarios).

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Dispatch Cost					29,780,000		
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Num. Suppl. with LOC		3.4%	1.8%	[illegible]	[illegible]	[illegible]	9.5%
Av. LOC per Suppl.		628	19	[illegible]	[illegible]	[illegible]	94
LOC	Tot.	37,576	323	[illegible]	[illegible]	[illegible]	14,217
	Conv.	0	67	[illegible]	[illegible]	[illegible]	79
	Non-Conv.	37,576	257	2,707	128,168,613	[illegible]	14,137
RS	Tot.	669	19	206	0	0	0
	Conv.	0	0	3	0	0	0
	Non-Conv.	669	19	203	0	0	0

Minimizing RS leads to 0 RS in these cases

Some advantages of convex hull pricing

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Incentives of market agents on the FERC dataset depending on the price (average over 11 scenarios).

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
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Av. LOC per Suppl.		628	19	37	148,232	4,577	94
LOC	Tot.	37,576	323	[illegible]	[illegible]	[illegible]	14,217
	Conv.	0	67	[illegible]	[illegible]	[illegible]	79
	Non-Conv.	37,576	257	[illegible]	[illegible]	[illegible]	14,137
RS	Tot.	669	19	[illegible]	[illegible]	[illegible]	0
	Conv.	0	0	3	0	0	0
	Non-Conv.	669	19	203	0	0	0

But it exacerbate the LOC

Some advantages of convex hull pricing

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5 Minimizing the RS, on the other hand, exacerbates the LOC significantly

Table 2
Incentives of market agents on the CWE dataset depending on the price (average over 12 scenarios).

		MP	CHP	ELMP	MMWP	MMWP*	MMWP**
Dispatch Cost					5,489,000		
Av. Price [€/MWh]		42.8	43.4	[illegible]	[illegible]	[illegible]	52.6
Num. Suppl. with LOC		33.2%	35.9%	[illegible]	[illegible]	[illegible]	64.3%
Av. LOC per Suppl.		3,528	278	[illegible]	[illegible]	[illegible]	27,066
LOC	Tot.	83,543	8,093	[illegible]	[illegible]	[illegible]	20,789,079
	Suppl.	83,543	6,810	[illegible]	[illegible]	[illegible]	1,250,017
	Net.	0	1,282	3,942	89,935,282	40,457,912	19,539,062
RS	Tot.	10,550	1,987	8,508	0	0	0
	Suppl.	10,550	1,987	8,508	0	0	0
	Net.	0	0	0	0	0	0

In presence of network constraint, this becomes dramatic

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Plan

Motivations	• Theoretical • Policy relevance: both in US and EU markets
Theoretical framework	• Formalize the problem • Solution to the problem — pricing schemes: marginal pricing, convex hull pricing…
Numerical simulations	• Numerical analysis on auction datasets • Cross comparison of different pricing schemes • Some advantages of convex hull pricing
Conclusion	

Conclusion

- Pricing the non-convexities in electricity auctions is a **long-lasting debate**
  - In the **US**: heterogeneous and changing policies
  - Recent discussions in **Europe** to reform the market pricing rule

- **Marginal pricing** could be an upgrade as compared to the current pricing rule: improvement in both **welfare** and **scalability**…

- But **Convex hull pricing comes with many benefits**
  - Significantly improves the incentives of the market participants
  - Ensures revenue shortfall remain contained
  - Guarantee that the LOC become relatively small when the market size increases

- While **minimizing the revenue shortfall**—or "make-whole payments"—may sound like a reasonable, target, it may also result in unbearable (and unbounded) lost opportunity costs

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