Price Formation with Non-Convexities

Theory and Applications for the Electricity Market

Nicolas Stevens

PhD Public Defense, December 2024

Supervisors
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Content

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Content

Electricity is an important sector of our economies

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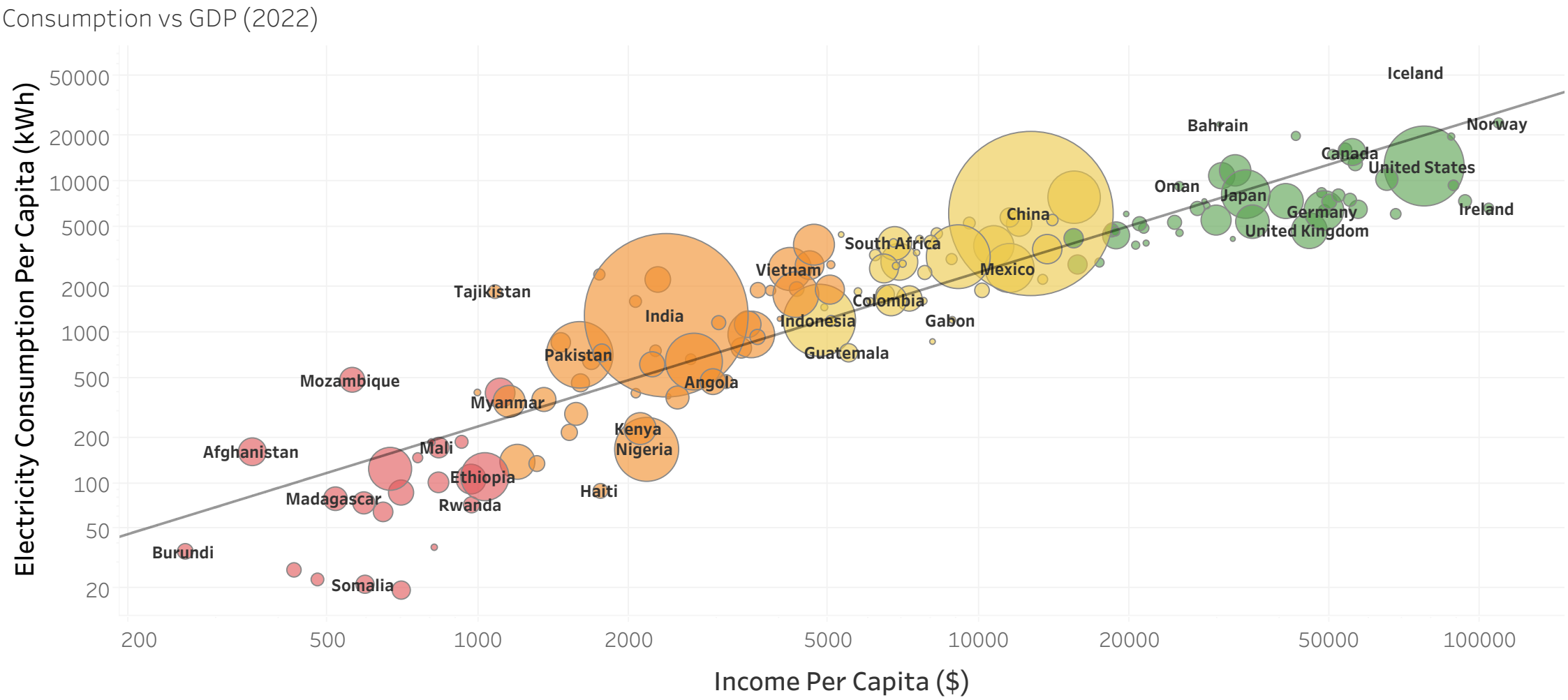

Source: https://public.tableau.com/app/profile/energyforgrowthhub/viz/final_ConsumptionvsGDP/Sheet1

Electricity is an important sector of our economies

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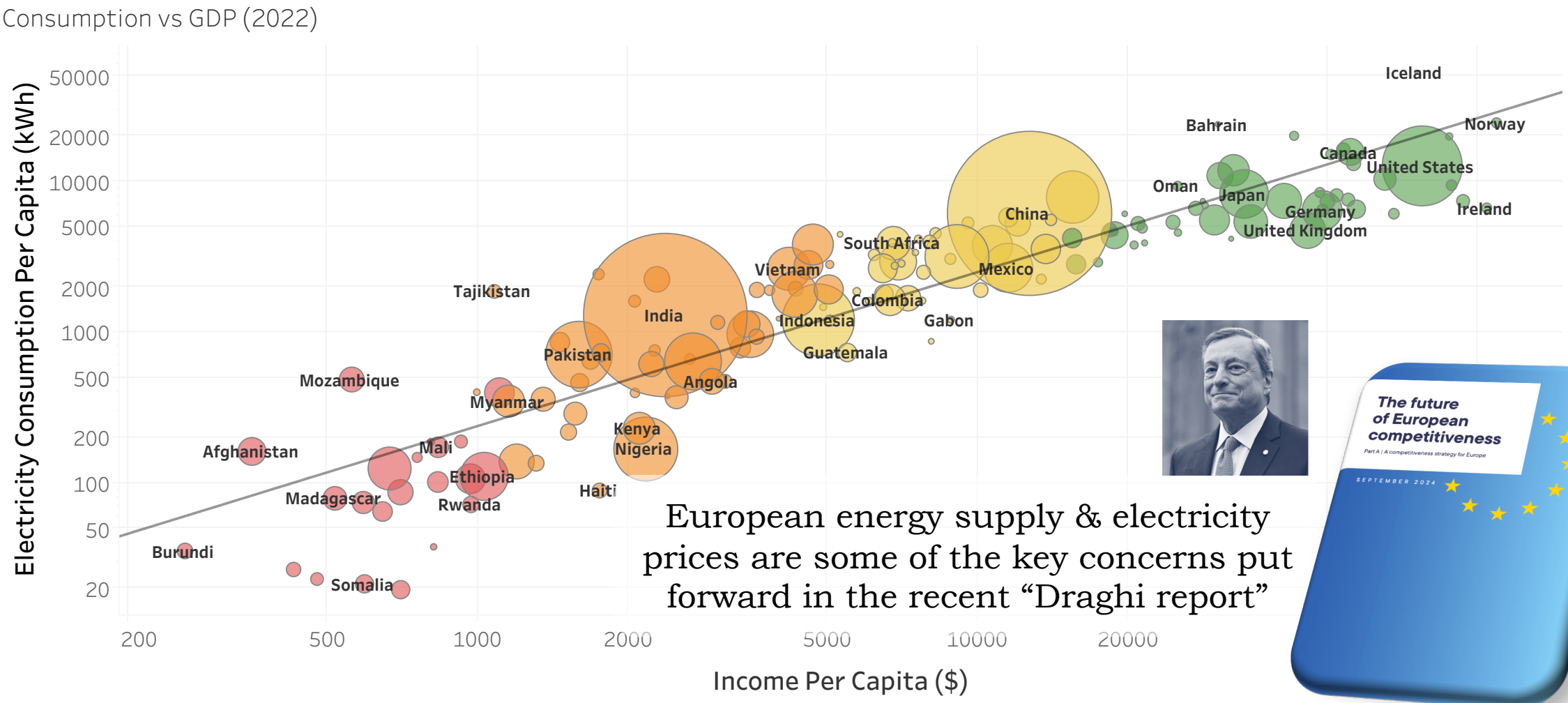


European energy supply & electricity prices are some of the key concerns put forward in the recent “Draghi report”

Source: https://public.tableau.com/app/profile/energyforgrowthhub/viz/final_ConsumptionvsGDP/Sheet1

Electricity production stands for ~25% of global CO_2 emissions

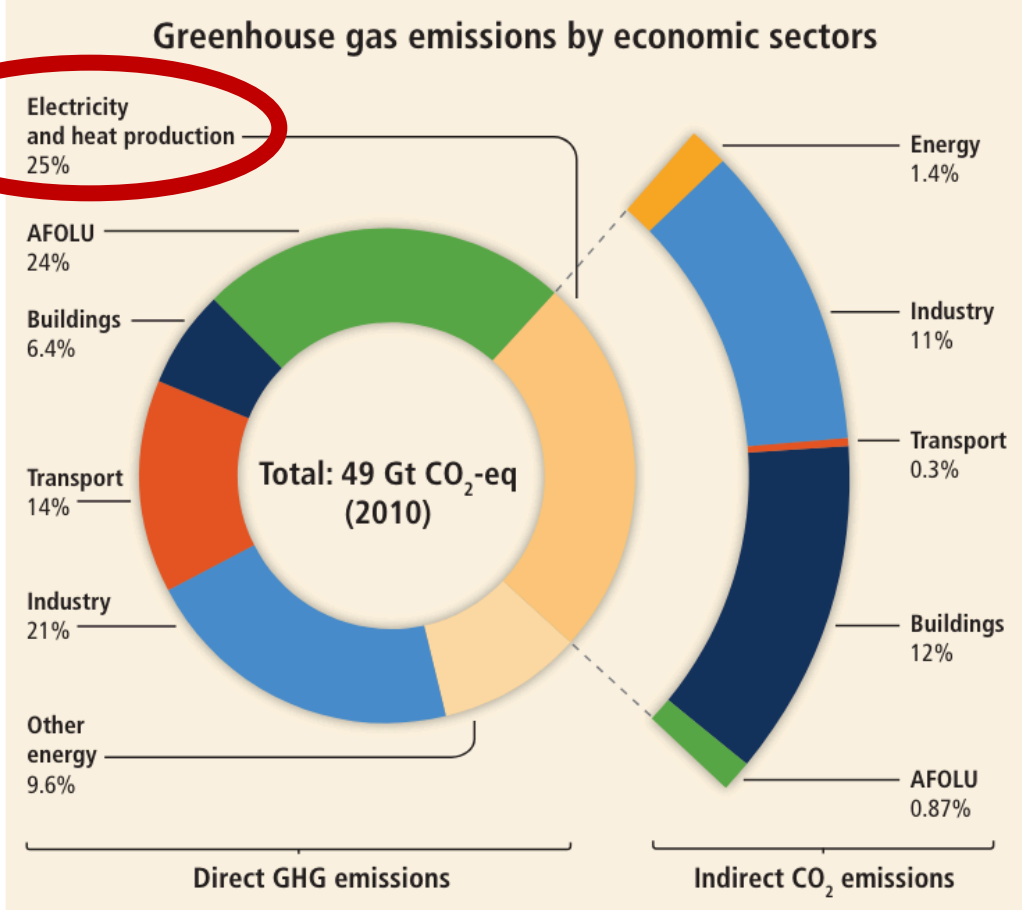


Figure 1.7 | Total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, $GtCO_2$-eq/yr) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in % of total anthropogenic GHG emissions) from five economic sectors in 2010. The pull-out shows how shares of indirect CO_2 emissions (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. 'Other energy' refers to all GHG emission sources in the energy sector as defined in WGIII Annex II, other than electricity and heat production *{WGIII Annex II.9.1}*. The emission data on agriculture, forestry and other land use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU) as described in Chapter 11 of the WGIII report. Emissions are converted into CO_2-equivalents based on 100-year Global Warming Potential (GWP_{100}), taken from the IPCC Second Assessment Report (SAR). Sector definitions are provided in WGIII Annex II.9. *{WGIII Figure SPM.2}*

[Source: IPCC 5th report (2014)]

* AFOLU stands for "Agriculture, Forestry and Other Land Use"

Renewable generation capacity in Belgium

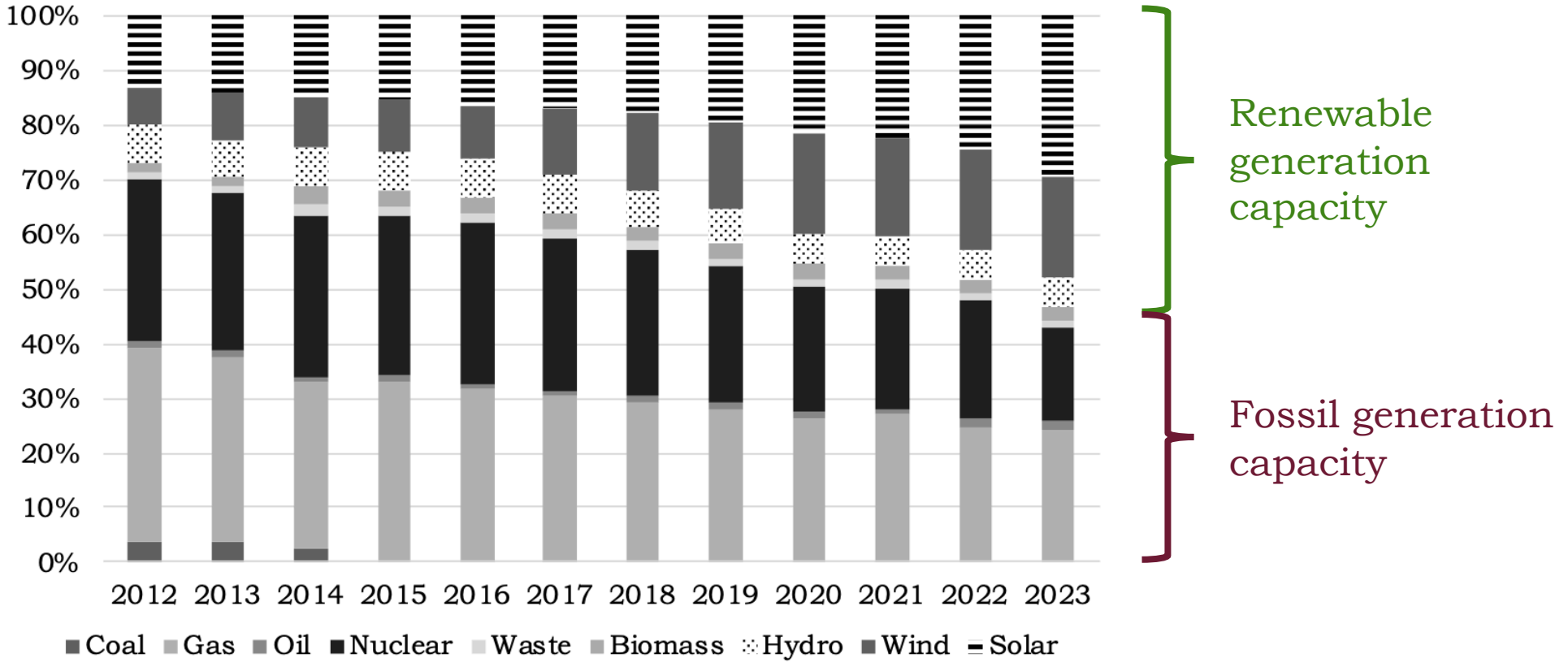
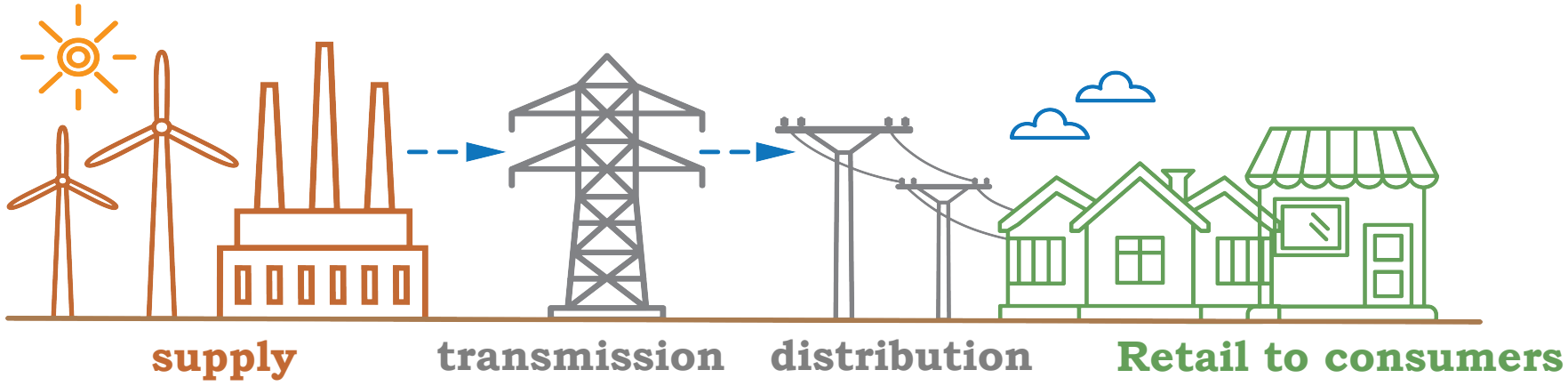


FIGURE 6.1: Electricity generation capacity in Belgium. [Data source: IRENA for wind and PV, Elia for the remaining technologies]

Electricity fundamentals

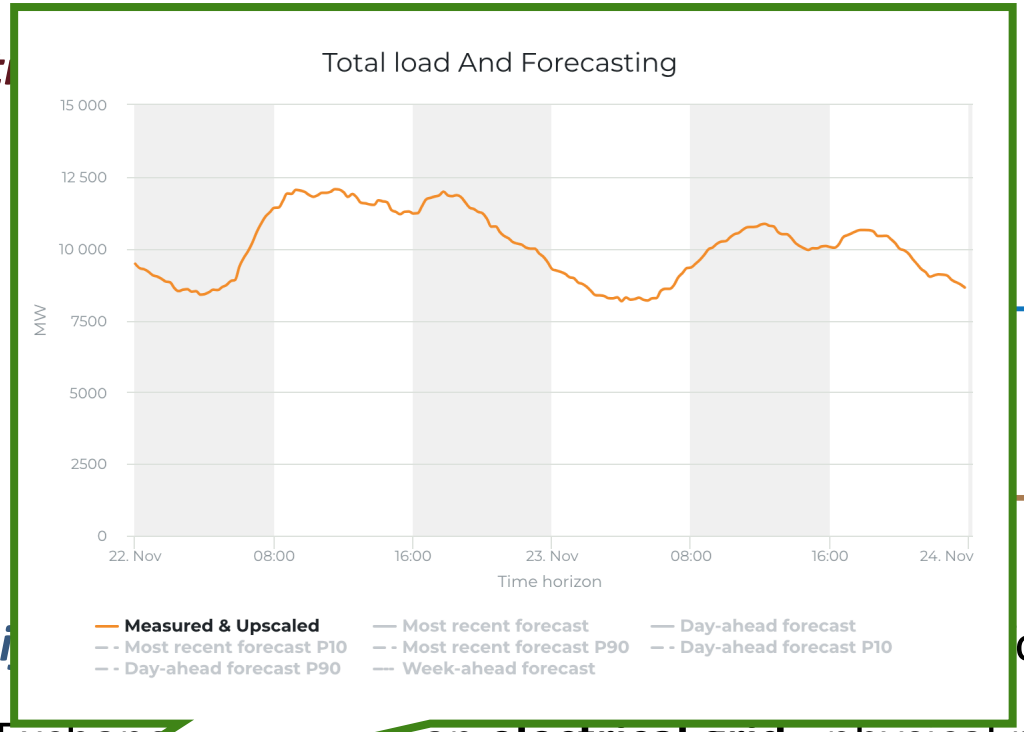
- ***Electricity supply chain:***

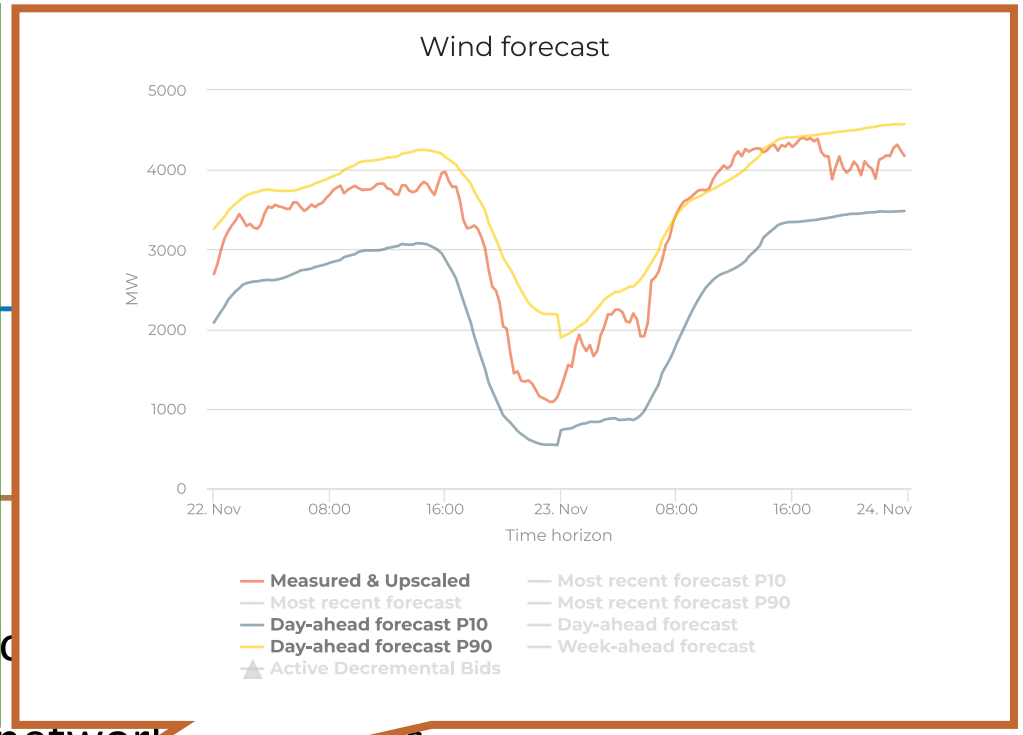


- ***Specificities of electricity as a commodity*** → need for coordination
  - Exchanged through an **electrical grid** : physical network constraints
  - **Demand** must be met just-in-time by **production**
  - **Difficult / expensive to store**
  - **Low elasticity** of demand (few substitutes & lack of metering)

Electricity fundamentals

- ***Electr***



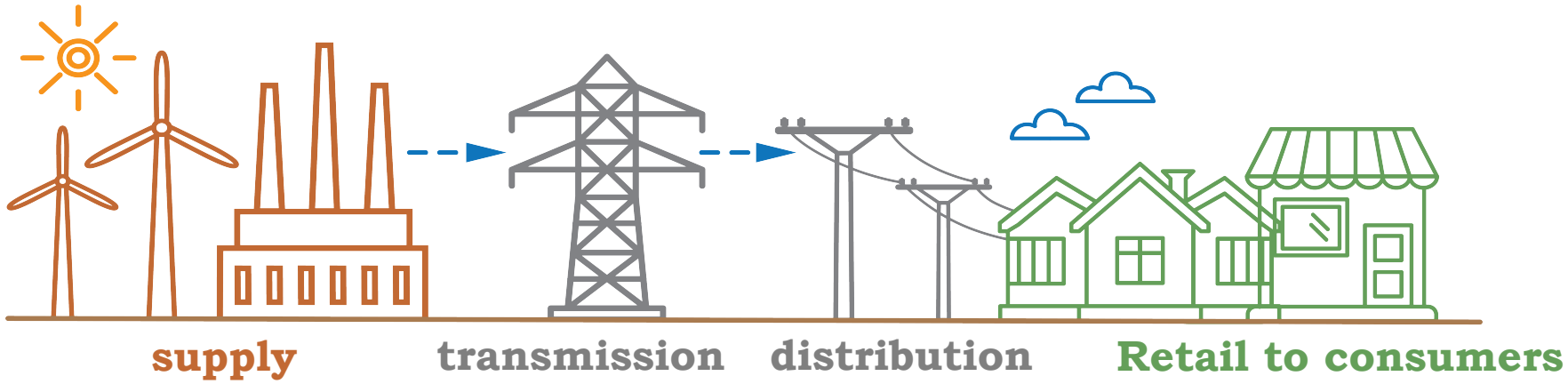


- ***Speci***

  - Exchan ugh an **electrical grid** : physical networ aints
  - **Demand** must be met just-in-time by **production**
  - **Difficult / expensive to store**
  - **Low elasticity** of demand (few substitutes & lack of metering)

The liberalization of power systems

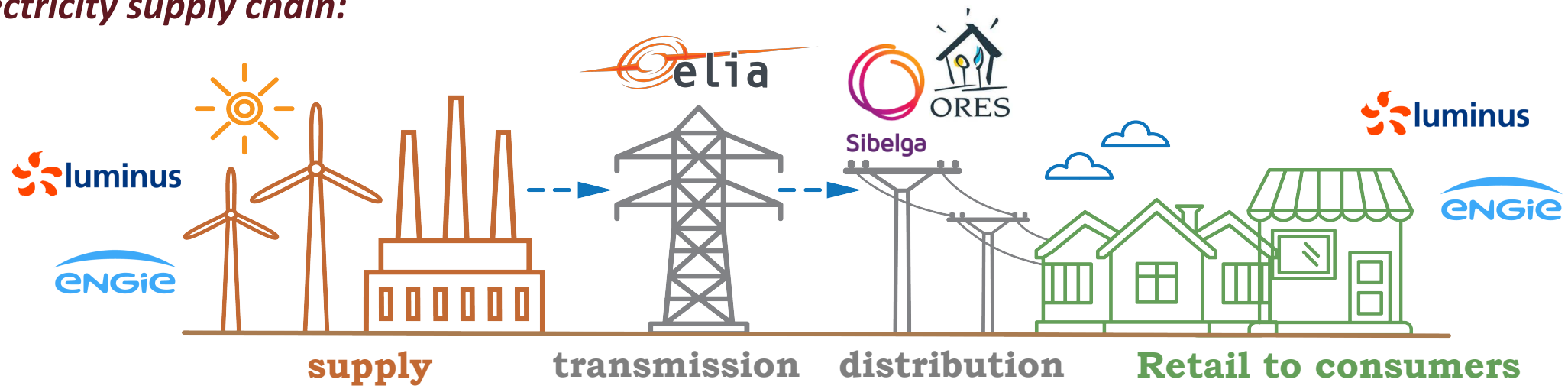
- ***Electricity supply chain:***



- ***Deregulation of power systems***:
  - From a **coordination by a single firm** (vertically integrated monopoly) to a **coordination through *market transactions*** (Coase, 1937)

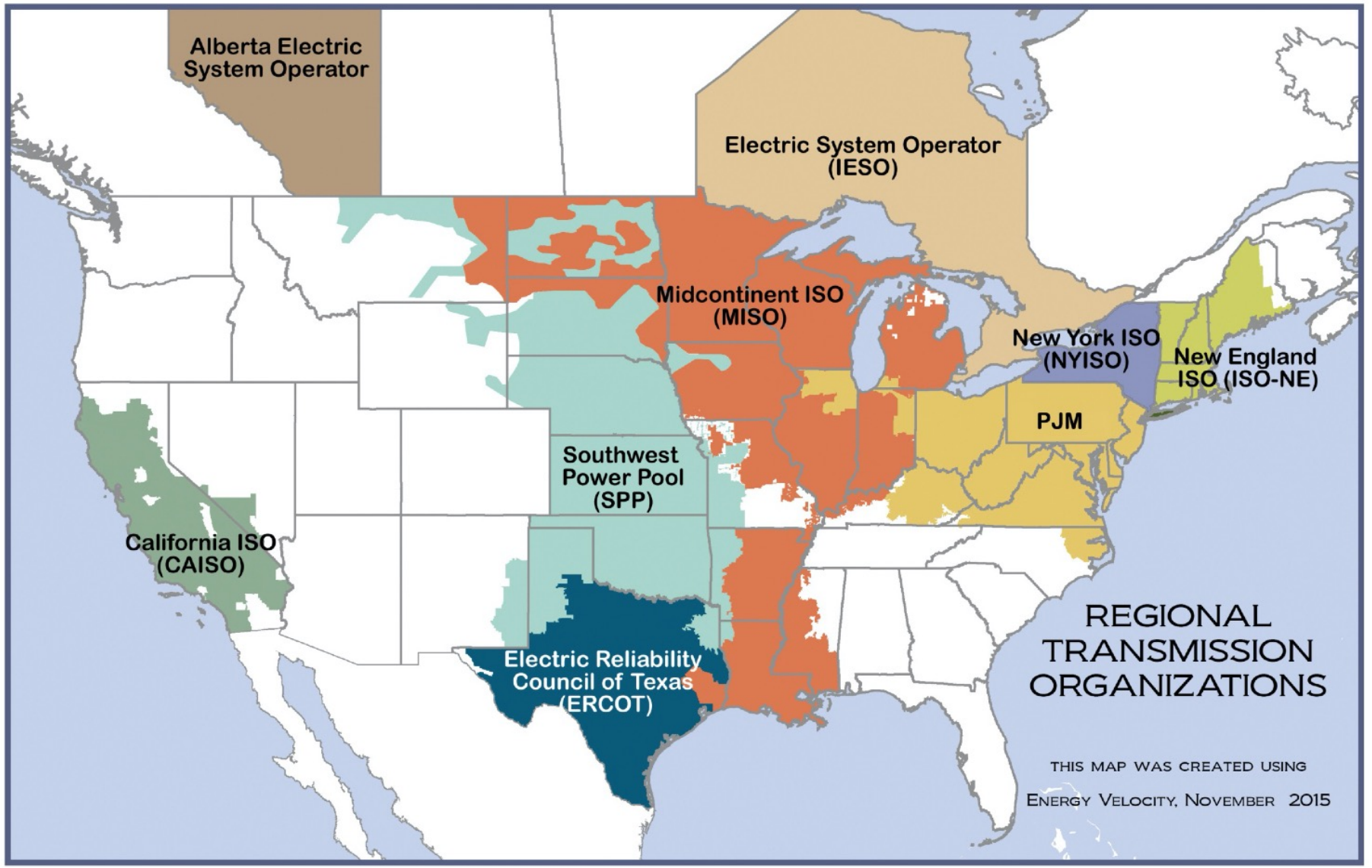
The liberalization of power systems

- ***Electricity supply chain:***



- ***Deregulation of power systems***:
  - From a **coordination by a single firm** (vertically integrated monopoly) to a **coordination through *market transactions*** (Coase, 1937)
  - A "vertical" separation of the competitive segments (**generation** and **retail**) from the natural monopoly segments (**transmission and distribution**)
  - *"the move to liberalizing the electricity sector […] was effectively a bet that the costs of any residual imperfections in competitive wholesale markets are smaller than the costs of imperfections associated with the behaviour of vertically integrated regulated monopolies."* (Joskow, 2019)

Electricity markets in the US

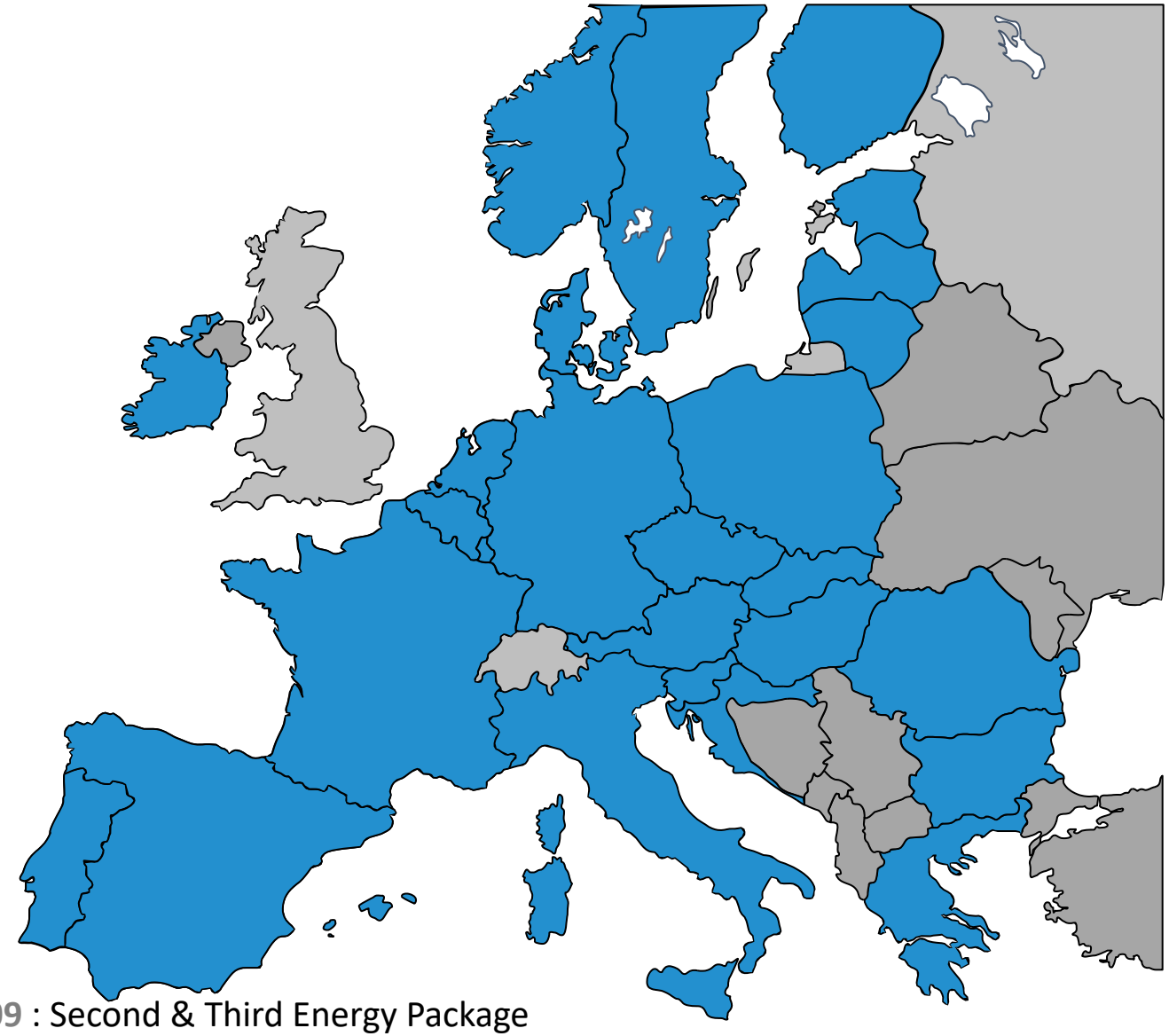


1992 : Energy Policy Act

creation of ISOs that operate the market

1990 2000 2010 2020

Electricity markets in Europe



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

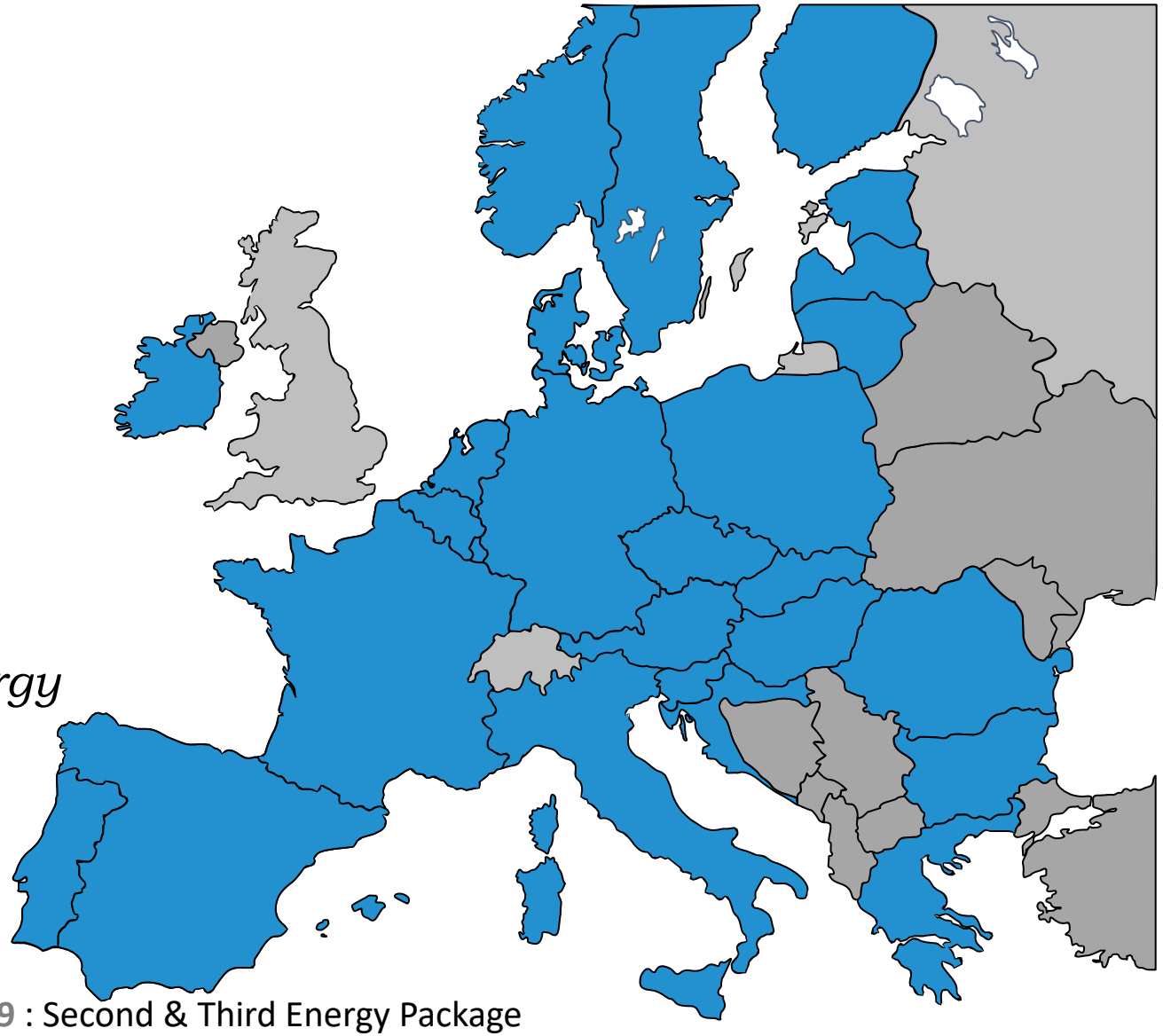
2014: Single Day-Ahead Coupling (SDAC), Price Coupling of Regions

1990 2000 2010 2020

Electricity markets in Europe

Liberalization implies that the price of electricity is the outcome of a market…

…and not a decision of the Minister of Energy



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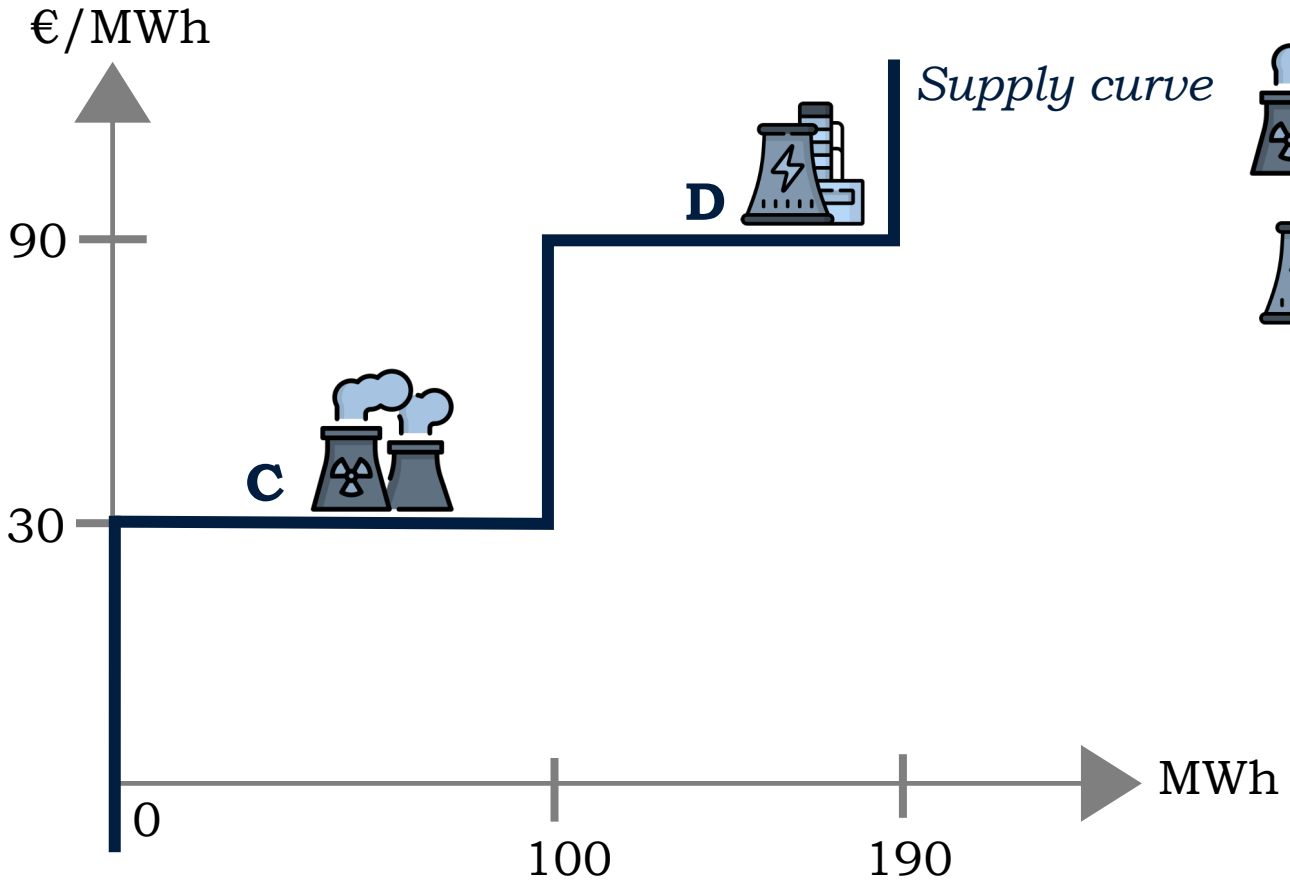
Content

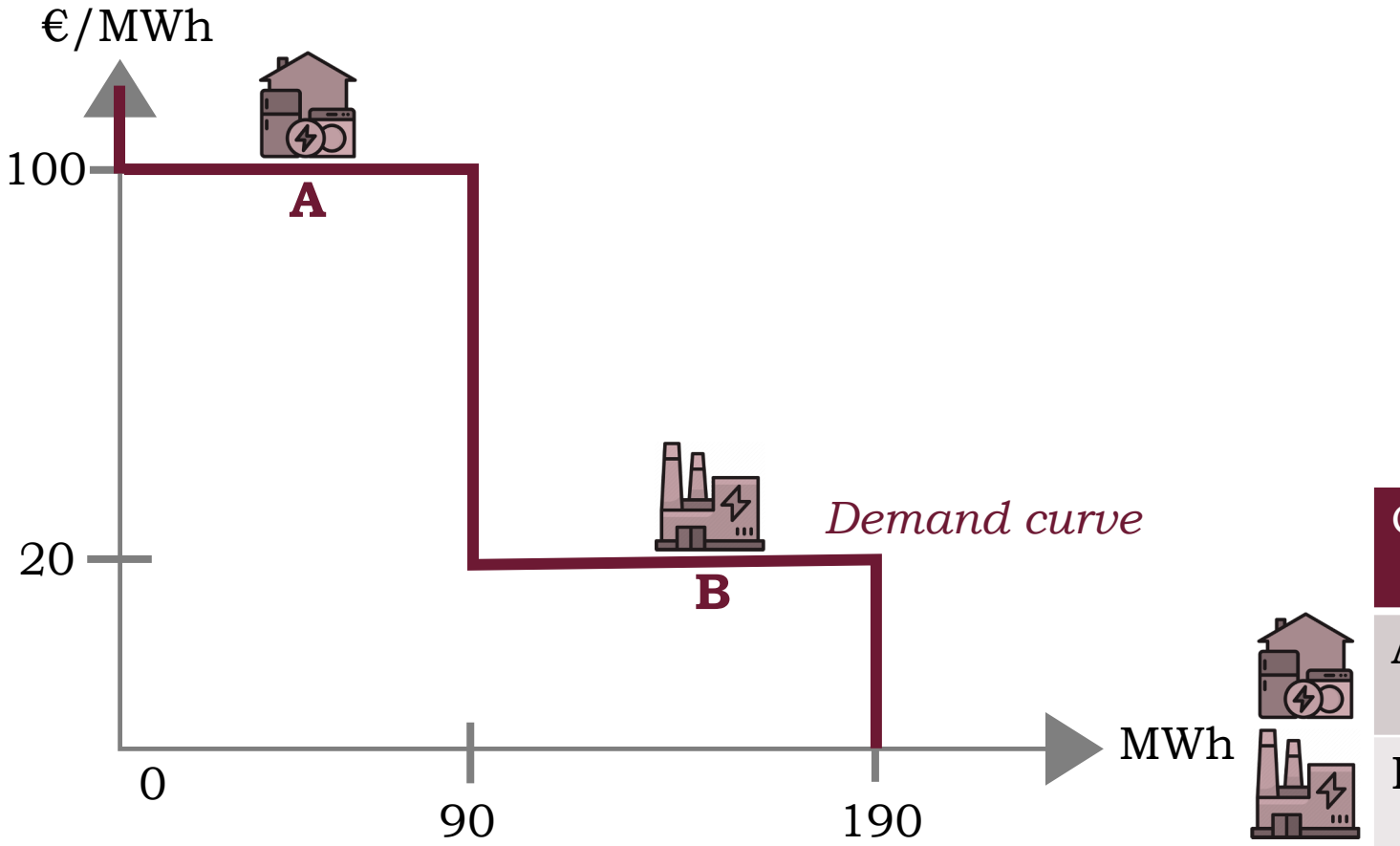
Market price fundamentals
Supply curve



Supply

Producer	Capacity [MW]	Cost [€/MWh]
C	100	30
D	90	90

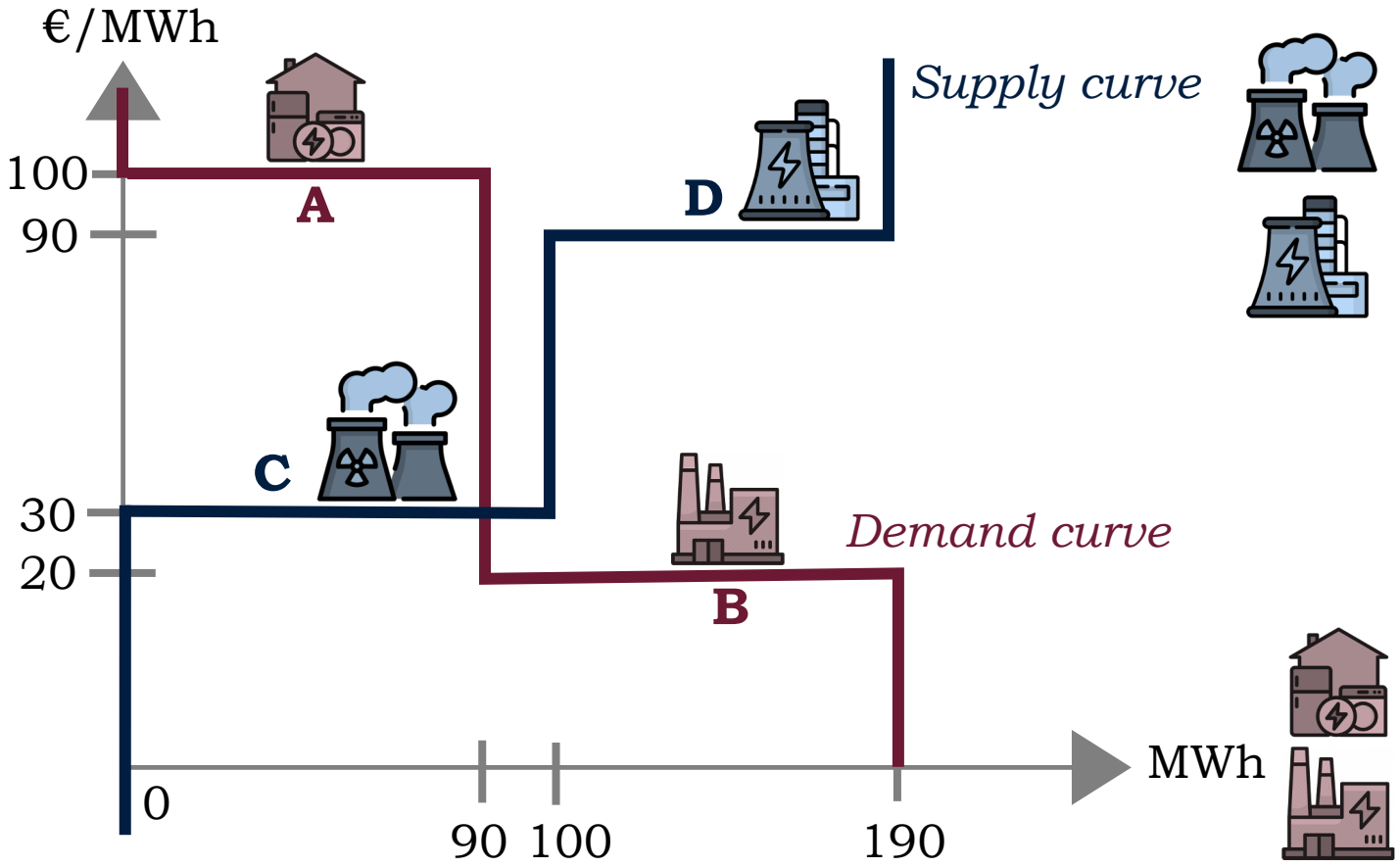
Market price fundamentals
Demand curve



Demand

Consumer	Demand Capacity [MW]	Willingness-to-pay [€/MWh]
A	90	100
B	100	20

Market price fundamentals
Market equilibrium



Supply

Producer	Capacity [MW]	Cost [€/MWh]
C	100	30
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Demand

Consumer	Demand Capacity [MW]	Willingness-to-pay [€/MWh]
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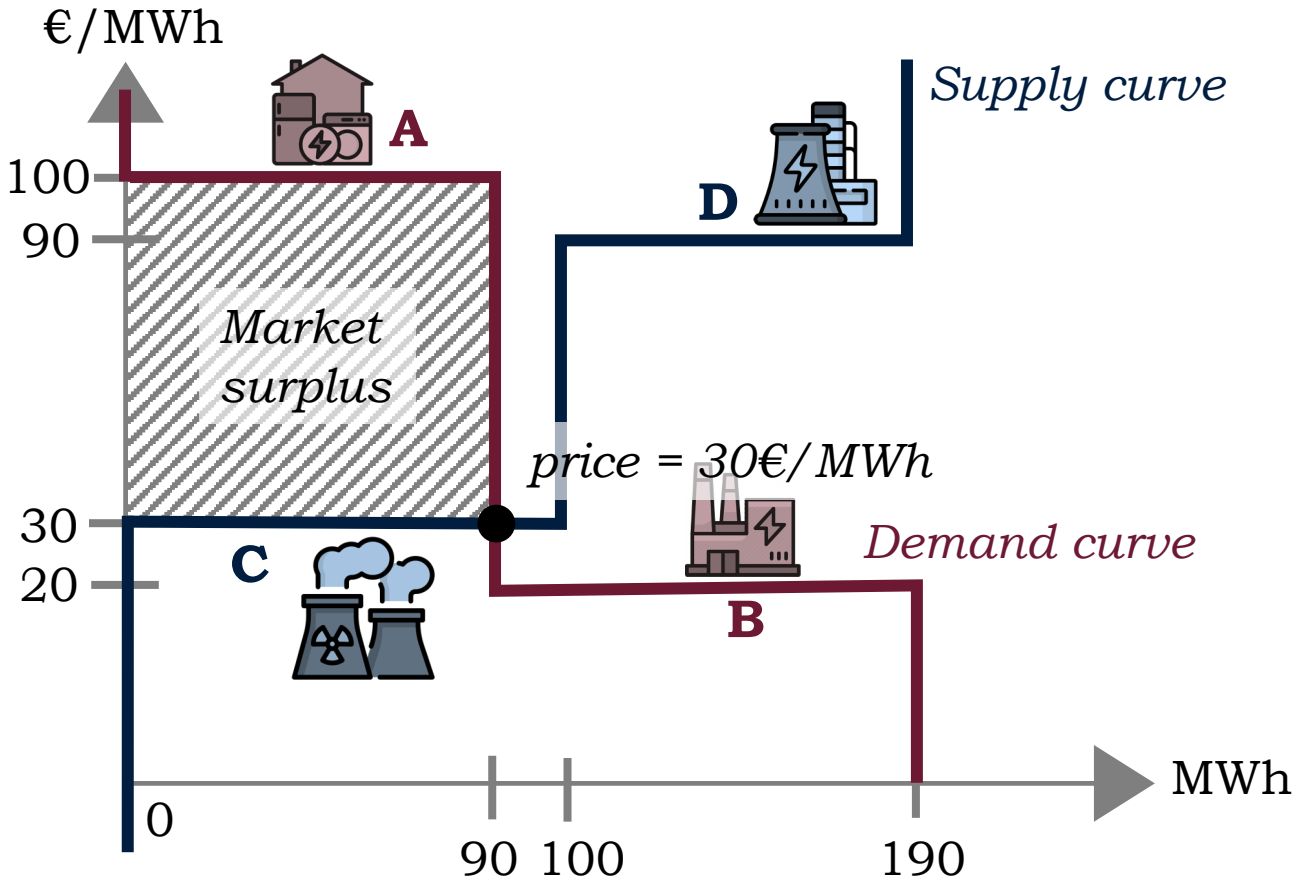
Market price fundamentals
Market equilibrium



3 key ideas:

- *Equilibrium* price
- Price = *marginal cost*
- Market allocation *maximizes the total surplus*

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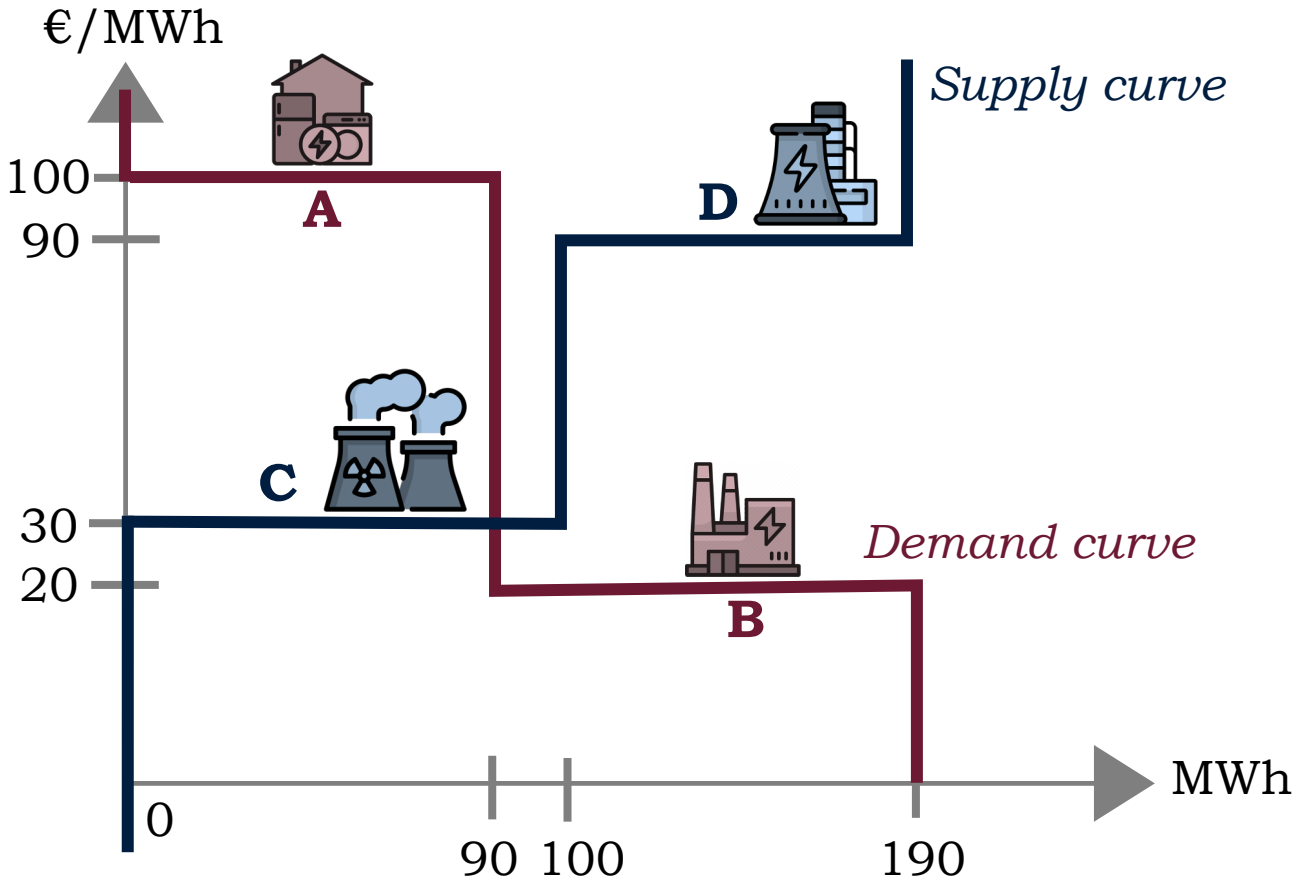
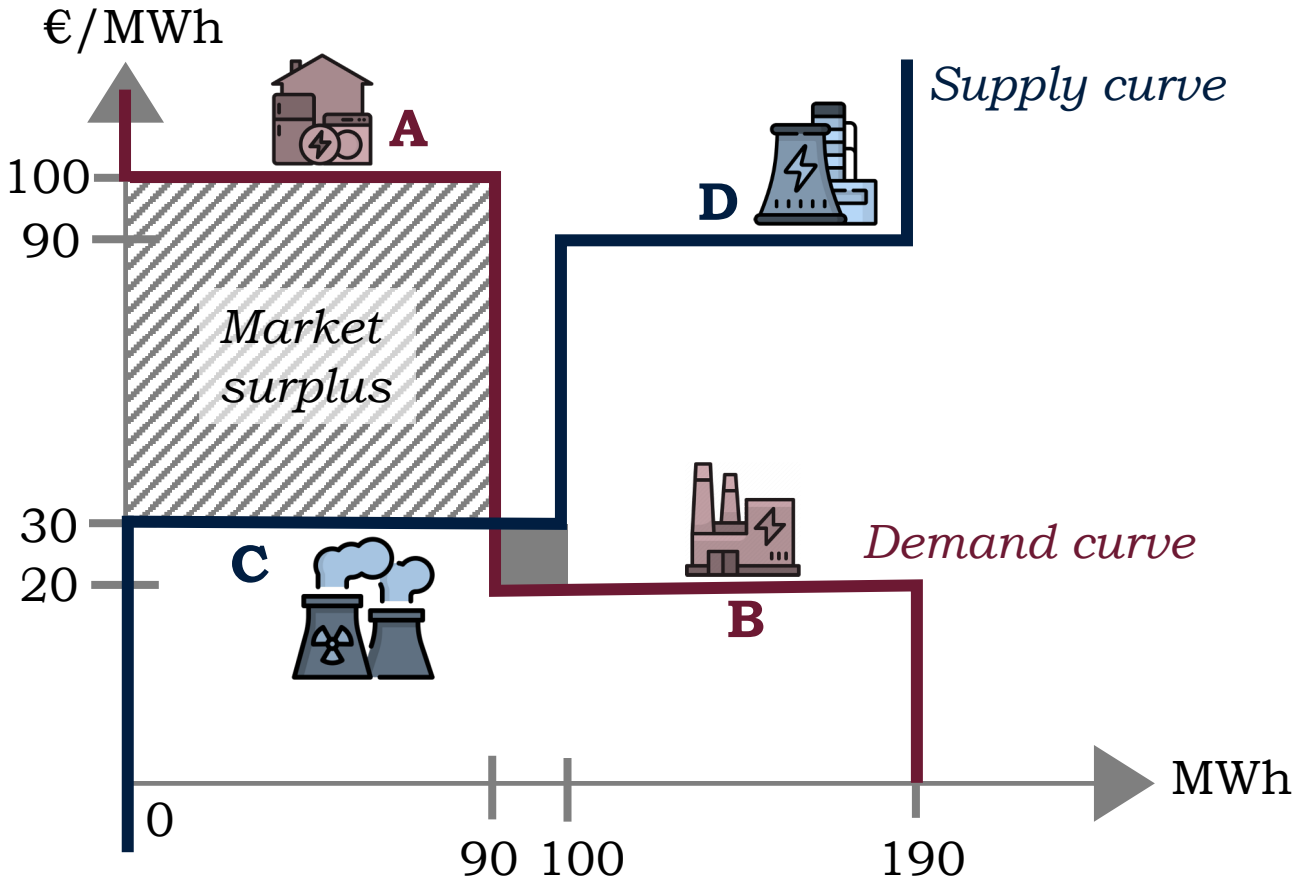
Pricing with indivisibilities



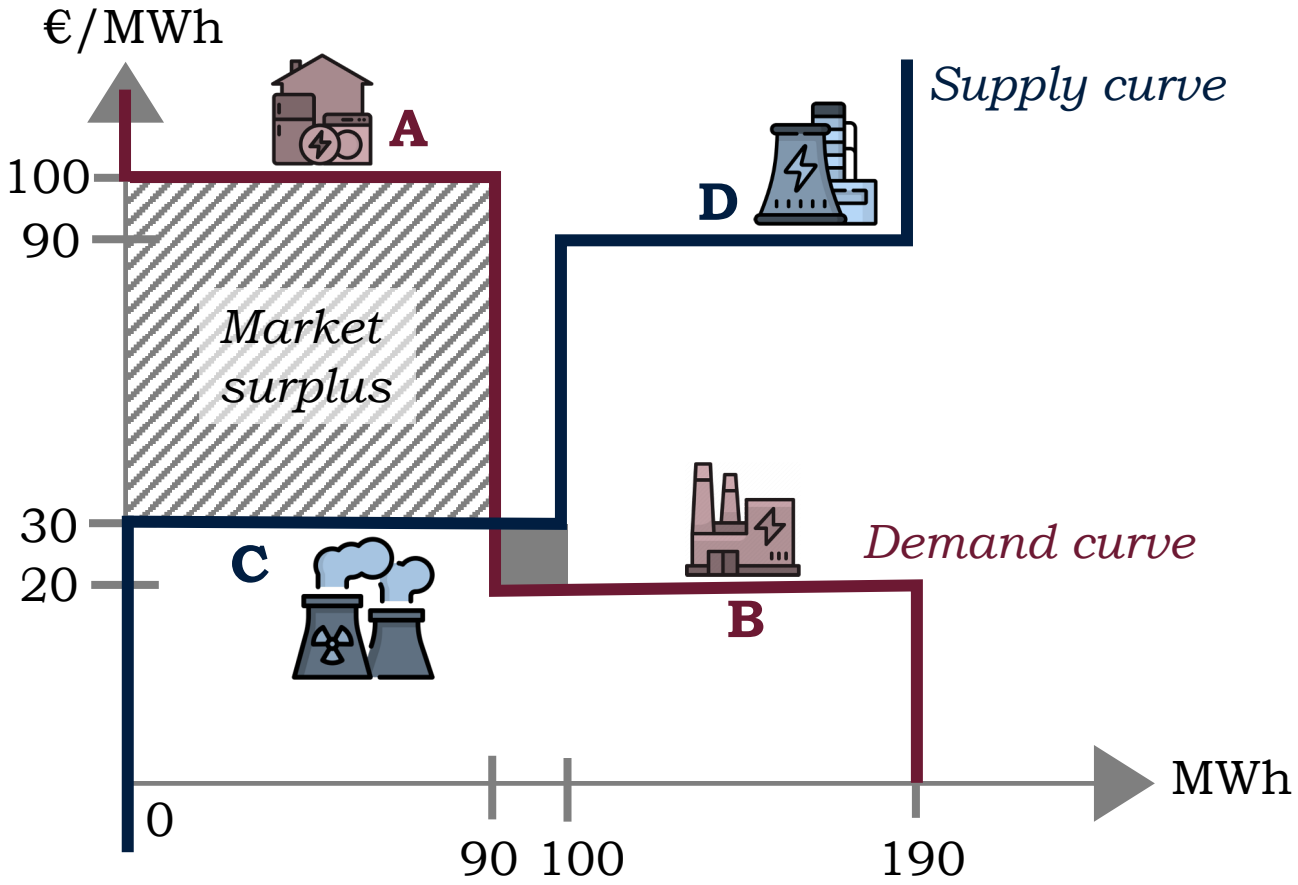
- What if **C** is ***indivisible*** (all-or-nothing)?

Pricing with indivisibilities



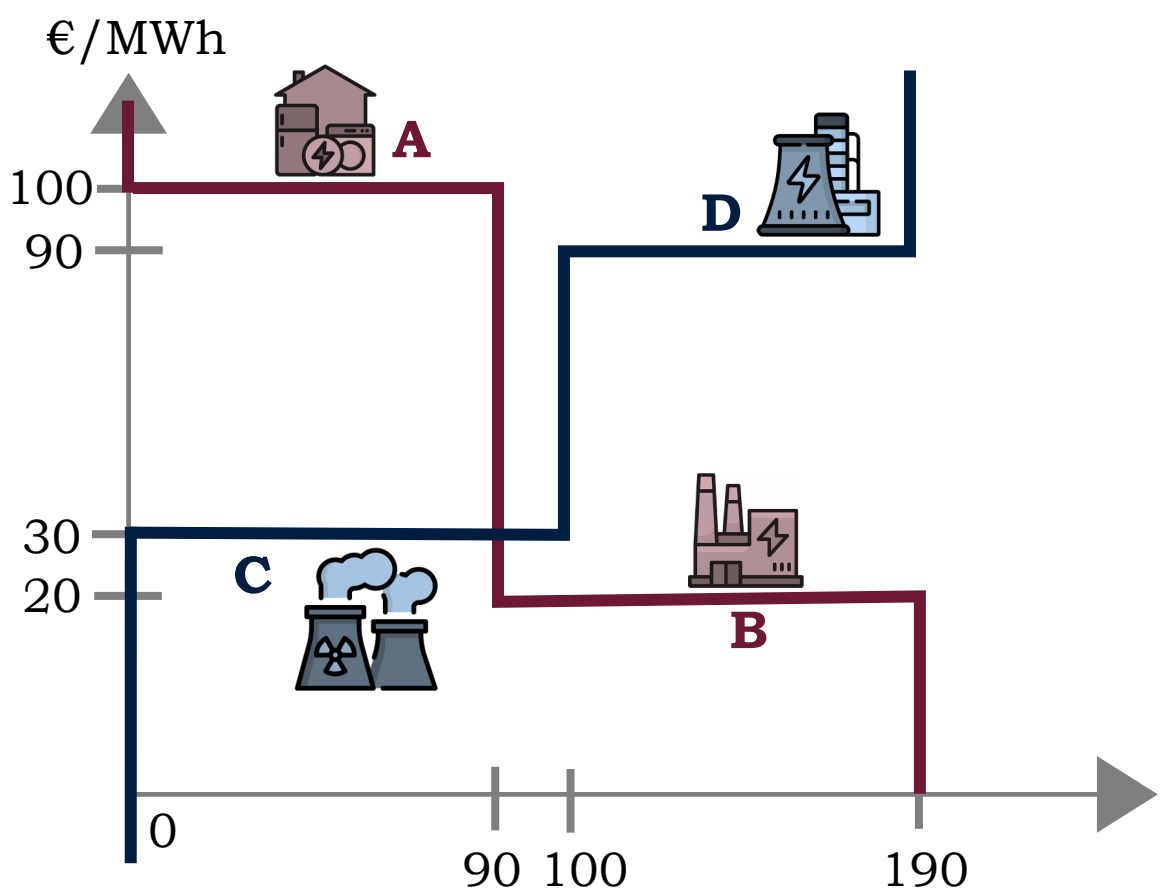
- What if **C** is ***indivisible*** (all-or-nothing)?
- Surplus maximizing solution: clear **A**, **C** and a fraction of **B**

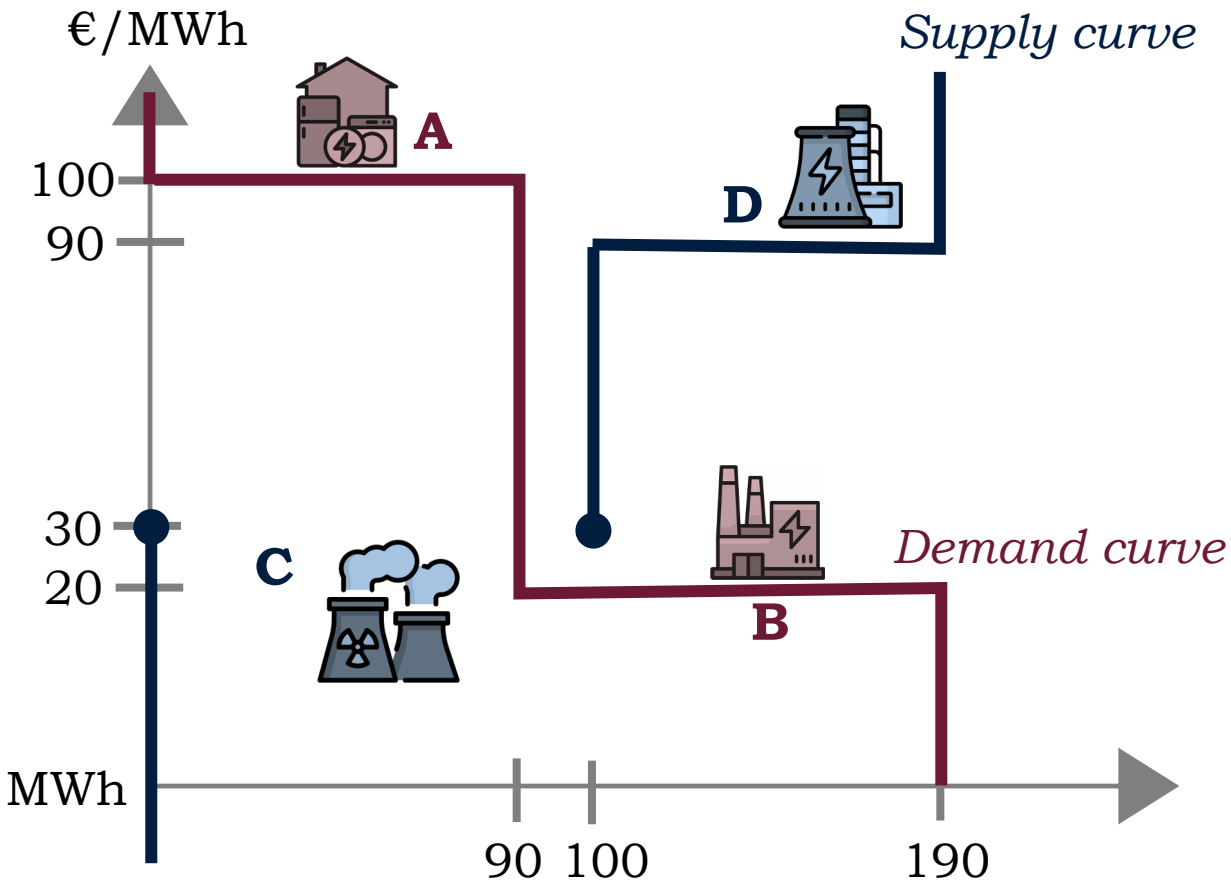
Pricing with indivisibilities



- What if **C** is ***indivisible*** (all-or-nothing)?
- Surplus maximizing solution: clear **A**, **C** and a fraction of **B**
- What is the 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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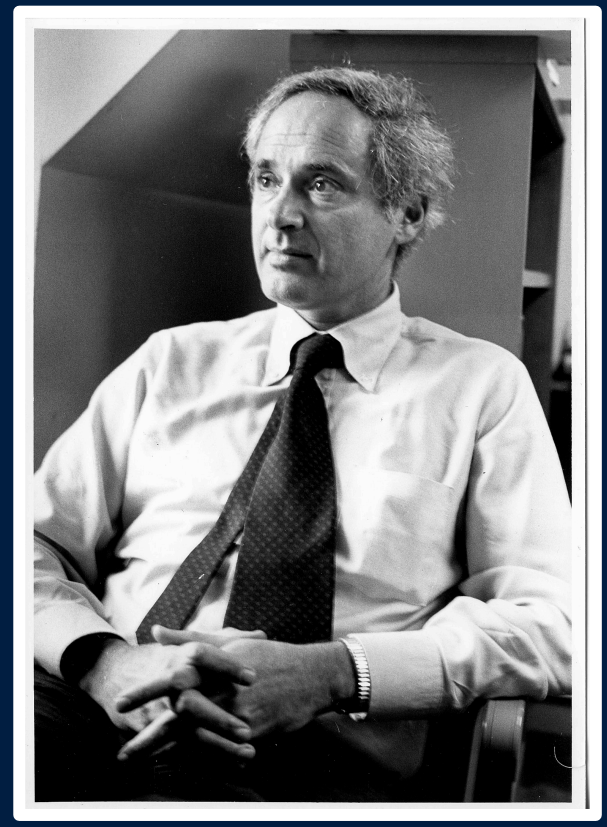
"in the presence of indivisibilities in production, prices simply don't do the jobs that they were meant to do"

(Scarf, 1994)



This is a problem encountered in most electricity markets

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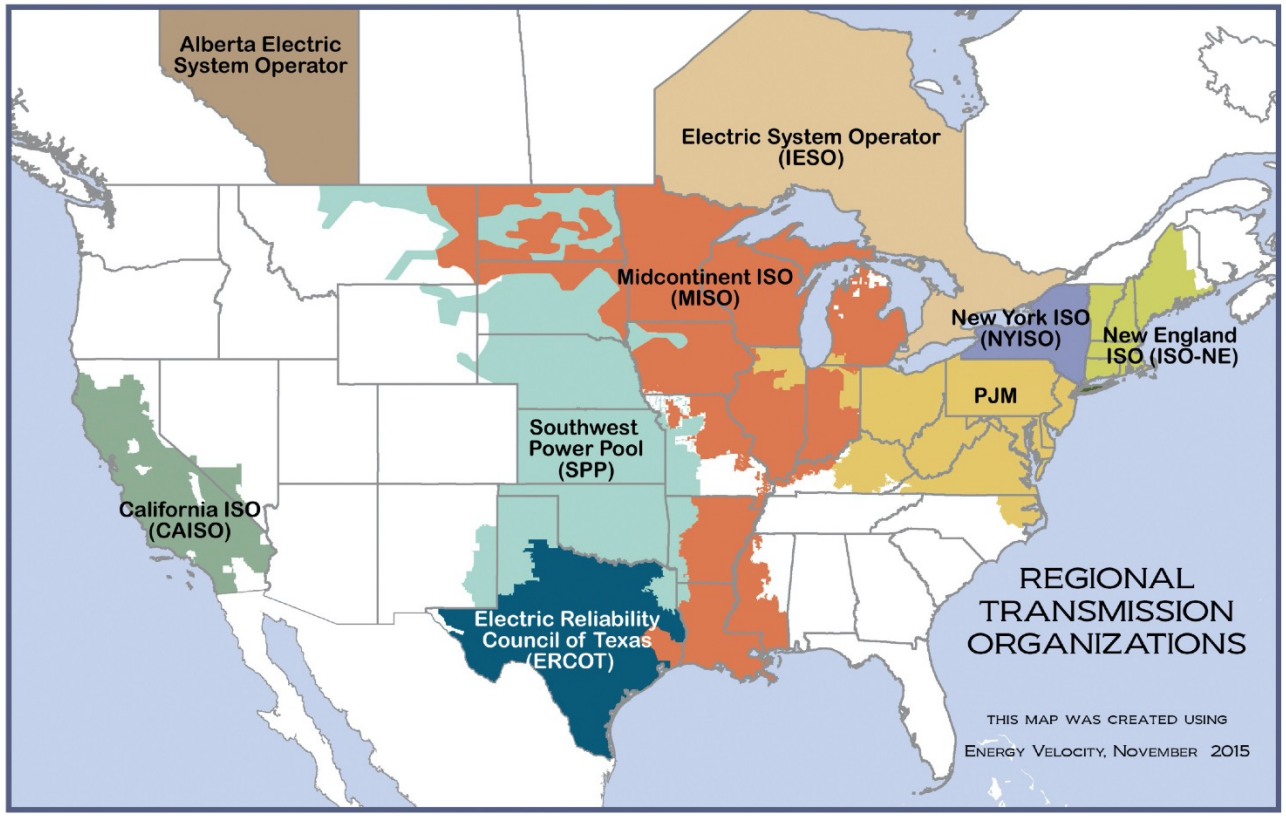
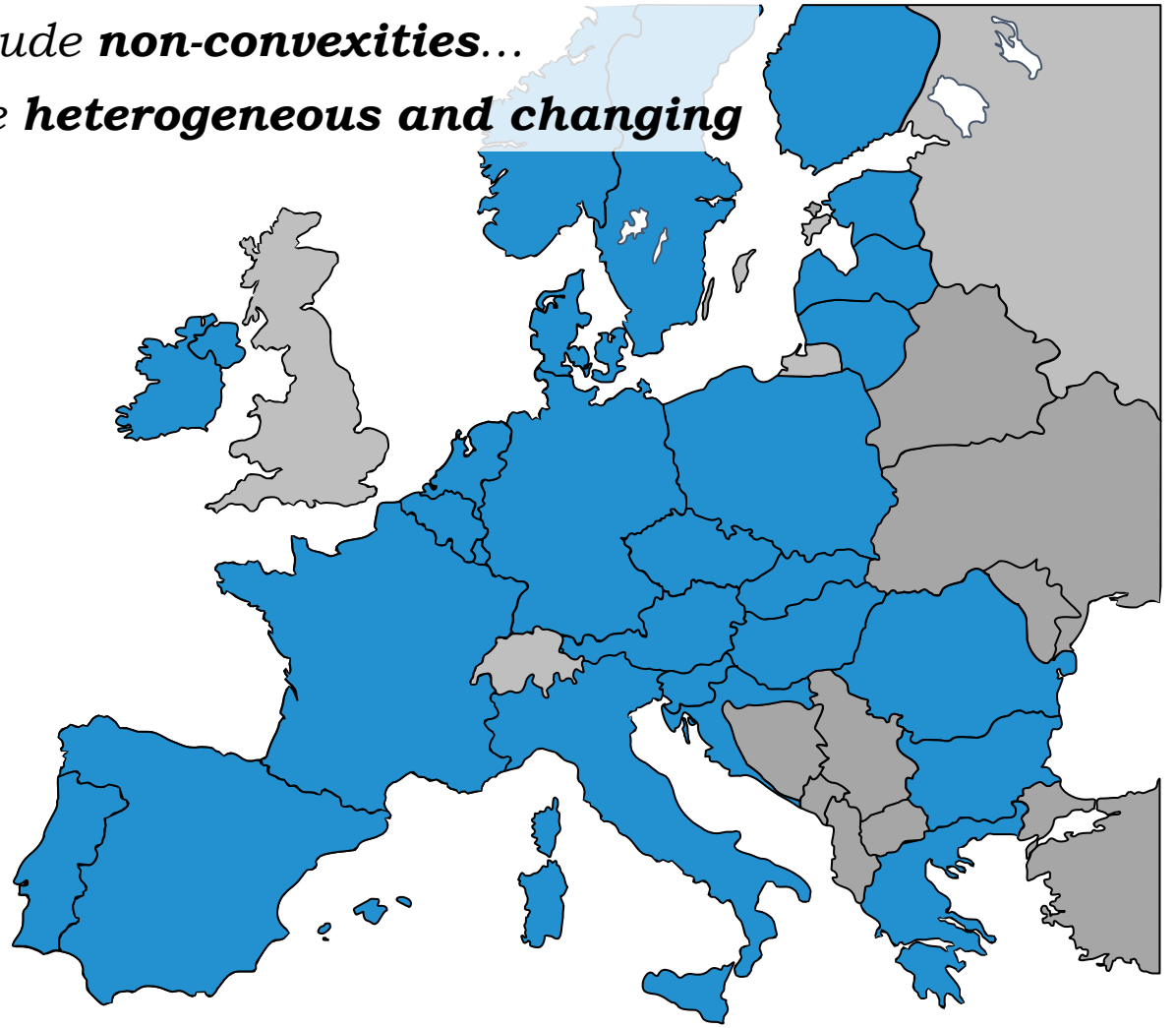
All the US markets as well as the European market include ***non-convexities****…*

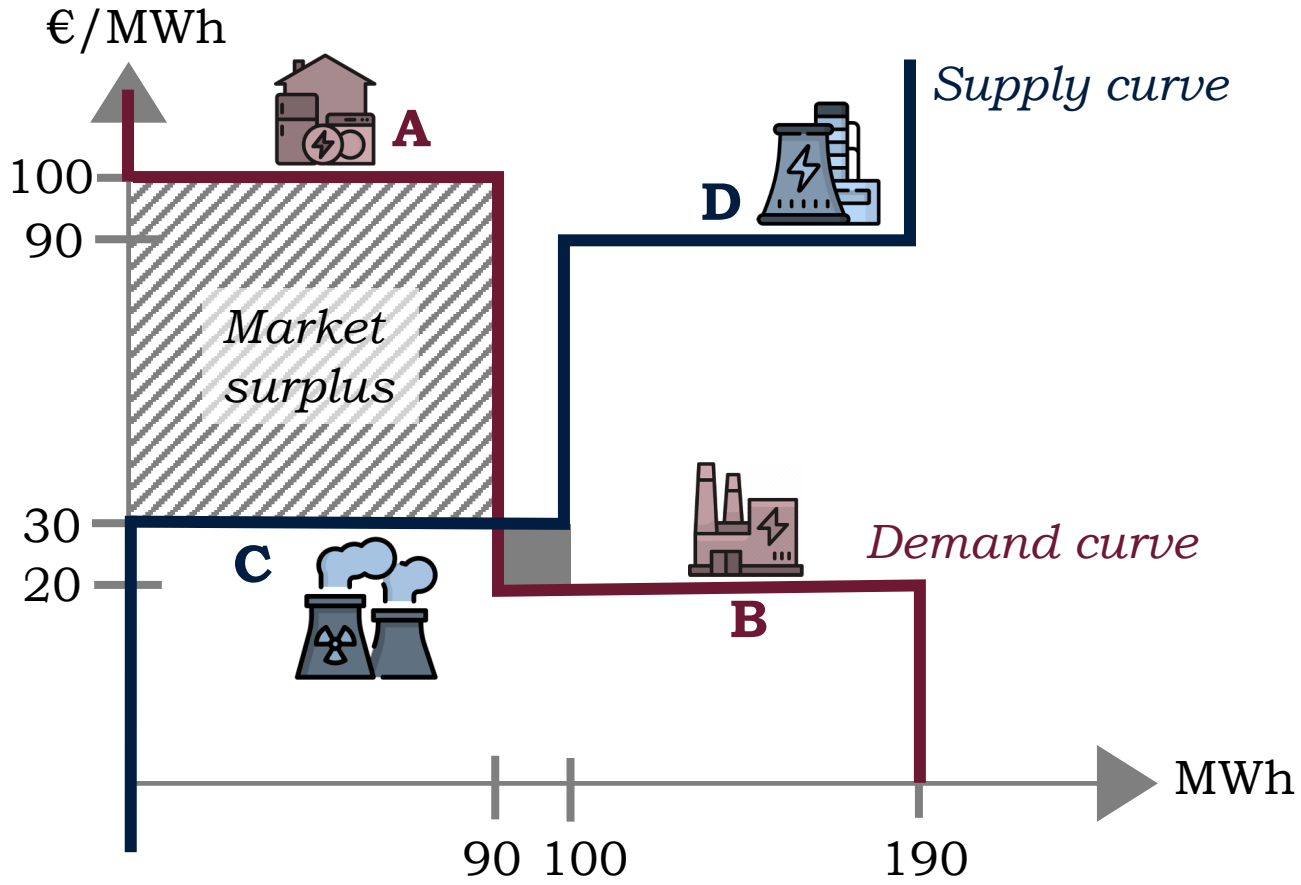
…& the pricing policies that have been adopted are ***heterogeneous and changing***





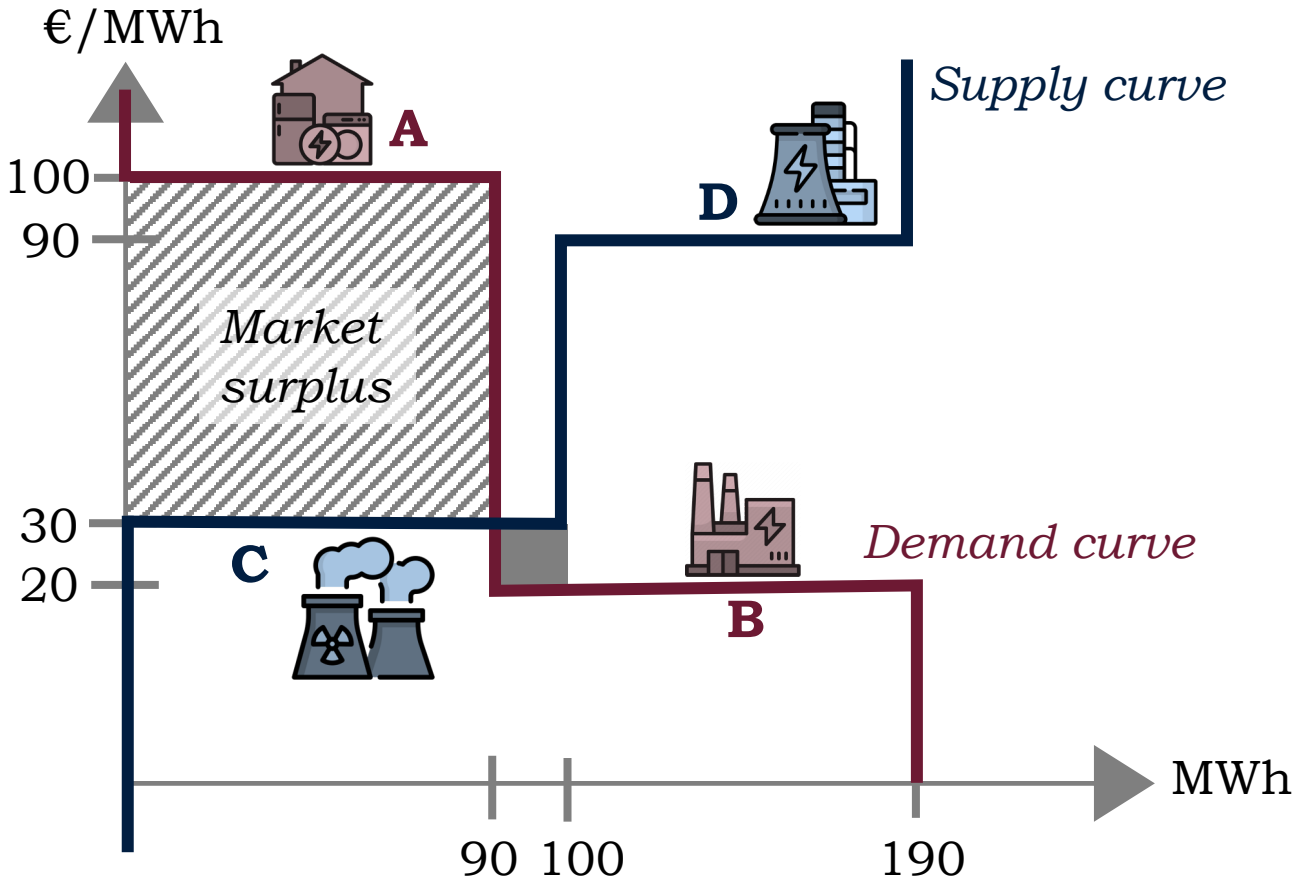
Pricing with indivisibilities

Option 1: Marginal pricing



- Marginal price: 20€/MWh
- Supplier C: loosing 10€/MWh
- Discriminatory payment of 1000€ to C

Pricing with indivisibilities
Option 2: "Convex Hull Pricing"



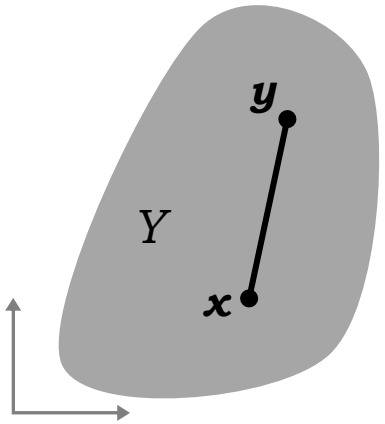
- Convex hull price: 30€/MWh
- Demand B: loosing 10€/MWh
- Discriminatory payment of 100€ to B

→ Convex hull price minimize the incentives to deviates from the cleared allocation

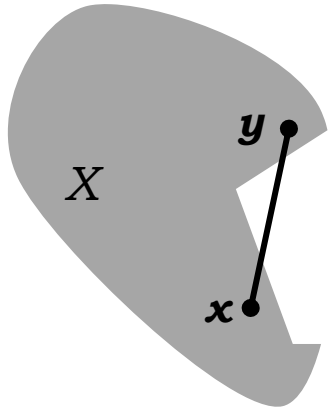
→ Most of the thesis is based on this idea

Content

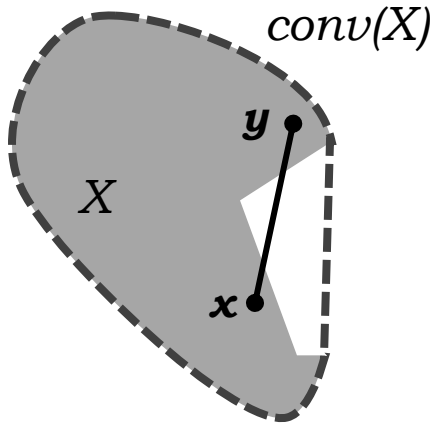
1 – Computing the *Convex Hull Prices*



Convex set

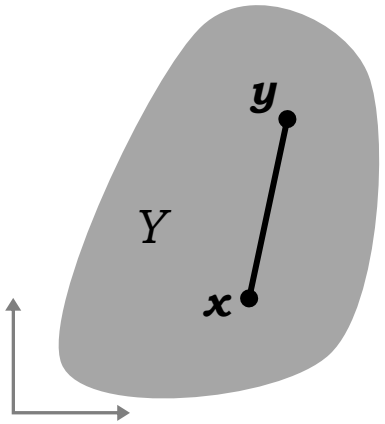


Non-convex set

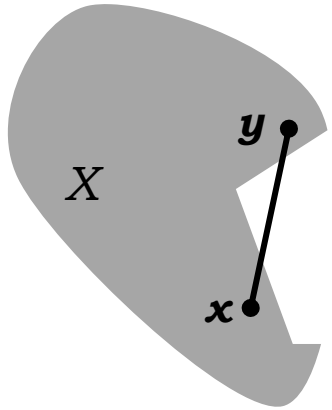


Convex hull of a non-convex set

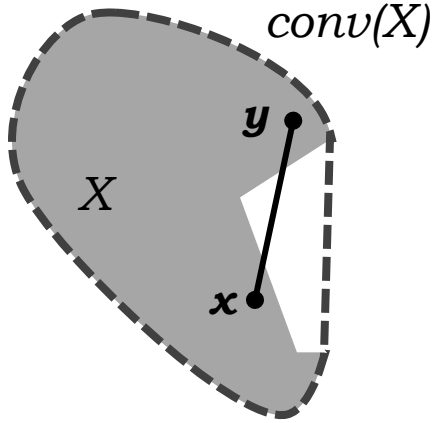
1 – Computing the *Convex Hull Prices*



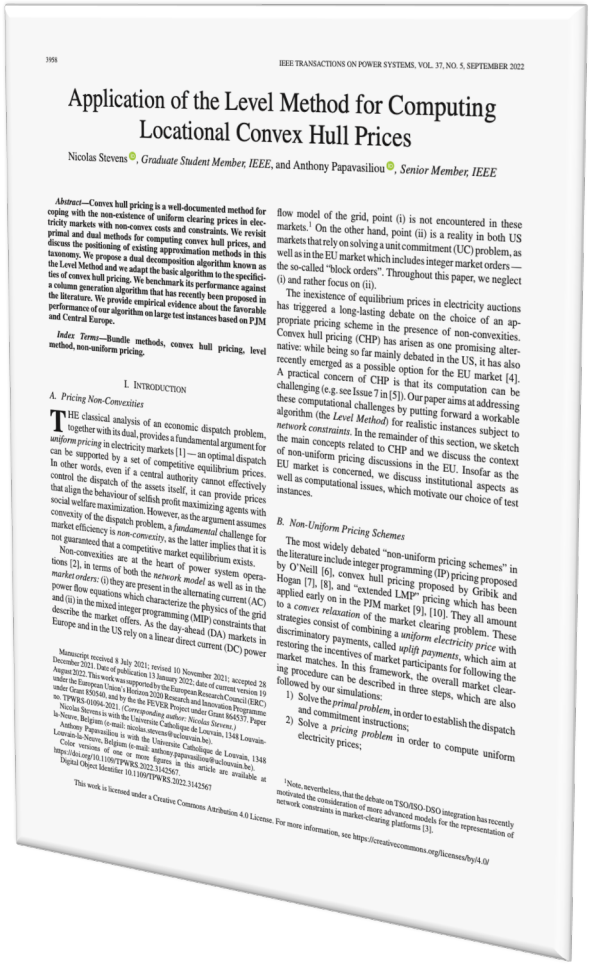
Convex set



Non-convex set



Convex hull of a non-convex set



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Application of the Level Method for Computing Locational Convex Hull Prices

Nicolas Stevens, *Graduate Student Member, IEEE*, and Anthony Papavasiliou, *Senior Member, IEEE*

***Abstract*—Convex hull pricing is a well-documented method for coping with the non-existence of uniform clearing prices in electricity markets with non-convex costs and constraints. We revisit primal and dual methods for computing convex hull prices, and discuss the positioning of existing approximation methods in this taxonomy. We propose a dual decomposition algorithm known as the Level Method and we adapt the basic algorithm to the specificities of convex hull pricing. We benchmark its performance against a column generation algorithm that has recently been proposed in the literature. We provide empirical evidence about the favorable performance of our algorithm on large test instances based on PJM and Central Europe.**

***Index Terms*—Bundle methods, convex hull pricing, level method, non-uniform pricing.**

I. Introduction

A. Pricing Non-Convexities

THE classical analysis of an economic dispatch problem, together with its dual, provides a fundamental argument for *uniform pricing* in electricity markets [1]—an optimal dispatch can be supported by a set of competitive equilibrium prices. In other words, even if a central authority cannot effectively control the dispatch of the assets itself, it can provide prices that align the behaviour of selfish profit maximizing agents with social welfare maximization. However, as the argument assumes convexity of the dispatch problem, a *fundamental* challenge for market efficiency is *non-convexity*, as the latter implies that it not guaranteed that a competitive market equilibrium exists.

Non-convexities are at the heart of power system operations [2], in terms of both the *network model* as well as in the *market orders*: (i) they are present in the alternating current (AC) power flow equations which characterize the physics of the grid and (ii) in the mixed integer programming (MIP) constraints that describe the market offers. As the day-ahead (DA) markets in Europe and in the US rely on a linear direct current (DC) power flow model of the grid, point (i) is not encountered in these markets.[1] On the other hand, point (ii) is a reality in both US markets that rely on solving a unit commitment (UC) problem, as well as in the EU market which includes integer market orders—the so-called "block orders". Throughout this paper, we neglect (i) and rather focus on (ii).

The inexistence of equilibrium prices in electricity auctions has triggered a long-lasting debate on the choice of an appropriate pricing scheme in the presence of non-convexities. Convex hull pricing (CHP) has arisen as one promising alternative; while being so far mainly debated in the US, it has also recently emerged as a possible option for the EU market [4]. A practical concern of CHP is that its computation can be challenging (e.g. see Issue 7 in [5]). Our paper aims at addressing these computational challenges by putting forward a workable algorithm (the *Level Method*) for realistic instances subject to *network constraints*. In the remainder of this section, we sketch the main concepts related to CHP and we discuss the context of non-uniform pricing discussions in the EU. Insofar as the EU market is concerned, we discuss institutional aspects as well as computational issues, which motivate our choice of test instances.

B. Non-Uniform Pricing Schemes

The most widely debated "non-uniform pricing schemes" in the literature include integer programming (IP) pricing proposed by O'Neill [6], convex hull pricing proposed by Gribik and Hogan [7], [8], and "extended LMP" pricing which has been applied early on in the PJM market [9], [10]. They all amount to a *convex relaxation* of the market clearing problem. These strategies consist of combining a *uniform electricity price* with discriminatory payments, called *uplift payments*, which aim at restoring the incentives of market participants for following the market matches. In this framework, the overall market clearing procedure can be described in three steps, which are also followed by our simulations:

1) Solve the *primal problem*, in order to establish the dispatch and commitment instructions;
2) Solve a *pricing problem* in order to compute uniform electricity prices;

[1]Note, nevertheless, that the debate on TSO/ISO–DSO integration has recently motivated the consideration of more advanced models for the representation of network constraints in market-clearing platforms [3].

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPWRS.2022.3142567.

Digital Object Identifier 10.1109/TPWRS.2022.3142567

Objectives & conclusions of the first thesis's contribution:

- Develop an **algorithm to compute the Convex Hull Prices**
- Our algorithm computes it on **realistic-size auction datasets** (1000 power units; 96 periods and up to 59 bidding zones)
- The largest instance is solved **in less than 10 minutes** (on a personal computer).
- **5 times faster** than the state-of-the art in the literature

2 – Economic properties of *Convex Hull Pricing*

Objective & conclusions of the second thesis's contribution:

- **Theoretical formalization & cross-comparison** of several pricing approaches
- **Numerical simulations** on realistic auction datasets
- On some advantages of convex hull pricing:
  - Incentives of market participants
  - Distributional analysis across market participants (suppliers, consumers & SO)
  - Market size : the magnitude of the problem that, relative to the total surplus, shrinks with the market size
  - Consistency between cost minimization and "LOC" minimization
  - And more

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On some advantages of convex hull pricing for the European electricity auction☆

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ABSTRACT

Since the liberalization of the power sector and the creation of wholesale electricity markets, the question of how to price the non-convexities that are present in the market has attracted the interest of both academics and practitioners. Over the years, US markets have studied and adopted different and evolving pricing rules. Since the "Trilateral Market Coupling" (2006), the European day-ahead market has opted for a notably different pricing rule. Recently, EU stakeholders have undertaken research to reform it, and have indicated an interest for some approaches that are discussed in the other side of the Atlantic. Our paper aims at contributing to the debate. We analyze six different pricing methods. We establish several mathematical properties for enabling their accurate comparison. Our findings are illustrated on stylized examples and numerical simulations that are performed on realistic datasets. Both theoretical and numerical evidences that are gathered in our paper point towards the advantages of convex hull pricing.

1. Introduction

Power auctions are notably characterized by the presence of non-convexities. In the US, these non-convexities emerge from the so-called unit commitment model, which has been run in control rooms since before the liberalization of the power sector took place. Although some economists have argued for simpler – convex – market models (cf. the arguments covered by Stoft (2002)), unit commitment has prevailed in many US auctions. In Europe, despite the fact that the market model is different, it also includes non-convex bids, the so-called "block orders" being the simplest example. Although the European market does not rely on *physical* unit commitment models, the non-convex orders also aim – indirectly at least – at providing the suppliers with the flexibility of representing the complex constraints of power generation into the auction. Non-convex multi-parts bids are a bet that the efficiency gained by a refined scheduling model are higher than the inefficiencies resulting from the increase in complexity. In particular, the main drawback of non-convexities is that they impede the existence of a competitive equilibrium. The "classical" marginal prices fail to support the efficient allocation of goods. The absence of equilibrium prices has resulted in various and evolving pricing practises among the US and EU markets.

The liberalization of the power sector in the US started in the 90s, encouraged by the government through the Energy Policy Act of 1992. The creation of the Independent System Operators (ISOs), that have assumed the role of operating the market, followed in the late 90s and early 2000s. Locational *marginal pricing* (LMP) has traditionally been adopted by many ISOs to clear the market, cf. Stoft (2002) and the historical account provided by EPRI (2019). Experience revealed several drawbacks of marginal pricing, especially the fact that short-term fixed costs are not reflected in the price signal which therefore does not provide adequate incentives to market participants. The inadequacy of marginal pricing has stimulated research about the right way to price non-convex power auctions. Convex hull pricing (CHP) (Hogan and Ring, 2003) has emerged as a promising – although contested (Schiro et al., 2015) – way to price energy in the presence of non-convex bids. Acknowledging these issues, several ISOs started moving away from marginal pricing. In 2014, the US Regulatory Commission launched a consultation about price formation in power auctions (FERC, 2014). In 2015, MISO implemented "Extended LMP" (ELMP), an approximation of convex hull pricing) and a similar proposal followed by PJM in 2017 (PJM, 2017). Other ISOs have implemented various "fast-start pricing" approaches (EPRI, 2019), which are variants of ELMP. They

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Conclusions & takeaways

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- Electricity is a **key sector of our economies** and a sector experiencing **significant changes** with the energy transition
- Since **liberalization of the power sector** twenty+ years ago, the electricity price is the outcome of a **market**
- In presence of non-convexities, **pricing rule is not obvious**: "classic" *marginal pricing* fails to support the efficient allocation of resources
- 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
- My thesis focused on the so-called **"convex hull pricing" approach**. Among others:
  - **Computational challenge**: develop an algorithm to compute it
  - **Economical properties**: several advantages of convex hull pricing

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Thank you!

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