Indivisibilities in Investment and the Role of a Capacity Market

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Join work with Yves Smeers & Anthony Papavasiliou

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Motivations for the work

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Investment Problem

- Principle at the time of restructuring: **market will solve the investment problem**
- Then the "**missing money**" problem arises and questioned the ability of the market to foster sufficient investments
- This problem has generated a considerable literature on the respective merits of different **market designs** (CRM, CfD, PPA, etc)

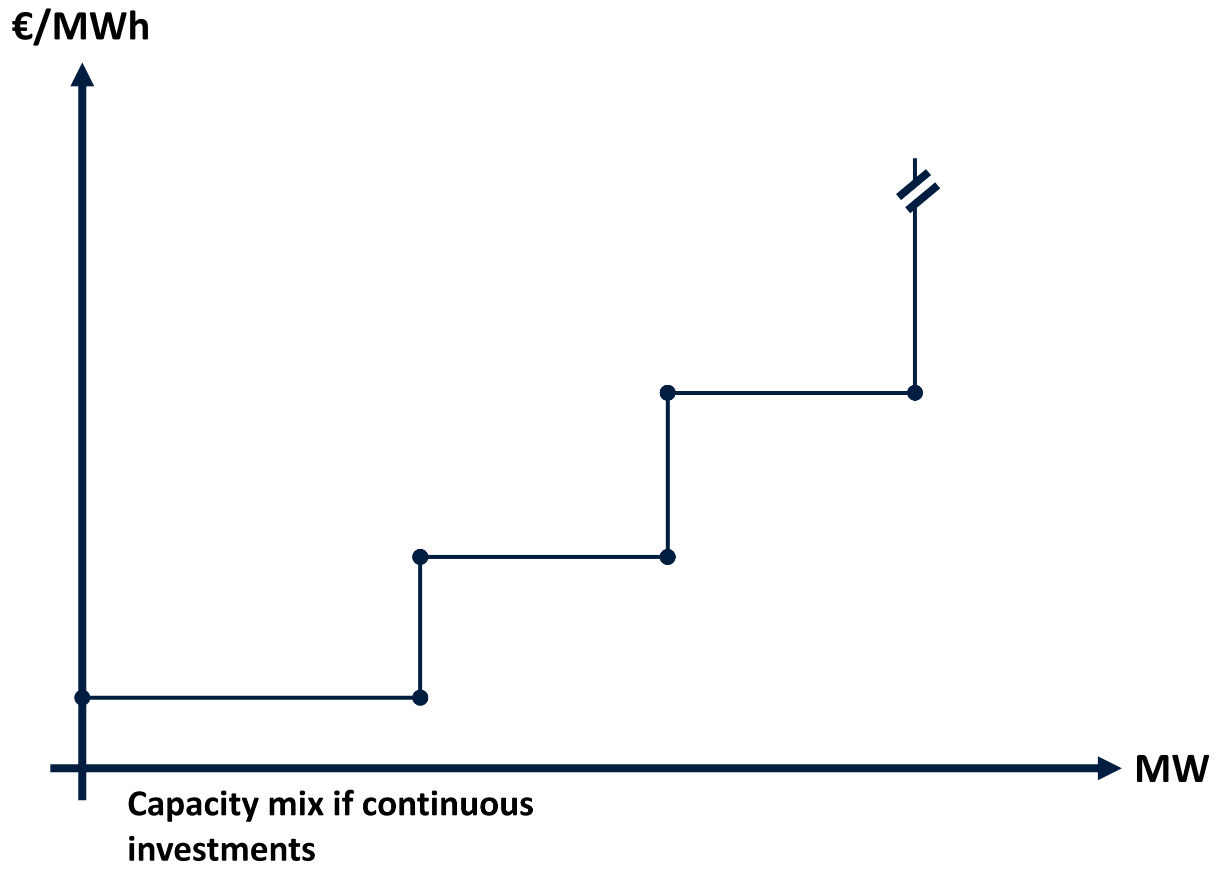
Indivisibility Problem

- It was quickly recognized that generation plants have **short-term "indivisibilities"** (start-up, etc.)
- These required some **public coordination** (design of pricing scheme, side payments)
- Indivisibilities also have a **long-term** dimension:
  - **Large fundamentally indivisible projects** (nuclear units, offshore wind island, etc.)
  - **Economies of scale**, learning by doing

Objective of the work—Explore the problem of **capacity expansion with discrete variables** (using the market to drive investment) and explore analogies with **missing money**

Method—Leverage the development on the **"pricing" of indivisibilities in unit commitment**

Intuitive introduction to the research idea



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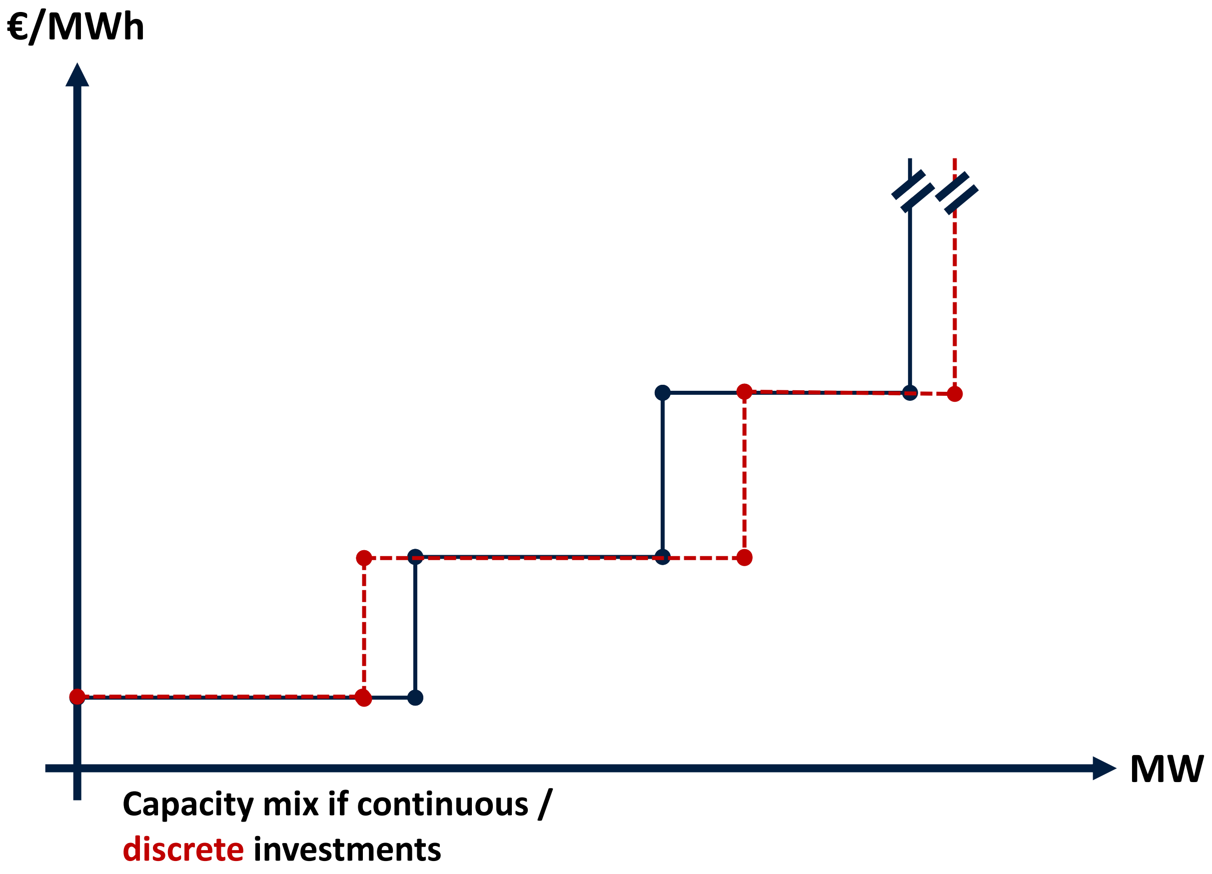

- Lumpiness of investment may **disturb the capacity mix**, as compared with continuous investments
- This may impact the **total system cost** which will be higher than if investments were continuous

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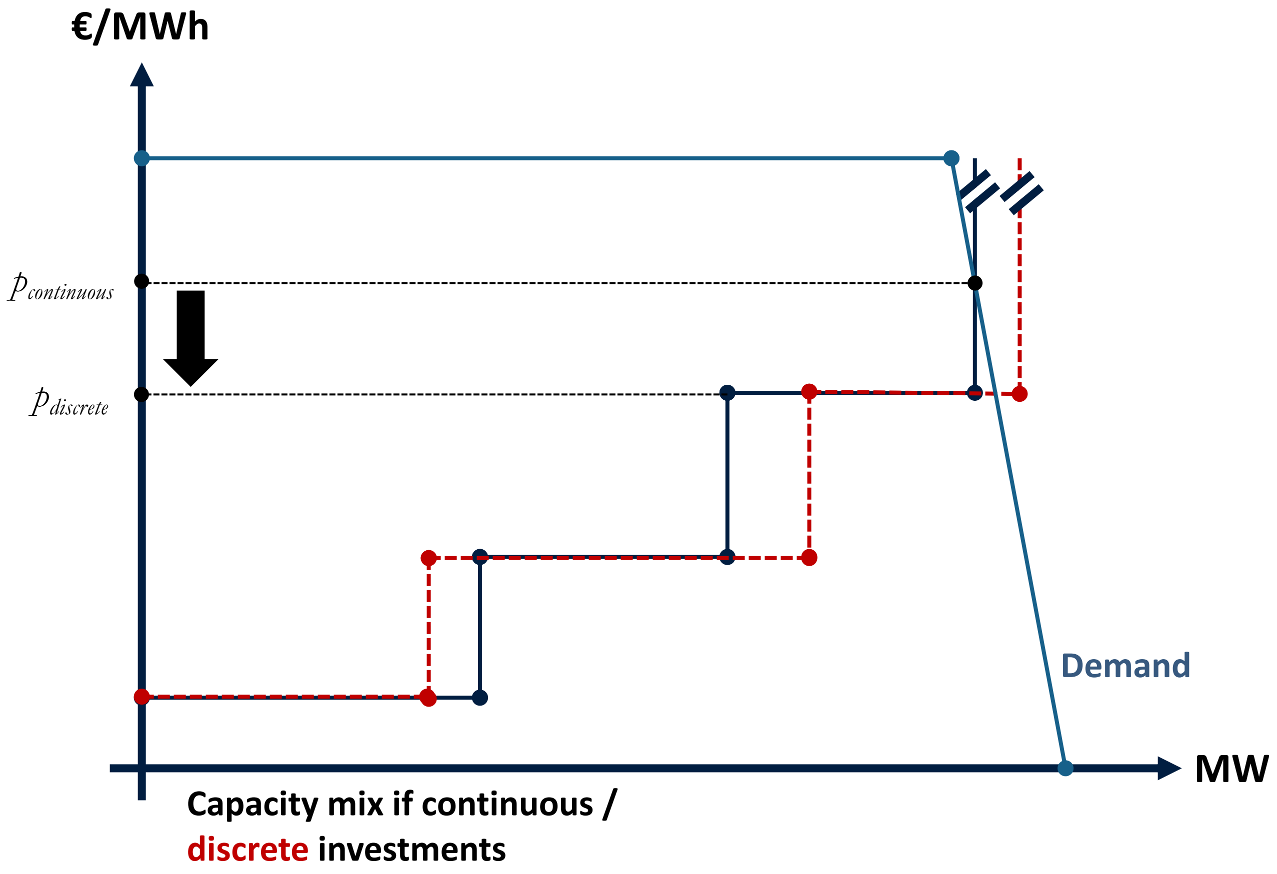

- Lumpiness of investment may **disturb the capacity mix**, as compared with continuous investments
- This may impact the **total system cost** which will be higher than if investments were continuous
- But lumpiness may **also impact prices**: if leading to slight "over-investments" compared to the continuous case (given load curtailment is expensive), lumpiness may reduce the price (especially given load is inelastic)
- This may in turn lead to a kind of "**missing money**"
- **Objectives** of the work
  - **Model and theory** of this "missing money"
  - Analyze **numerically** the magnitude of it
  - Analyze **market solutions** to the problem (**CRM**)

Plan

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The **long-term** indivisibilities

- The continuous investment problem
- The lost opportunity cost under the discrete investment problem
- Illustration on a toy example

Solution(s) to the indivisibilities

- Discriminatory payments
- Uniform price solution and capacity markets
- Illustration on a toy example

Numerical Results

- ENTSO-E capacity expansion model
- Models and data description
- Results

Conclusion

- Perspective for future research

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The continuous investment problem

In the **continuous investment problem**, there exists a uniform energy price π_t with a welfare-maximizing allocation $(d_t^*, x_g^*, q_{g,t}^*)$ that constitute a competitive equilibrium (Boiteux, 1949/1960)

$$\max_{q,x,d \geq 0} \sum_t \Delta T_t V_t d_t - \sum_g \sum_t \Delta T_t MC_g q_{g,t} - \sum_g IC_g x_g \quad (1a)$$

Minimize total costs (operational + investment)

$$(\Delta T_t \pi_t) \quad d_t \leq \sum_g q_{g,t} \quad \forall t \quad (1b)$$

Market clearing constraint (supply = demand)

$$(\Delta T_t \mu_{g,t}) \quad q_{g,t} \leq x_g \quad \forall g, t \quad (1c)$$

Link between investment and operation

$$(\Delta T_t \eta_t) \quad d_t \leq D_t \quad \forall t \quad (1d)$$

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Investment in g

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Production of g in t

Investment in g

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Consumption in t | Production of g in t | Investment in g

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The discrete investment problem

The discrete investment problem **turns the investment decisions into binary variables**: investment into lumps of capacity $P_{g,i}^{max}$

$$\max_{q,x,d} \sum_t \Delta T_t V_t d_t - \sum_{g \in \mathcal{G}} \left(\sum_t \Delta T_t MC_g q_{g,t} + \sum_i x_{g,i} IC_{g,i} \right) \quad \text{(3a)}$$

$$\sum_{g \in \mathcal{G}} q_{g,t} \geq d_t \quad \forall t \in \mathcal{T} \quad \text{(3b)}$$

$$q_{g,t} \leq \sum_i P_{g,i}^{max} x_{g,i} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(3c)}$$

$$q_{g,t} \geq 0 \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \quad \text{(3d)}$$

$$x_{g,i} \in \{0,1\} \quad \forall g \in \mathcal{G}, i \quad \text{(3e)}$$

$$0 \leq d_t \leq D_t \quad \forall t \in \mathcal{T} \quad \text{(3f)}$$

Illustration on a numerical example (Scarf, 1994)

	Capacity [MW] (P^{max})	Investment Cost (IC)	Marginal Cost (MC)
Smokestack	16	53	3
High Tech	7	30	2

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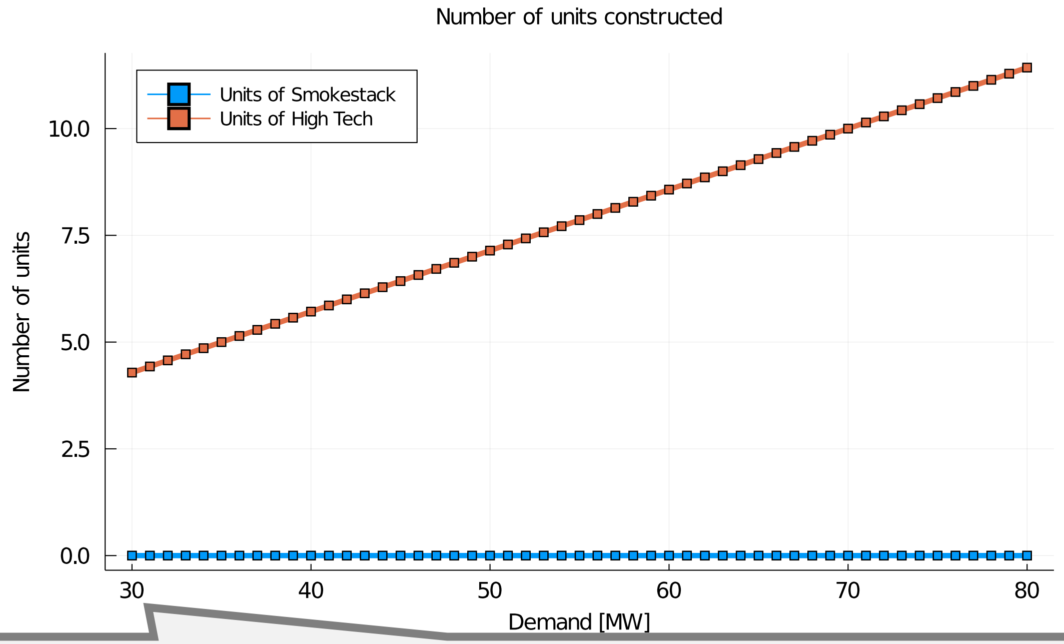
Continuous investment



Smooth investment decisions
+ **A long-term competitive equilibrium exists**
(price=6.3125€/MWh) → both technologies have incentives to implement the efficient outcome

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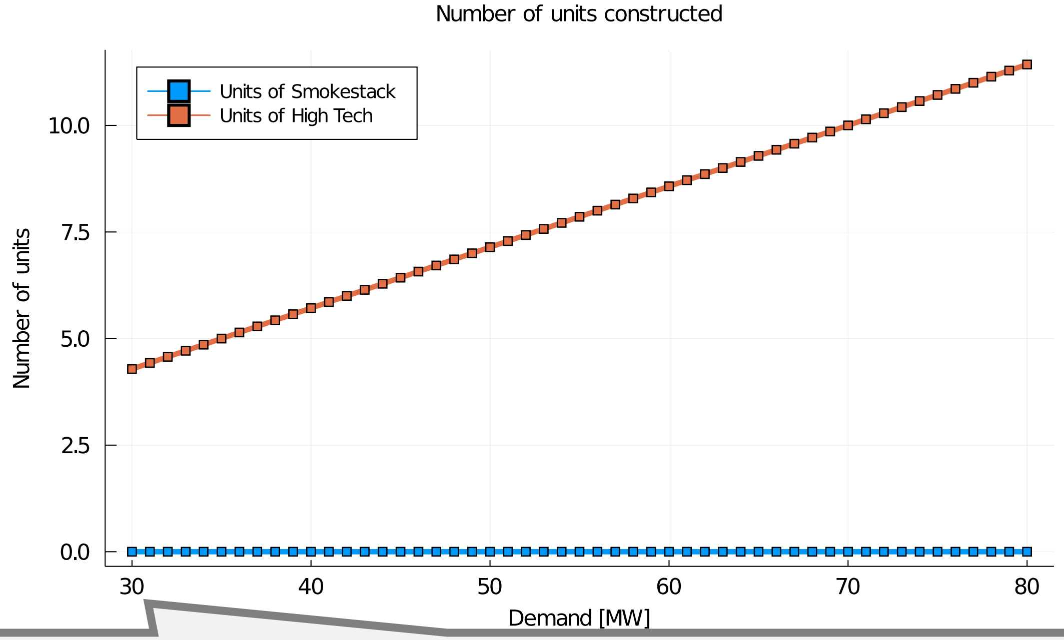

Smooth investment decisions
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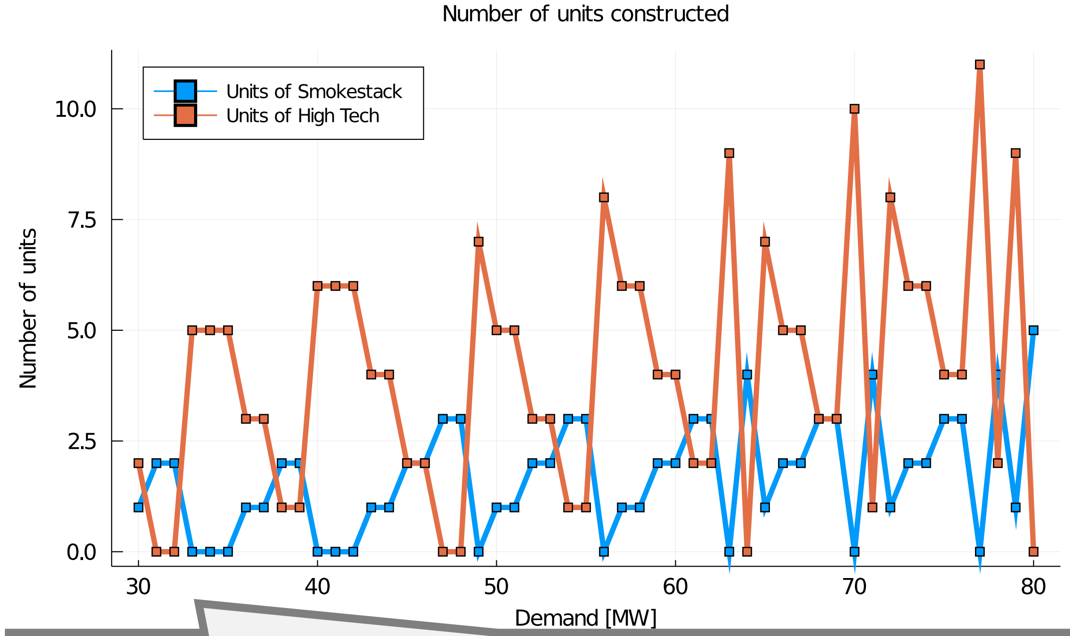
Discrete investment



Cycling effect
+ **A long-term competitive equilibrium does NOT exists**
→ There will be incentives to deviate from efficient outcome

Long-term Lost Opportunity Costs

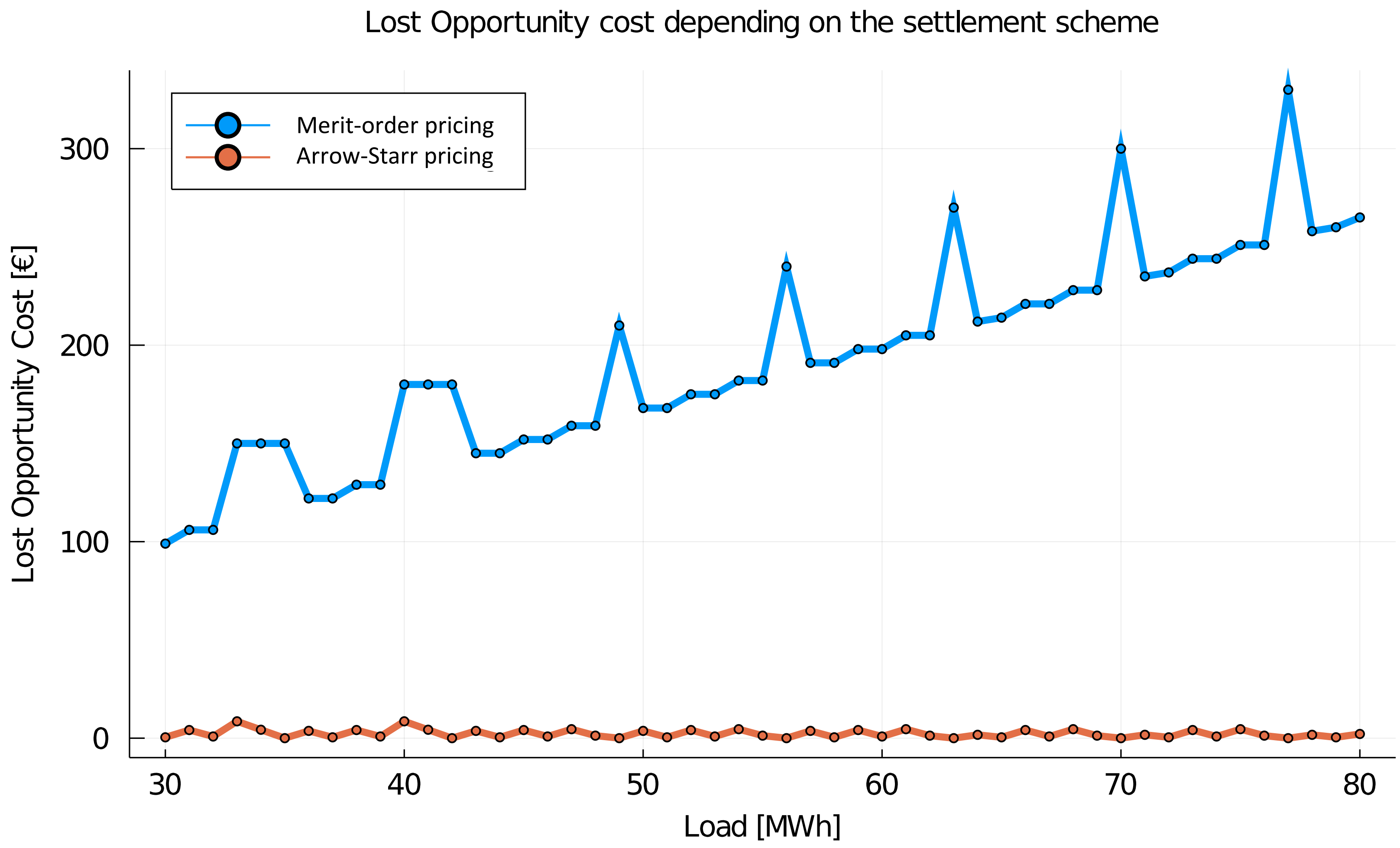
Definition 5 (Long-term Lost Opportunity Cost) The lost opportunity cost (LOC) is the difference between the selfish maximum profit under self-scheduling and the as-cleared profit (with allocation (q^*, x^*, d^*)) under price π. For each supplier g, it is expressed as:

$$0 \leq LOC_g(\pi) = \overbrace{\max_{(q,x)_g \in \mathcal{X}_g} \mathcal{P}_g(q, x, \pi)}^{\text{selfish maximum profit}} - \overbrace{\mathcal{P}_g(q^*, x^*, \pi)}^{\text{as-cleared profit}} \tag{7}$$

Intuitively, given the market price, some agents will :

- Either have the incentive to exit the market (facing a **revenue shortfall**)
- Or have the incentive to to build more than what is socially optimum (facing a **foregone opportunity**)

Illustration on a numerical example



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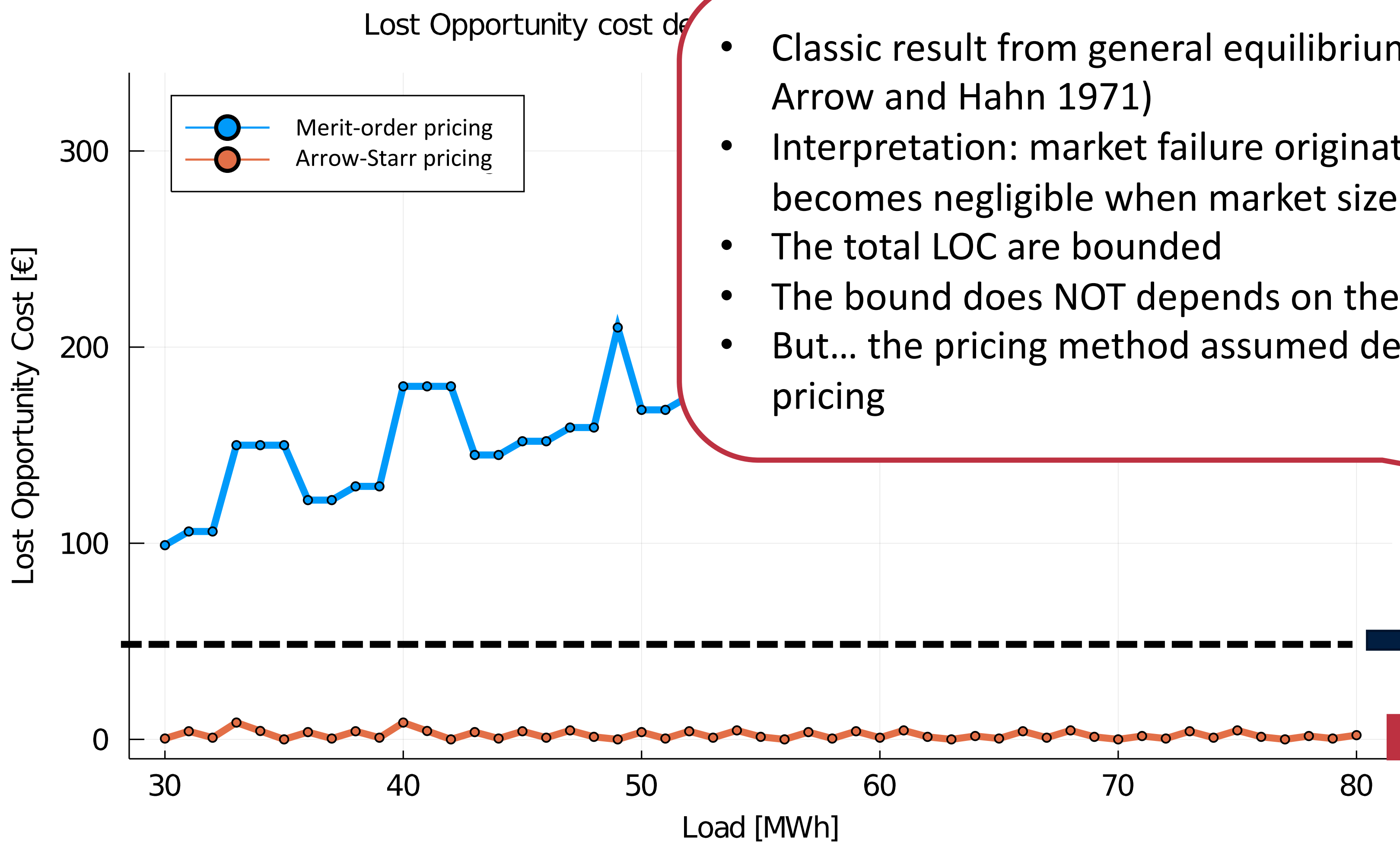
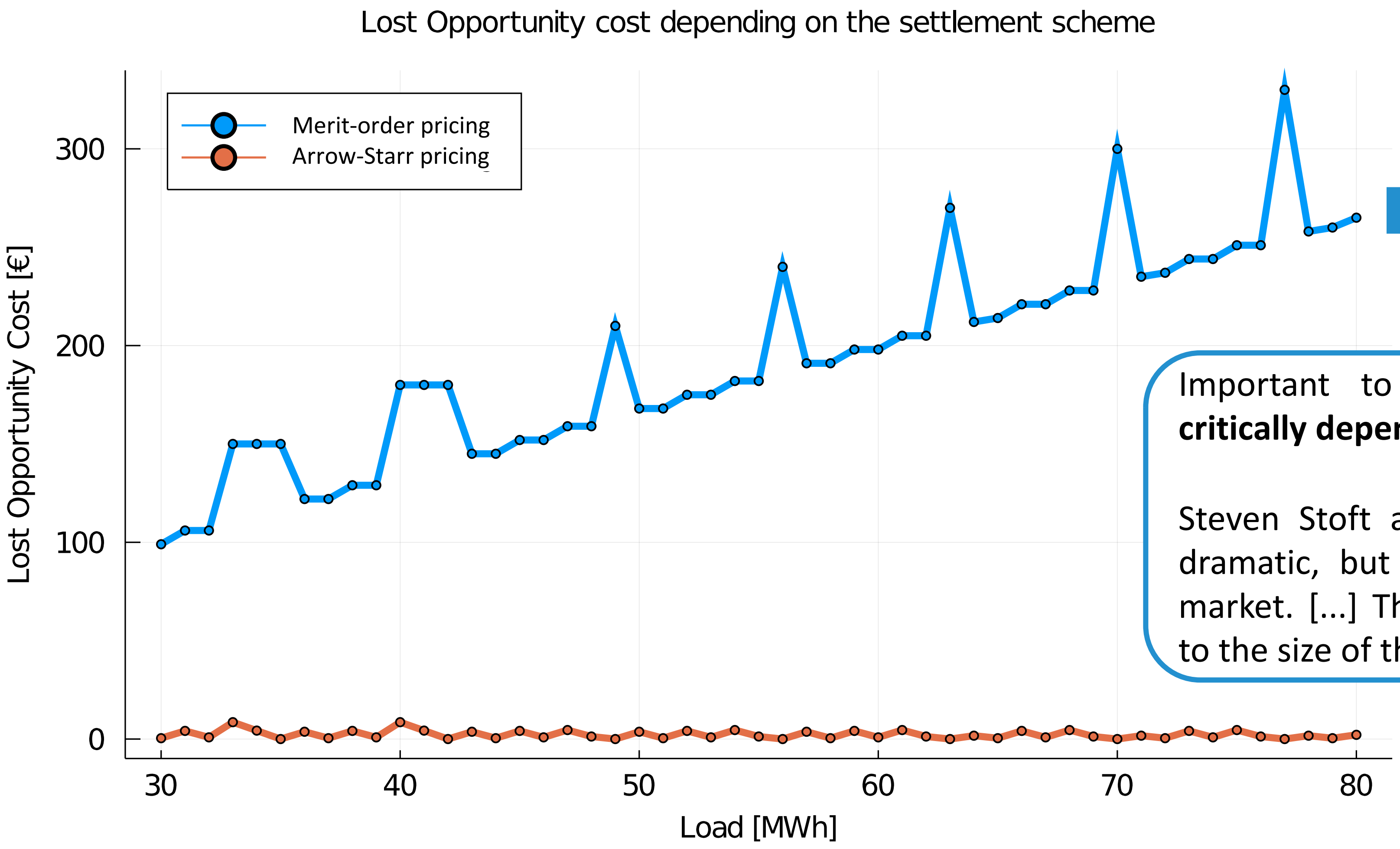


- Classic result from general equilibrium theory (Starr 1969; Arrow and Hahn 1971)
- Interpretation: market failure originating from indivisibilities becomes negligible when market size grows
- The total LOC are bounded
- The bound does NOT depends on the number of suppliers!
- But… the pricing method assumed departs from merit order pricing

The bound is **52€**

The LOC does not seem to grow with the market size

Illustration on a numerical example



The LOC DOES grow with the market size under **merit-order pricing**

Important to notice that **the previous result critically depends on the assumed pricing scheme!**

Steven Stoft argues: “this impact of lumpiness is dramatic, but it occurs in an unrealistically small market. [...] This inefficiency declines in proportion to the size of the market.” (Stoft, 2002)

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Conclusion	• Perspective for future research

Market incompleteness: discriminatory prices solution

- **What is broken** by the presence of indivisibilities in the investment decisions **is the possibility to achieve a perfect coordination** of private agents solely by means of a **uniform energy price signal**

- A purely **decentralized market** do not lead to a welfare-maximizing investment

- **O’Neill (2005)** : mitigate the LOC by **extending the set of commodities**
  - Two commodities : energy and capacity
  - Uniform price of energy & discriminatory prices for capacities
  - O’Neill shows that this is a market equilibrium

Uniform capacity price solution?

- Motivation: Capacity markets are currently a much debated topic in power system economics
- Can we find a **uniform (capacity) price** way to mitigate the LOC?

Definition (Profit Under Energy and Capacity prices). *The agent g is assumed to maximize its selfish profit function $\mathcal{P}_g$ defined as follows:*

$$\max_{\substack{(c,p,x)\mid \\ (5c),(5d) \\ (5e)}} \mathcal{P}_g(c,p,x,\pi^E,\pi^C) = \max_{\substack{(c,p,x)\mid \\ (5c),(5d) \\ (5e)}} \left\{ \sum_t \pi_t^E p_{g,t} + \pi^C \sum_i P_{g,i}^{max} x_{g,i} - \sum_t MC_g p_{g,t} - \sum_i IC_{g,i} x_{g,i} \right\} \quad (18)$$

Uniform price capacity market
The capacity auction model

Definition 10 (Discrete Capacity Auction) The capacity auction minimizes the cost of satisfying the inelastic capacity demand C^{min}:

$$\min_{x} \quad \sum_{g\in\mathcal{G}} \left(\sum_{i\in\mathcal{I}_g} x_{g,i} IC_{g,i} - \sum_{i\in\mathcal{I}_g} P^{max}_{g,i} x_{g,i} \sum_{t\in\mathcal{T}_g} \Delta T_t (\pi^M_t - MC_g) \right)$$

Agents' bids: investment cost – profit from energy market

$$(\pi^C) \quad \sum_{g\in\mathcal{G}} \sum_{i\in\mathcal{I}_g} P^{max}_{g,i} x_{g,i} \geq C^{min}$$

"Market clearing constraint": capacity target set by the SO

$$x_{g,i} \in \{0,1\} \quad \forall g \in \mathcal{G},\ i \in \mathcal{I}_g$$

→ **Theorem**: the capacity price resulting from the above auction (under some assumptions), reduces the Lost Opportunity Cost (LOC) of the market agents

Illustration on a numerical example

The LOC are mitigated by the uniform capacity price …but not reduced to 0

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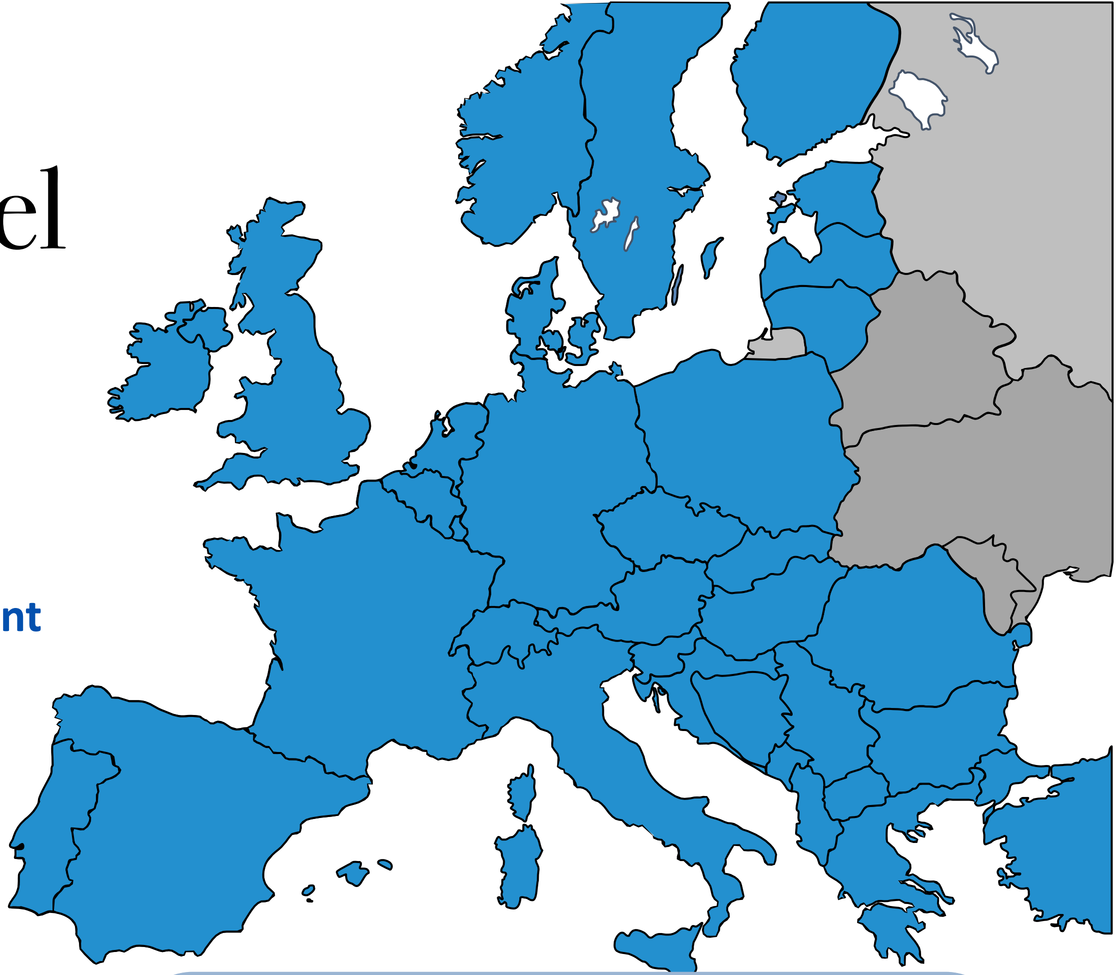
EU Capacity expansion model

- **To what extend does this theoretical problem materialize in big (realistic) systems?**
- Based on ENTSO-E data (**European Resource Adequacy Assessment (ERRA)***)
- Both operations and **investment decisions are convex** in ERRA (essentially for computational reasons)
- Our **objectives:**
  - Simulate the continuous model
  - Simulate the discrete model
  - Simulate the capacity market as previously described



KEY FIGURES*

- Geographical ext.: **37** countries
- Bidding Zones: **56**
- Target year: **2025**
- Num. of Techno.: **20**

*European resource adequacy assessment, 2021

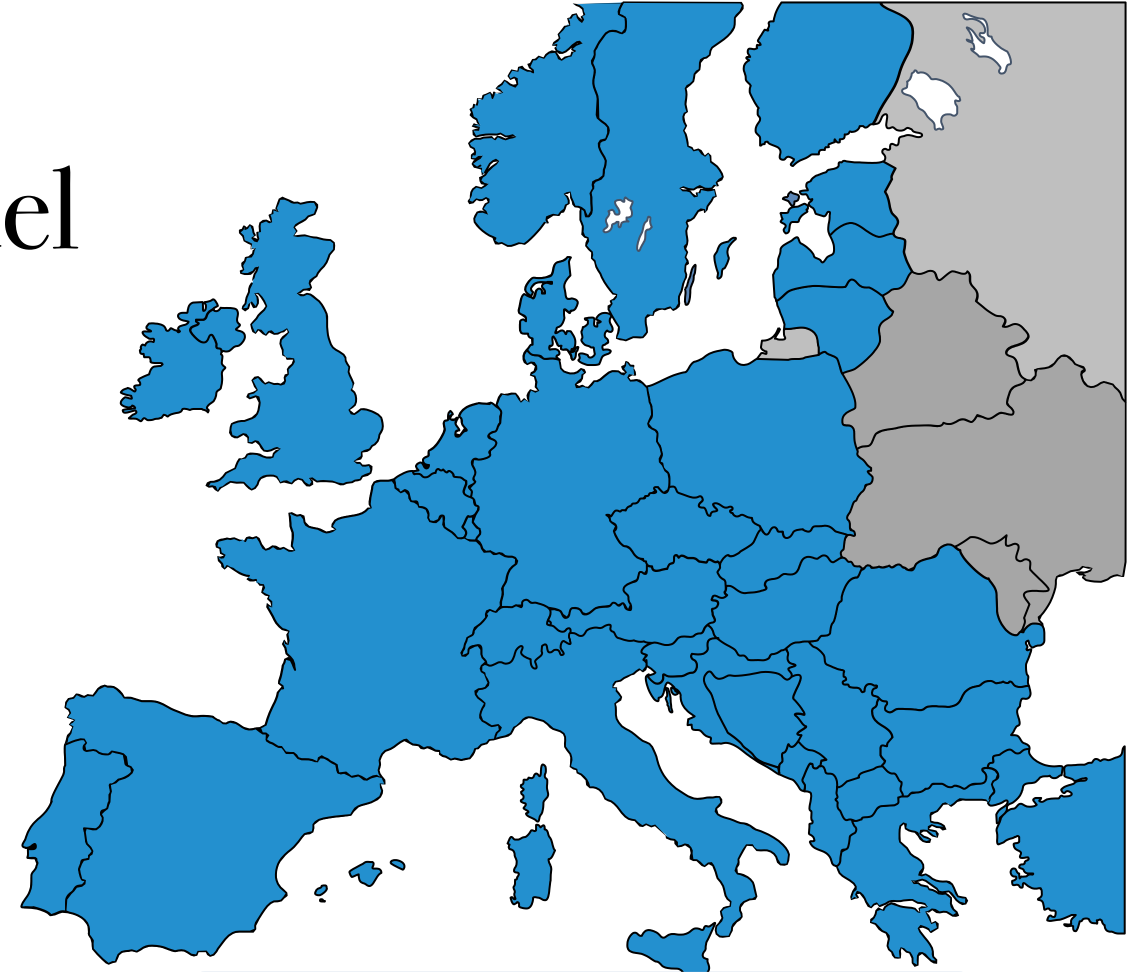
EU Capacity expansion model

- **Minimization of total cost** (investment + operational costs), Load curtailment valued at VOLL

- **Operational constraints** (all *convex* sources of production):
  - Thermal production
  - Batteries (load shifting)
  - Demand response (load shedding)
  - 4 types of hydro power plants

- **Network constraints**: convex, mainly cross-border ATC lines

- **Investment decisions**:
  - Investment in **new** MW of production units
    → essentially unlimited
  - Retirement of **existing** MW of production units
    → limited for many technologies



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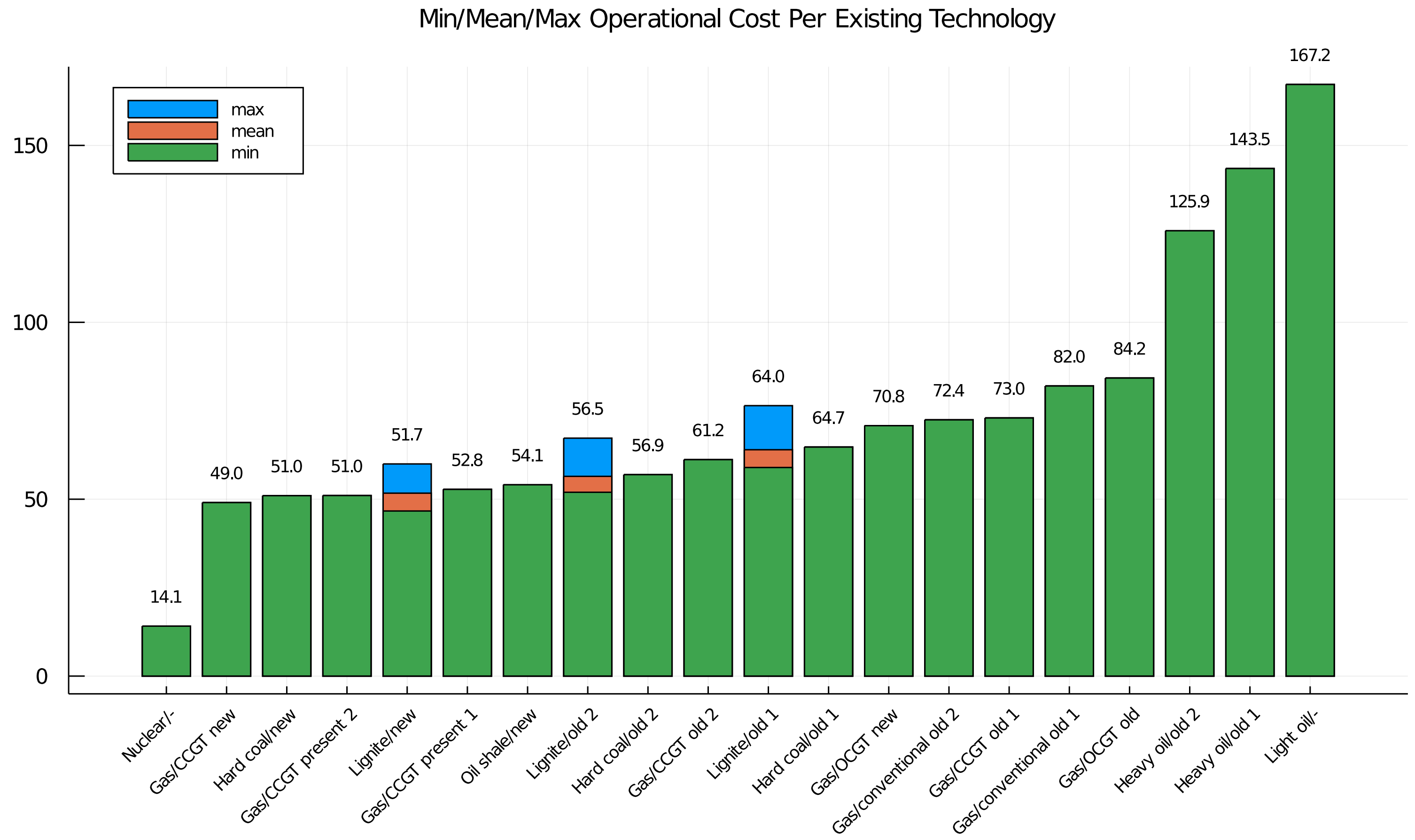
The EU input data

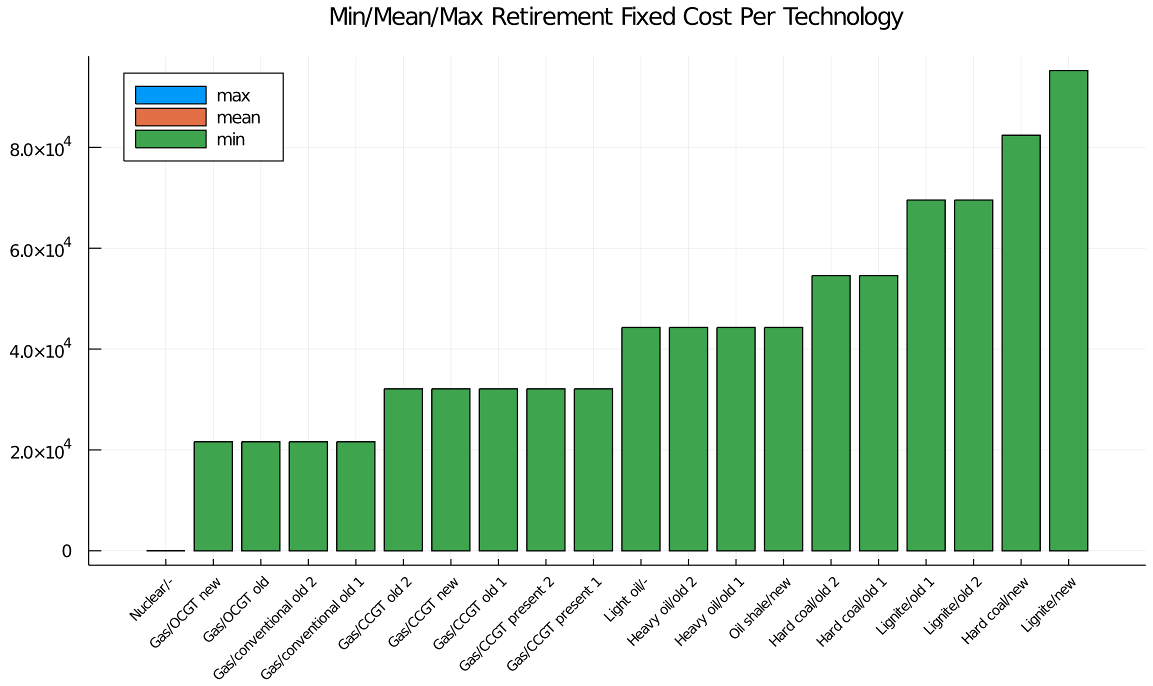
Merit order (Operational cost) of the entire system



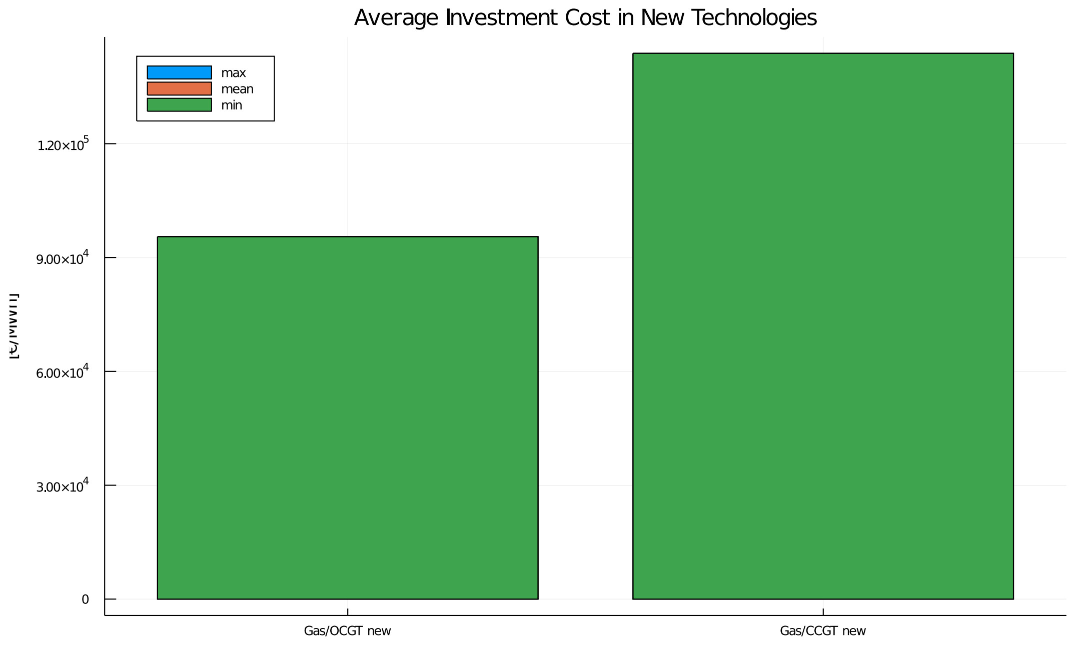
The EU input data

Fixed costs

Retirement of Existing installed capacity



Investments in New installed capacity



The results

	Total Cost		
	Cont.	Disc.	Inc.
...			
1989	7.385e10	7.409e10	0.3%
...			
2014	7.228e10	7.258e10	0.4%
...			
Average	7.637e10	7.657e10	0.3%

Simulations performed over 31 net load scenarios

1

In terms of TOTAL COST, the inclusion of lumpiness of investment leads to an increase of **+0.3%.**

The results

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	Total Cost		
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…			
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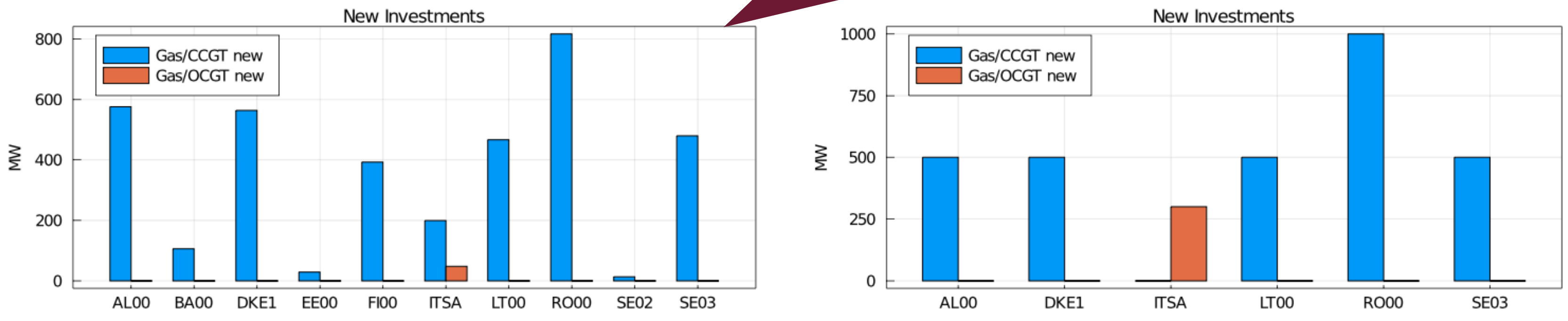
…			
Average	7.637e1		

2

It also leads to some rearrangement in terms of commissioning / decommissioning decisions



(a) Continuous model (b) Discrete model

Fig. 5: Commissioning decisions under the continuous and discrete model for the scenario 2014.

The results

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3 The essential difference with the continuous case is that the agents now have incentives to deviates from the welfare-maximizing investment!

		Without capacity market			With capacity market		
		New units	Exist units	Total	Inelastic	Elastic	No Coord.
...							
1989	LOC	3.534e8	1.376e8	4.91e8	4.863e8	6.354e8	1.144e9
	$RS^{\in LOC}$	1.802e7	0.0	1.802e7	1.335e7	4.154e7	3.244e7
	FO	3.354e8	1.376e8	4.73e8	4.73e8	5.939e8	1.111e9
...							
2014	LOC	1.052e8	3.202e8	4.254	[illegible]	[illegible]	[illegible]
	$RS^{\in LOC}$	6.925e7	3.171e8	3.864	[illegible]	[illegible]	[illegible]
	FO	3.599e7	3.061e6	3.905	[illegible]	[illegible]	[illegible]
...							
Averages							
	LOC	6.528e8	4.754e8	1.128e9	7.0e8	9.149e8	1.404e9
	$RS^{\in LOC}$	9.598e7	3.477e8	4.437e8	1.463e7	2.29e7	2.385e7
	FO	5.568e8	1.277e8	6.846e8	6.854e8	8.92e8	1.38e9

The **LOC are significant** although we are considering a large system: among all the possible commissioning (resp. decommissioning) decisions, **11%** (resp. **10%**) face a positive LOC.

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The results

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There are some plants that should be constructed/not retired while loosing money:

- **67%** of effective commissioning come with a RS
- On average, RS stands for **22%** of the investment cost.

The results

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There are some agents that are willing to build more capacity than what is socially optimum to construct
Concretely, some technologies have a non-zero profit: they earn a “discreteness rent” of 3740 €/MW/year (for a 500MW CCGT it means **1.87 M€/year**)

The results

The **capacity price**, compared to the sole energy remuneration, allows to **reduce the shortfall of revenue** for both the new and existing plants, **without increasing the opportunity costs.**

4

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...							
Averages							
	LOC	6.528e8	4.754e8	1.128e9	7.0e8	9.149e8	1.404e9
	$RS^{\in LOC}$	9.598e7	3.477e8	4.437e8	1.463e7	2.29e7	2.385e7
	FO	5.568e8	1.277e8	6.846e8	6.854e8	8.92e8	1.38e9

On average, the inclusion of a CRM:

- Reduces by 40% the LOC
- Reduces by 95% the Revenue Shortfall

The results

The **capacity price**, compared to the sole energy remuneration, allows to **reduce the shortfall of revenue** for both the new and existing plants, **without increasing the opportunity costs.**

4

We made a sensitivity with two designs that depart from the ideal settings of our Proposition

If a CRM could mitigate the LOC stemming from indivisibilities, flaws in CRM design may also exacerbate the problem!

		Without capacity market			With capacity market		
		New units	Exist units	Total	Inelastic	Elastic	No Coord.
...							
1989	LOC	3.534e8	1.376e8	4.91e8	4.86[illegible]	[illegible]	[illegible]
	$RS^{\in LOC}$	1.802e7	0.0	1.802e7	1.33[illegible]	[illegible]	[illegible]
	FO	3.354e8	1.376e8	4.73e8	4.73e8	5.939e8	1.111e9
...							
2014	LO[illegible]	[illegible]	[illegible]	[illegible]	[illegible]e7	2.678e8	1.328e9
	$RS^{\in LO}$[illegible]	[illegible]	[illegible]	[illegible]	[illegible]e7	4.362e7	3.012e7
	F[illegible]	[illegible]	[illegible]	[illegible]	[illegible]e7	2.242e8	1.297e9
...							
	Averages						
	LOC	6.528e8	4.754e8	1.128e9	7.0e8	9.149e8	1.404e9
	$RS^{\in LOC}$	9.598e7	3.477e8	4.437e8	1.463e7	2.29e7	2.385e7
	FO	5.568e8	1.277e8	6.846e8	6.854e8	8.92e8	1.38e9

Plan

The long-term indivisibilities

- The continuous investment problem
- The lost opportunity cost under the discrete investment problem
- Illustration on a toy example

Solution(s) to the indivisibilities

- Discriminatory payments
- Uniform price solution and capacity markets
- Illustration on a toy example

Numerical Results

- ENTSO-E capacity expansion model
- Models and data description
- Results

Conclusion

- Perspective for future research

Conclusion

- We **identified and analyzed** a problem not extensively discussed in the literature—**the discrete investment problem**
- We characterized the **theoretical magnitude of the LOC** and we show how it depends of the pricing rule considered
- We have seen that a **CRM could play a role in mitigating the LOC**, provided that the capacity target is well-designed
- We make an assessment of this theoretical problem and solutions on (1) a **toy example** and (2) on a **realistic (European-wide) system** which suggest the relevance of both the problem and the solution

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Thank you!

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Competitive Equilibrium

Definition 4 (Competitive Walrasian Equilibrium) The allocation (q^*, x^*, d^*) together with the market price π constitute a competitive Walrasian equilibrium if

(i) for each supplier g, $(q^*, x^*)_g$ optimizes its profit maximization problem (5) under price π ; d^* optimizes the load profit maximization problem (6) under price π ;

(ii) the market clears ($\sum_{g \in \mathcal{G}} q^*_{g,t} \geq d^*_t \quad \forall t \in \mathcal{T}$).

Marginal / "Merit-order" pricing

Definition 1 (Marginal Pricing) Let x^{**} be the values of the binary variables optimizing problem (3). The marginal prices are defined as the dual variables π^M obtained from solving the following (convex) problem, in which the variables x of problem (3) are fixed to x^{**}:

$$\max_{d,q} \sum_{t \in \mathcal{T}} \Delta T_t V_t d_t - \sum_{g \in \mathcal{G}} c_g((q, x^{**})_g) \tag{4a}$$

$$(\Delta T_t \pi_t^M) \quad \sum_{g \in \mathcal{G}} q_{g,t} \geq d_t \qquad \forall t \in \mathcal{T} \tag{4b}$$

$$(q, x^{**})_g \in \mathcal{X}_g \qquad \forall g \in \mathcal{G} \tag{4c}$$

$$d \in \mathcal{X}_d \tag{4d}$$

Convex Hull Pricing

Definition 7 (Convex Hull Pricing) The convex hull prices π^{CH} are defined as the dual variables obtained from solving the following convex problem:

$$z_D^* = \max_{d,q,x} \sum_{t \in \mathcal{T}} \Delta T_t d_t V_t - \sum_{g \in \mathcal{G}} c_g((q,x)_g) \tag{9a}$$

$$(\Delta T_t \pi_t^{CH}) \quad \sum_{g \in \mathcal{G}} q_{g,t} \geq d_t \qquad \forall t \in \mathcal{T} \tag{9b}$$

$$(q,x)_g \in \operatorname{conv}(\mathcal{X}_g) \qquad \forall g \in \mathcal{G} \tag{9c}$$

$$d \in \mathcal{X}_d \tag{9d}$$

New plants details

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Table 5: Detailed analysis of agents incentives for the *new* plants (commissioning) for scenario 2014.

Zone	Technology	Investment	Profit	LOC	$RS^{\in LOC}$	FO
SE04	CCGT new	0×500	0.0	3.05e6	0.0	3.05e6
DKE1	CCGT new	1×500	-1.871e6	1.871e6	1.871e6	0.0
LT00	CCGT new	1×500	2.007e6	2.007e6	0.0	2.007e6
AL00	CCGT new	1×500	-1.626e7	1.626e7	1.626e7	0.0
FI00	CCGT new	0×500	0.0	1.164e7	0.0	1.164e7
EE00	CCGT new	0×500	0.0	7.328e6	0.0	7.328e6
RO00	CCGT new	2×500	-3.284e7	3.284e7	3.284e7	0.0
SE02	CCGT new	0×500	0.0	3.468e6	0.0	3.468e6
SE01	CCGT new	0×500	0.0	2.199e6	0.0	2.199e6
SE03	CCGT new	1×500	1.733e6	3.466e6	0.0	3.466e6
ITSA	OCGT new	1×300	-1.828e7	1.828e7	1.828e7	0.0
LV00	CCGT new	0×500	0.0	2.829e6	0.0	2.829e6

Existing plant details

Table 6: Detailed analysis of agents incentives for *existing* plants (decommissioning) for scenario 2014 (sample).

Zone	Technology	In Place	Investment	Profit	LOC	$RS^{\in LOC}$	FO
DKE1	Light oil	529	-2 × 100	-2.871e6	2.618e6	2.618e6	0.0
GR03	Light oil	277	-0 × 100	-3.632e6	2.622e6	2.622e6	0.0
PT00	CCGT present 1	990	-0 × 450	-1.367e6	1.243e6	1.243e6	0.0
HU00	CCGT old 2	976	-0 × 400	-1.726e7	6.407e6	6.407e6	0.0
BE00	CCGT present 2	3550	-0 × 450	-6.709e6	5.953e6	5.953e6	0.0
FR00	CCGT present 2	5148	-0 × 450	-7.521e7	7.231e7	7.231e7	0.0
UK00	CCGT old 2	15010	-3 × 400	3.173e7	2.757e6	0.0	2.757e6
UK00	CCGT old 1	593	-1 × 400	146800.0	303600.0	0.0	303600.0
RS00	Lignite new	1106	-0 × 300	-2.863e7	2.33e7	2.33e7	0.0
ES00	CCGT present 1	24499	-12 × 450	-1.492e8	5.452e7	5.452e7	0.0