Artificial Intelligence and the Electricity System: Opportunities and Pitfalls in the Energy Transition

2024 POWERWEB INSTITUTE ANNUAL CONFERENCE

Prof. dr. J.K. (Koen) Kok

Department of Electrical Engineering, Eindhoven University of Technology, The Netherlands

EINDHOVEN UNIVERSITY OF TECHNOLOGY

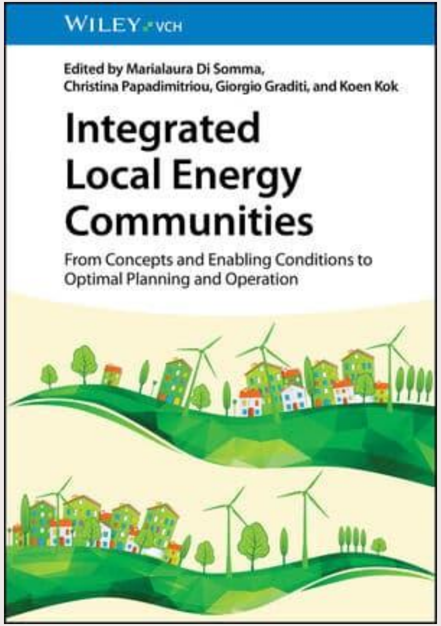
Koen Kok, Full Professor Intelligent Energy Systems

Email:
j.k.kok@tue.nl

EDUCATION

- BSc in Electrical Engineering
- BSc in Technical Informatics
- MSc in Computer Science
- PhD in Computer Science

Notable Publications



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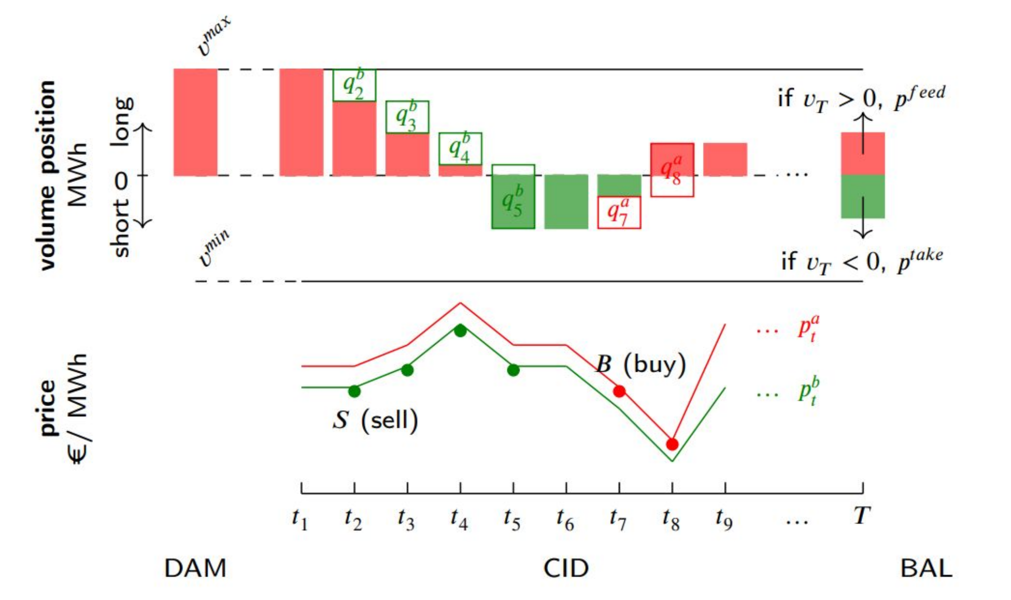
AI for Power Systems

Some Examples

Statistical Arbitrage Trading Agents

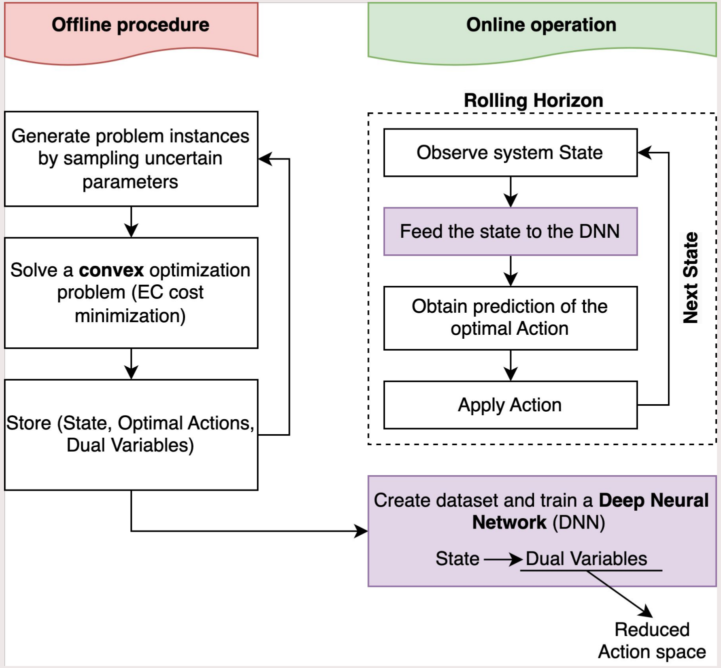
- Reinforcement Learning Agents
- Model chain with Price Forecasting Models feeding the Agent
- Data Augmentation
- Technical Indicators



[Demir 2022], [Demir 2021], [Demir 2020a], [Stappers 2020]
[Demir, S. (2023). Statistical Arbitrage Trading on Electricity Markets Using Deep Reinforcement Learning. Phd Thesis, TU/e]

Combining optimization and machine learning to manage distributed flexibility

- Energy management of an Energy Community (EC) under uncertainty
- The EC manager has access to historical data (e.g., prices), but can only infer an interval of the parameters that are **private** to agents (end-users)
- The problem can be modeled as a Markov Decision Process (MDP)
- Challenges with standard MDP-solving frameworks: 1) constraint satisfaction, 2) tractability
- Combine ideas from surrogate modeling, duality theory, online optimization, and neural networks



[1] G. Tsaousoglou, K. Mitropoulou, K. Steriotis, N.G. Paterakis, P. Pinson, E. Varvarigos, "Managing distributed flexibility under uncertainty by combining deep learning with duality", *IEEE Trans. Sustainable Energy*, 2021.
[2] G. Tsaousoglou, I. Sartzetakis, P. Makris, N. Efthymiopoulos, E. Varvarigos, N.G. Paterakis, "Flexibility aggregation of temporally coupled resources in real-time balancing markets using machine learning", *IEEE Trans. Industrial Informatics*, 2022.

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MEGAMIND

Measuring, Gathering, Mining and Integrating Data for Self-management in the Edge of the Electricity System

“MEGAMIND aims to develop a **techno-regulatory transition pathway** for the electricity ecosystem on the level of the distribution grid.”
https://megamind.energy/

TU/e Eindhoven University of Technology · Erasmus University Rotterdam · Tilburg University · TU Delft · TNO · University of Twente · Enexis Netbeheer · Equans · IBM · Liander · Smart State Technology · Stedin · TenneT · Transdev · PwC

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NWO TTW Perspective Program

- Innovation with economic and social impact
- Large-scale approach
- Development of new technology
- Close collaboration between scientists and industry.

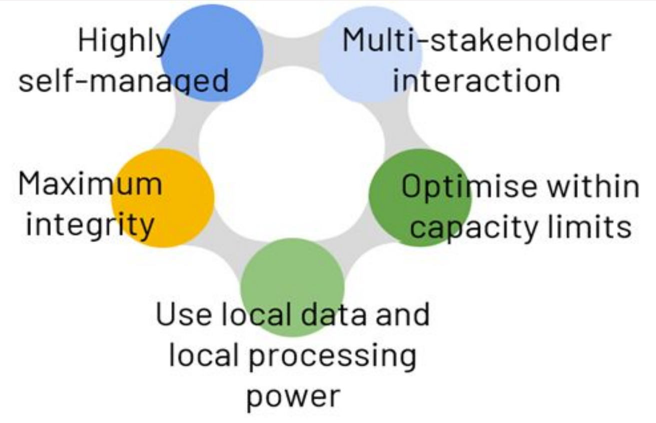
MegaMind:

- 8 PhDs & 2 PostDocs
- 9 Partners from the sector
- 6 Knowledge Institutes

MegaMind Research Program

MEGAMIND aims to develop a techno-regulatory transition pathway for the electricity ecosystem on the level of the distribution grid.

We envision a highly self-managed system that automatically and dynamically steers electrical energy flows considering the technical boundaries of the network and while the energy transition unfolds.



Digitization Waves in Regional Electricity Systems

New Operational Paradigms (Future)

Localized Energy Markets
Massive Electricity Storage
Power Electronic Transformers

- Energy Routing
- Internet of Energy

Second Digitalization Wave (Now):

Increased Self-organization:

- Energy Hubs, Energy Communities
- Congestion Management

Big Data, AI & Digital Twins

First Digitalization Wave (2000-2015):

Smart Metering
Substation Automation (IEC61850 Standards)
Smart Grid Pilots

AI and the Electricity Sector

- AI allows to process large amounts of data and make better predictions, forecasts and optimization in at least 3 key areas:

  - **Management and operation of infrastructure**
    - Forecast production and consumption
    - Monitor system health or predict network state
    - Decision-support systems for voltage control

  - **Optimization in the electricity market**
    - Predict electricity production and consumption to estimate capacity.
    - Automate parts of the bidding process.
    - Optimize bidding strategies
    - Determine market prices on the intraday electricity market

  - **Consumer/prosumer products and services to improve energy use (e.g., HEMS)**

https://publications.jrc.ec.europa.eu/repository/handle/JRC129319

Twin Transitions in the EU: **Digital and Green**

Noorman; Espinosa Apráez; Lavrijssen, AI and Energy Justice. Energies 2023, 16, 2110. https://doi.org/10.3390/en16052110

MegaMind

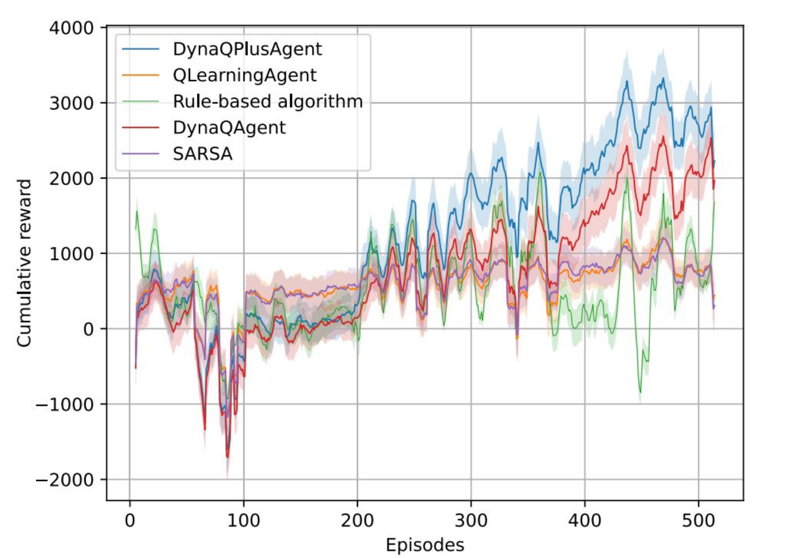
Some Results

Coping with Concept Drift

EV Charging Optimization in a Changing Environment

Concept Drift:

- The underlying characteristic of a modeled phenomena changes over time, decreasing model accuracy.

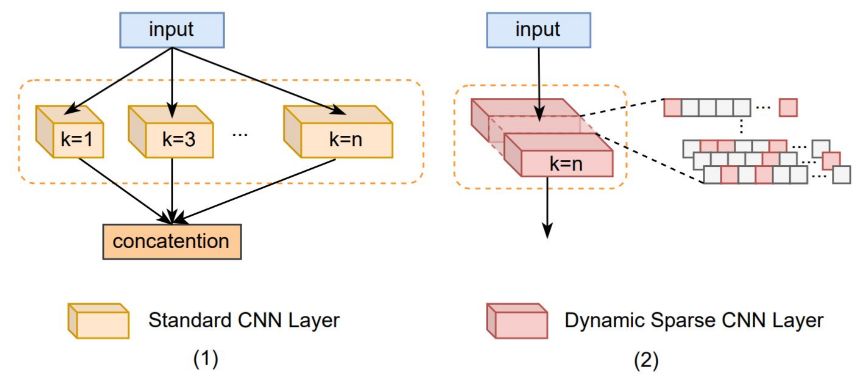


Poddubnyy, A., Nguyen, P. H., & Slootweg, J. G. (2023). Online EV charging controlled by reinforcement learning with experience replay. Sustainable Energy, Grids and Networks, 36, Article 101162.

Dynamic Sparse Neural Networks

Developed for Time Series Classification

- Decreasing computational complexity of time series classification
- Application to State Estimation under development



Q. Xiao, *et.al., “*Dynamic Sparse Network for Time Series Classification: Learning What to “See””, *NeurIPS 2022*

TSO-DSO Coordination for flexibility utilization

Flexibility from providers in distribution networks (DN) can help:

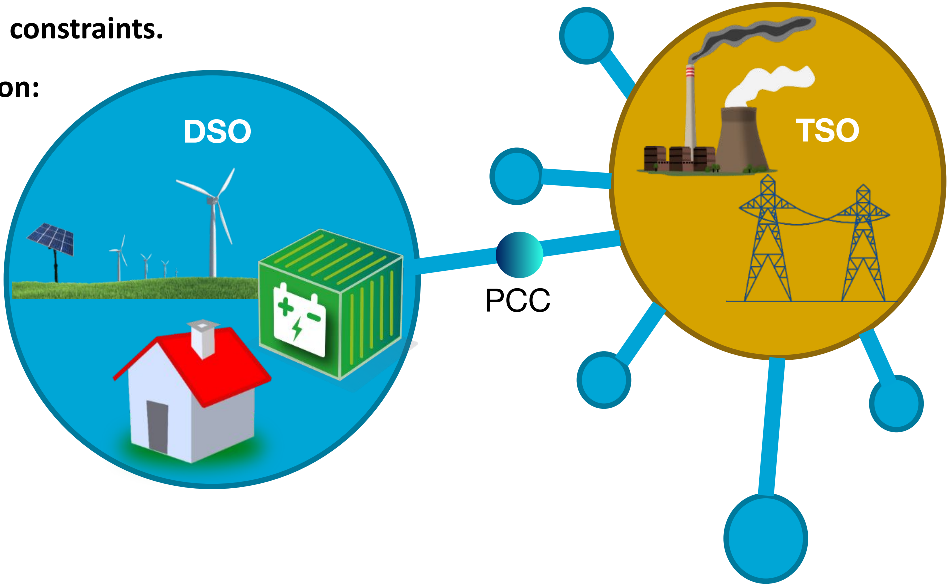
- Congestion
- Balancing

TSOs need to anticipate the available flexibility to use it in their operation

DSOs need to ensure that said flexibility respects DN constraints.

 DSO-managed approach for TSO-DSO coordination:

- Using Flexibility Areas (FAs)
- Respecting confidentiality of information



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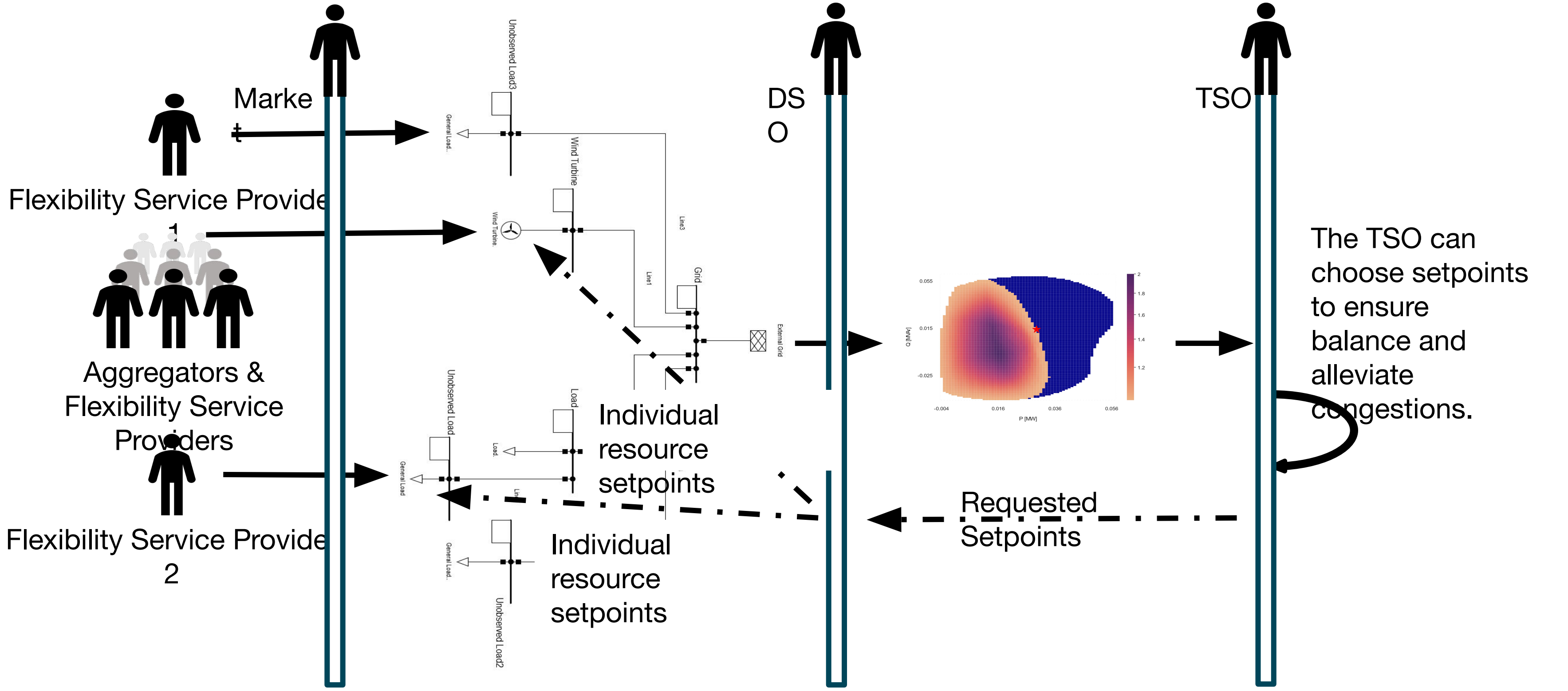
Flexibility Areas in the TSO-DSO Coordination



1: Flexibility offers and their location

2: Estimating Aggregated Flexibility Area at the PCC

3: Choosing Setpoint

D. Chrysostomou, J. L. R. Torres and J. L. Cremer, "Tensor Convolution-Based Aggregated Flexibility Estimation in Active Distribution Systems," in *IEEE Transactions on Smart Grid, 2024*.

Possible harms/risks of AI in the Electricity Sector

- **Management and operation of infrastructure**
  - Safety
  - (Un)fairness
  - Unclear distribution of responsibility/accountability
  - Privacy/data protection concerns (e.g., smart meter or device data?)

- **Optimization of electricity market**
  - Price issues (surges, collusion, lack of price transparency)
  - Congestion
  - Unclear responsibilities to resolve deviations
  - Cybersecurity risks

- **Consumer/prosumer products and services to improve energy use (e.g., HEMS)**
  - Privacy/data protection concerns
  - Nudging – what about autonomy?
  - Lack of price transparency
  - Inequal access to technology

Tilburg Institute for Law, Technology, and Society

The AI Act

- Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 – Published in the OJ on 12 July 2024.
- Entered into force on 1 August 2024
- Fully applicable as of 2 August 2026, with some exceptions.

- **Objectives (Art. 1 and Recital 1):**
  - Improving the functioning of the internal market by introducing harmonized rules for the placing on the market, putting into service and the use of AI systems
  - promoting the uptake of human centric and trustworthy artificial intelligence while ensuring a high level of protection of protection against harmful effects of artificial intelligence systems
  - Supporting innovation.

Tilburg Institute for Law, Technology, and Society

FINDINGS

- The AI Act follows an **"all or nothing" approach** that is predominantly focused on safety and fundamental rights concerns □ it does not capture other important concerns from the electricity sector (e.g., fairness, equitable access, well functioning market, security of supply, consumer protection) □ **potential to guide responsible AI in the sector is limited.**
- The AI Act doesn't say much about non-high risk AI systems □ but incentivizes voluntary application (e.g., codes of conduct or following the Ethics Guidelines of the AI HLEG).
- Lack of clear sustainability requirements for AI systems □ particularly important for the electricity sector in the context of the Green & Digital transitions.
- **Yet, the responsible development of AI in the electricity sector is not completely unregulated** □ e.g., GDPR, cybersecurity laws, electricity market laws, etc. □ Further research is required to map the most pressing gaps.

GO-e Project

Solving Congestion with Distributed Decision Making

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Beyond the technical potential of flexibility

A large-scale comparison study of congestion management instruments in the built environment

Koen Kok, Gijs Verhoeven, Bart van der Holst

Electricity Grids in the Centre of Attention

FINANCIAL TIMES

SEPTEMBER 4 2023

Renewable energy

There is no green future for Europe without an upgraded power grid

Electrifying the EU economy must be made easier, cheaper and quicker

Save

Business

The grid's big looming problem: Getting power to where it's needed

Biden's infrastructure plan, if it gets final approval, has its work cut out for it

NOS NEWS • REGIONAL NEWS † 16-09-2021, 13:51

Electricity grid full in Amsterdam and other parts of North Holland in the coming years

NOS NEWS • ECONOMY † 17-09-2021, 17:24

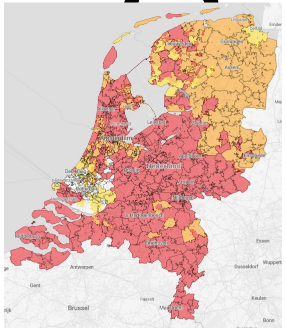
Concerns about a full electricity grid: grid operator and employers want action

nieuwsuur

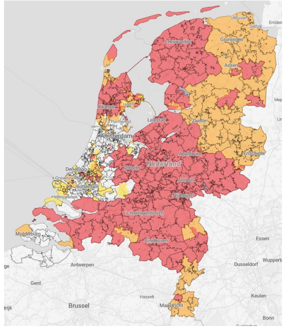
NEWS HOUR • DOMESTIC • ECONOMY † 02-09-2021, 20:39

'The Dutch power grid threatens to get stuck'

Consumption



Generation



September 2024

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Electrification of Residential Areas

Can the DSO Keep up?

- Fuel-switch in NL Household Heating (Natural Gas E)
- Individual house owners as well as Housing Corps.
- Developments outside DSO visibility
  - No notification obligation
  - Also, the DSO has no legal way to prevent or steer developments
- Some older MV-LV Transformers:
  - protection against short-circuits, not against overloading

Can flexibility help resolve these problems?

- How effectively grid operators can activate flexibility in the built environment using different instruments?
- What factors play a role in these instruments?

Instruments

Simulation Approach

Findings

Outlook

Instruments

Simulation Approach

Findings

Outlook

Instruments to activate flexibility

- DSOs can activate flexibility using different types of instruments
- Three main types based on the EU Clean Energy Package:

1. **Tariff Instruments**
2. **Market-based Instruments**
3. **Non-market-based Instruments**

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Options researched based on consultation with DSOs:

1. **Tariff Instruments**
   - Bandwidth tariff
   - Weighted peak tariff
   - Seasonal Time of Use tariff
2. **Market-based Instruments**
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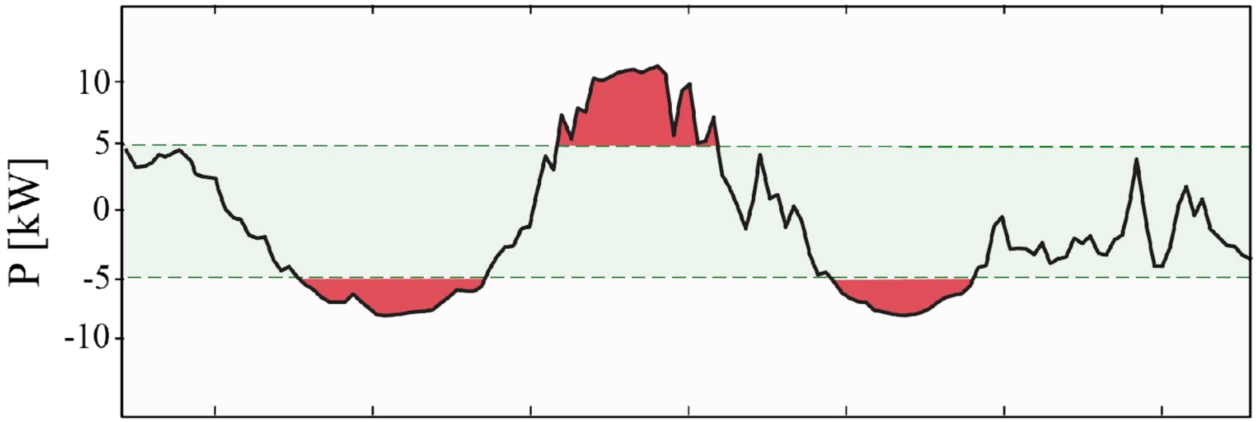
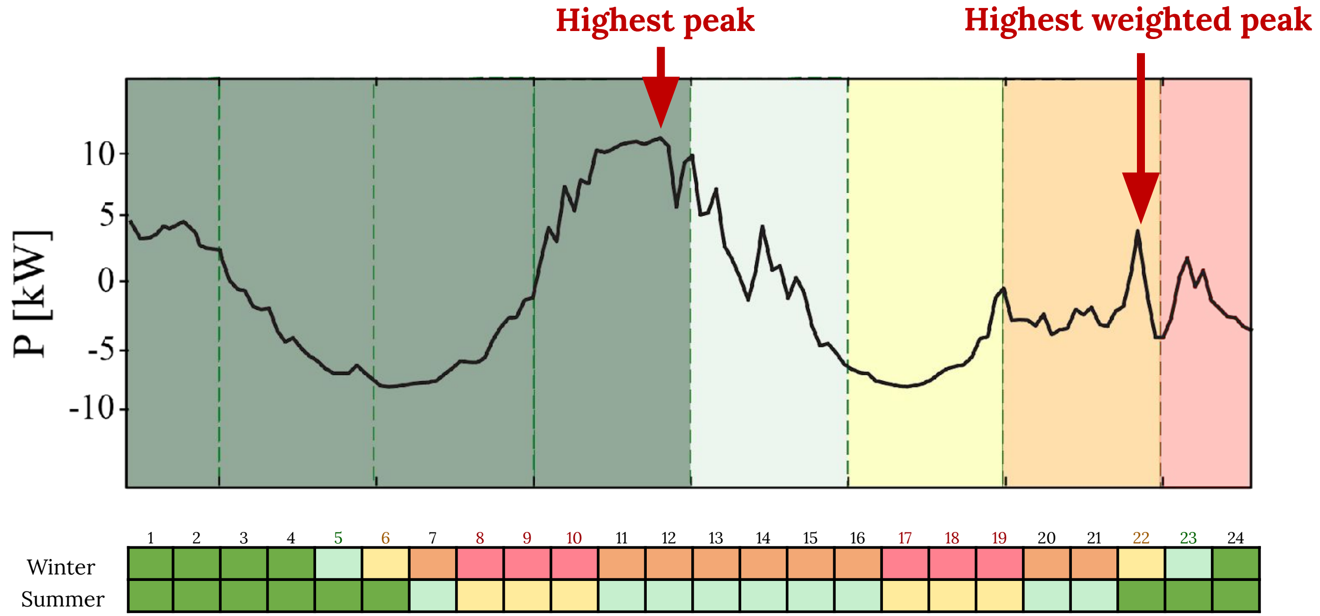
Bandwidth tariff

- Free to use bandwidth for normal/current network tariff
- Additional costs for kWh exceeding bandwidth



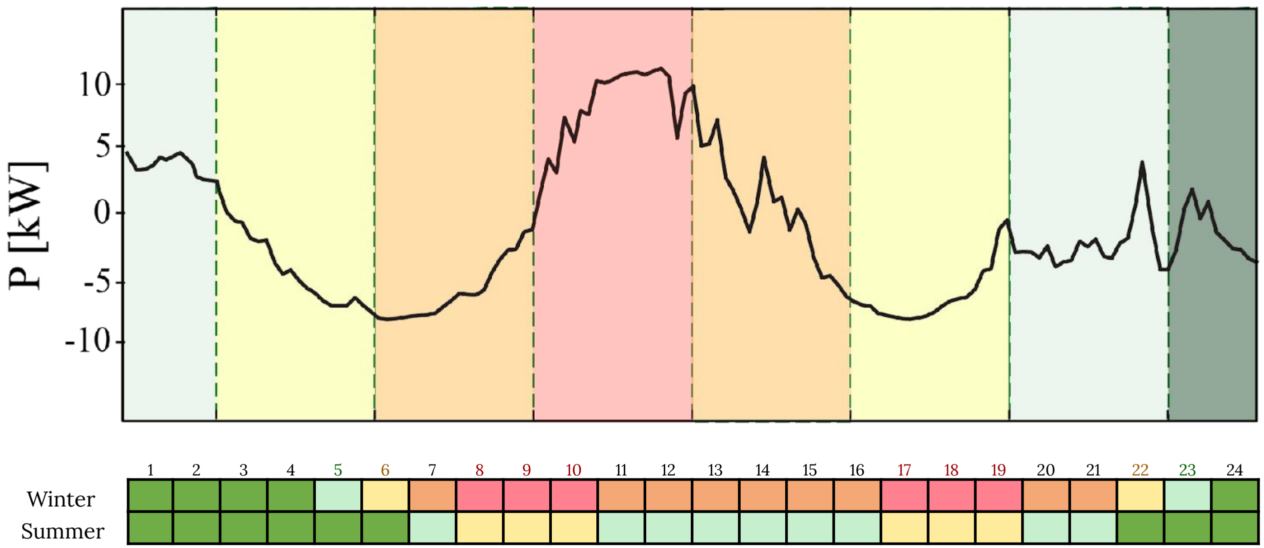
Weighted Peak Tariff

- Fixed cost per kW for highest peak in period
- Peak is weighted with weightfactor depending on zone



Seasonal Time of Use tariff

- Per season/hour kWh-price depending on zone
- Costs for average grid usage similar to costs current network tariff



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   - Capacity Restriction Contracts
   - Redispatch Contracts
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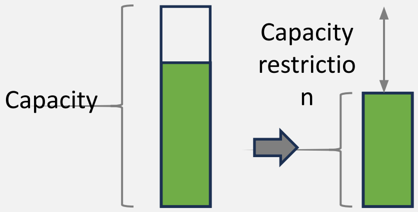
Market-based instruments

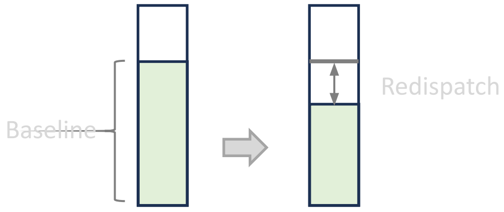
Capacity Restriction Contract

- Contract with CSP
- DSO activates at 8:30 D-1
- Capacity of the connections is restricted to 4kW max
- A fixed compensation per kW



Redispatch Contract

- Contract with CSP
- DSO activates at 20:00 D-1
- The CSP offers the required energy in GOPACS
- For the DA-prices +/- a bonus/discount



CRC activation

00:00 **08:30** D-1 00:00 D 00:00

Market-based instruments

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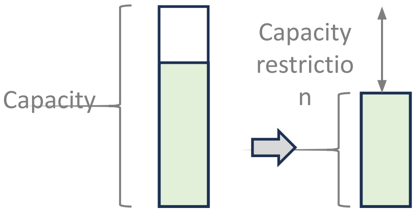

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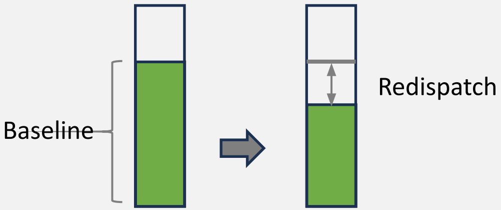

CSP sends prognosis to DSO

Market-based instruments

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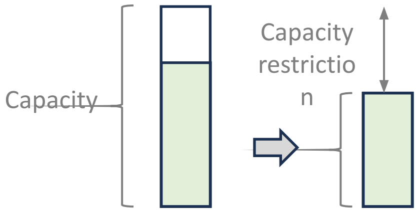

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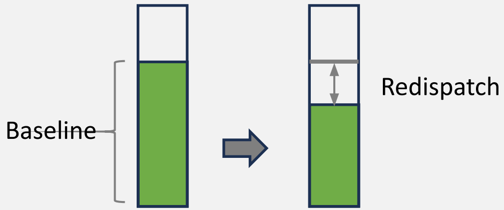

CSP sends bids to GOPACS and DSO pays the spread

00:00 **20:00** 00:00 D 00:00

Market-based instruments

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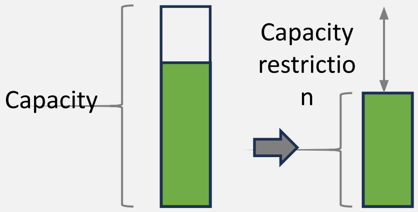

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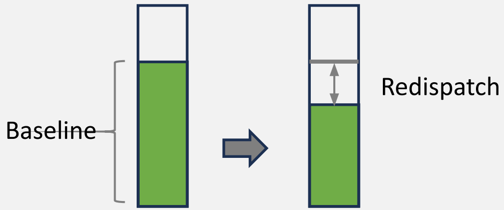
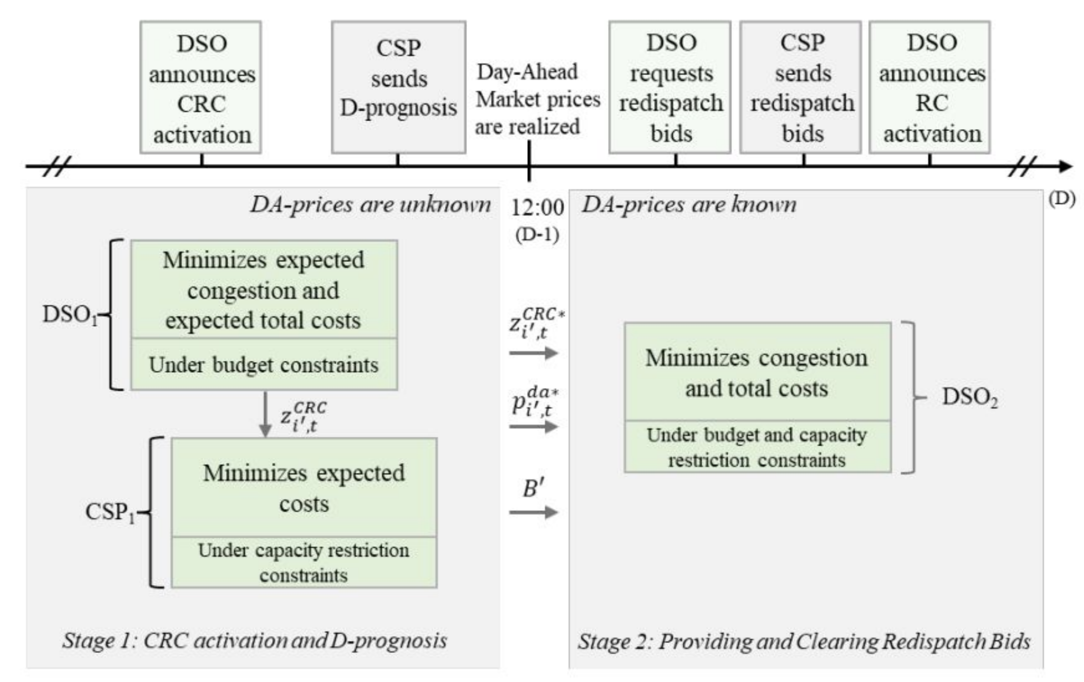


Contracts and Model



Bart van der Holst, Gijs Verhoeven, Phuong H. Nguyen, Johan Morren, Koen Kok, The activation of congestion service contracts for budget-constrained congestion management, Electric Power Systems Research, Volume 235, 2024.

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1 Tariff Instruments

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2 Market-based Instruments

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- (Temporary) Transport limitations

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2	**Market-based Instruments**	- Capacity Restriction Contracts - Redispatch Contracts
3	**Non-market-based Instruments**	- (Temporary) Transport limitations

Instruments

Simulation Approach

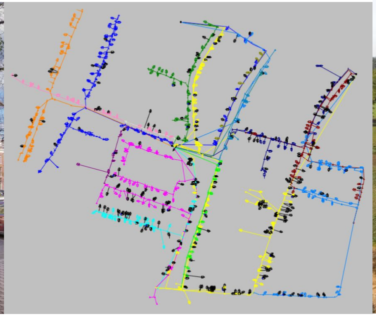
Findings

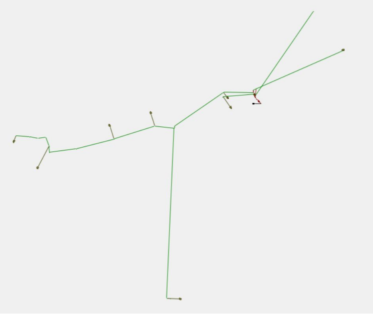
Outlook

Simulation ingredients

- Neighborhoods:
  - Not all neighborhoods and networks will provide the same flexibility opportunities

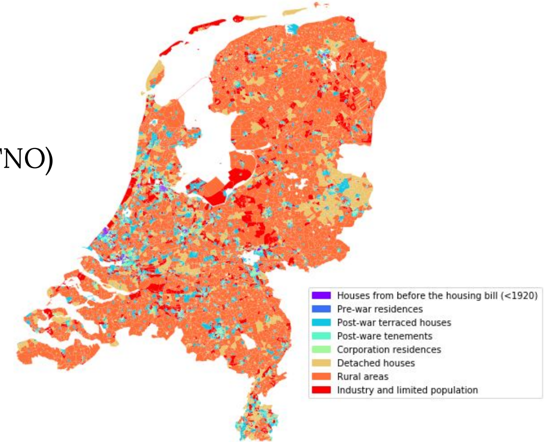
Historic city center **vs** **Rural area**



Simulation ingredients

- Neighborhoods:
  - We use 10 low voltage networks selected by DSOs
  - From 7 different "archetypical" neighborhoods (identified by TNO)
    - Post-war terraced houses
    - Detached houses
    - Rural areas
    - Etc.



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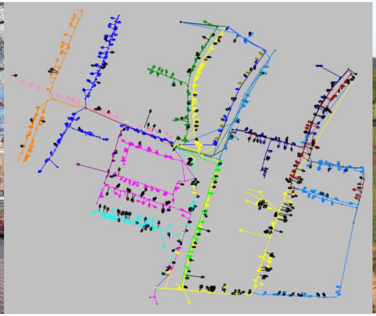
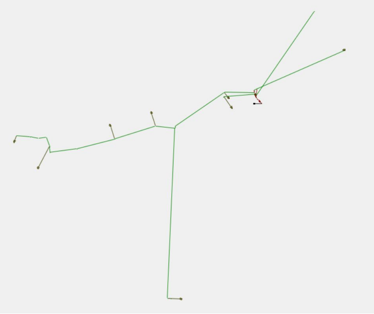
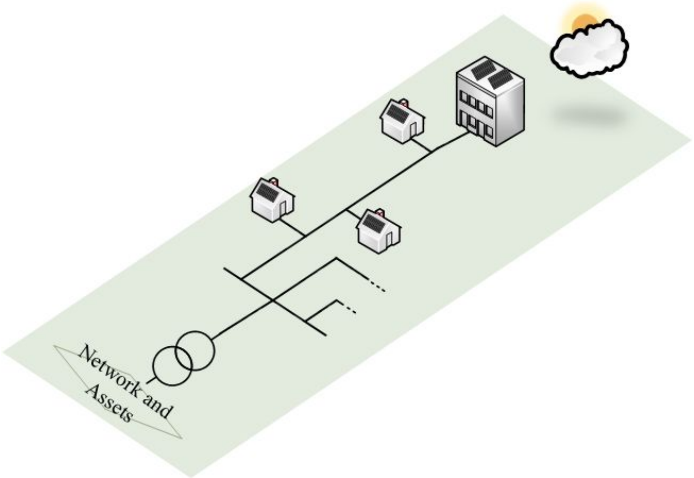




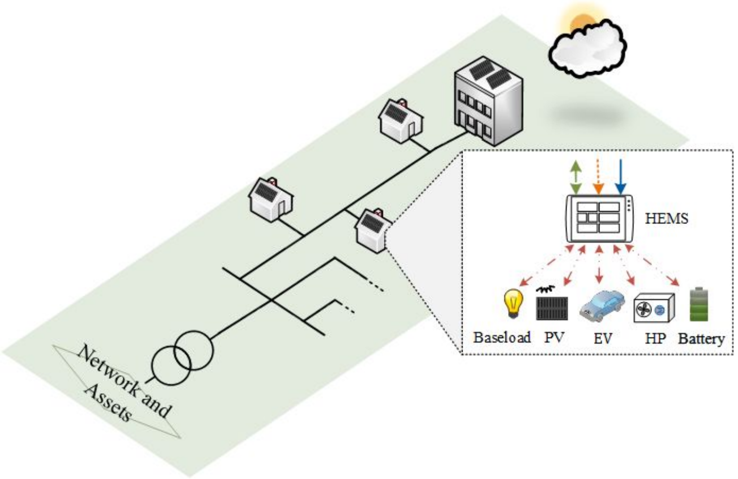
Simulation ingredients

- Neighborhoods:
  - LV network
  - Houses



Simulation ingredients

- Neighborhoods:
  - LV network
  - Houses with/without HEMS
  - Assets:
    - Baseload
    - PV on roofs
    - Electric Vehicles
    - (hybrid-) heat pumps
    - Home batteries



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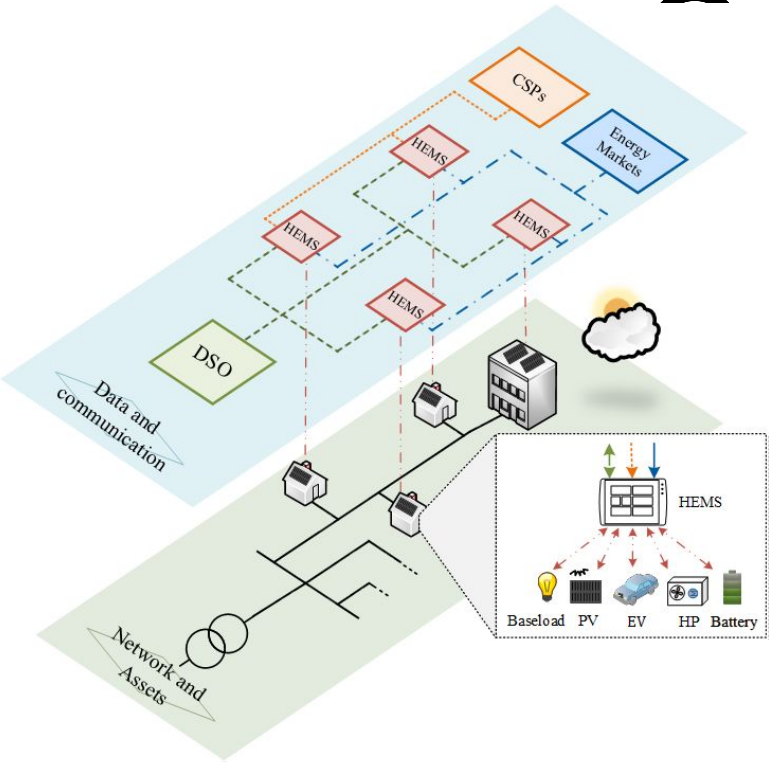
    - Home batteries
  - DSO
  - Aggregators/CSPs
  - Electricity markets
    - Day-Ahead, GOPACS and imbalance



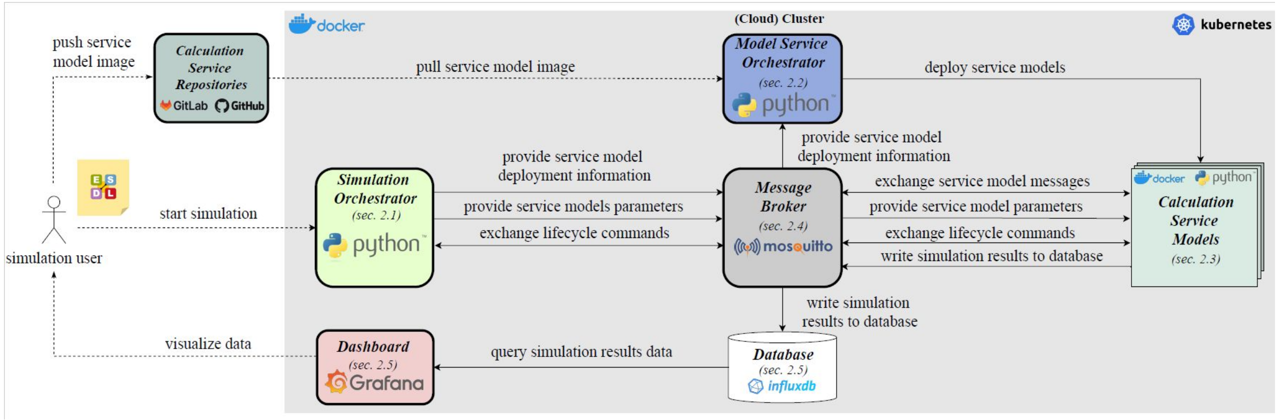
Scenarios

- Growth and distribution of flexible assets for 2030 according to DSOs
- Market prices from 2023
- 3 winter days and 3 summer days
- Including the existing netting scheme
- Aggregators can or cannot do passive balancing
- Variable degrees of controllability and dynamic energy contracts

Business as Usual 2030	Realistic 2030: Moderate controllability	Extreme 2030: Extreme controllability
• 0% of houses have a HEMS • 0% houses have a dynamical contract	• 50 % houses a HEMS • 25 % houses dynamical contract	• 100 % houses a HEMS • 100 % houses dynamical contract

New Platform: DOTS Energy

- Open-source Simulation Platform developed together with TNO
- Large-scale simulations energy systems
- Distributed agent-based



https://github.com/dots-energy/calculation-service-generator

B. van der Holst, G. Verhoeven, E. Matthijssen, M. Vrijlandt, R. Plug, A. van der Meer, and K. Kok, "A dynamic bandwidth tariff assessment in a Dutch distribution network using a novel scalable distributed simulation," The 27th International Conference and Exhibition on Electricity Distribution (CIRED), 2023.

Instruments

Simulation Approach

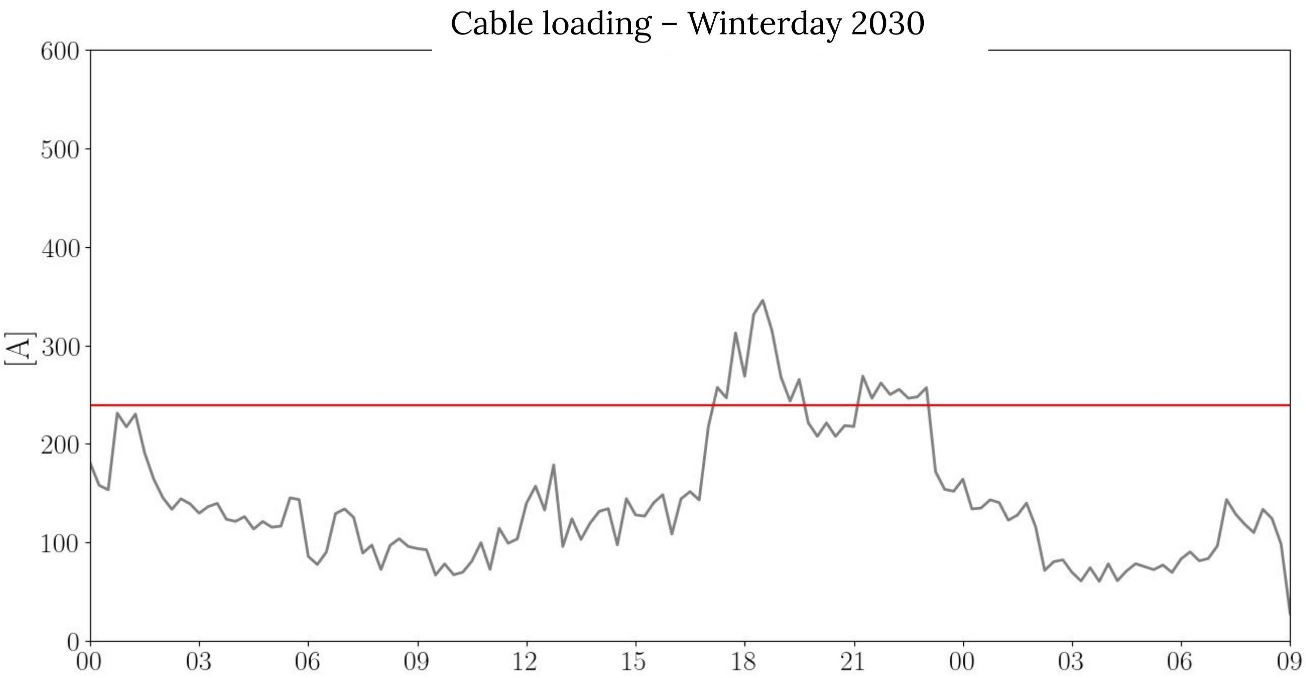
Findings

Outlook

The growth of controllability and dynamic electricity contracts can reduce peak loads, but with high adoption this will make congestion worse

Congestion problems

- **Business as Usual** – No controllability, no dynamic electricity contracts



Congestion problems

- **Business as Usual** – No controllability, no dynamic electricity contracts
- **Realistic** – 50% connections controllable, 25 % connections dynamic electricity contracts

Cable loading – Winterday 2030

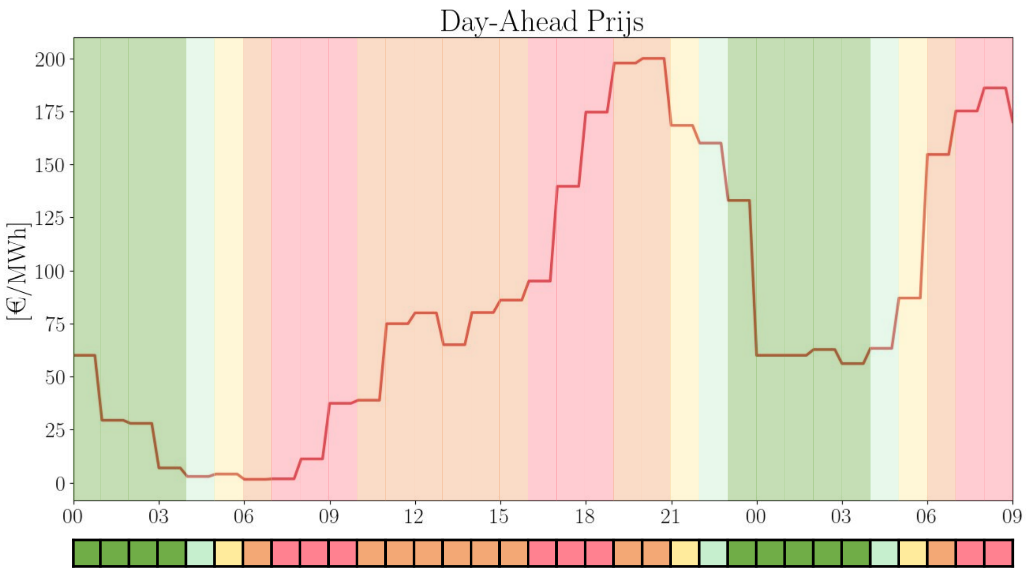
Congestion problems

- **Business as Usual** – No controllability, no dynamic electricity contracts
- **Realistic** – 50% connections controllable, 25 % connections dynamic electricity contracts
- **Extreme** – 100% connections controllable, 100 % connections dynamic electricity contracts

Cable loading – Winterday 2030

The robustness of tariff instruments against synchronization with market prices is essential for their impact on congestion problems

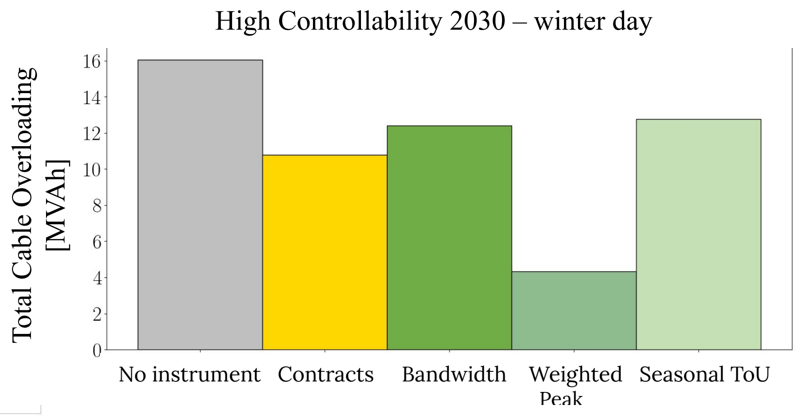
The influence of market prices

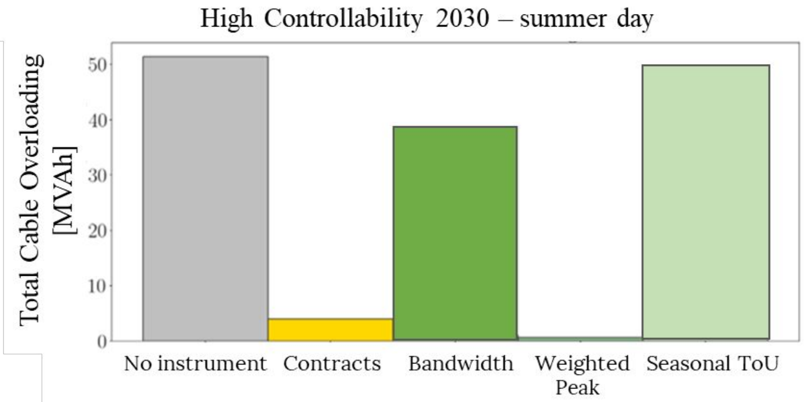


- Coincidence of low market prices and grid tariffs can lead to synchronization
- Limited effectiveness of tariff instrument without robustness towards to energy markets

Adopting both grid tariffs and contracts can reduce rebound and synchronization effects

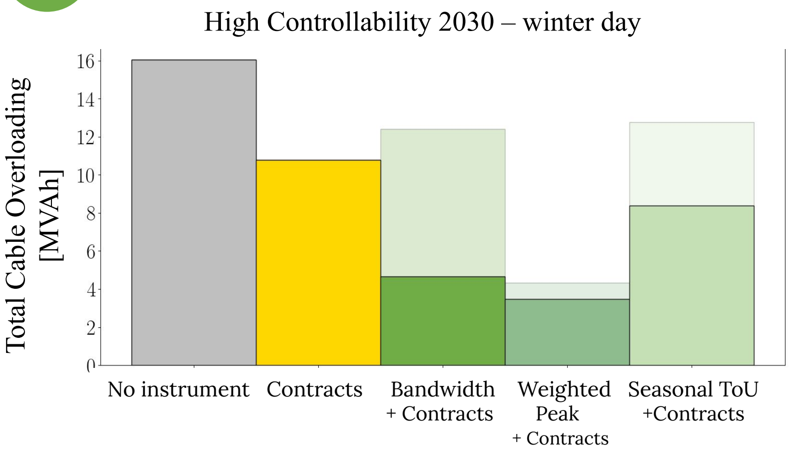
Combining Tariffs and Contracts

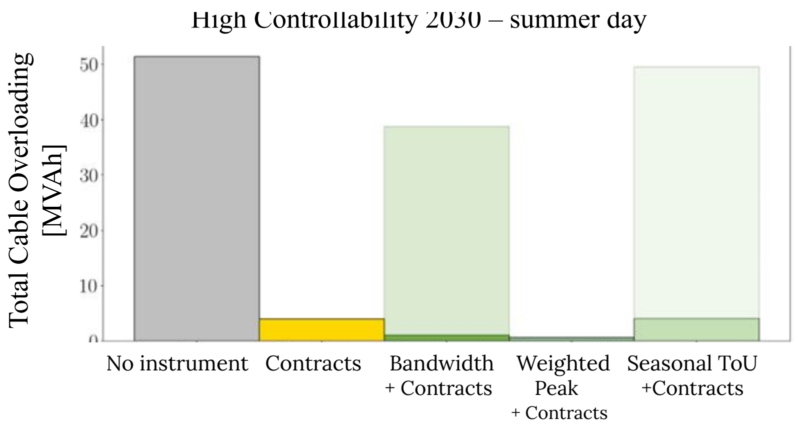




- Congestion not always resolved
- Weighted peak tariff most effective tariff
- Contracts can cause rebounds at time steps where no congestion was expected
- (redispatch) contracts are very effective in summer

Combining Tariffs and Contracts





- Congestion not always resolved
- Weighted peak tariff most effective tariff
- Contracts can cause rebounds at time steps where no congestion was expected
- (redispatch) contracts are very effective in summer
- Combining tariffs and contracts reduces the overloading

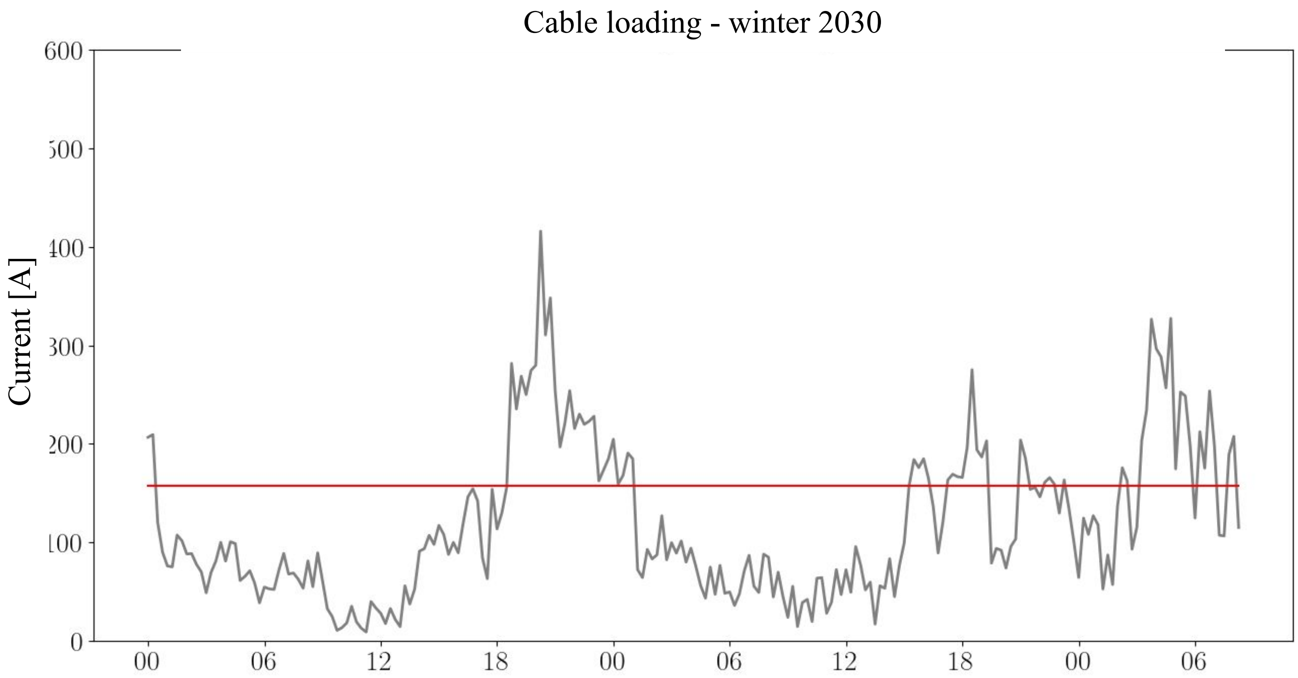
GO e

Congestion characteristics will change significantly if aggregators start doing passive grid balancing

Then, a new instrument/mechanism would be required

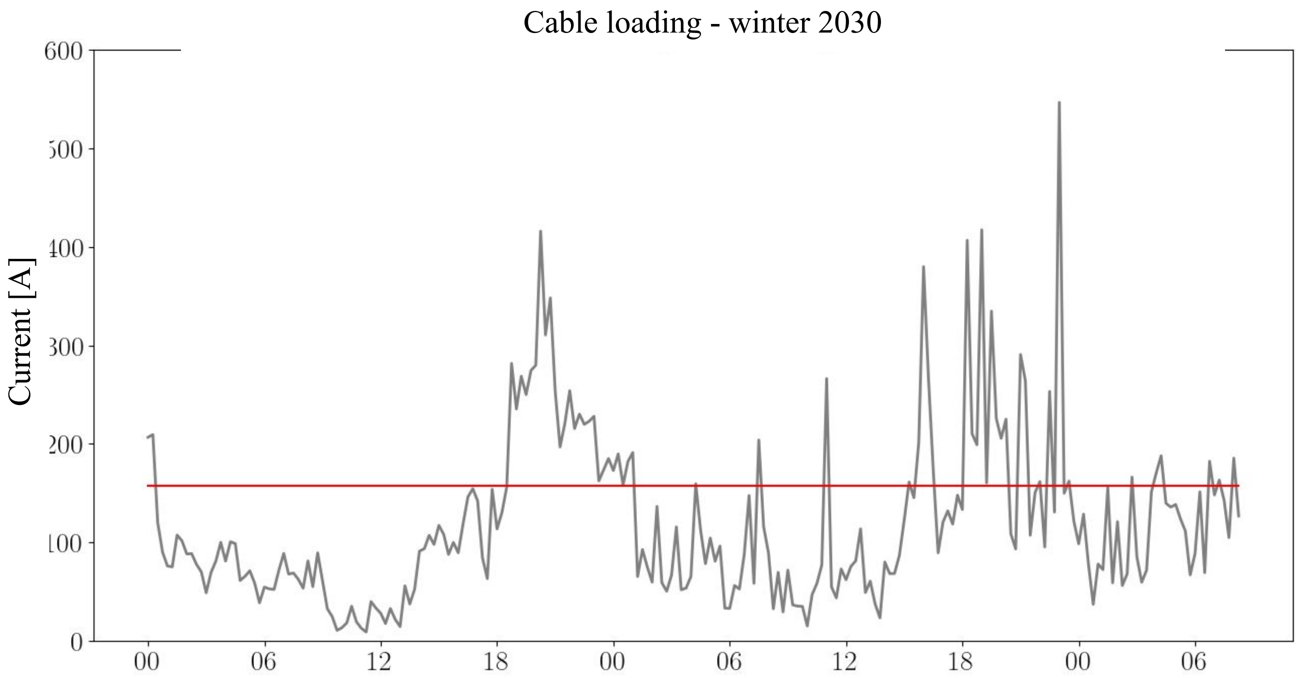
Passive balancing

- No reacting to imbalance prices – no contracts



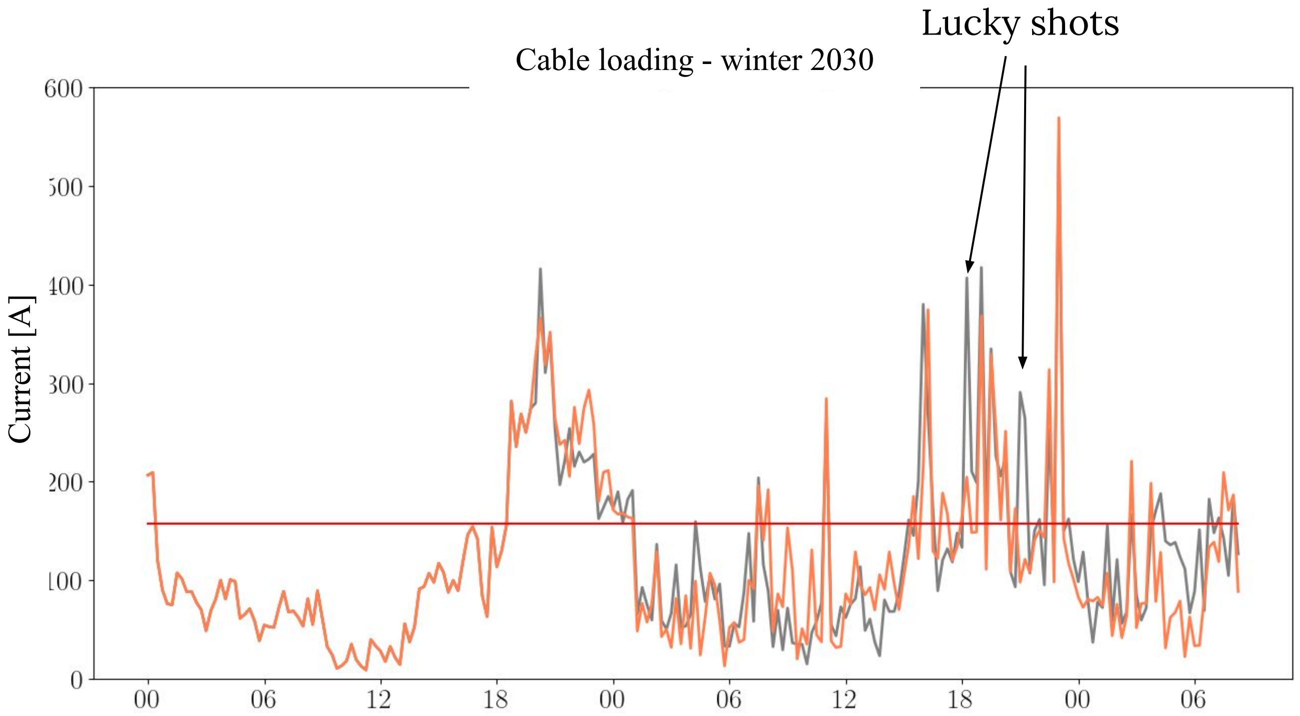
Passive balancing

- **Reacting to imbalance prices – no contracts**



Passive balancing

- Reacting to imbalance prices – no contracts
- Reacting to imbalance prices - with contracts



Simulation Study Outcomes

- Three tarif instruments have been tested, plus two contract instruments
- All instruments relieve congestion under circumstances.
- Combinations of one tariff and one contract instrument work best.
- If a larger group of connected customers (households in the study) start reacting to real-time commodity prices the positive effect on congestion disappear.

- → Academia – Industry Knowledge Gap

- English version of the report is in preparation (Journal paper)
- Interview on the topic (English): https://www.tue.nl/en/news-and-events/news-overview/09-07-2024-smarter-incentives-prevent-grid-congestion.
- Report (Dutch): Downloadable through the link above and project website.

Instruments

Simulation Approach

Findings

Outlook

Some trends…

- Electricity use is increasing and synchronizing further
- Electricity is increasingly traded close to the real time
- Flexibility need for the short-term is increasing
- Flexibility is increasingly sourced from the distribution networks

Will congestion be part of the solution?

- Congestion management vrs increasing network utilization
- Congestion management instruments should (dynamically) take the value of flexibility on the commodity markets into account
- Fusion of Market operations and Systems operations needed in the long run
  - Network-aware commodity markets
  - Use network constraints as constraints to the commodity market outcomes
- Be aware of mechanism lock-ins
  - Current innovation wave is problem-oriented
  - Do we keep transition pathways to the ideal 2035-2050 system open?

A new coordination mechanism is needed for the electricity system

- In the Grid Edge, Distributed AI fits the challenge
- How to ensure Transparency, Fairness, Privacy, etc.?
- How to bridge the Knowledge Gap?

Closing Remarks: What do we learn?

- The Energy Transition needs interdisciplinary development
- Developing techno-regulatory transition paths is of key importance
  - Piecemeal innovation steps will lead to a sub-optimal end-solution
  - Technology and Regulation need to be developed in interaction.
- Distributed Artificial Intelligence is a Key Enabling Technology

Thank you for your attention,…

…and keep hugging pilons!

Liander
TenneT
agro energy
eco
Technolution
itho daalderop
STEDIN.NET
Netbeheer Nederland
Eneco
GreenChoice
ETPA Energy Trading Platform
Smart State Technology
IBM
Enexis Netbeheer
Gasunie
Equans Empowering Transitions
Tilburg University
CWI
TU Delft
TU/e
Phase to Phase
ElaadNL
University of Twente.
Topsector Energie Innovatie voor een duurzame toekomst
DNV
pwc
Tata Steel
TNO
netherlands eScience center
NEN
NWO
Witteveen + Bos
connexxion wij zijn transdev

Just to name a few…