Overview of European TSO-DSO Coordination Platforms and Distribution Locational Marginal Pricing under Generation and Network Scarcity Conditions

Anthony Papavasiliou, National Technical University of Athens (NTUA), Greece

April 21, 2026

FITNESS Spring School “New Market Models in Distribution Networks”

Universidad de Castilla-La Mancha, Spain

Outline

- TSO-DSO coordination platforms
    - Sources
    - Overview of EU platforms
    - Detailed discussion of studied platforms
    - Conclusions
- The case for local markets
    - Base scenario
    - Distribution network oversupply
    - Scarcity
- Inscribed boxes
    - Inscribing a box in a polyhedron
    - Application to power flow
    - Application to reserve deliverability
- Conclusions
- Appendix

TSO-DSO coordination platforms

Sources

Overview of EU platforms

Detailed discussion of studied platforms

Conclusions

Bibliographic sources

[1] T. Schittekatte and L. Meeus, “Flexibility Markets: Q&A with Project Pioneers,” Utilities policy, vol. 63, p. 101017, 2020

[2] Mezghani, I., Stevens, N., Papavasiliou, A., & Chatzigiannis, D. I. (2022). Hierarchical coordination of transmission and distribution system operations in European balancing markets. IEEE Transactions on Power Systems, 38(5), 3990-4002

[3] Frontier Economics (for ENTSO-E), “Review of Flexibility Platforms,” 2021

[4] Chondrogiannis, S., Vasiljevska, J., Marinopoulos, A., Papaioannou, I., & Flego, G. (2022). Local electricity flexibility markets in Europe. Joint Research Centre (JRC), Tech. Rep. EUR 31194 EN

[5] CEER Report on Regulatory Frameworks for European Energy Networks 2022, Annex 6, General case study

[6] E-Distribuzioni, Impiego dei servizi ancillari forniti da risorse di energia distribuite per l’esercizio della rete di distribuzione

[7] Niccolo Corsi, Flessibilità e modelli di mercato locale dell’energia elettrica, masters thesis, Politechnico di Torino, 2023

[8] BeFlexible, “DEMO 1 Methodological report”, 2023

[9] Areti, “Presentazione RomeFlex ai Service Providers”, 2023

[10] GME, "Progetto Pilota Romeflex e Mercato della Flessibilità”, 2023

[11] Enedis, “Règlement de consultation V1.4”, 2024

[12] Desegaulx, A., Kuhn, T., Dupin, H., & Chevalier, S. (2020, September). Enedis two-step market approach to local flexibilities. In CIRED 2020 Berlin Workshop (CIRED 2020) (Vol. 2020, pp. 803-806). IET

[13] Dronne, Theo, Fabien Roques, and Marcelo Saguan. "Local flexibility market: Which design for which needs?." In CIRED 2020 Berlin Workshop (CIRED 2020), vol. 2020, pp. 721-723. IET, 2020

Expert interviews

- Yves Langer (Smart Vision, ENERA Platform)
- Philippe Vassilopoulos (EPEX SPOT, involved in the development of ENERA and EPEX LEM)
- Gesa Melzer (senior project manager at NODES)
- Evyatar Littwitz (Es-geht, German DSO)
- Lukas Albert and Beatrix Schmitt (Stadtwerk Hassfurt, German DSO)
- Ercole De Luca and Altomonte Daniele (Areti, Italian DSO)
- Stefano Alaimo and Fabrizio Carboni (GME, Italian power exchange)
- Matthew Billson and Ayan Kanhai Aman (PicloFlex platform)
- Alex Howard (UKPN, UK DSO)
- Nathan Billion (Enedis, French DSO)

TSO-DSO coordination platforms

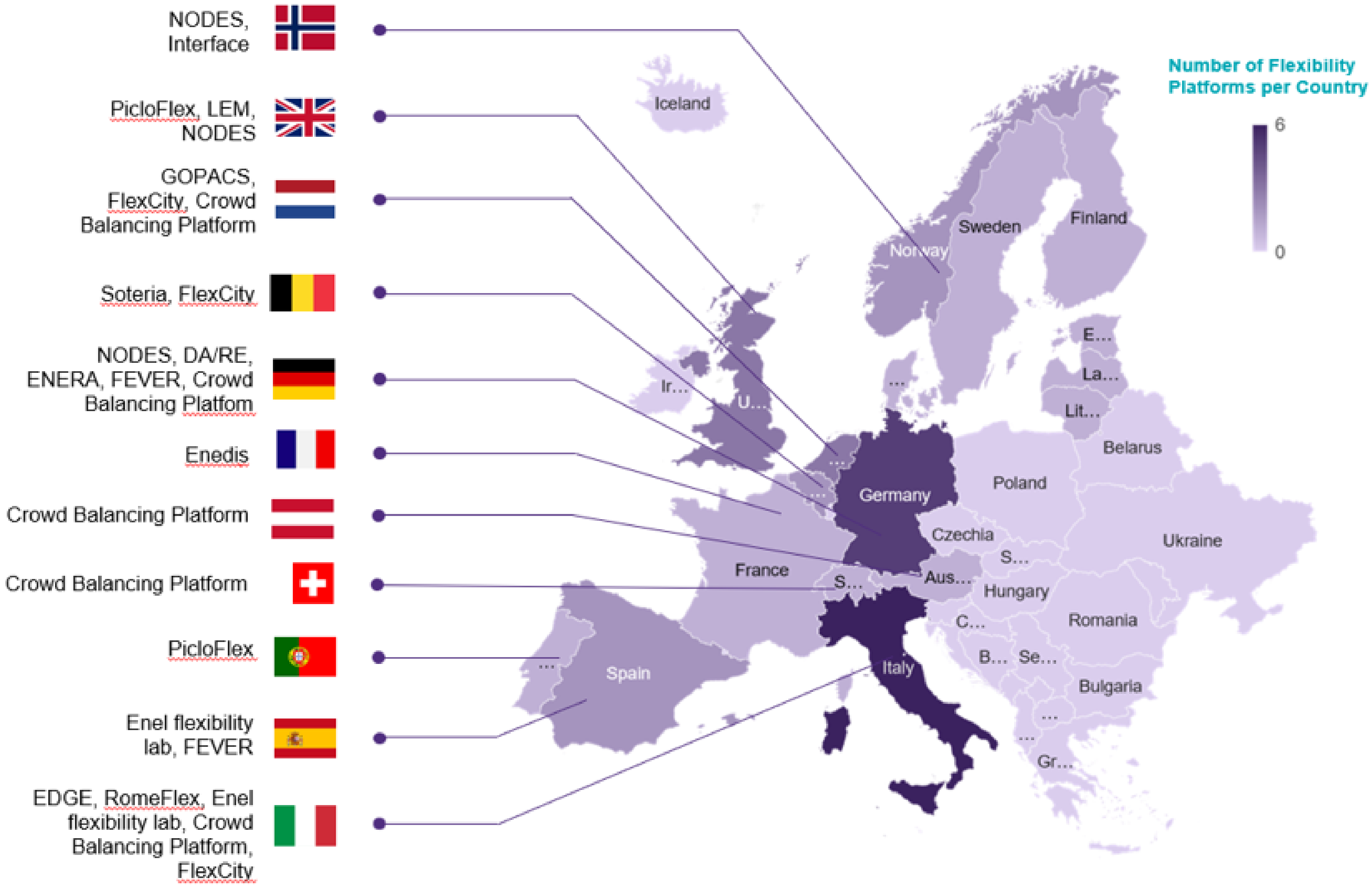
Sources

Overview of EU platforms

Detailed discussion of studied platforms

Conclusions

Pilot Platforms	• FlexRome • Enera • EDGE • Soteria • Enel flexibility lab • Crowd Balancing Platform • FEVER
Commercial Platforms	• PicloFlex • NODES • GOPACS • FlexCity • DA/RE • Interrface • Local Energy Market (LEM)



Geographical coverage

- Diversity of geographical scope
  - Countries may have several commercial platforms operating
  - At a regional level there is a single platform that is active
  - We note that there are no regulations preventing more than one platform from being regionally active
- The regulatory framework is critical
  - Countries with advanced DSO regulation have the most advanced commercial solutions (e.g. Italy, UK), while countries with weak DSO regulation are well behind (e.g. France, Germany)
  - We note that several pilot initiatives have been active in Germany
    - These have not gone through to a commercial phase due to the lack of proper regulation

Offered services and products

- Congestion management is the dominant offered service
  - Other needs relate to investment deferral, restoration and voltage control
  - This also translates to a diversity of time scales: long-term procurement (e.g. Piclo) as well as day-ahead or close-to-real-time operation (e.g. GOPACS)
- Closed-gate versus continuous matching
  - Certain platforms favor closed-gate auctions, e.g. EPEX LEM
  - Others are based on continuous matching, e.g. GOPACS
- Diversity of integration to wholesale markets
  - Some platforms are mindful of the interaction of flexibility products with existing wholesale markets (e.g. GOPACS, RomeFlex)
  - Other platforms are quite disconnected from existing wholesale markets (e.g. Enedis, PicloFlex)

Platform	Ownership	Geography of operation	Products	Commercial readiness	Liquidity	Participation in other markets
ENERA	EPEX SPOT (power exchange)	Germany, counties Aurich, Frisia and Wittmund	Like intraday products definition	Terminated after pilot phase	---	Yes, intra-day market
NODES	• Formerly owned by Nord Pool (power exchange) • Now owned by NODES (independent entity)	Norway, Sweden and Canada	• Two products: short-term and long-term • Wide range of parameters	Commercial	• 8000 MWh of traded volumes	Unclear
PicloFlex	Owned by Piclo (independent entity)	UK, USA, Australia, Portugal and Italy	• Definition adapted to country • UK: 4 products • Italy: 3 products	Commercial	• Over 300 000 flexibility assets • 2.6 GWh of procured flexibility • € 86 million awarded in contracts	No
EDGE	• Pilot owned by E-Diztribuzione (Italian DSO) • E-Distribuzione contracted PicloFlex	Italy, provinces of Cuneo, Benevento, Foggia and Venice	3 products: regulation of active power, regulation of reactive power, emergency	Pilot	• First tenders conducted in 2024	No
RomeFlex	• Areti (Italian DSO) • GME (Italian power exchange)	Rome (Italy)	Forward market and spot market products	Early commercial	• First tenders conducted in November 2023	Fully integrated to the wholesale market
GOPACS	• System operators: Dutch TSO TenneT and Dutch DSOs Enexis, Liander, Rendo, Stedin, Westland Infra	Netherlands	Procurement is a combination of two orders • a buy order • a sell order	Commercial	• Over 90 GWh of flexibility has been procured via GOPACS by TenneT • Over 110 MWh procured by DSO Liander	Integrated in the intraday market
Enedis	• DSO Enedis	France	3 services: congestion management, enhance work planning, investment deferral	Commercial	• In 2023 Enedis awarded 4 flexibility contracts, significantly more activity in 2024	No
EPEX LEM	• EPEX	UK	Upward/downward energy activations	Commercial	During the trial phase: 201 MWh reservation contracts, 90 MWh of volume delivered/activated	No

TSO-DSO coordination platforms

Sources

Overview of EU platforms

Detailed discussion of studied platforms

Conclusions

Offered products and services: comparative table

Platform	GUI	Products definition	Products offered to other markets?	Capacity payments	Activation payments
ENERA	Same as intraday EPEX SPOT API	Follows definition of intraday products	Yes, to intraday	No	Yes
NODES	Accessible through NODES website	• Two categories of products: short-term and long-term • Wide range of parameters	Unclear	Yes for long-term products, no for short-term products	Yes
PicloFlex	Yes	• Definition adapted to country • UK: 4 products • Italy: 3 products	No	Yes	Yes
RomeFlex	Yes	Forward market and spot market	Fully integrated to the wholesale market (DA+ID)	Just for forward market product	Yes
GOPACS	Via the intraday GUI	• Products are standardized to intraday format • Procurement is a combination of two orders, a buy and a sell order	Connected to intraday market	No	Yes
Enedis	Yes, but offers are sent by email	3 services: congestion management, enhance work planning, investment deferral	No	Depends on the service offered	Yes, for all services (or non-performance penalties)
EPEX LEM	Through EPEX GUI	Upward and downward energy activations	No	Depends on the product	Yes

Characteristics of products

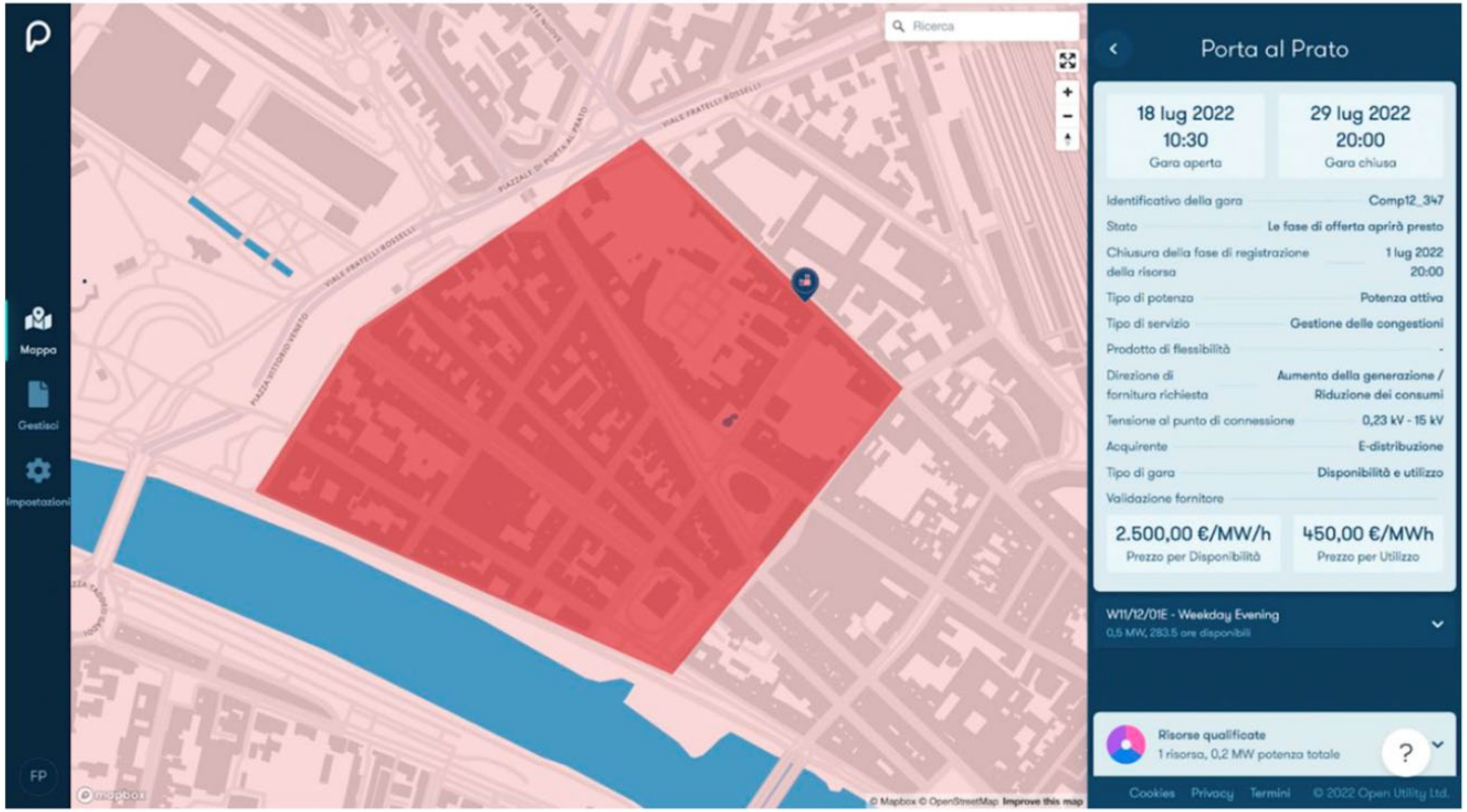
- Products can typically be classified in one of the following three categories
  - Regulation of active power, regulation of reactive power, emergency services
  - We note that the regulation of active power (typically covering congestion management) is the most commonly offered service

- There is a diversity of time-scales within products and platforms
  - Long-term products refer to the commitment to deliver flexibility over a time horizon, typically lasting months or years (e.g. PicloFlex)
    - These have an associated capacity payment to ensure their availability
  - Short-term products ensure their availability over a fixed window of time, typically hours (e.g. NODES)
    - These do not have an associated capacity payment
  - There is typically an activation payment

Characteristics of products (II)

- Regulation of active power
  - DSO procures the ability to access a change in service provider input/output based on network conditions close to real time
- Regulation of reactive power
  - The network operator procures the ability of a service provider to deliver an agreed change in output following a network abnormality
- Emergency services
  - Following a loss of supply, the network operator instructs a provider to remain off supply, reconnect with lower demand, or reconnect and supply generation to support increased and faster load restoration under depleted network conditions

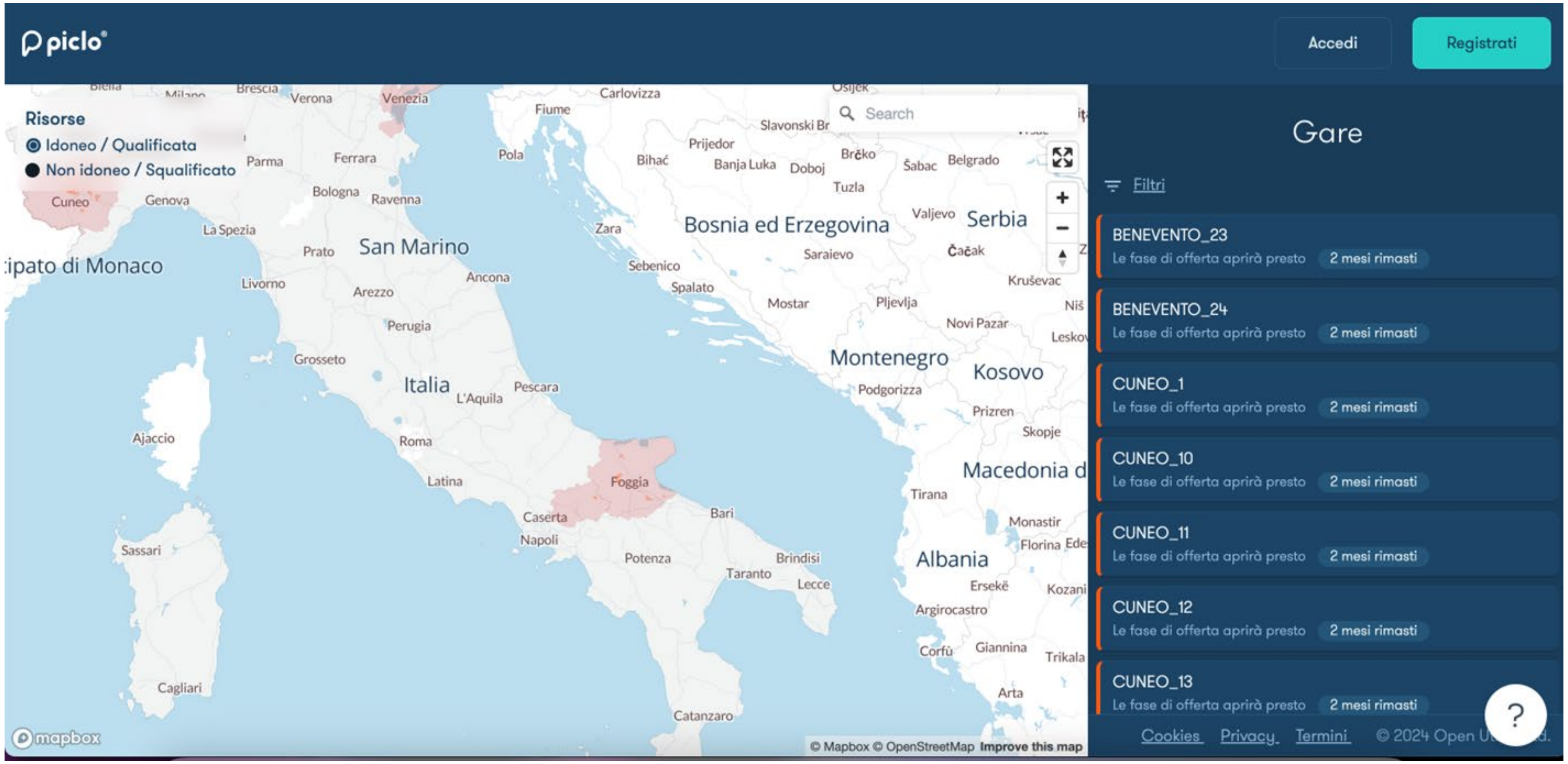
Specifications of products



The product specifications can typically be seen in the platform. As an example, within the PicloFlex platform the user can see the following specifications:

- Minimum flexible capacity
- Minimum utilization
- Minimum utilization duration capability (in minutes)
- Maximum ramping period
- Availability agreement period
- Utilization instruction notification period

Interface of platforms

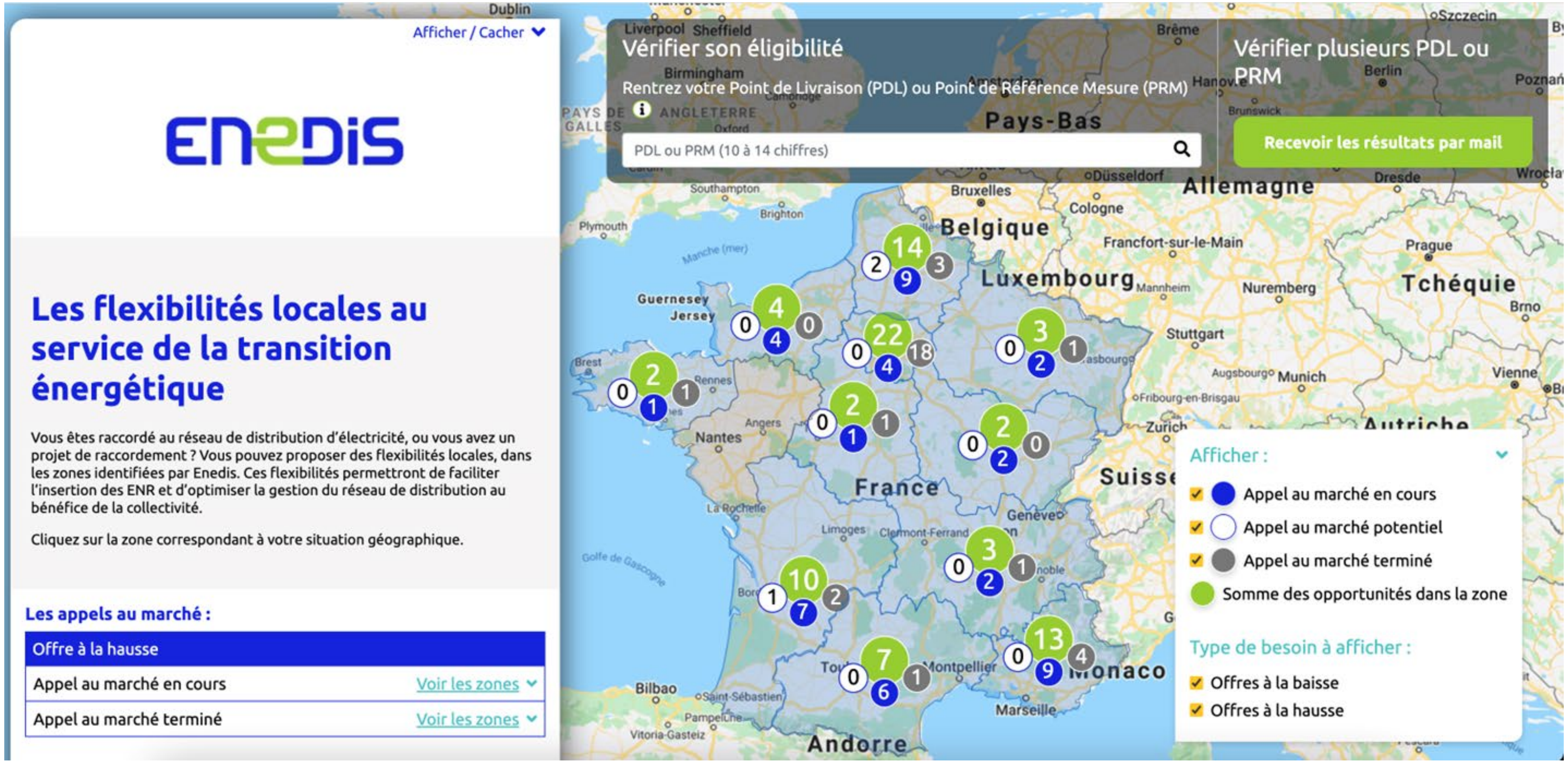


Flex platforms commonly provide a graphical interface to communicate with flexibility service providers

The PicloFlex interface includes:

- Geographical location of the tenders
- Tender service specifications
- Tender financial offer
- Offers are submitted within the platform

Interface of platforms (II)



Another example is the Enedis interface, the main difference is that this interface does not allow the submission of offers, these are submitted by email

Role of DSO: comparative table

Platform Yes	Ownership	Incentive of network operators	Are there participation fees?	Participation criteria
ENERA	EPEX SPOT (power exchange)	No financial incentive	Did not go through to commercial phase	There were, not clear which ones
NODES	• Formerly owned by Nord Pool (power exchange) • Now owned by NODES (independent entity)	Unclear	Yes	- Assets in place - Metering data
PicloFlex	Owned by Piclo (independent entity)	• Piclo favors a TOTEX approach • Italian regulation favors pilot tests	• The DSO pays an annual subscription fee • The FSPs can participate free of charge	Technical and regulatory assessment
RomeFlex	• Areti (Italian DSO) • GME (Italian power exchange)	• Italian regulation favors pilot tests • Claim made that all EU regulators will push for OPEX remuneration in the future	Power exchanges typically charge participation fees that are proportional to the volume that is traded	Technical and regulatory assessment
GOPACS	• System operators: Dutch TSO TenneT and Dutch DSOs Enexis, Liander, Rendo, Stedin, Westland Infra	• Unclear	• Defined in accordance with system operators • If operators agree that FSPs are relieved of fees then system operators pay expenses • Otherwise expenses are shared	• Similar criteria as intraday market
Enedis	• DSO Enedis	• CAPEX approach for France, low incentives	• No	• The asset has to be connected to the geographical location of the tenders
EPEX LEM	• EPEX	• UK has a TOTEX approach • There is an opportunity for every pound saved to return 50% to customers and 50% to shareholders	• The DSO pays an annual subscription fee • The FSPs can participate free of charge	• The DSO allows flexibility from all levels

Platform ownership

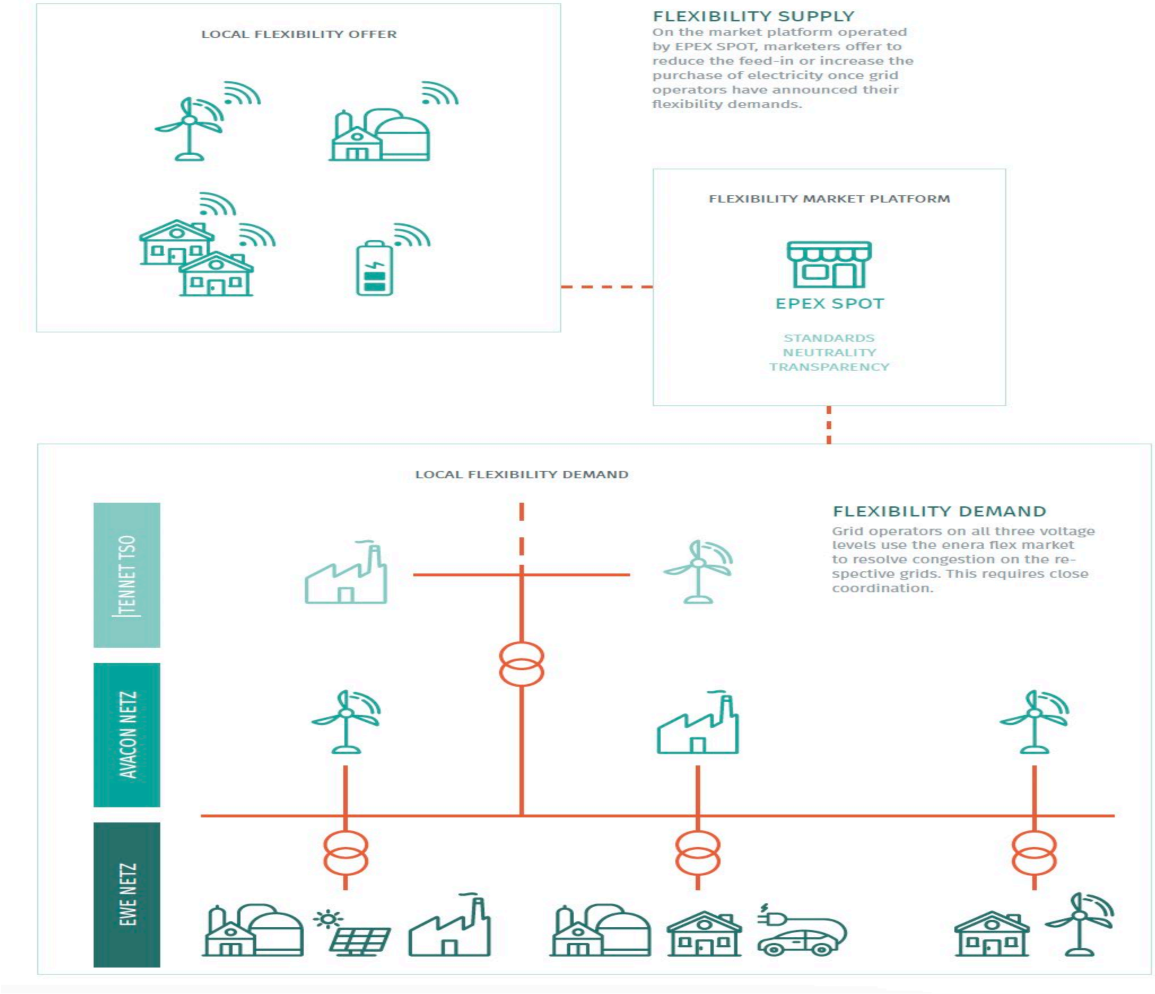
- Typically, platforms are owned and operated by third parties
  - These are neutral entities without active assets in the market
  - It is argued that this configuration allows for market neutrality
  - Examples of third parties include software companies (Piclo) and power exchanges (EPEX)
  - There are some exceptions where the DSO owns and operates the platform (Enedis, GOPACS)

- DSOs normally appear as customers within flexibility platforms
  - DSOs contract a specific flexibility platform
  - The DSOs normally assume the costs of operating the flexibility platform, the flexibility providers are not charged any fees for their participation

DSO incentives

- DSO incentives vary depending on the specific country
  - The incentives come along with a proper regulation
  - Countries with an advanced regulation have higher liquidity of flexibility markets (e.g. Italy or the UK)
  - PicloFlex, for example, recommends a TOTEX approach
    - This allows the DSO to be reimbursed for the costs associated to running the platform
- There is extensive R&D
  - Even though the regulation may still not be in place, there is a proliferation of R&D activities (e.g. in Germany)
  - Some of these R&D pilots have later seen a commercial phase (not necessarily in the country where the pilots were established)

Platform/DSO communication



- The figure (taken from ENERA final report) presents the typical platform/DSO communication paradigm
- DSOs submit flexibility offers to the platform
  - The platform is typically operated by a third party
- Flexibility Service Providers submit flexibility offers
- The platform matches offer bids with demands

Overview of technical requirements

- Remote readable meters
- Heating meters (for district heating)
- PQM (power quality measurement devices)
  - Measures current/voltage, all three phases, installed in transformer stations, you also get measurement of frequency and power factor
- Edge PMUs: measure similar quantities as PQMs, more commonly used for phasor measurements
- New energy management systems sometimes equipped with communication capabilities between PQMs and control center (e.g. in Germany)
- Communication paths between energy management system and control center
- No need to renovate control center
- Unclear if optimization software/technology is installed at control centers (possibly not, some platforms have internal optimization engines)

Arrangements between aggregators and prosumers

- Regarding new services, there are roughly three sources of flexibility
  - Renewables: These consist of dispatchable portfolios, the aggregator sends a setpoint
  - Demand response schemes: These relate to industry activities, here the aggregator sends a signal on how to shift loads
  - Batteries

- The aggregator, as a service provider, can have a fixed and variable remuneration scheme
  - The variable remuneration scheme is motivated by incentives and is widely adopted in practice
  - If the aggregator is performing well, they are commissioned a reward fee per kWh activated
  - There can be a fixed component, which relates to the fixed costs of the aggregator (e.g., setting up the software, infrastructure, etc)

TSO-DSO coordination platforms

Sources

Overview of EU platforms

Detailed discussion of studied platforms

Conclusions

Conclusions

- Commercial maturity
  - Our subjective impression is that Piclo appears to be the most commercially advanced platform among the ones studied
  - Nevertheless, UKPN (one of the major UK DSOs) decided to move from Piclo to EPEX (Local Energy Market)
  - Other commercially mature platforms involve power exchanges (e.g. Areti in Italy, where GME is active)
- Diversity of platform ownership
  - It seems that most commercial platforms are not owned/operated by DSOs
  - But some platforms are an exception to this rule, e.g. GOPACS and Enedis: unclear whether there may be conflicts of interest in such cases
- DSO regulatory framework is a key driver of adoption
  - Countries with advanced DSO regulation have the most advanced solutions (e.g. Italy, UK)
  - And countries with weak DSO regulation are well behind (e.g. France, Germany)

Conclusions (II)

- Diversity of integration to wholesale markets
  - Some platforms are mindful of interaction of flexibility products with existing wholesale markets (e.g. GOPACS, RomeFlex)
  - Other platforms are quite disconnected from existing wholesale markets (e.g. Enedis, PicloFlex)
- Diversity of selection criteria
  - Some platforms are based on pure price competition (e.g. GOPACS)
  - While others are a mix of technical qualifications and economic criteria (e.g. Enedis)
  - Awarded prices are often as-bid

Conclusions (III)

- Congestion management is the dominant service offered by these platforms
  - Other encountered needs: investment deferral, restoration, voltage control
  - This also translates to a diversity of time scales: long-term procurement (e.g. ENEDIS) as well as day-ahead or close-to-real-time operation (e.g. GOPACS)
- Closed gate versus continuous matching
  - Certain platforms favor closed-gate auctions, e.g. EPEX LEM
  - Others are based on continuous matching, e.g. GOPACS, and exploit existing infrastructure of operating markets

The case for local markets

Base scenario

DN over-supply

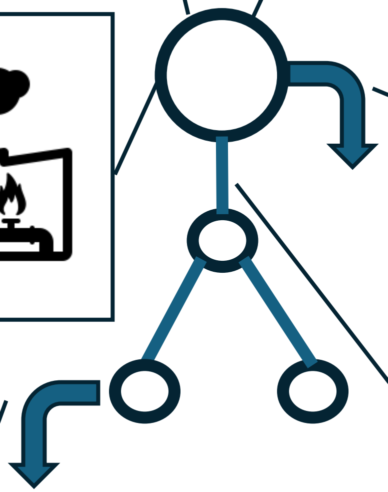
Scarcity

Consider a future version of the Belgian system

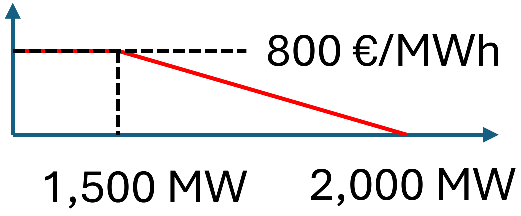
Nuclear + imports (inflexible)
Pmax: 4,500 MW
Marg. cost: $MC(p) = 10$ €/MWh

Pumped hydro (flexible)
Pmax: 1,400 MW
Flexible: 1,400 MW
Marg. cost: $MC(p) = 0.1786p$ €/MWh

Thermal
Pmax: 8,600 MW
Flexible: 1,300 MW
Marg. cost: $MC(p) = 100$ €/MWh



Transmission load
8,400 MW (inflexible)
Transmission ORDC



Distribution load
Valuation: 300 €/MWh
5,000 MW (total)
Flexible: 1,000 MW

Distribution network
Capacity: 3,000 MW

Understanding the overall condition of the system

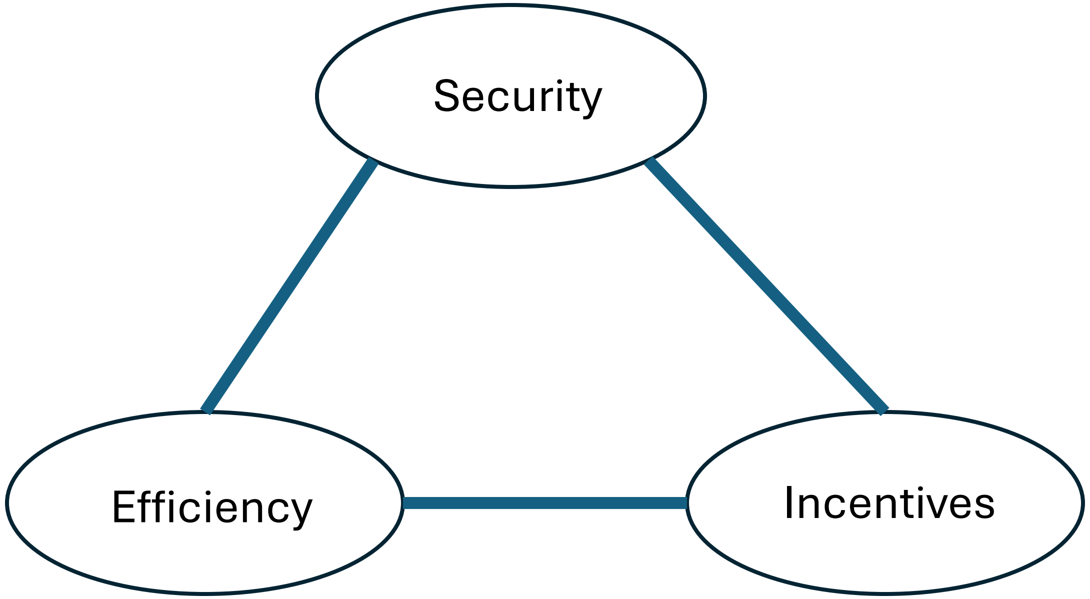
- Total capacity requirements:
  - Reserve: 2,000 MW
  - Energy: 13,400 MW
- Total capacity available:
  - Flexible: 1,300 MW (thermal) + 1,400 MW (pumped hydro) + 1,000 MW (distribution) = 3,700 MW
  - Inflexible: 7,300 MW (thermal) + 4,500 MW (nuclear/imports) = 11,800 MW
- All in all:
  - Total capacity needed is 15,400 MW and 15,500 MW is available
  - Flexible capacity needed is 2,000 MW and 3,700 MW is available
- But also: the distribution load is higher than what distribution lines can serve

Alternative market designs

- **Proposed**: locational, with reserve deliverability
- **Aggressive**: ignore distribution network capacity when sourcing reserve
- **Conservative**: ignore distribution network assets when sourcing reserve
- **Status quo**: ignore network completely

Key performance indicators of alternative market designs

- **Lost opportunity cost** (€): indicator of alignment between optimal dispatch and incentives
- **Redispatch** (MW): indicator of the extent to which a market design threatens network security
- **Efficiency** (€)



Proposed design

Energy price at transmission set by thermal being marginal

Reserve price at transmission set by surplus of flex capacity

Reserve flow not exhausting DN line upstream, because DN already serving large distribution load downstream

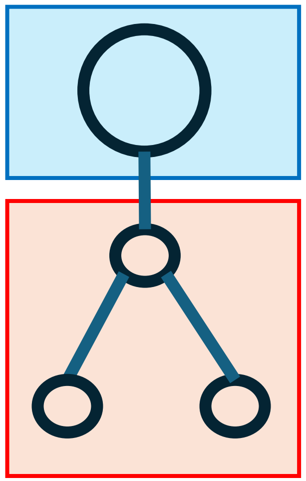
Energy: 100 €/MWh
Reserve: 0 €/MWh

E: 4,500 MW
R: 0 MW

E: 6,340.1 MW
R: 786.5 MW

E: 559.9 MW
R: 456 MW

E: -8,400 MW



Flow reserve: 757.4 MW

Flow energy: 3,000 MW

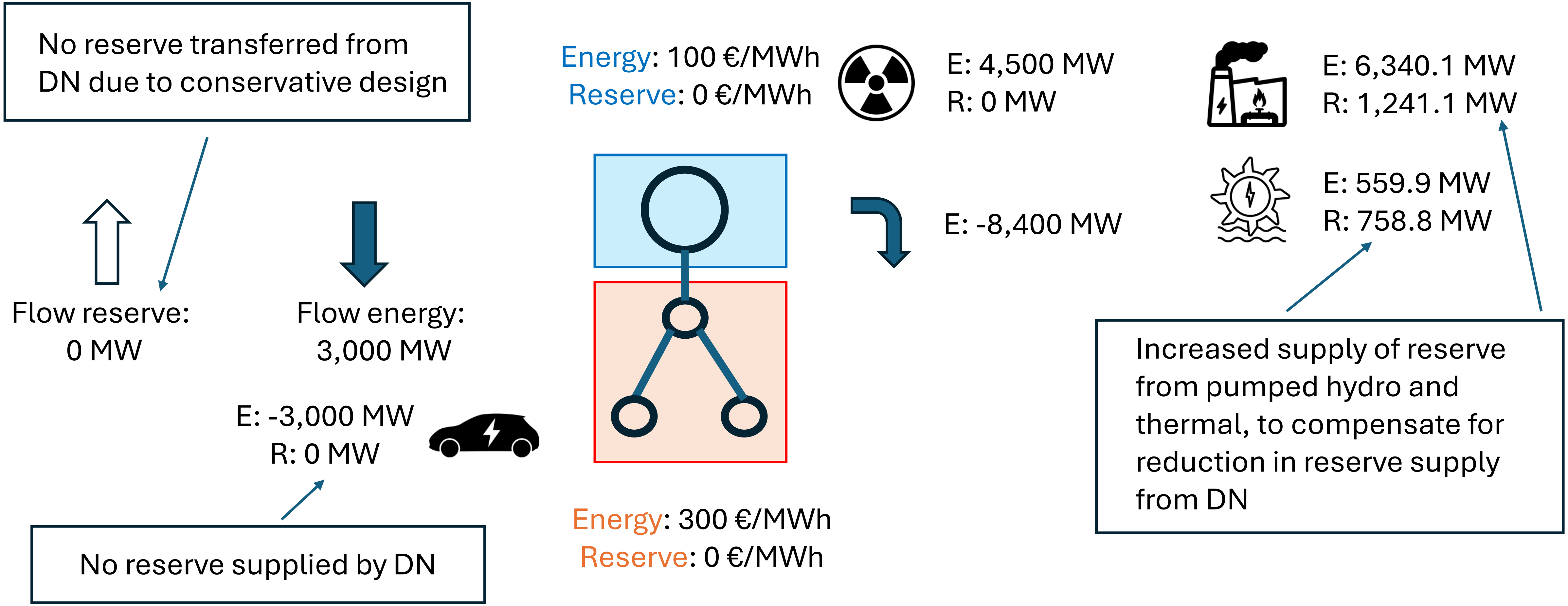
E: -3,000 MW
R: 757.4 MW

Energy: 300 €/MWh
Reserve: 0 €/MWh

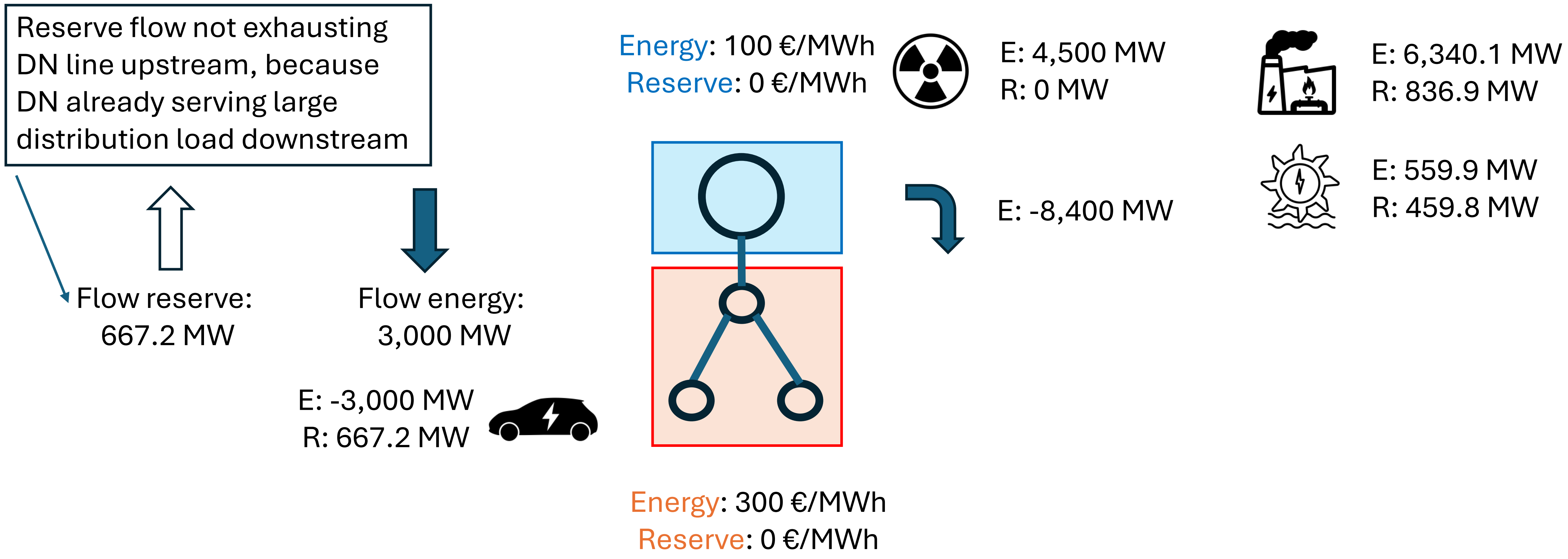
Reserve price at distribution set equal to reserve price at transmission since distribution line not congested

Energy price at distribution set by demand not being fully met

Conservative design



Aggressive design



Status quo

Distribution line flow exceeds line capacity

Excess production from thermal due to excess demand in DN

Energy: 100 €/MWh
Reserve: 0 €/MWh

E: 4,500 MW
R: 0 MW

E: 8.340.1 MW
R: 225 MW

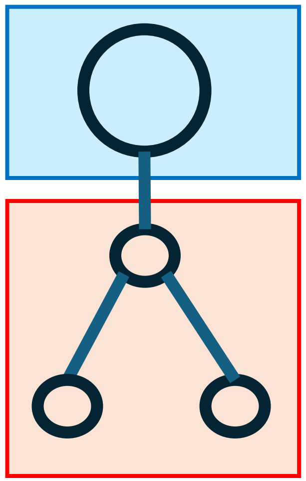
E: 559.9 MW
R: 806 MW

E: -8,400 MW

Flow reserve:
968.9 MW

Flow energy:
5,000 MW

E: -5,000 MW
R: 968.9 MW



Ignoring network constraints results in a uniform price for the entire network

Energy: 100 €/MWh
Reserve: 0 €/MWh

Comparative analysis

	LOC [€]	Redispatch [MW]	Efficiency [€]
Proposed	0	0	9,992,996
Conservative	0	0	9,993,000
Aggressive	0	0	9,993,000
Status quo	400,000	4,000	10,393,000

Reflection of trouble in DN: physical demand needs to stay low, but price signal encourages full consumption

This welfare increase is artificial and driven by violation of network constraints

Takeaways

- As long as generation capacity at transmission level is not depleted, the conservative design comes very close to the proposed design, simply by reshuffling reserve supply from DN to TN
- Aggressive design is identical to the proposed design, because the DN is not overloaded: sizing of DN lines corresponds to high loads, and DN line capacity thus exceeds upstream reserve committed by aggressive design
- Status quo violates network constraints, explains much of the motivation for existing flexibility platforms

The case for local markets

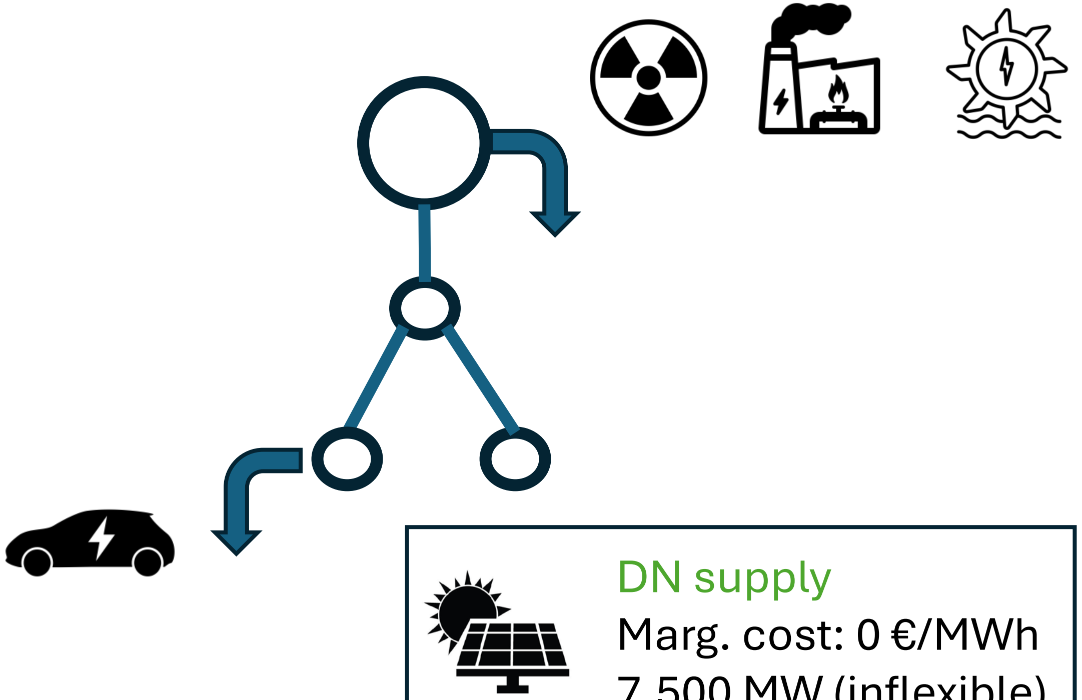
Base scenario

DN over-supply

Scarcity

Distribution network oversupply

- Consider a scenario of distribution system over-supply, e.g. because of distributed renewables
- Concretely, we add a supply of 7,500 MW in the distribution network



DN supply
Marg. cost: 0 €/MWh
7,500 MW (inflexible)

Proposed design

Energy price at transmission set by thermal being marginal

Distribution line not loaded, the system is in a situation of oversupply and can absorb reserve also from the TN

Energy: 100 €/MWh
Reserve: 0 €/MWh

E: 4,500 MW
R: 0 MW

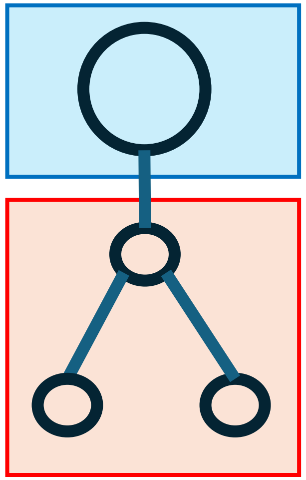
E: 840.1 MW
R: 786.5 MW

E: 559.9 MW
R: 456 MW

E: -8,400 MW

Flow reserve: 298.7 MW

Flow energy: 2,500 MW



E: -5,000 MW
R: 298.7 MW

E: 7,500 MW
R: 0 MW

Energy: 100 €/MWh
Reserve: 0 €/MWh

Conservative design

No reserve transferred from DN due to conservative design

Flow reserve: 0 MW

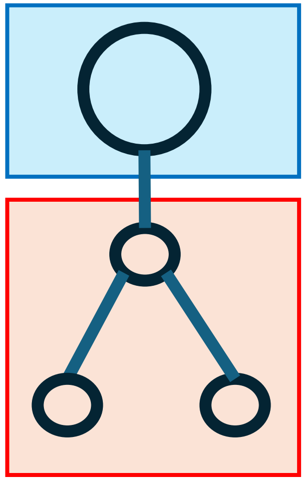
Flow energy: 2,500 MW

Energy: 100 €/MWh
Reserve: 0 €/MWh

E: 4,500 MW
R: 0 MW

E: 840.1 MW
R: 1,248 MW

E: 559.9 MW
R: 751.8 MW



E: -8,400 MW

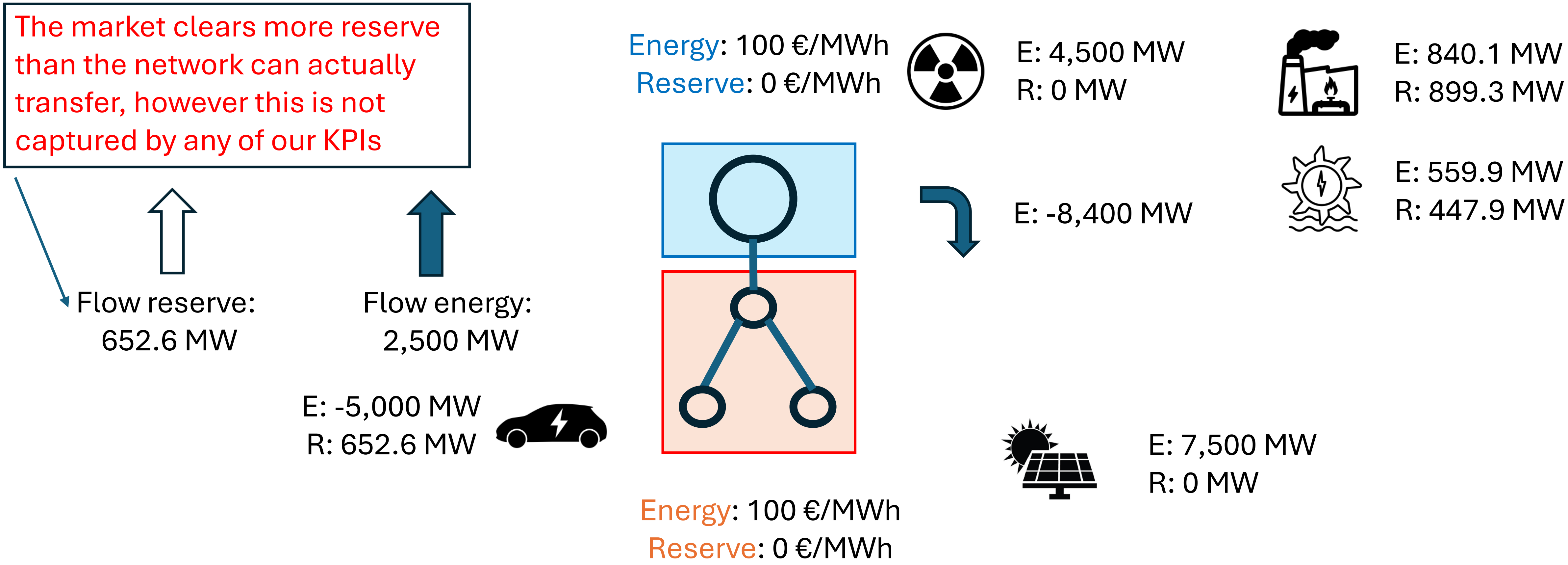
E: -5,000 MW
R: 0 MW

E: 7,500 MW
R: 0 MW

Energy: 100 €/MWh
Reserve: 0 €/MWh

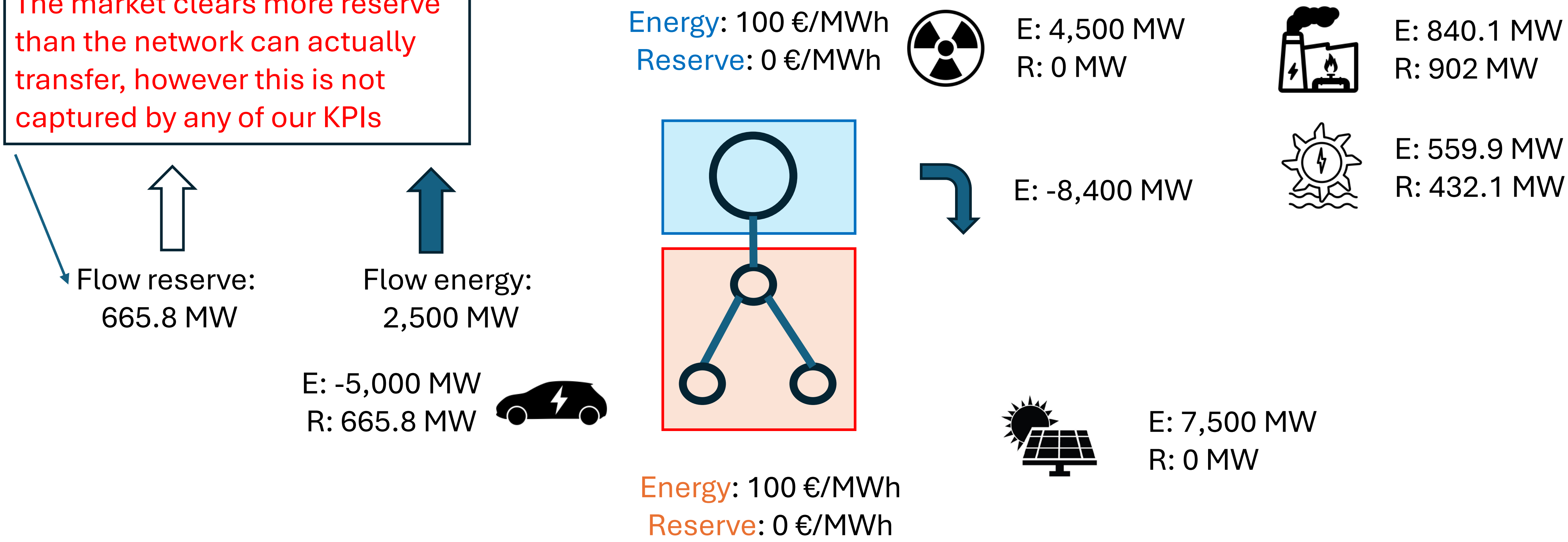
No reserve supplied by DN

Aggressive design



Status quo

The market clears more reserve than the network can actually transfer, however this is not captured by any of our KPIs



Comparative analysis

	LOC [€]	Redispatch [MW]	Efficiency [€]
Proposed	0	0	11,143,000
Conservative	0	0	11,143,000
Aggressive	0	0	11,143,000
Status quo	0	0	11,142,996

Takeaways

- The conservative design attains the same performance as the proposed, since the transmission network resources are adequate for covering the reserve requirements of the system
- The aggressive and status quo designs over-promise reserve, however this is not captured by our KPIs

The case for local markets

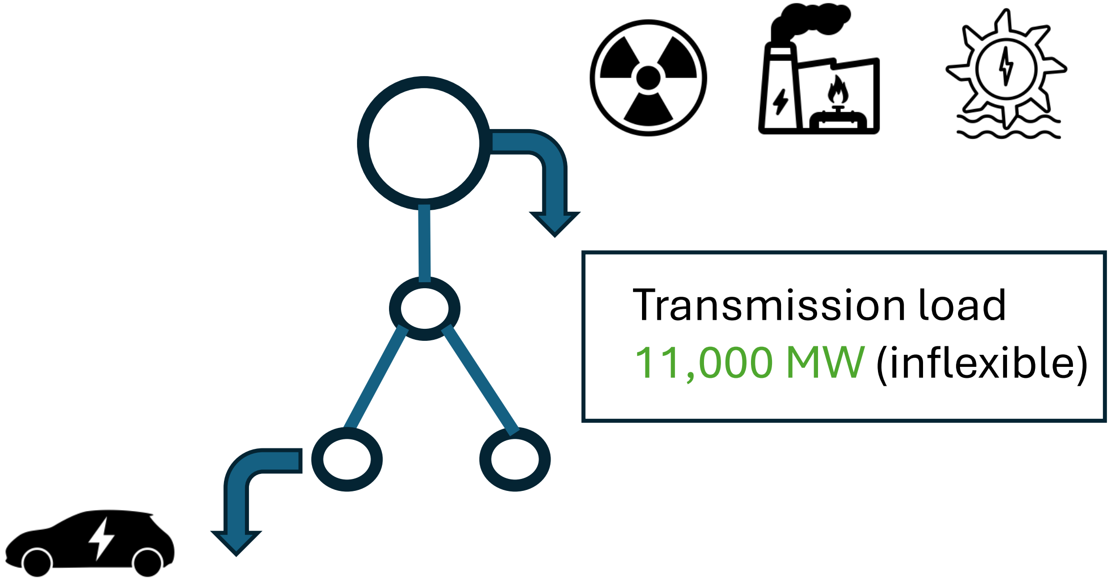
Base scenario

DN over-supply

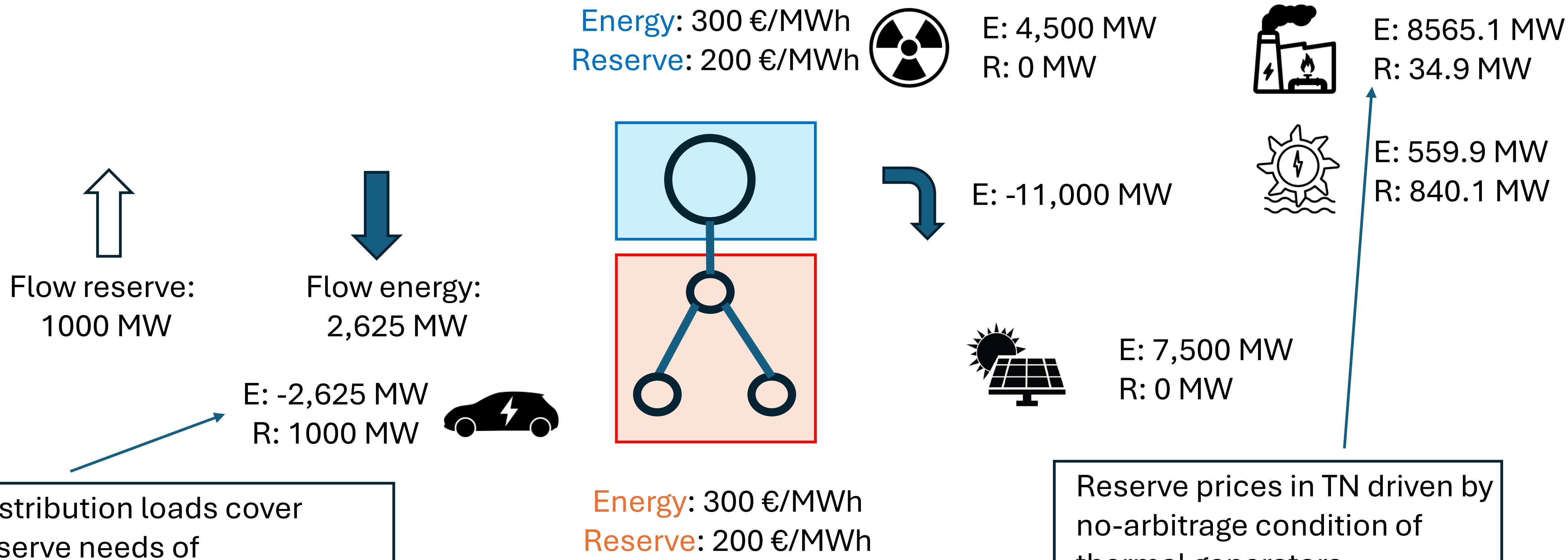
Scarcity

Scarcity

- Consider a case of overall system scarcity, e.g. because of low renewable output and excessive load
- Concretely, we increase the demand of the transmission network



Proposed design



Distribution loads cover reserve needs of transmission system, up the point that the DN allows

Reserve prices in TN driven by no-arbitrage condition of thermal generators

Conservative design

No reserve transferred from DN due to conservative design

Flow reserve:
0 MW

Flow energy:
1,625 MW

E: -1,625 MW
R: 0 MW

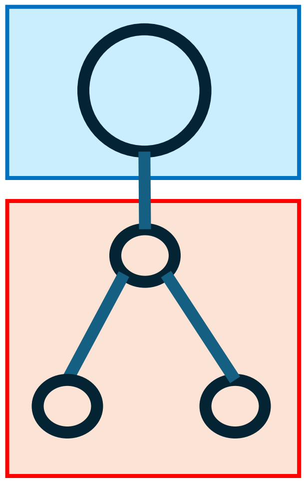
Energy: 300 €/MWh
Reserve: 200 €/MWh

E: 4,500 MW
R: 0 MW

E: 7565.1 MW
R: 1,034.9 MW

E: 559.9 MW
R: 840.1 MW

E: -11,000 MW



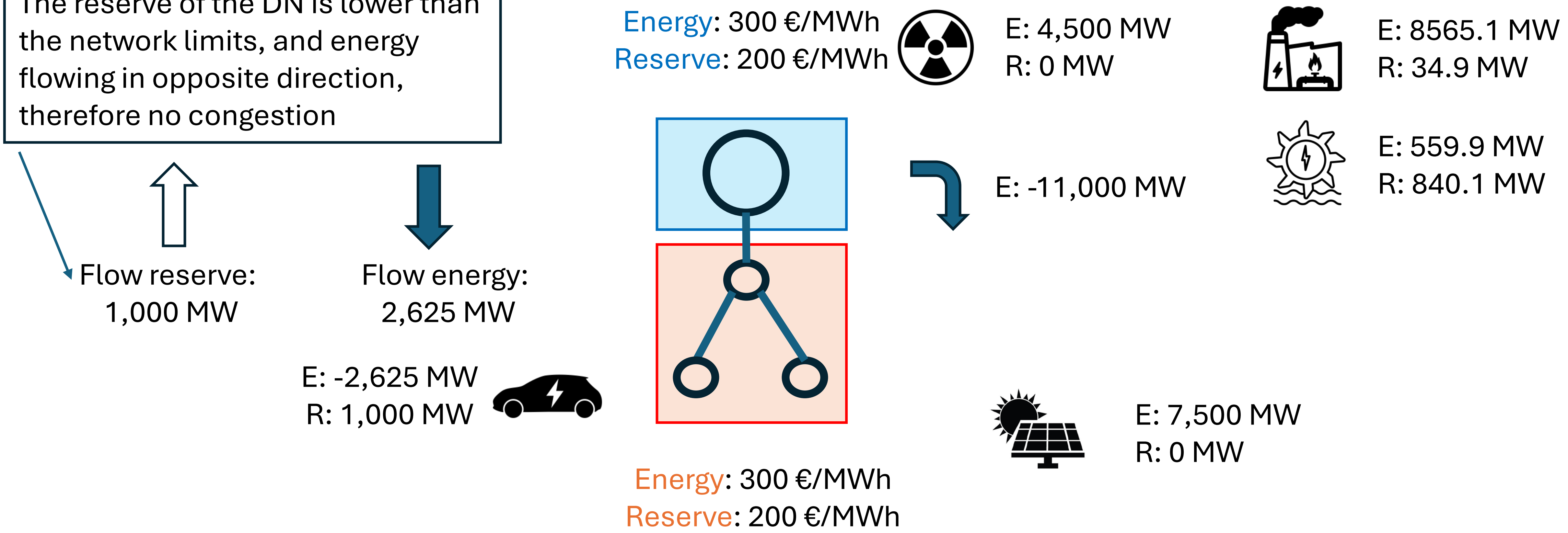
Energy: 300 €/MWh
Reserve: 0 €/MWh

Collapse in reserve price coherent with the fact that DN loads not asked to provide reserve to TN

Line not congested downstream, because valuation of distribution loads not high enough (300 €/MWh)

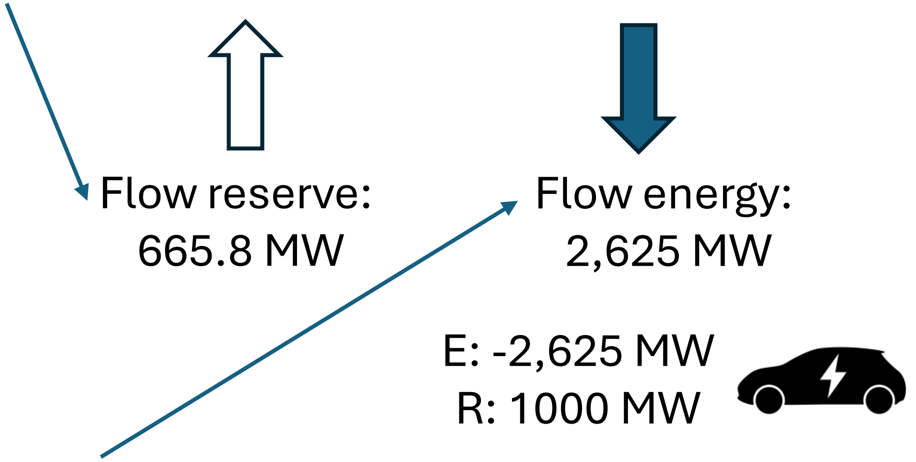
Aggressive design

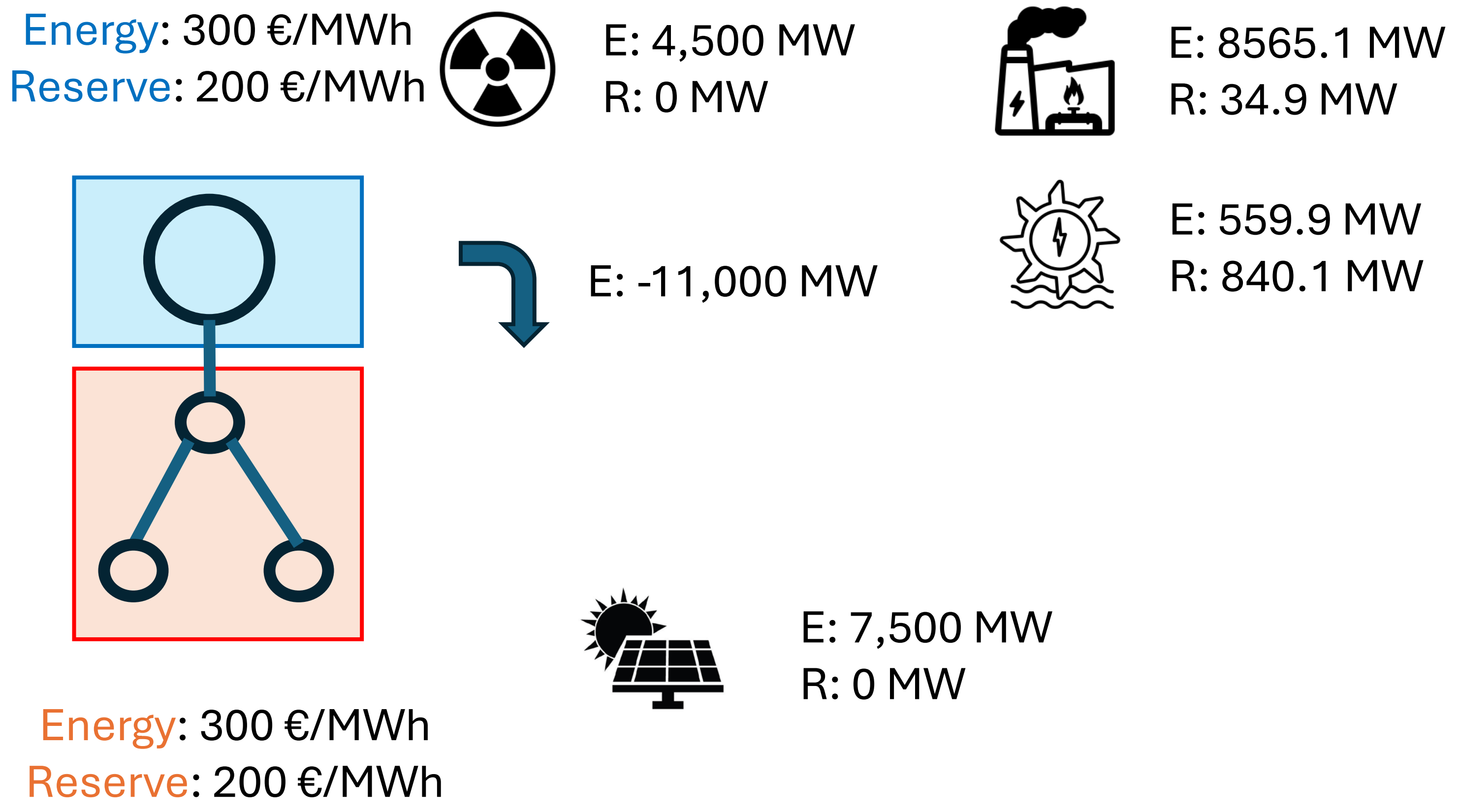
The reserve of the DN is lower than the network limits, and energy flowing in opposite direction, therefore no congestion



Status quo

The reserve of the DN is lower than the network limits, and energy flowing in opposite direction, therefore no congestion





Because of generation scarcity, power drawn by distribution loads is not enough to cause congestion

Comparative analysis

	LOC [€]	Redispatch [MW]	Efficiency [€]
Proposed	0	0	12,245,496
Conservative	1,000,000	0	12,045,500
Aggressive	0	0	12,245,496
Status quo	0	0	12,245,496

Severe incoherence in price signals: line not congested, but DN prices much lower than TN prices

Non-negligible welfare losses

Takeaways

- The conservative design results in deterioration of welfare because valuable reserve is not supplied to the transmission network which requires it in conditions of scarcity
  - This is accompanied by incoherent price signals, with DN reserve prices being zero despite the fact that the network has space to offer for delivering reserve from DN resources to the TN
- The aggressive design performs identically to the proposed design: the DN reserve is offered to the TN, and the upstream flow that could occur is not a problem since (i) the flexibility of the DN resources is lower than the network capacity, and (ii) the energy flow is downstream, which means that reserve and energy are flowing in opposite directions and thus their effect on network stress is not additive
- The status quo design performs identically to the proposed design: the distribution network draws less power than that which the network can handle due to generation scarcity

The big picture

Color coding:
- **Green**: no problems detected
- **Orange**: problems detected, but not by our KPIs
- **Red**: problems detected by our KPIs

	Base	DN oversupply	Scarcity
Proposed			
Conservative			
Aggressive			
Status quo			

The proposed design is the only one which does not face problems under any conditions

Inscribed boxes

Inscribing a box in a polyhedron

Application to power networks

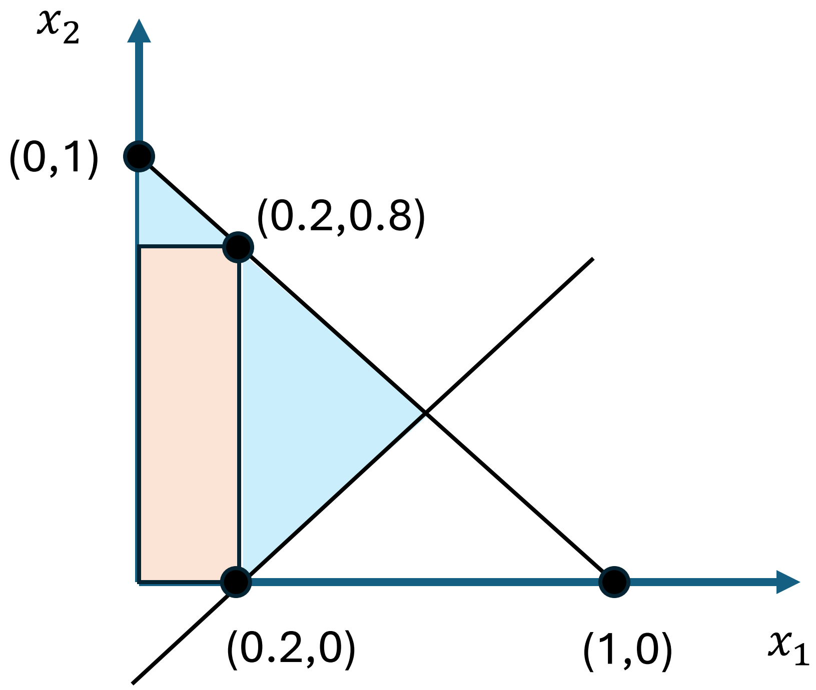
Application to reserve deliverability

Inscribing a box in a polyhedron

- Denote a box with lower corner χ and upper corner $\chi + \psi$ (with $\psi \geq 0$) as $\mathcal{B}(\chi, \chi + \psi)$
- **Lemma 1** [1] (rephrased): Given the polyhedron $X = \{x: Ax \leq b\} \subseteq \mathbb{R}^n$, the conditions which ensure that the box $\mathcal{B}(\chi, \chi + \psi)$ is contained within the polyhedron X are $A\chi + A^+\psi \leq b, \psi \geq 0,$ where A^+ is the positive part of A

Example

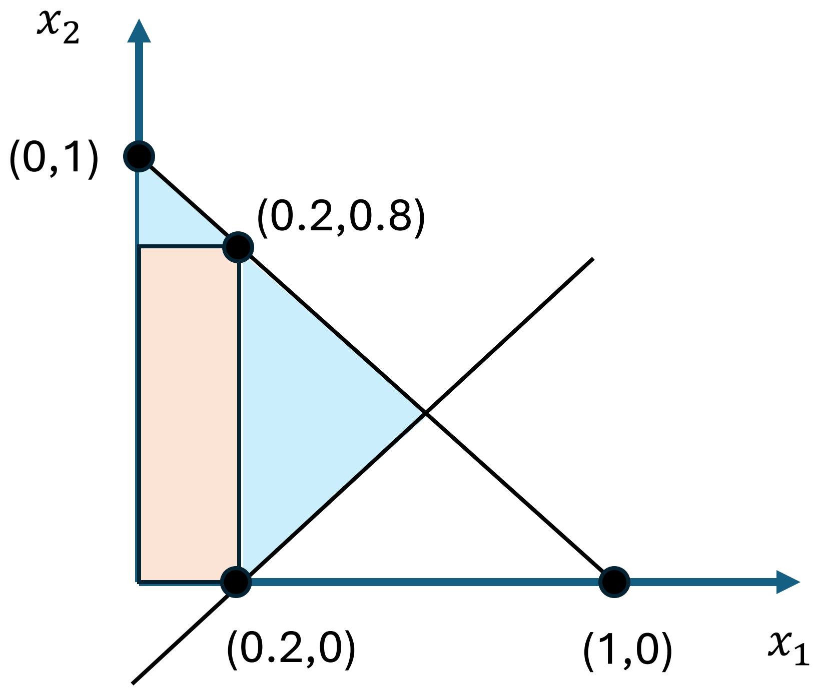
- Consider the polyhedron
$$X = \{(x_1, x_2): x_1 + x_2 \leq 1, x_1 - x_2 \leq 0.2, x_1 \geq 0, x_2 \geq 0\}$$
- The conditions for a box $\mathcal{B}(\chi, \chi + \psi)$ to be contained in X, $\mathcal{B}(\chi, \chi + \psi) \subseteq X$ are as follows
$$\chi_1 + \chi_2 \leq 1, \chi_1 - \chi_2 \leq 0.2$$
$$\chi_1 + \psi_1 + \chi_2 \leq 1, \chi_1 + \psi_1 - \chi_2 \leq 0.2$$
$$\chi_1 + \chi_2 + \psi_2 \leq 1, \chi_1 - (\chi_2 + \psi_2) \leq 0.2$$
$$\chi_1 + \psi_1 + \chi_2 + \psi_2 \leq 1, \chi_1 + \psi_1 - (\chi_2 + \psi_2) \leq 0.2$$
$$\psi_1, \psi_2 \geq 0$$
- Bemporad's [1] lemma states that this set of conditions, which grows exponentially in the dimension of the considered space, can be replaced by
$$\chi_1 + \psi_1 + \chi_2 + \psi_2 \leq 1, \chi_1 + \psi_1 - \chi_2 \leq 0.2$$
$$\psi_1, \psi_2 \geq 0$$
- This result is important, because it allows us to express $m \cdot 2^n$ conditions equivalently as m conditions, where m is the number of constraints describing the polytope/number of rows of A



Example (II)

- The box $\mathcal{B}((0,0),(0.2,0.8))$ is indicated in pink
- Its corners are (0,0), (0,0.2), (0, 0.8) and (0.2, 0.8)
- We can check that $\mathcal{B}((0,0),(0.2,0.8)) \subseteq X$ in two ways:
  - Each of its corners is in the box. This amounts to checking that the inequalities defining X are satisfied for every one of the $2^2 = 4$ corners
  - Alternatively, we confirm that $\chi = (0,0)$ and $\psi = (0.2,0.8)$ satisfy the following constraints:

$$\chi_1 + \psi_1 + \chi_2 + \psi_2 \leq 1$$
$$\chi_1 + \psi_1 - \chi_2 \leq 0.2$$
$$\psi_1, \psi_2 \geq 0$$

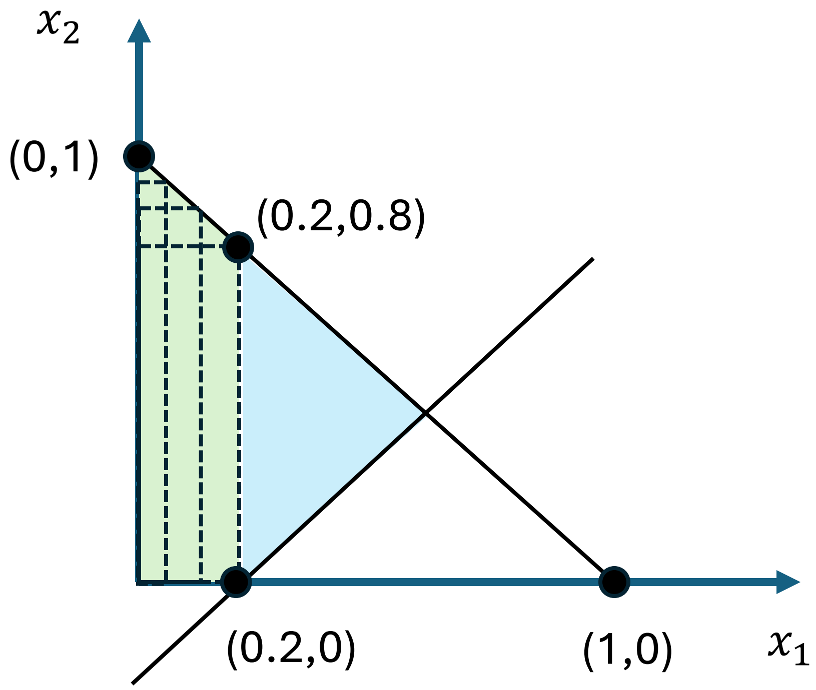


Example (III)

- If we choose one corner of the box to be the origin, we have the following set of constraints

$$\psi_1 + \psi_2 \leq 1$$
$$\psi_1 \leq 0.2$$
$$\psi_1, \psi_2 \geq 0$$

- This turns out to be the union of all boxes with origin 0 which are contained in X (indicated in the figure in green)
- **Useful mnemonic**: The green set is obtained by taking the original polytope, making all variables non-negative, and dropping those variables with a negative coefficient (for inequalities of the $\leq$ type)



Inscribed boxes

Inscribing a box in a polyhedron

Application to power networks

Application to reserve deliverability

Net injections and bilateral transactions

- Consider the triangular network of Oren's paper on FTRs [2] indicated in the figure
- Assuming identical susceptances on lines, and given the line limits indicated in the figure, the feasible set of net injections can be described as

$$\frac{2}{3}r_1 + \frac{1}{3}r_2 \leq 300 \text{ (Line } 1 \rightarrow 3)$$

$$\frac{1}{3}r_1 + \frac{2}{3}r_2 \leq 220 \text{ (Line } 2 \rightarrow 3)$$

$$-100 \leq \frac{1}{3}r_1 - \frac{1}{3}r_2 \leq 100 \text{ (Line } 1 \leftrightarrow 3)$$

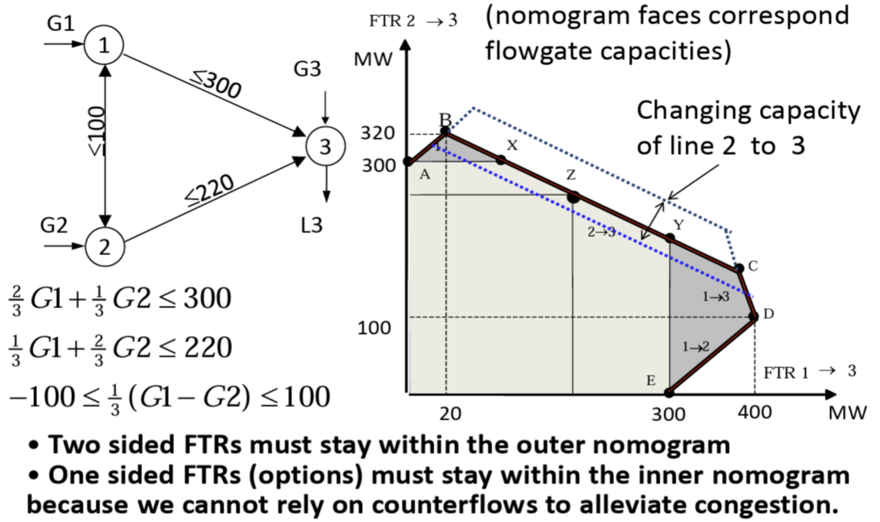


Figure 3: Feasibility region of FTR options and obligations and the effect of flowgate capacity rating

Net injections and bilateral transactions (II)

- FTRs are essentially bilateral trades/shipments of power between two locations
- Let us denote $f_{(m,n)}$ as the FTR (shipment of power) from m to n
- We are interested in moving from net injection space (r) to flow space (f)
- Then, for every location, we have

$$r_m = \sum_{n \in N} f_{(m,n)}$$

- Returning to the example of Oren [2], we have

$$r_1 = f_{(1,2)} + f_{(1,3)}$$
$$r_2 = f_{(2,3)} - f_{(1,2)}$$
$$r_3 = -f_{(1,3)} - f_{(2,3)}$$

Net injections and bilateral transactions (III)

- Based on Oren's chosen example, he seems to assume that $f_{(1,2)} = 0$ (since no loads in either of the locations?), so let's drop $f_{(1,2)}$
- And he further seems to assume that $f_{(1,3)}, f_{(2,3)} \geq 0$
- The polytope (dark gray in figure) is then expressed in f space as

$$\frac{2}{3} f_{(1,3)} + \frac{1}{3} f_{(2,3)} \leq 300$$

$$\frac{1}{3} f_{(1,3)} + \frac{2}{3} f_{(2,3)} \leq 220$$

$$-100 \leq \frac{1}{3} f_{(1,3)} - \frac{1}{3} f_{(2,3)} \leq 100$$

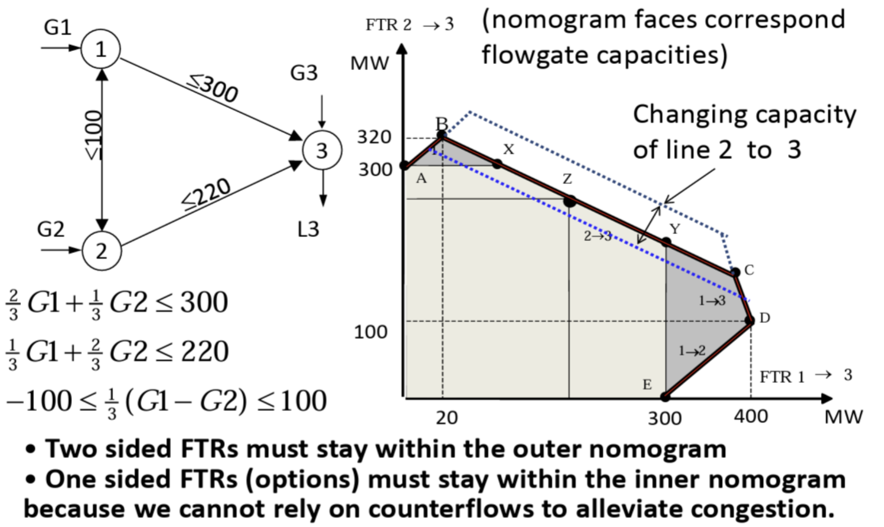


Figure 3: Feasibility region of FTR options and obligations and the effect of flow-gate capacity rating

Inscribing a box

- Applying Bemporad's lemma 1 [1] to the polytope, we have the following set of constraints describing the union of all boxes which are contained in the set of feasible bilateral trades:

$$\frac{2}{3} f\psi_{(1,3)} + \frac{1}{3} f\psi_{(2,3)} \leq 300$$

$$\frac{1}{3} f\psi_{(1,3)} + \frac{2}{3} f\psi_{(2,3)} \leq 220$$

$$\frac{1}{3} f\psi_{(1,3)} \leq 100, \frac{1}{3} f_{(2,3)} \leq 100$$

$$f\psi_{(1,3)} \geq 0, f\psi_{(1,3)} \geq 0$$

- This is precisely the light gray box in the figure of Oren

- Applying Bemporad's lemma 1 [1] to the polytope, we have the following set of constraints describing the union of all boxes which are contained in the set of feasible bilateral trades:

$$\frac{2}{3} f\psi_{(1,3)} + \frac{1}{3} f\psi_{(2,3)} \leq 300$$

$$\frac{1}{3} f\psi_{(1,3)} + \frac{2}{3} f\psi_{(2,3)} \leq 220$$

$$\frac{1}{3} f\psi_{(1,3)} \leq 100, \frac{1}{3} f_{(2,3)} \leq 100$$

$$f\psi_{(1,3)} \geq 0, f\psi_{(1,3)} \geq 0$$

- This is precisely the light gray box in the figure of Oren

Connection between scenarios and inscribed boxes

- An FTR option can be interpreted as a bilateral trade which may or may not happen
- Each corner of the box is a “scenario” corresponding to a configuration of trades being activated or not
- For instance, the orange box corresponds to a trade of 300 MW between nodes 2 and 3, and a trade of 20 MW between nodes 1 and 3
- And the four points in the figure correspond to the following 4 scenarios of bilateral trade:
  - Bottom left corner of the box: 0 MW of $2 \rightarrow 3$ trade and 0 MW of $1 \rightarrow 3$ trade
  - Upper left corner of the box: 300 MW of $2 \rightarrow 3$ trade and 0 MW of $1 \rightarrow 3$ trade
  - Bottom right corner of the box: 0 MW of $2 \rightarrow 3$ trade and 20 MW of $1 \rightarrow 3$ trade
  - Upper right corner of the box: 300 MW of $2 \rightarrow 3$ trade and 20 MW of $1 \rightarrow 3$ trade

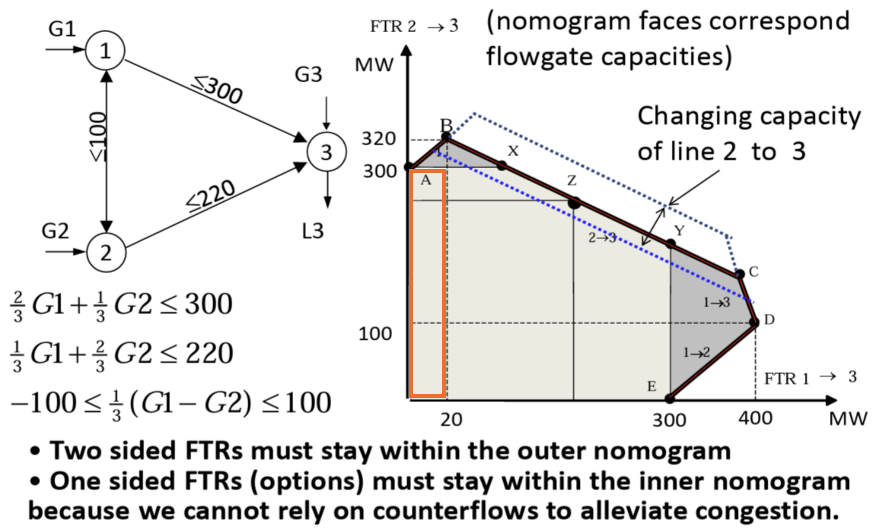


Figure 3: Feasibility region of FTR options and obligations and the effect of flow-gate capacity rating

Inscribed boxes

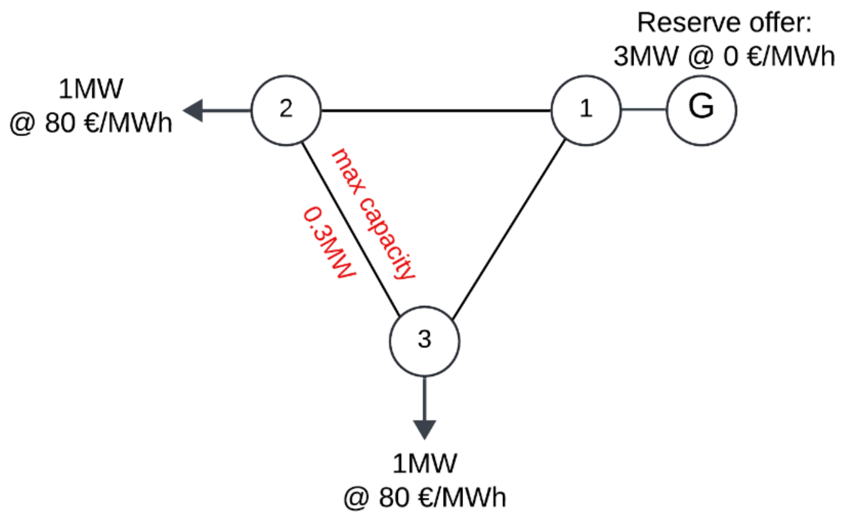
Inscribing a box in a polyhedron

Application to power networks

Application to reserve deliverability

Reserve deliverability

- Trading reserve is much like FTR options: trades may or may not be activated
- It became apparent to us, during a project with ENTSOE on the application of co-optimization in day-ahead market clearing and numerous follow-up studies [3, 4], that the inscribed boxes framework can be used in this context
- To understand why, consider the problem of trading reserve in the triangle network indicated in the figure



Reserve deliverability as a stochastic program

- We can formulate the problem as a stochastic program with decision-dependent uncertainty:

$$\max_{r,dr,nr} \sum_{l \in RL} VR_l \cdot dr_l - \sum_{g \in G} OC_g \cdot r_g$$

$$nr_{ns} = \sum_{g \in G_n} r_{g,s} - dr_{l(n)} \cdot \mathbb{I}_{l(n),s}, n \in N, s \in S$$

$$(nr_{ns}, n \in N) \in \mathcal{N}, s \in S$$

$$r_{gs} \leq r_g, g \in G, s \in S$$

$$dr_l \leq DR_l, l \in RL$$

$$r_g \leq P_g, g \in G$$

$$r, dr \geq 0$$

- Here, $\mathbb{I}_s$ is an indicator variable which is equal to 1 if TSO l activates in scenario s, 0 otherwise
- This formulation is not scalable, because it grows exponentially in the number of TSOs
- For instance, there are 61 bidding zones in Europe, so imagine a growth of the EUPHEMIA formulation by an order of 2^{61}, clearly hopeless

Applying inscribed boxes to reserve deliverability

- We develop the expression $(nr_{ns}, n \in N) \in \mathcal{N}, s \in S$ in detail:

$$\sum_{n \in N} PTDF_{kn} \cdot nr_{ns} \leq F_k, k \in K$$

- Again, the idea is to move from net injection space to bilateral trades space, with $nr_{ns} = \sum_{m \in N} fr_{(n,m),s}$
- The analysis tells us that the set of scenarios corresponds to the corners of a box
- And as long as this box is contained within the power flow constraints, we can have net injections nr_{ns} which satisfy the stochastic programming formulation
- But without an explicit consideration of scenarios!
- How we ensure that we can find r_{gs} which are also feasible for the remaining constraints is another question [5], not addressed here

Tractable formulation of reserve deliverability

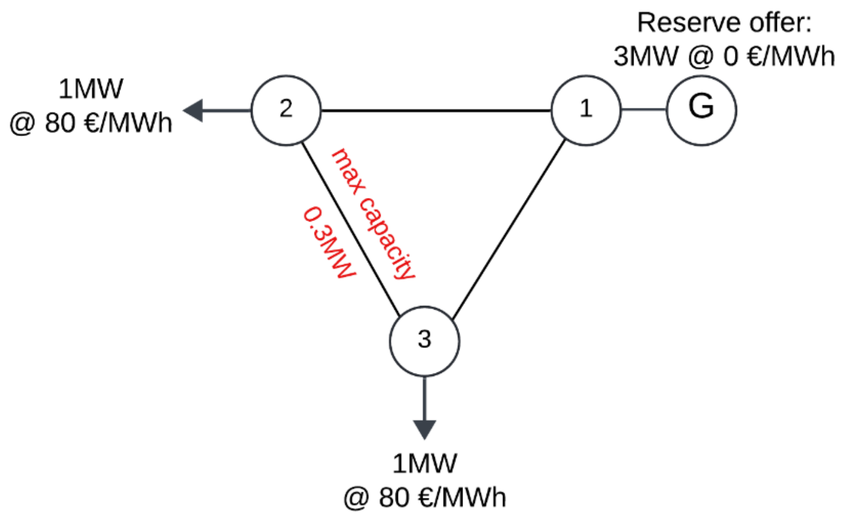
- To summarize, we can formulate the overall model as follows, where E is the set of directed edges in the network:

$$\max_{r,dr,nr,fr} \sum_{l \in RL} VR_l \cdot dr_l - \sum_{g \in G} OC_g \cdot r_g$$
$$nr_n = r_g - dr_{l(n)}, n \in N$$
$$nr_n = \sum_{m \in N} f_{(n,m)} \ , n \in N$$
$$\sum_{(n,m) \in E} \max(PTDF_{kn} - PTDF_{km}, 0) \cdot fr_{(n,m)} \le F_k, k \in K$$
$$dr_l \le DR_l, l \in RL$$
$$r_g \le P_g, g \in G$$
$$r, dr \ge 0$$

- Note we have applied inscribed boxes in the orange constraint
- No scenarios ⇒ scalable!
- Because of the above analysis, we conclude that this model is equivalent to the formulation of Caramanis [6] for TSO-DSO coordination in radial distribution networks

Example revisited

- The short-sighted thing to do would be to match 2 MW of reserve supply in node 1 with 1 MW of reserve demand in node 2 and 1 MW of reserve demand in node 3
- This would actually be an infeasible matching for the stochastic program: what if TSO2 activates fully and TSO3 not at all?
- The inscribed boxes formulation (and optimal solution) is to match 1.8 MW of reserve supply in node 1 with 0.9 MW of reserve demand in node 2 and 0.9 MW of reserve demand in node 3



References

[1] Bemporad, Alberto, Carlo Filippi, and Fabio D. Torrisi. "Inner and outer approximations of polytopes using boxes." *Computational Geometry* 27.2 (2004): 151-178

[2] Oren, Shmuel S. "Point to point and flow-based financial transmission rights: Revenue adequacy and performance incentives." Financial Transmission Rights: Analysis, Experiences and Prospects. London: Springer London, 2012. 77-94

[3] N-SIDE, AFRY, "CZC allocation with cooptimisation", November 2020

[4] N-SIDE and SDAC MSD, SDAC MSD Cooptimization Roadmap Study, available online: https://www.nemo-committee.eu/assets/files/co-optimizationroadmap-study-.pdf

[5] D. Avila, A. Papavasiliou, M. Pavesi, M. Viehhauser, "Welfare Benefits of Transitioning to Co-Optimization of Energy and Reserves in Europe", under review

[6] Caramanis, Michael, et al. "Co-optimization of power and reserves in dynamic T&D power markets with nondispatchable renewable generation and distributed energy resources." *Proceedings of the IEEE* 104.4 (2016): 807-836

Thank you

Questions?

For more information:

https://ap-rg.eu/

papavasiliou@mail.ntua.gr

Appendix

Notation: sets

- G: set of generators
- L: set loads
- LR: set of reserve loads
- E: set of directed edges in the network
- K: set of network constraints

Notation: parameters

- $MBR_l(\cdot)$: valuation of reserve load l
- $MB_l(\cdot)$: valuation of energy load l
- $MC_g(\cdot)$: marginal cost of generator g
- R_g: flexibility limit of asset g
- P_g: capacity limit of generator g
- D_l: capacity limit of energy load l
- DR_l: capacity limit of reserve load l
- $PTDF_{kn}$: PTDF of node n on line k
- F_k: flow limit of network constraint k

Notation: variables

- p_g: production of generator g
- r_g: reserve of asset g
- d_l: energy demand of energy load l
- dr_l: reserve demand of reserve load l
- f_k: energy flow on link k
- $fr_{(m,n)}$: reserve trade between nodes m and n
- ne_n: net energy injection in node n
- nr_n: net reserve injection in node n

Market models: common constraints

$$\max_{p,d,r,dr,ne,nr,f,fr} \sum_{l \in RL} \int_0^{dr_l} MBR_l(x)dx + \sum_{l \in L} \int_0^{d_l} MB_l(x)dx - \sum_{g \in G} \int_0^{p_g} MC_g(x)dx$$

$$(\mu R_g): r_g \leq R_g, g \in G$$

$$(\mu R_l): r_l \leq d_l, l \in L$$

$$(\mu_g): p_g + r_g \leq P_g, g \in G$$

$$(\nu_l): d_l \leq D_l, l \in L$$

$$(\nu R_l): dr_l \leq DR_l, l \in RL$$

$$(\rho_n): ne_n = \sum_{g \in G_n} p_g - \sum_{l \in L_n} d_l, n \in N$$

$$(\rho R_n): nr_n = \sum_{g \in G_n} r_g - \sum_{l \in RL_n} dr_l, n \in N$$

$$(\varphi): \sum_{n \in N} ne_n = 0$$

$$p, d, r, dr, fr \geq 0$$

Proposed design

$$(\psi_k): f_k = \sum_{n \in N} PTDF_{kn} \cdot ne_n \,, k \in K$$

$$(\psi r_n): nr_n = \sum_{m \in N:(n,m) \in E} fr_{(n,m)} - \sum_{m \in N:(m,n) \in E} fr_{(m,n)} \,, n \in N$$

$$(\lambda_k^+): f_k + \sum_{(n,m) \in E} \max(PTDF_{n,k} - PTDF_{m,k}, 0) \cdot fr_{(n,m)} \leq F_k, k \in K$$

$$fr \geq 0$$

Conservative design

$$(\psi_k): f_k = \sum_{n \in N} PTDF_{kn} \cdot ne_n \, , k \in K$$

$$fr_{(n,m)} = 0, (n, m) \in E$$

$$(\lambda_k^+): f_k \leq F_k, k \in K$$

- Idea: do not source reserves from distribution networks

Aggressive design

$$(\psi_k): f_k = \sum_{n \in N} PTDF_{kn} \cdot ne_n, k \in K$$

$$(\psi r_n): nr_n = \sum_{m \in N:(n,m) \in E} fr_{(n,m)} - \sum_{m \in N:(m,n) \in E} fr_{(m,n)}, n \in N$$

$$(\lambda_k^+): f_k \cancel{+ fr_k} \leq F_k, k \in K$$

- Idea: ignore impact of reserve provision on network

Status quo

$$(\psi_k): f_k = \sum_{n \in N} PTDF_{kn} \cdot ne_n, k \in K$$

$$(\psi r_n): nr_n = \sum_{m \in N:(n,m) \in E} fr_{(n,m)} - \sum_{m \in N:(m,n) \in E} fr_{(m,n)}, n \in N$$

$$\cancel{(\lambda_k^+): f_k + fr_k \leq F_k, k \in K}$$

- Idea: ignore network altogether