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Centre for intelligent electricity distribution
- to empower the future Smart Grid

Norwegian Centre for Environment-friendly Energy Research

Designing grid tariffs and local electricity markets for peak demand reduction in distribution grids

CINELDI-webinar, November 30th, 2022

Sigurd Bjarghov

Welcome to my PhD defence!

- @Elbygget, Gløshaugen
- December 15th
- Zoom link will be available

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Agenda

- Introduction & research questions
- Grid tariff design
- Local electricity market design
- Main findings
- Take-aways

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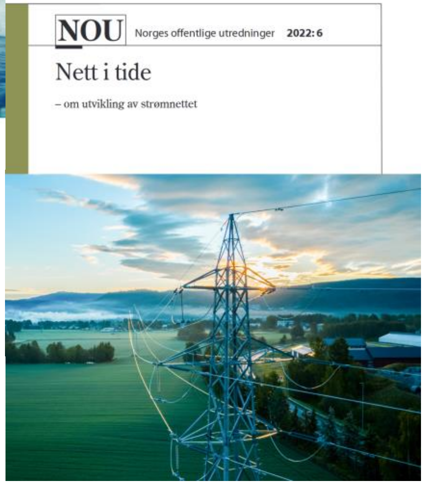
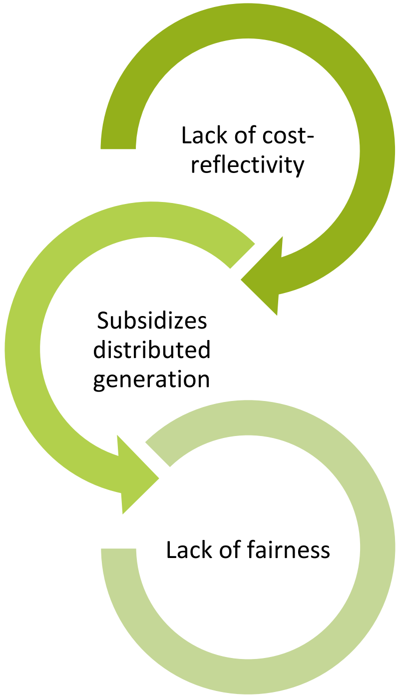
Drivers

- Need to reduce GHG emissions
- High need for more grid capacity, fast
- Higher share of distributed renewable generation



Need for a redesign of grid tariffs



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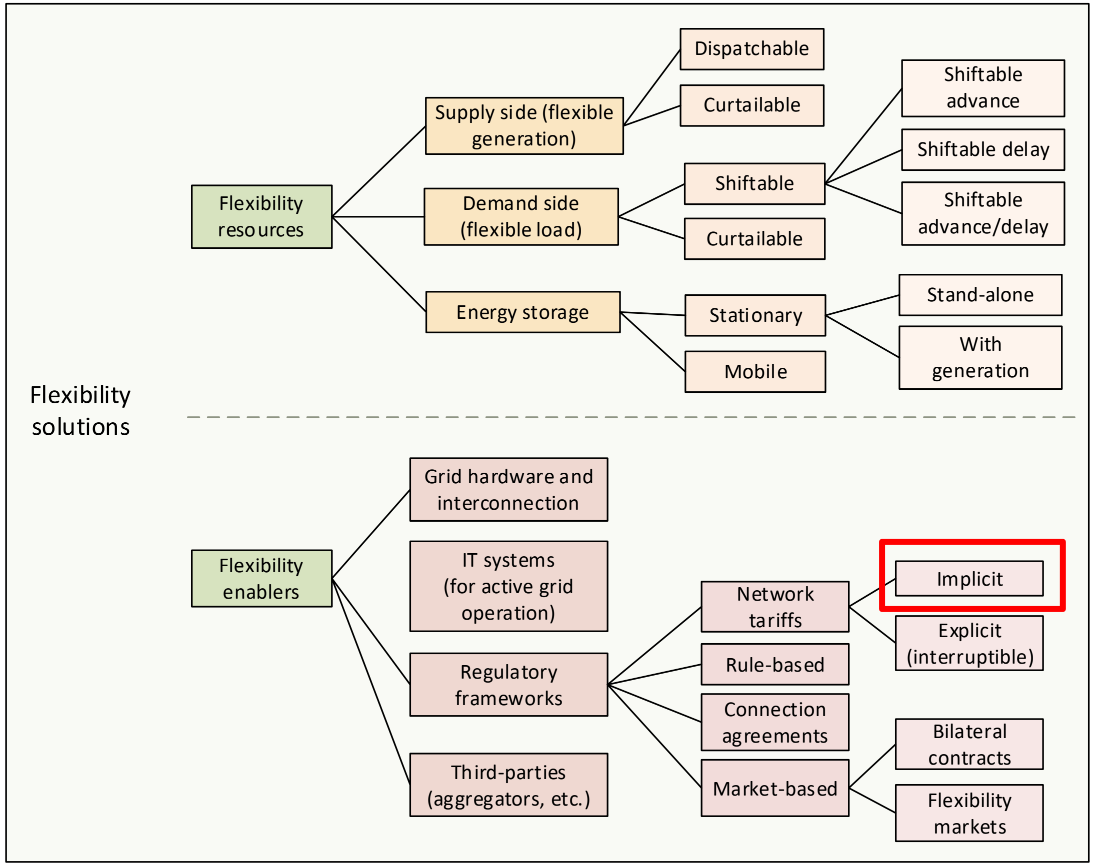
Flexibility solutions



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Annual grid tariff costs in Norway

DSO

Varsel om inntektsrammer for 2022 eksl Statnett

19,3 mrd.

Investeringer og høyere rente gir større kapitalkostnader

Økte kraftpriser gir større nettapskostnader

+

TSO

Varsel om inntektsrammer for 2022 for Statnett

9,9 mrd.

Investeringer og høyere rente gir større kapitalkostnader

Økning i nettaps- og systemansvarskostnader

Flaskehalsinntekter vil dempe tarifføkning

=

Varsel om inntektsrammer for 2022 - samlet

29,2 mrd.

Anmodet nettselskaper med merinntekt til å utbetale denne i 2022

Selskaper med mindreinntekt kan søke om dispensasjon fra å styre saldo mot null

Ingen sammenheng mellom økning i inntektsrammer og ny nettleiemodell

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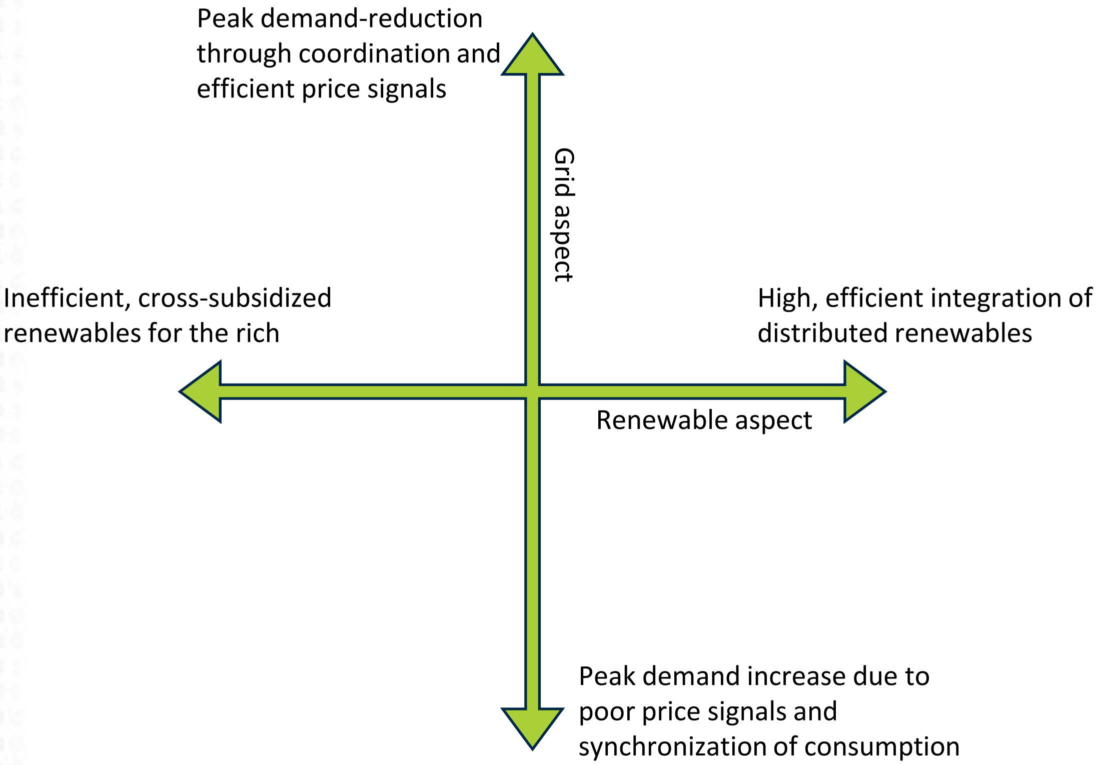
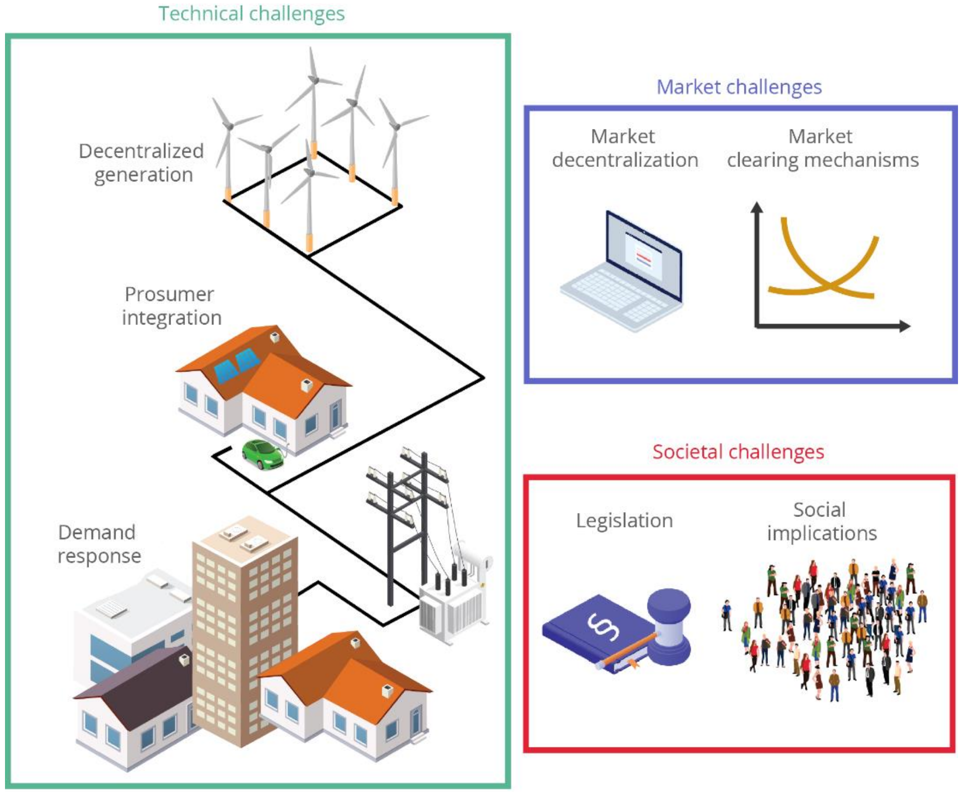
The point tariff system

- One measurement point per customer
- Costs-scheme is static, regardless of system state
- Increasing share of behind-the-meter generation
  - New market participants in the power system

Local electricity markets





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Research questions

- Research questions:

RQ1: How well do capacity-based grid tariffs and local electricity markets synergize in order to incentivize consumers to reduce peak demand?

RQ2: How well do capacity subscription tariffs perform in terms of cost reflectivity, cost recovery and fairness?

RQ3: Which grid tariffs designs are the most cost reflective and efficient at reducing peak demand at different grid levels?

RQ4: Aiming to reduce peak demand, is there a price signal conflict between electricity spot prices and grid tariffs?

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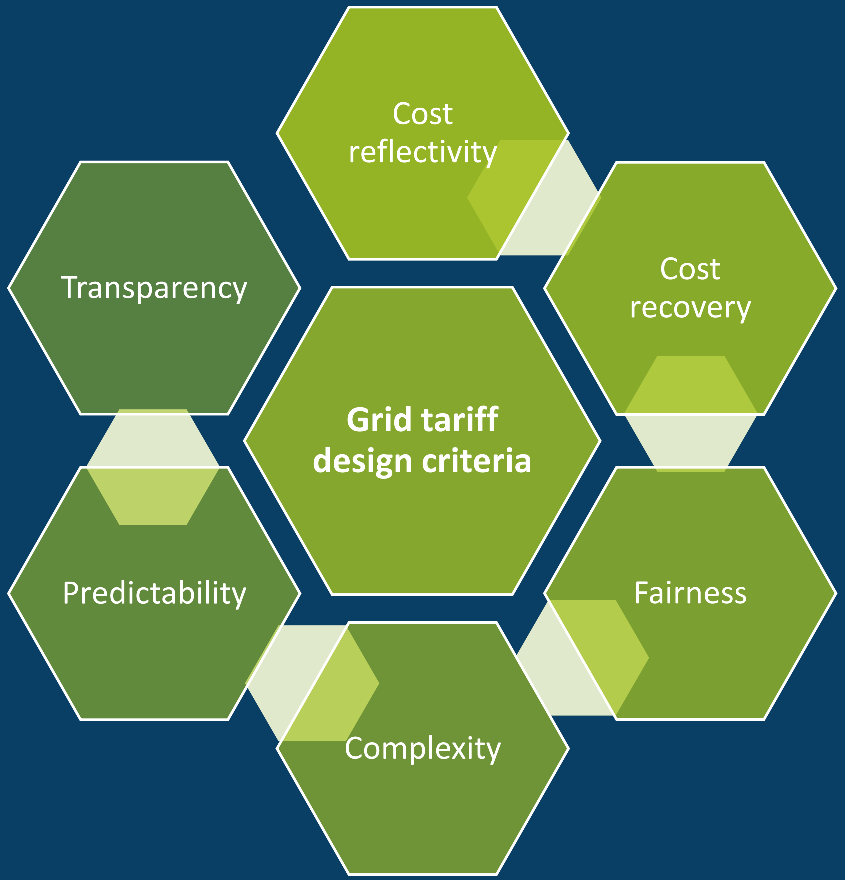
Grid tariff design criteria



Investigated eight grid tariffs

Energy-based
- Volumetric
- Time-of-use
- Critical peak pricing

Capacity-based
- Measured peak demand
- Capacity subscription
- Dynamic capacity subscription

Hybrid
- Standard, continuous version
- Norwegian version

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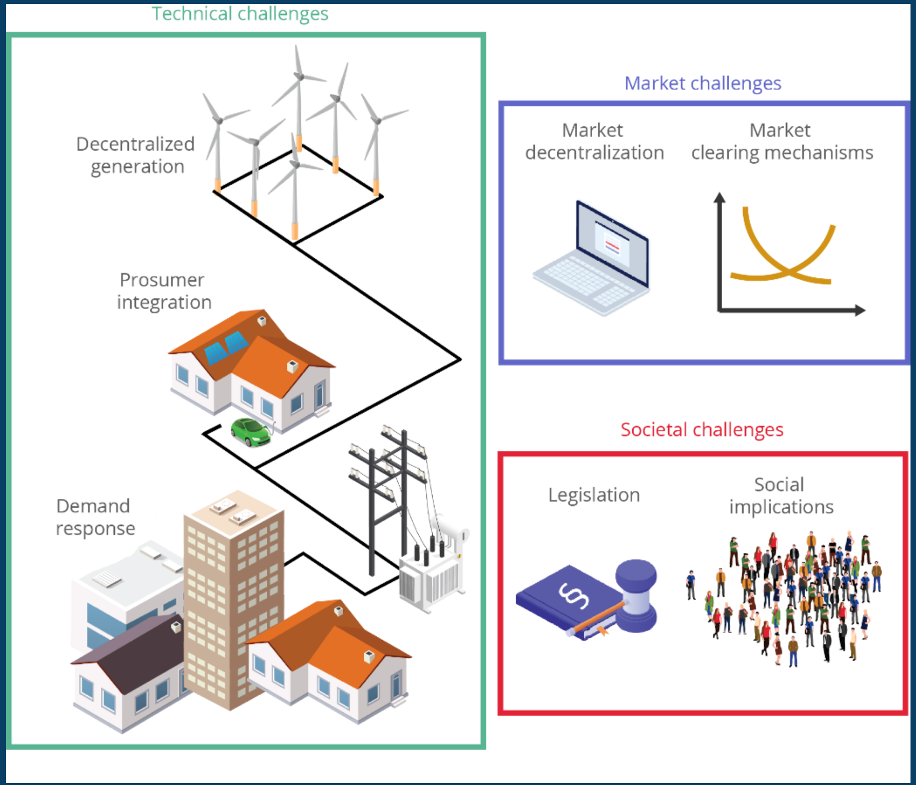
Local electricity markets

- Design aspects
  - Strategy: cooperative vs competitive
  - Market clearing: centralized vs decentralized
  - Trading mechanism: auction, market clearing, supply-demand
  - Price formation: uniform vs discriminatory
  - Location: static or dynamic

Challenges of local electricity markets

1. Distribution of generation
2. Distribution of demand response
3. Decentralization of markets
4. Legal boundaries
5. Social implications



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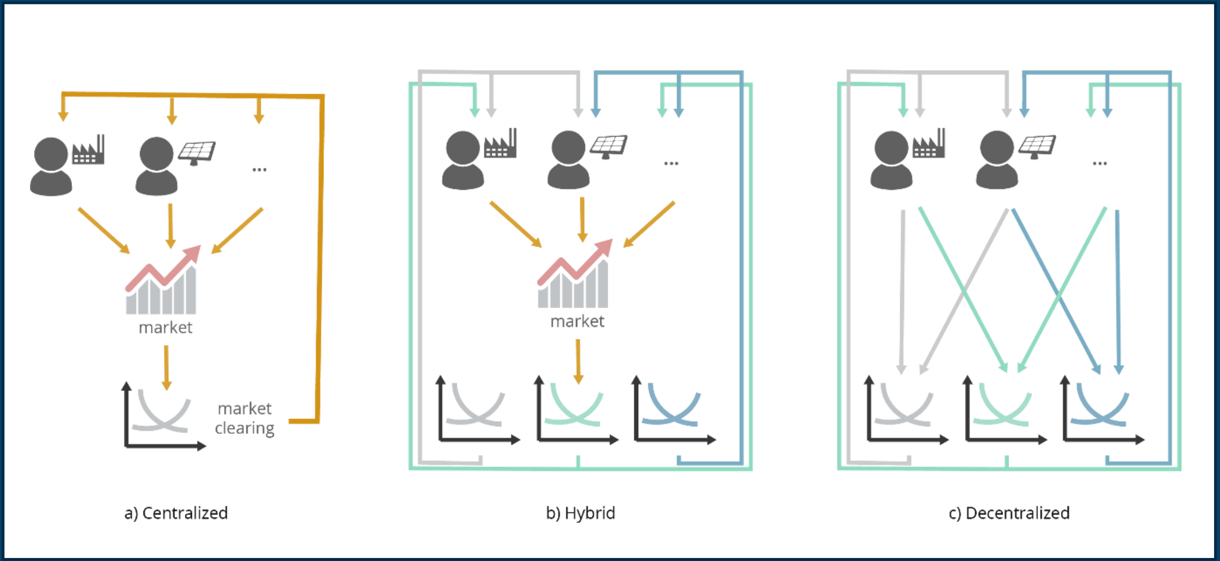
Design aspects of local electricity markets

- Market clearing topology



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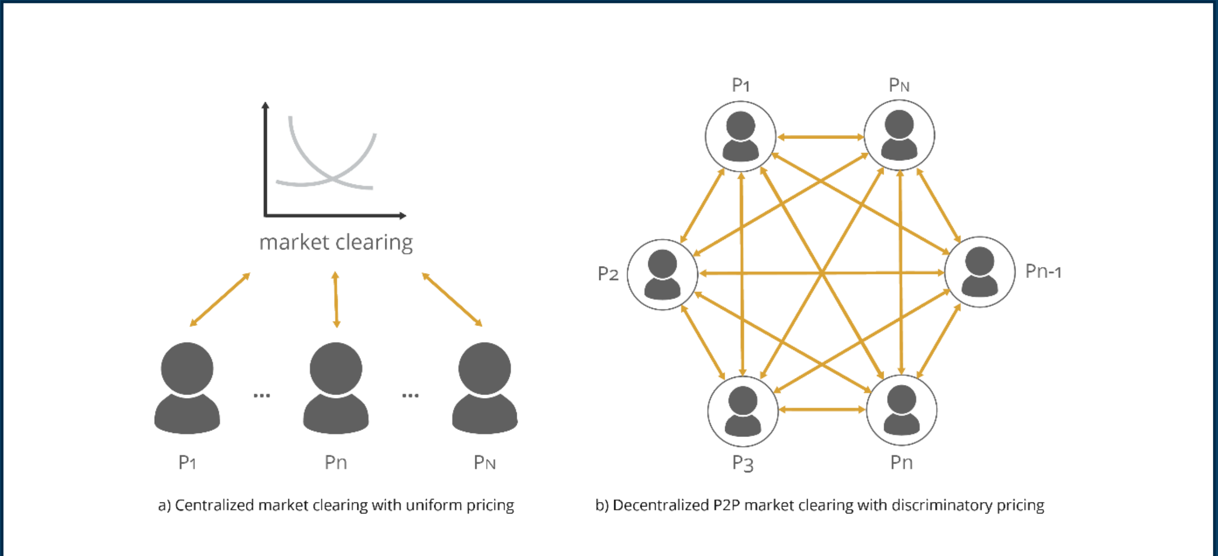
Design aspects of local electricity markets

- Market clearing topology
- Price formation



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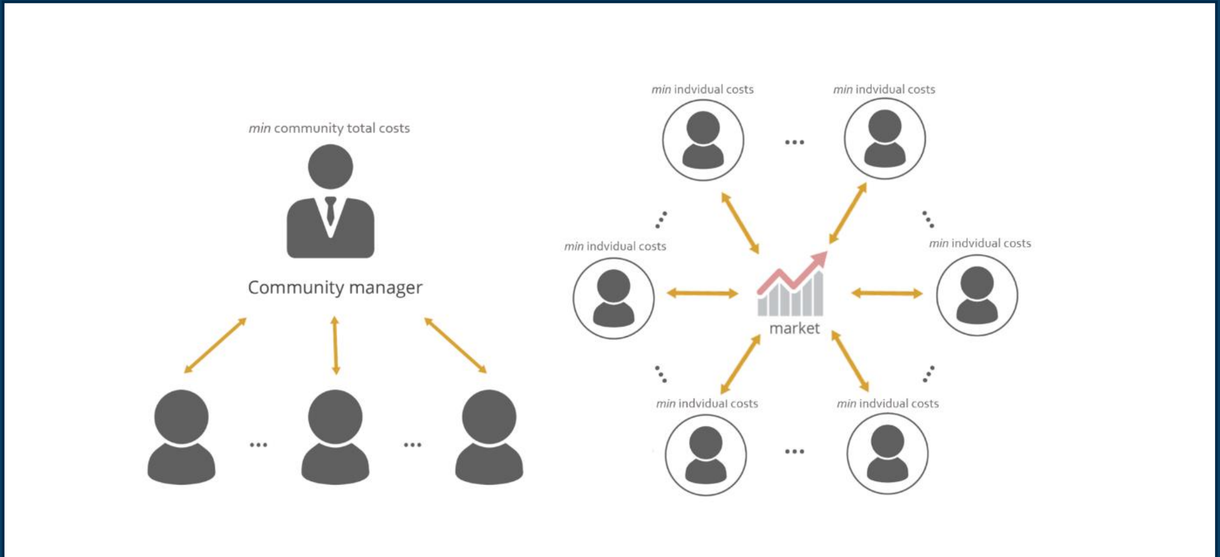
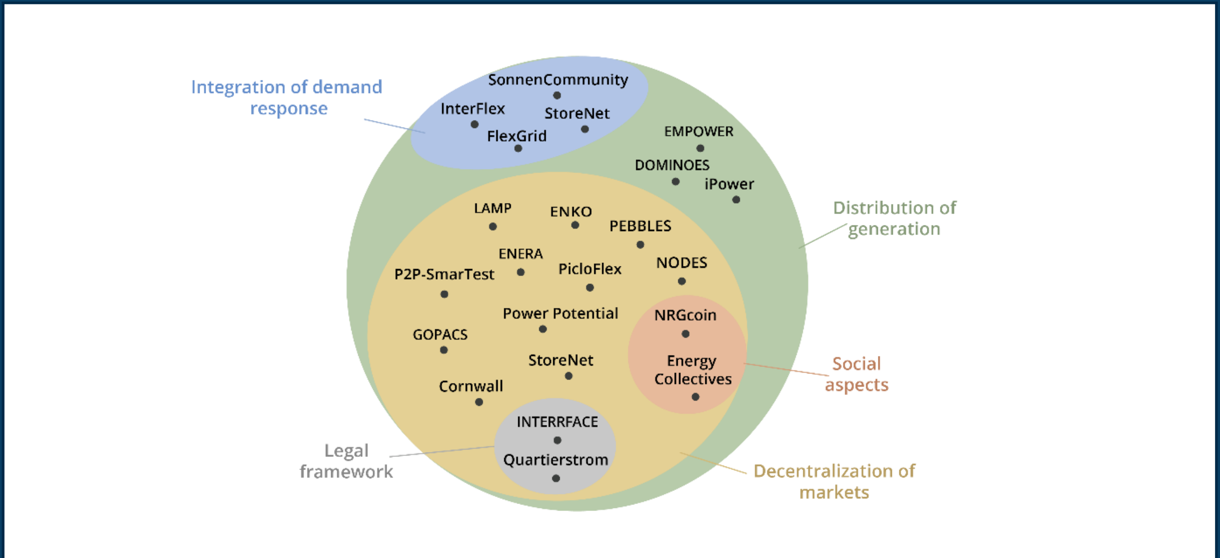
Design aspects of local electricity markets

- Market clearing topology
- Price formation
- Strategy



Design aspects of local electricity markets

- Market clearing topology
- Price formation
- Strategy
- Pilot projects



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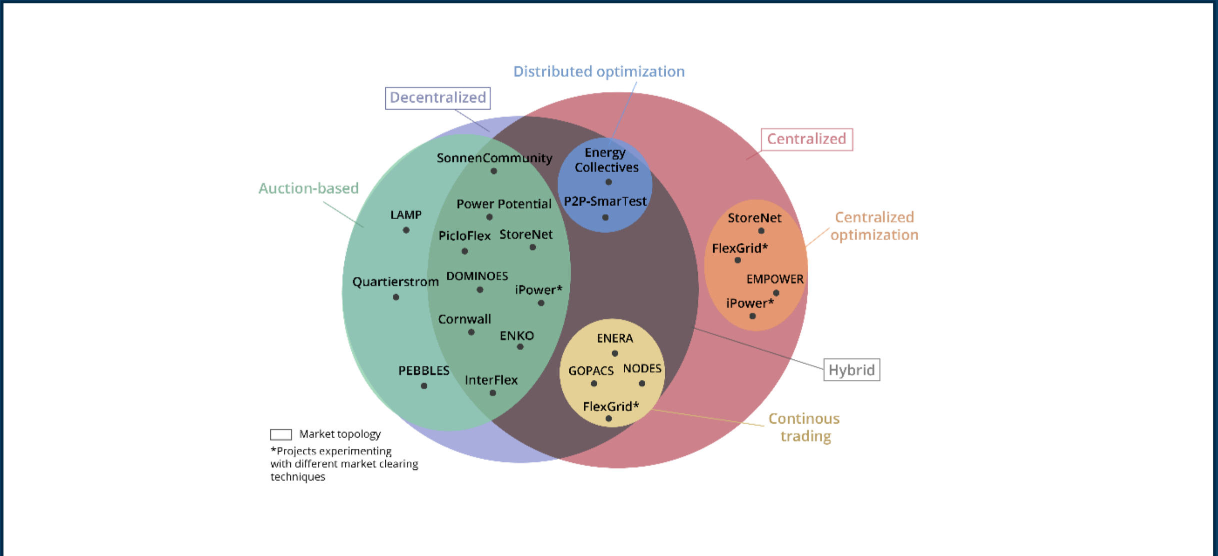
Design aspects of local electricity markets

- Market clearing topology
- Price formation
- Strategy
- Pilot project challenges
- Pilot project modelling



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Main findings

- Research questions:

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RQ4: Aiming to reduce peak demand, is there a price signal conflict between electricity spot prices and grid tariffs?

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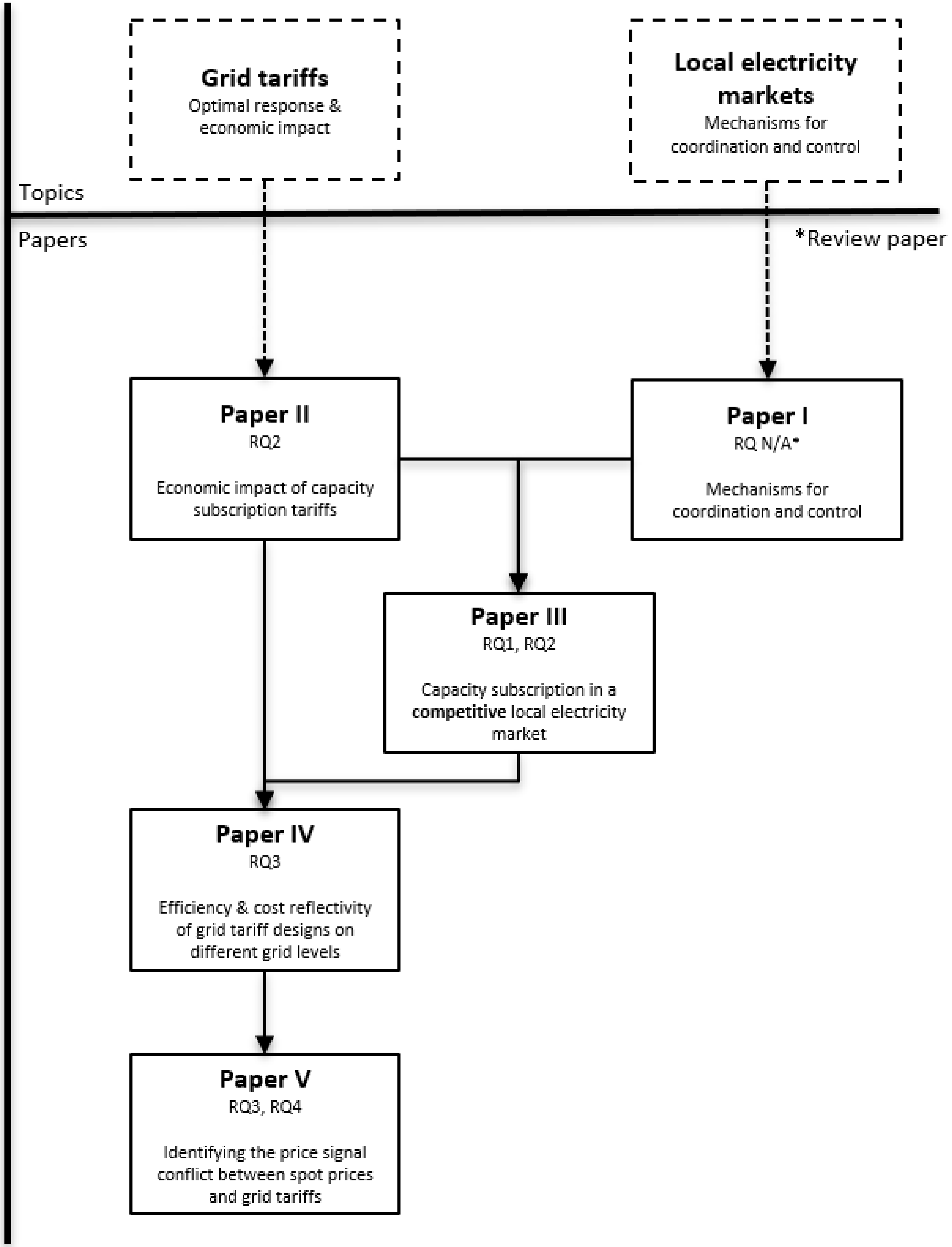

Main findings

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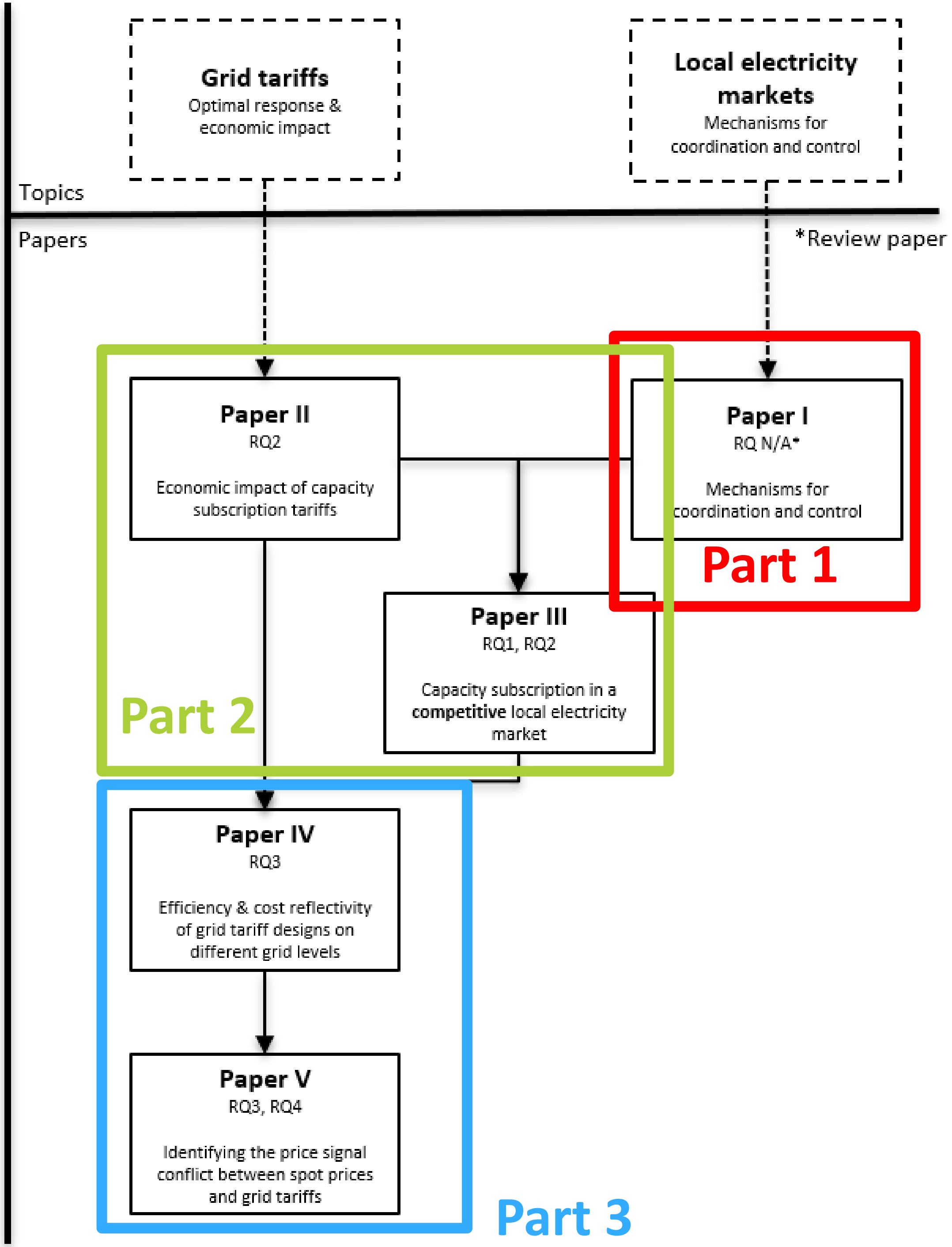

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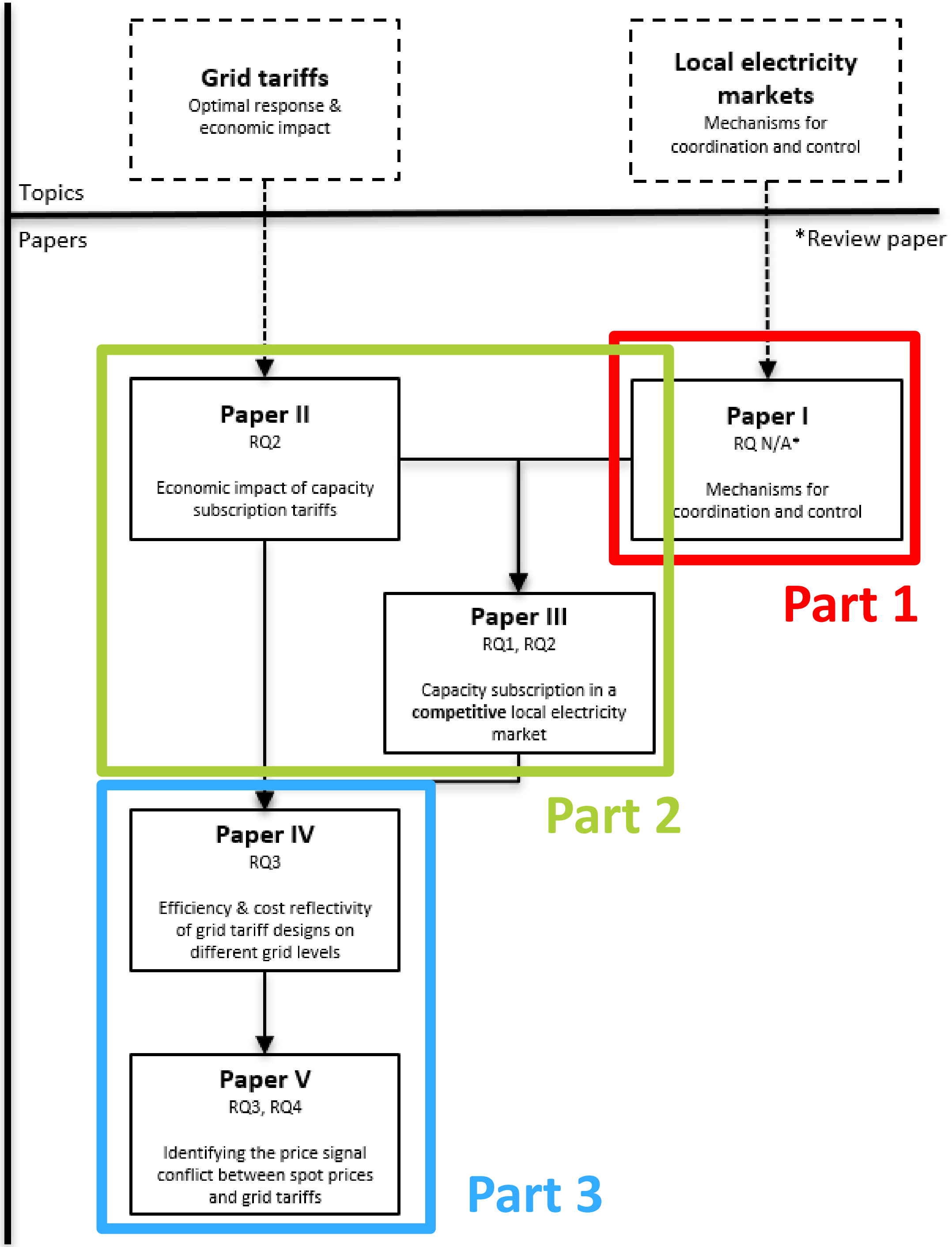
Main findings

Local electricity markets & grid consideration

Capacity subscription & local electricity markets

Grid tariff design for peak demand reduction



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Main findings

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Grid tariff design for peak demand reduction

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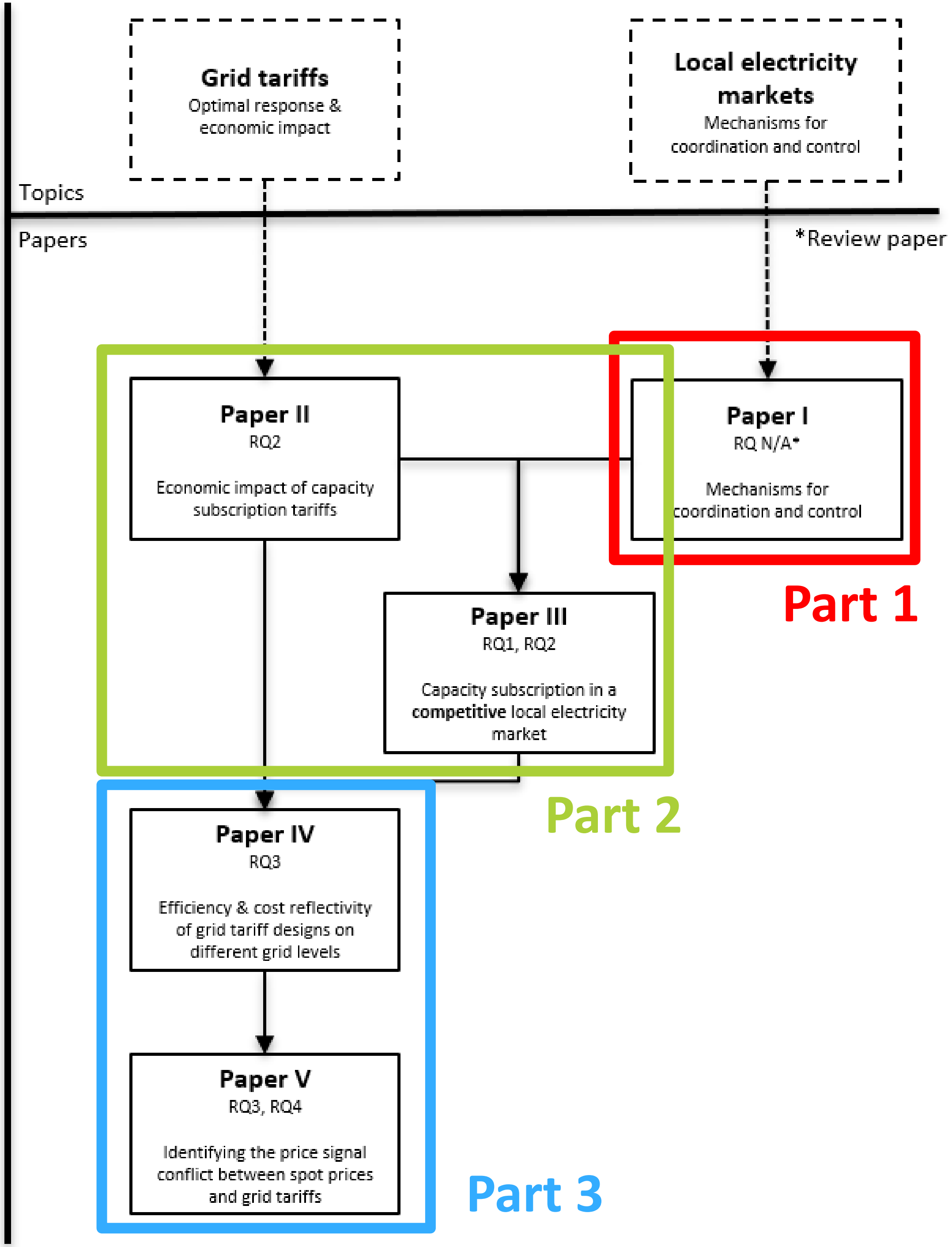
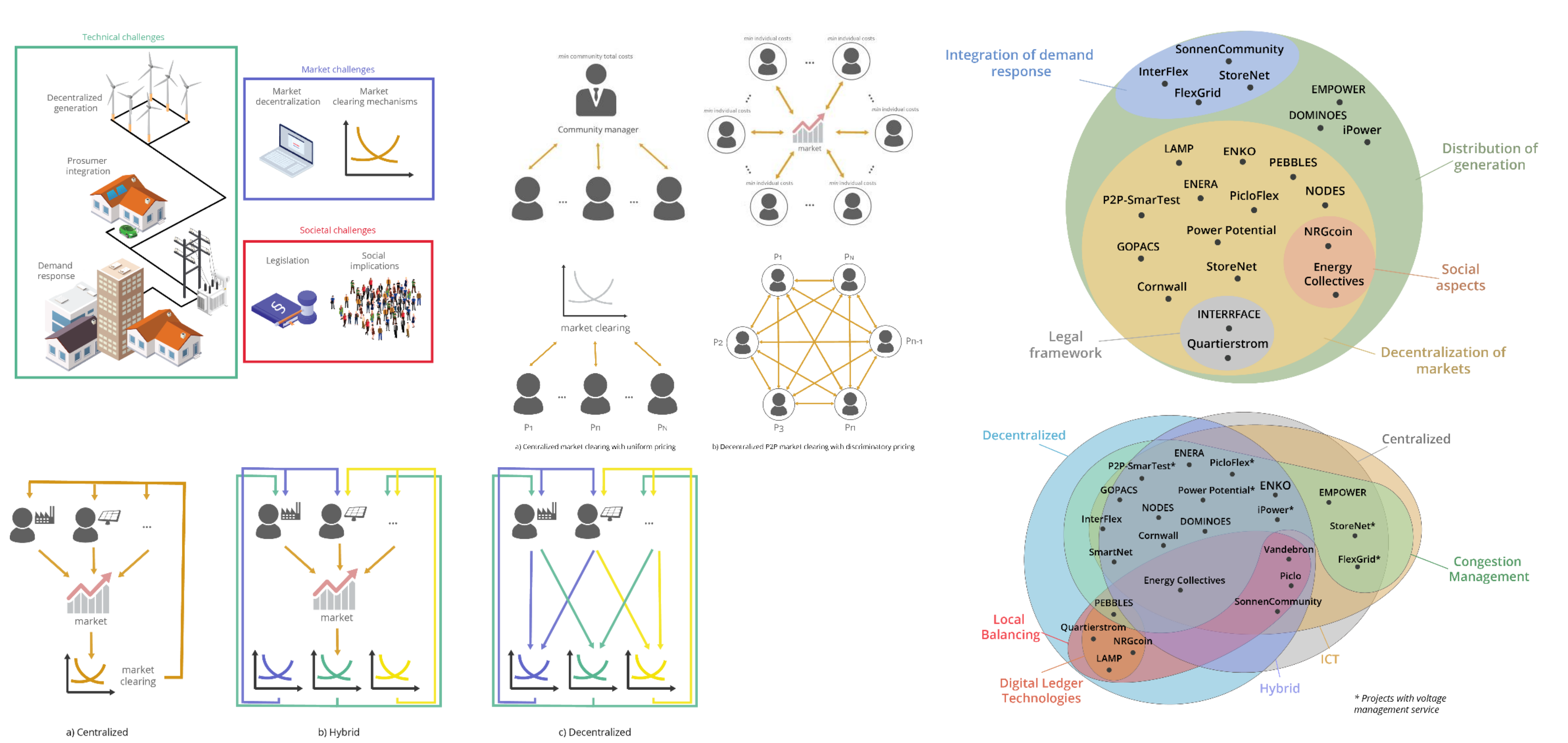


Part 1 – Local electricity markets



Part 1 – main findings

- Wanted to consider how local electricity markets could solve grid related challenges
- Merge the gap between tariffs, policy and local electricity markets
- **RQ1**: How well do capacity-based grid tariffs and local electricity markets synergize in order to incentivize consumers to reduce peak demand?

TABLE 6. Literature on market challenges.

Paper	Centralized market clearing	Decentralized market clearing	Balancing products	Demand response
[93]	x			
[70]		x		
[94]		x		
[95]		x		
[96]	x	x		x
[97]	x			
[98]	x		x	
[62]	x			x
[99]		x		
[100]	x			
[101]	x			
[102]		x		
[103]	x		x	x
[104]	x			
[105]		x		x
[48]	x			
[107]	x			
[108]		x		
[109]	x		x	x
[110]	x			x
[111]	x		x	x
[112]	x	x	x	x
[113]		x		x
[114]	x			x
[115]	x			x
[116]	x			
[117]	x			x
[118]	x			x
[119]	x			
[120]	x			x
[121]	x			x
[122]	x			
[123]	x		x	x
[124]		x		
[125]	x			x
[81]	x	x		x
[128]			x	
[129]		x		
[131]		x		x
[132]		x		
[118]			x	
[134]	x			
[135]	x			
[136]	x			x
[137]		x		x
[138]	x		x	x
[139]	x			x
[140]	x			x
[141]	x			x
[142]	x			
[143]		x		
[144]	x			x
[145]	x			
[146]	x	x		x
[147]		x		

TABLE 5. Literature on grid related challenges.

Paper	AC PF	DC PF	Congestions	Voltages	Tariffs	Policy
[93]	x		x	x		
[70]					x	x
[94]	x		x	x		
[95]	x		x	x		
[96]	x		x	x	x	
[97]	x		x	x		
[98]	x		x	x	x	
[62]		x	x	x		
[102]		x	x	x		x
[105]			x			x
[107]	x		x	x		
[108]		x	x			
[109]		x	x			
[110]		x	x			
[112]		x	x			
[115]			x		x	x
[116]	x		x	x		
[117]	x		x	x		
[119]		x	x		x	
[120]			x		x	
[121]			x		x	x
[122]			x		x	x
[81]		x	x			
[128]	x			x		
[129]	x		x	x		
[133]	x			x		
[134]	x		x	x		
[137]			x			
[138]	x		x	x		
[139]	x		x	x		
[140]			x			
[141]	x		x	x		
[142]	x		x	x		
[86]	x	x	x	x		
[143]		x	x			
[144]	x		x	x		
[145]	x		x	x		
[146]	x		x	x		
[147]	x		x	x		

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Main findings

Local electricity markets & grid consideration

Capacity subscription & local electricity markets

Grid tariff design for peak demand reduction

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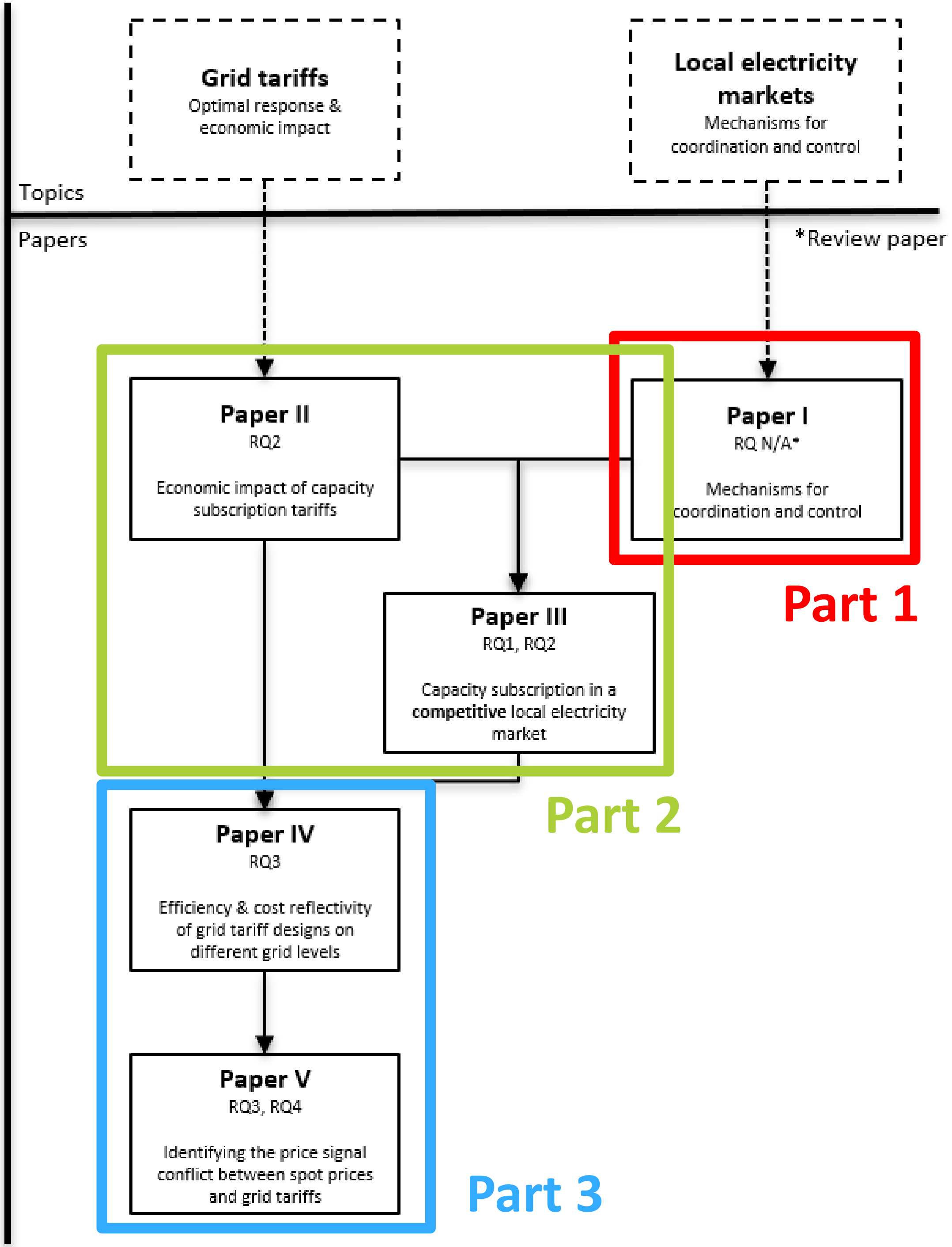
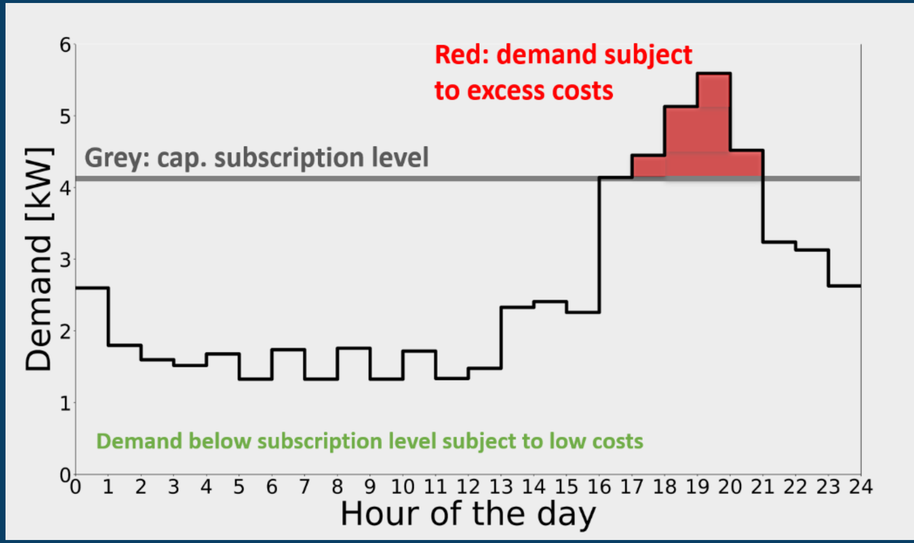


Part 2 – Synergy of capacity subscription tariffs and local electricity markets

- Capacity subscriptions require ex-ante choices
- Moves risk decision from DSO to consumer
- Opens for a number of challenges



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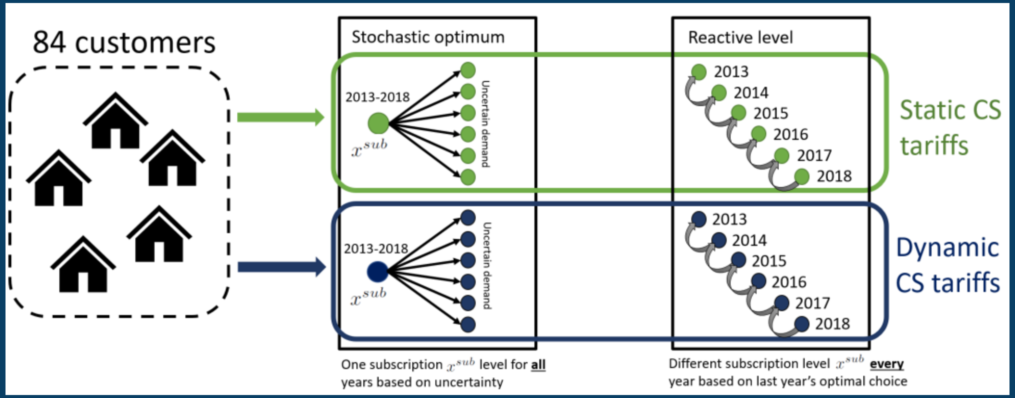
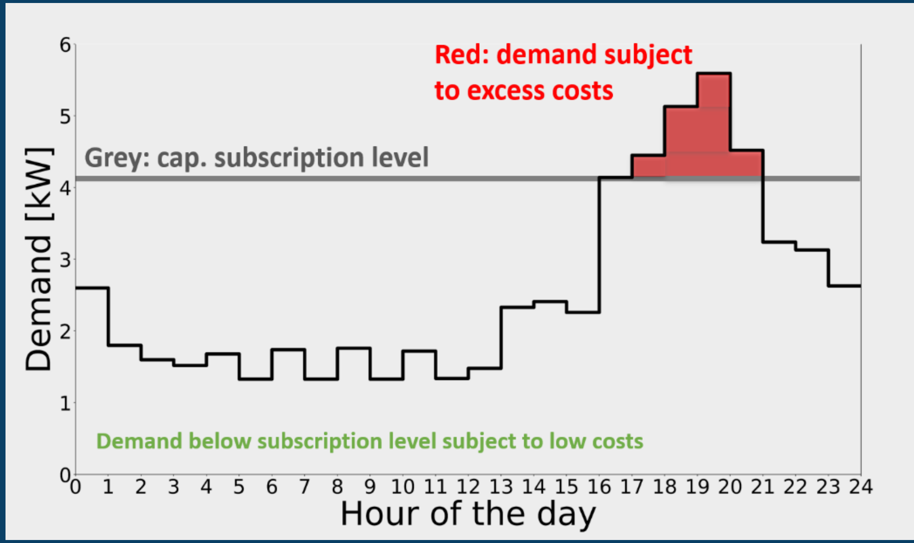
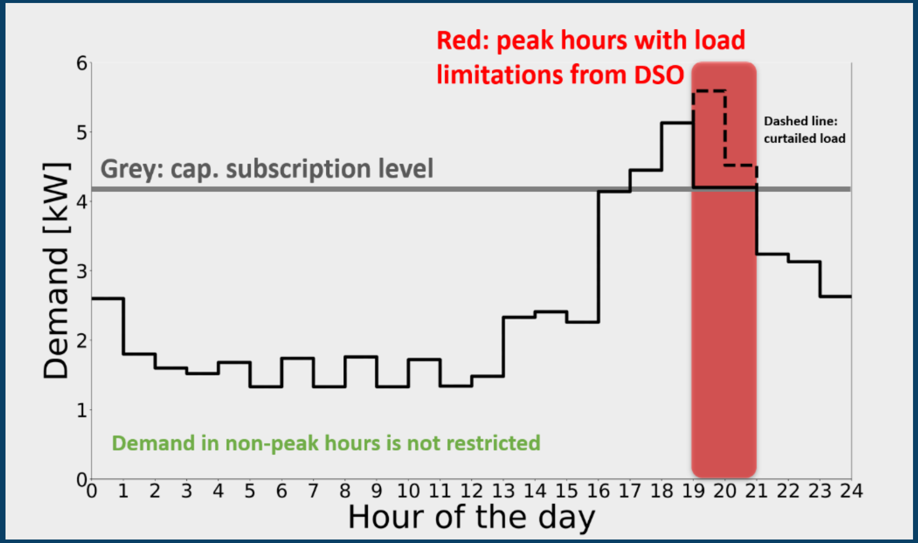
Capacity subscription

- Assess cost recovery, fairness and cost reflectivity
- Static and dynamic tariff
- Developed a two-stage stochastic program to find optimal subscription level under uncertainty



Static and dynamic capacity subscription





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Part 2 – main findings

- Finding optimal subscription level is "easy"
- Cost recovery is stable for static capacity subscription tariffs
- Cost recovery is unstable for dynamic capacity subscription tariffs
- Capacity subscriptions are more cost reflective, and hence more fair (economically speaking)

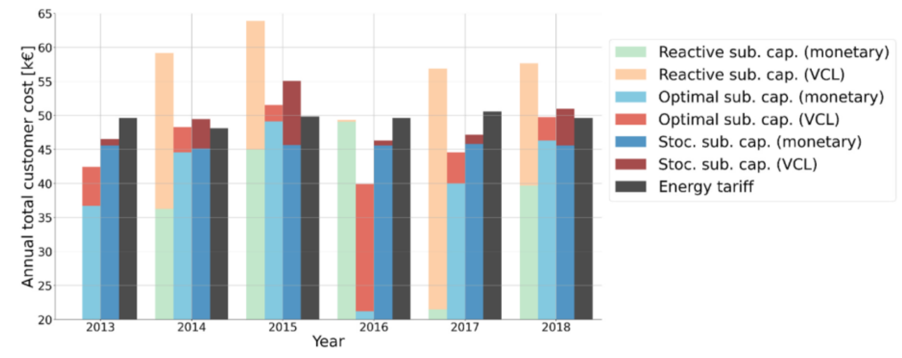
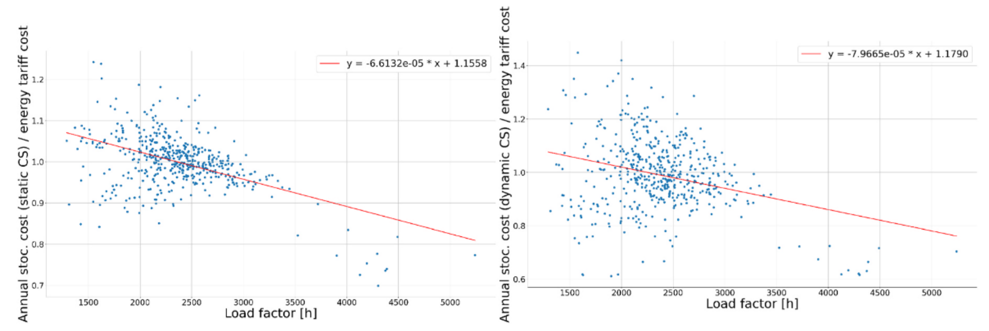


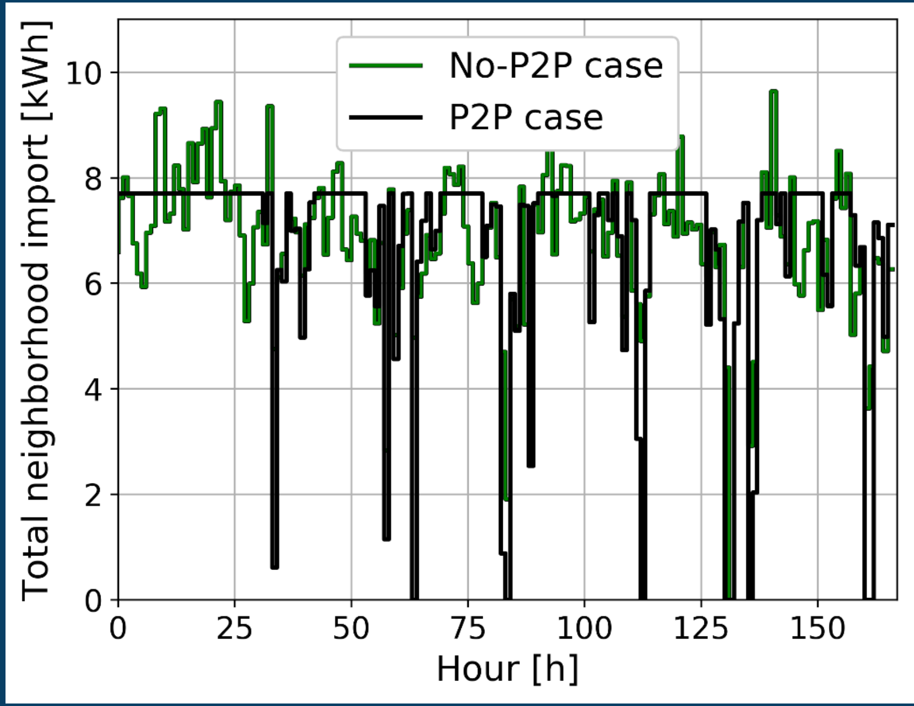
Fig. 12. Aggregated annual consumer costs under the different approaches (dynamic CS).



(a) Static CS tariff. (b) Dynamic CS tariff.

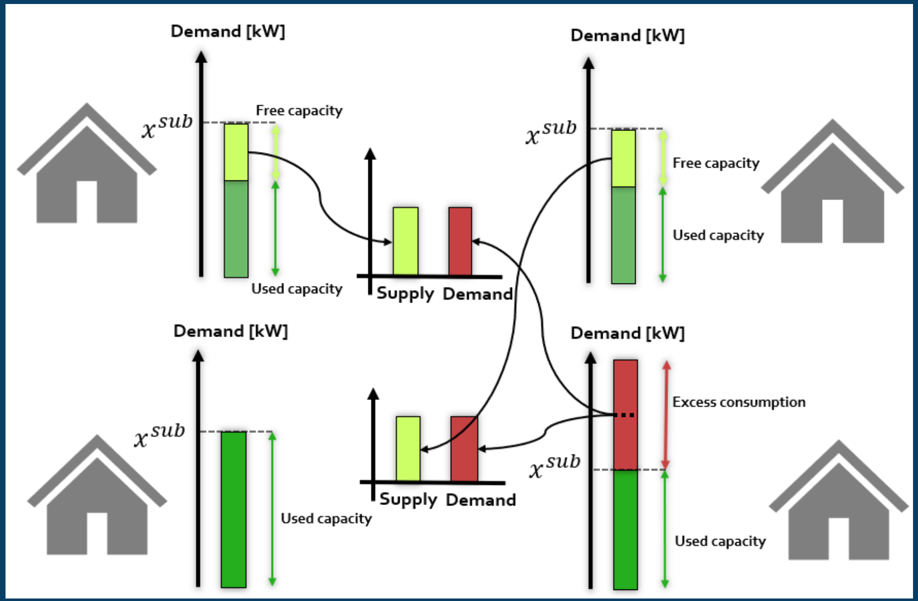
Part 2 – capacity subscription and local electricity markets

- Local electricity markets facilitate coordination between customers by accounting for the coincidence factor
- Capacity subscription tariffs and local electricity markets achieve similar results as centralized control
  - Fits well with point tariff system



Part 2 – capacity subscription and local electricity markets

- Local electricity markets facilitate coordination between customers by accounting for the coincidence factor
- Capacity subscription tariffs and local electricity markets achieve similar results as centralized control
    - Fits well with point tariff system
- Essentially creates a local market for renting capacity



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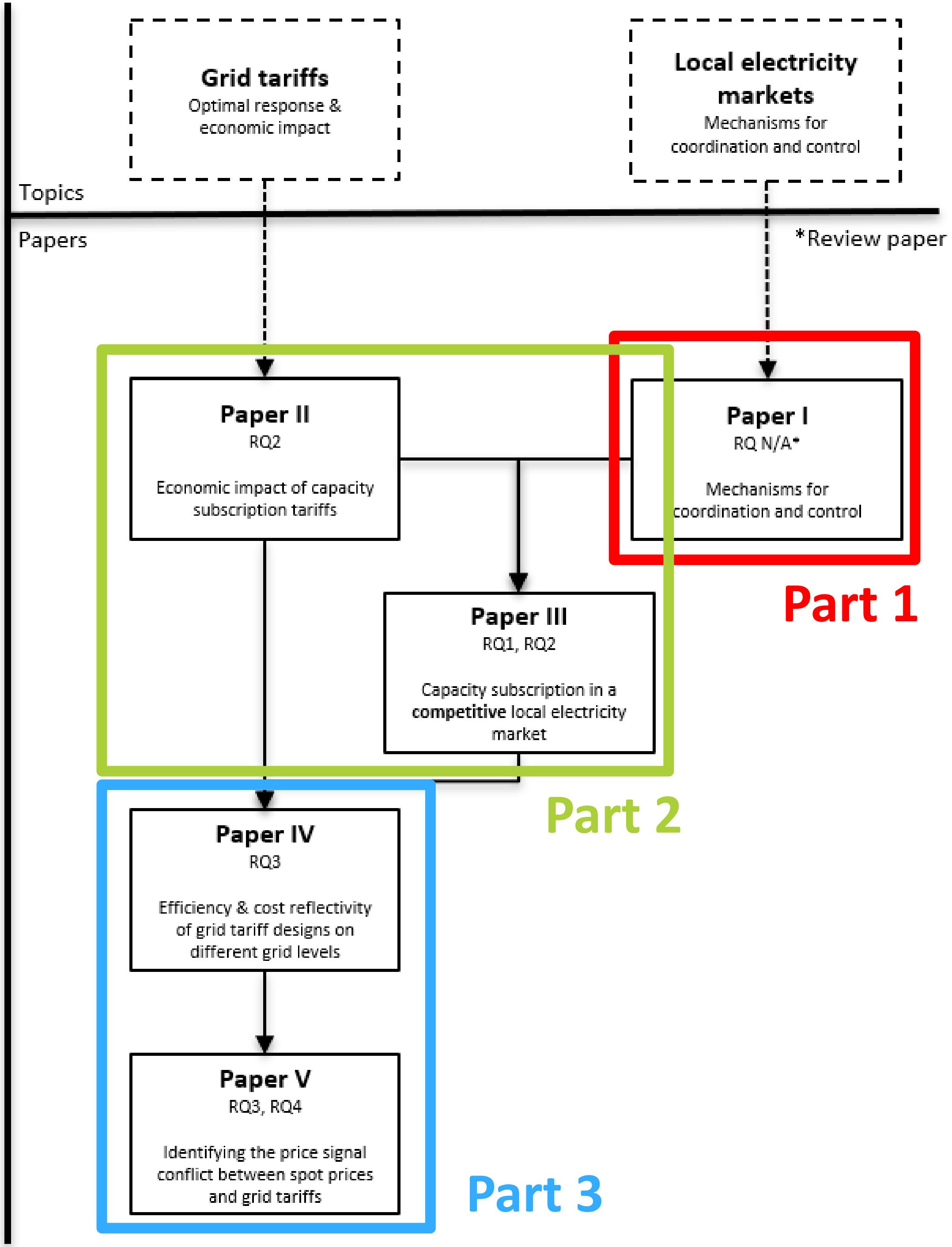
Main findings

Local electricity markets & grid consideration

Capacity subscription & local electricity markets

Grid tariff design for peak demand reduction



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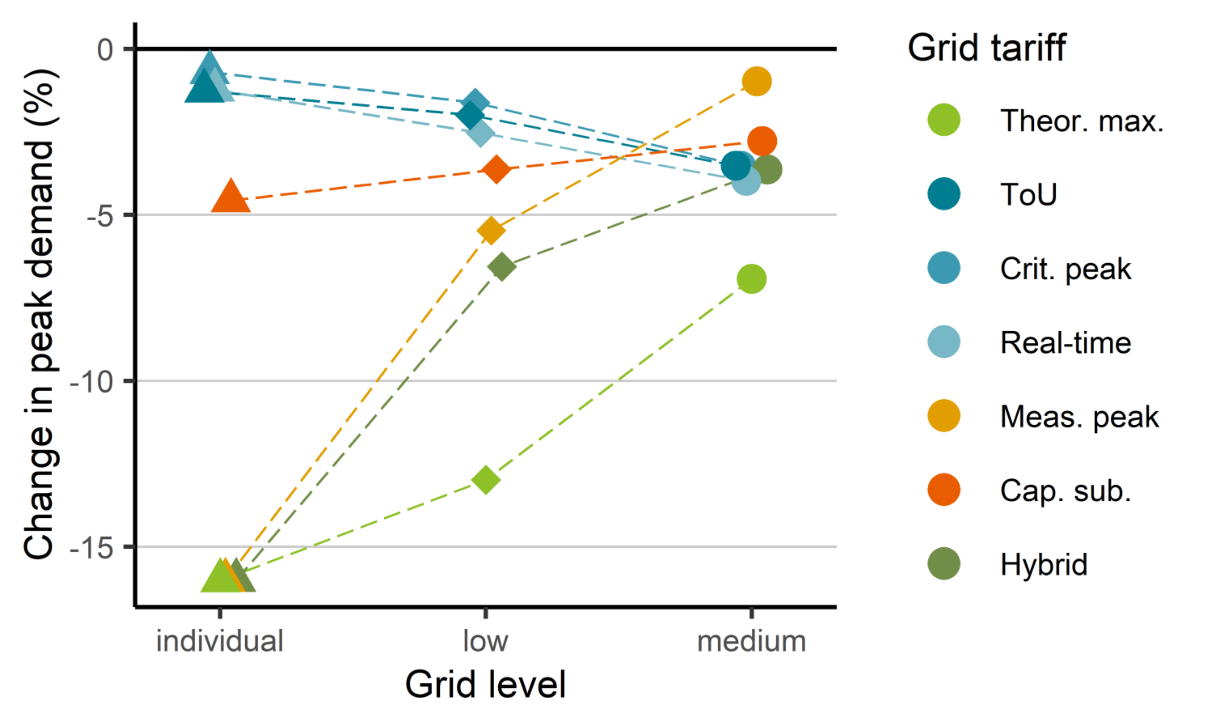
Part 3 – Grid tariff design for peak demand reduction

- Goal: Compare grid tariff designs and their potential to reduce peak demand at different grid levels
- Applied to a large, real case study
- Describe grid tariff design parameters on a more fundamental level



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Research questions and methodology

- Consumer optimization, minimizing individual consumer costs based on:
  - Cost of grid tariffs
  - Flexibility constraints
  - Discomfort costs of using flexibility
  - (Cost of electricity)
- Assumptions
  - All consumers are subject to the same tariff
  - All consumers are flexible (but averagely)

RQ3: Which grid tariffs designs are the most cost reflective and efficient at reducing peak demand at different grid levels?

RQ4: Aiming to reduce peak demand, is there a price signal conflict between electricity spot prices and grid tariffs?

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Comparison of six grid tariff designs

- Time-of-use
- Critical peak pricing
- Real-time pricing
- Measured peak demand
- Capacity subscription
- Hybrid (Time-of-use + measured peak demand)

Tariff design parameters	Energy-based tariffs			Capacity-based tariffs		Hybrid
	ToU	Crit. peak	Real-time	Cap. sub.	Meas. peak	
Decisive cost component	Energy			Capacity		Both
Peak basis	Grid			Individual		Both
Peak rate period setting	Ex-ante			Ex-post		Both

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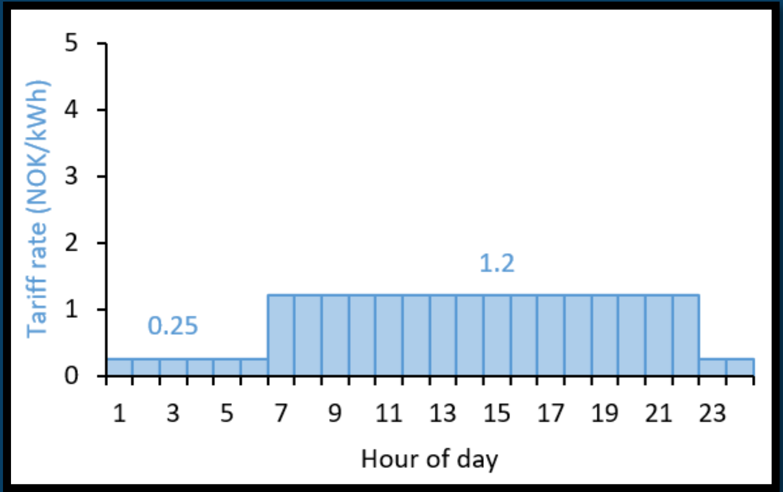
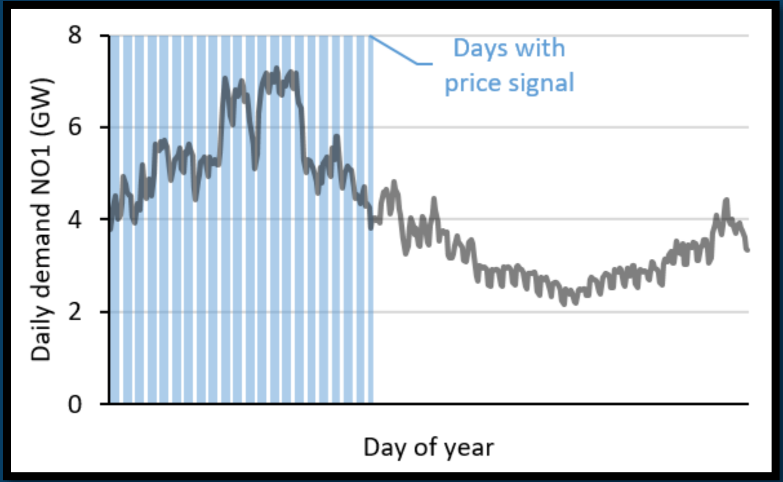
Energy-based: Time-of-use

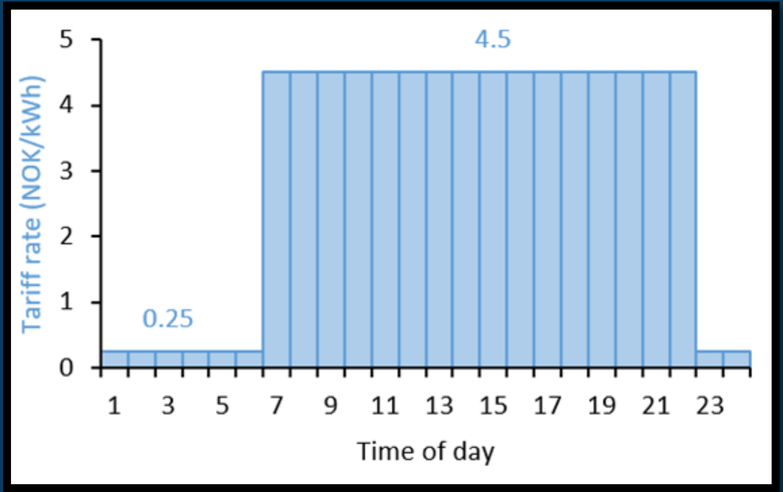
- Two cost levels
  - 06-22, high energy term
  - 22-06, small energy term
- Only active during
  - Weekdays
  - November-March

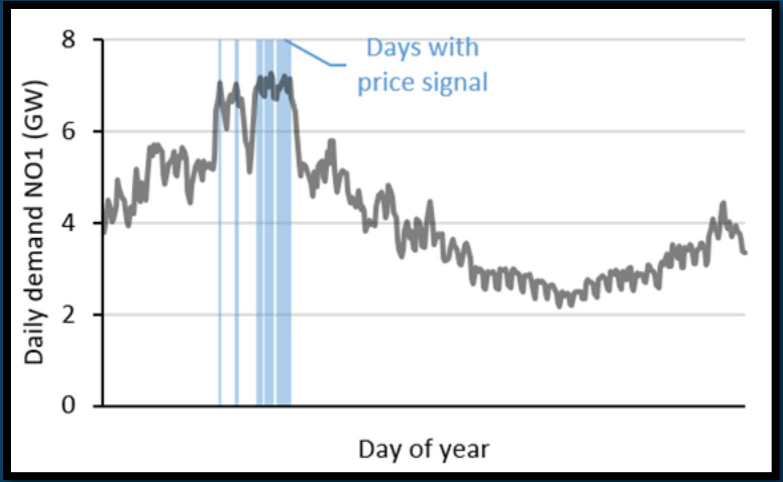




Energy-based: Critical peak pricing

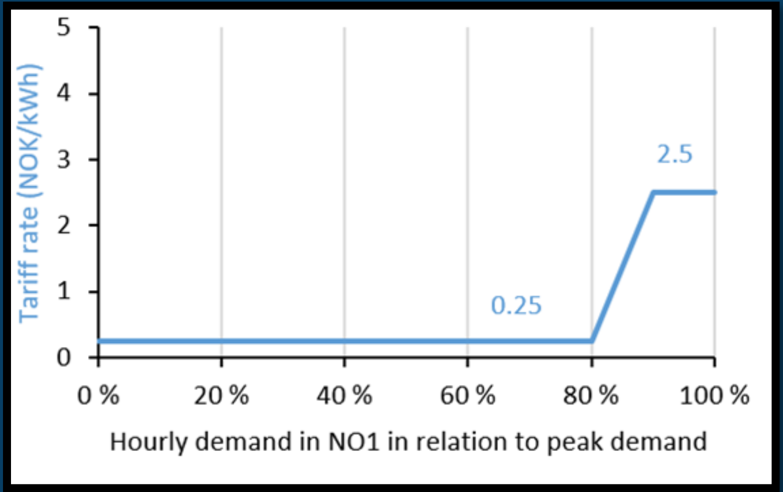
- Two cost levels
  - 06-22, high energy term
  - 22-06, small energy term
- Only active during the 20 days with the highest peak loads in NO1

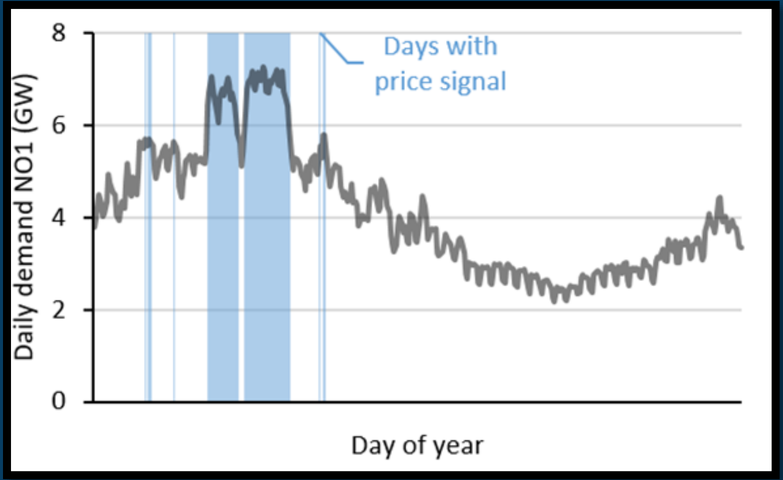




Energy-based: Real-time pricing

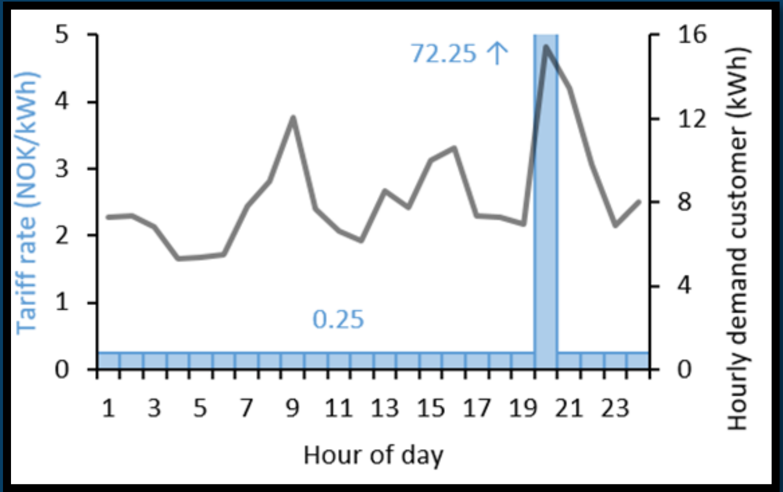
- Energy term increases linearly when the demand in NO1 is >80% of the peak demand
- Fixed when >90% of the peak demand

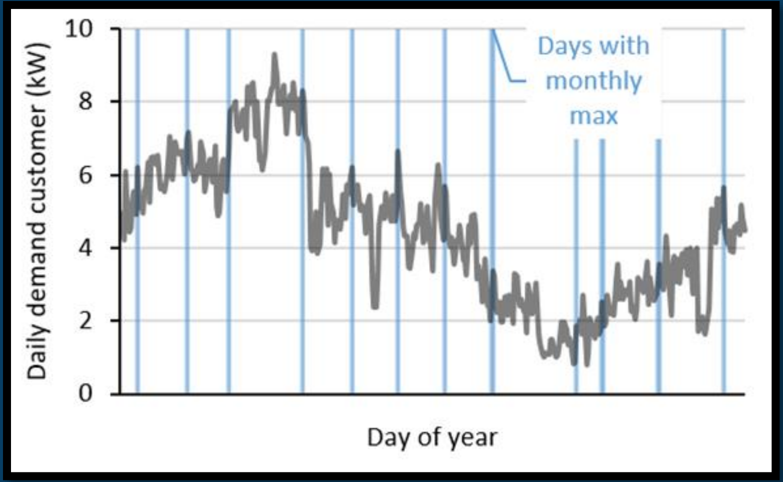




Capacity-based: Measured peak demand

- Energy term increases linearly when the demand in NO1 is >80% of the peak demand
- Fixed when >90% of the peak demand





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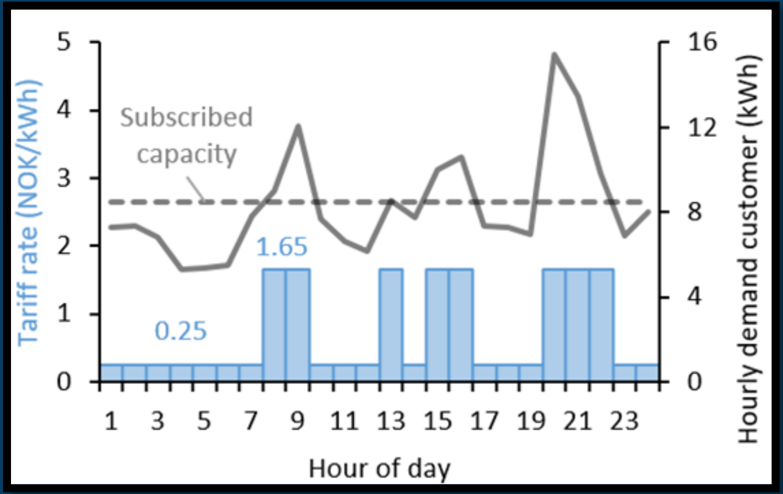
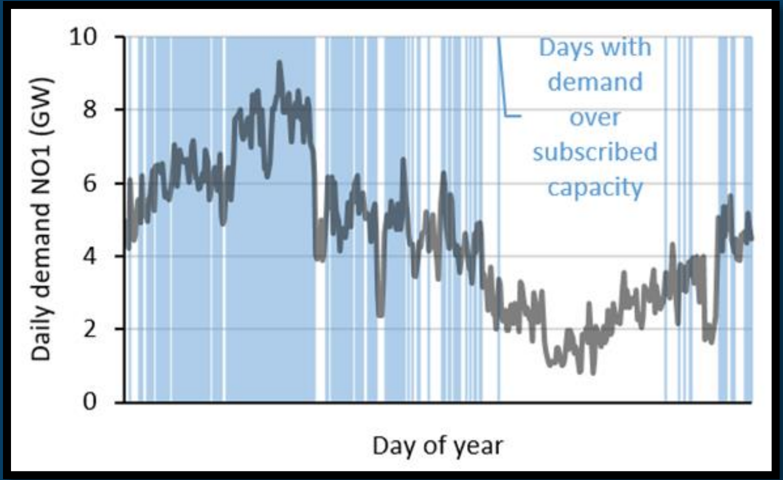
Capacity-based: Capacity subscription

- Optimal subscribed capacity based on individual load data
- Consumption above the subscription level is subject to an excess energy term





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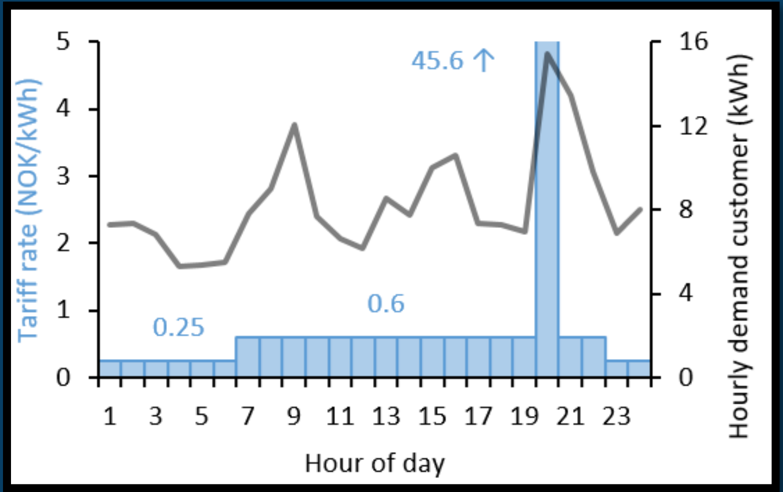
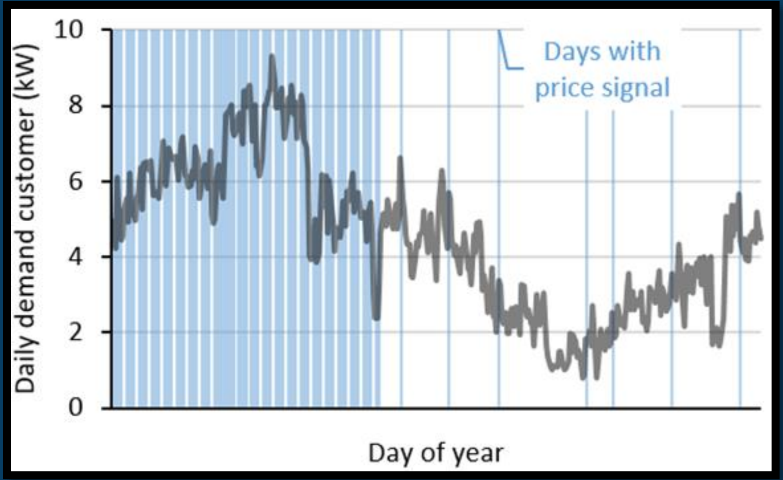
Hybrid: Time-of-use + meas. peak.

- Mix of time-of-use and measured peak demand
- Close to the current Norwegian model
  - (but without the steps!)





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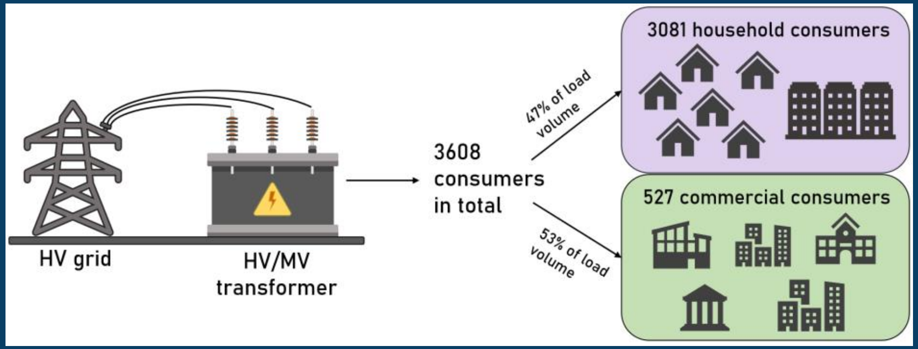
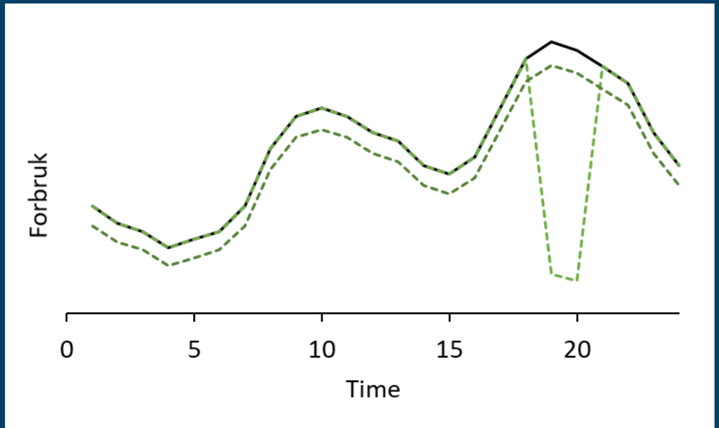
Case study

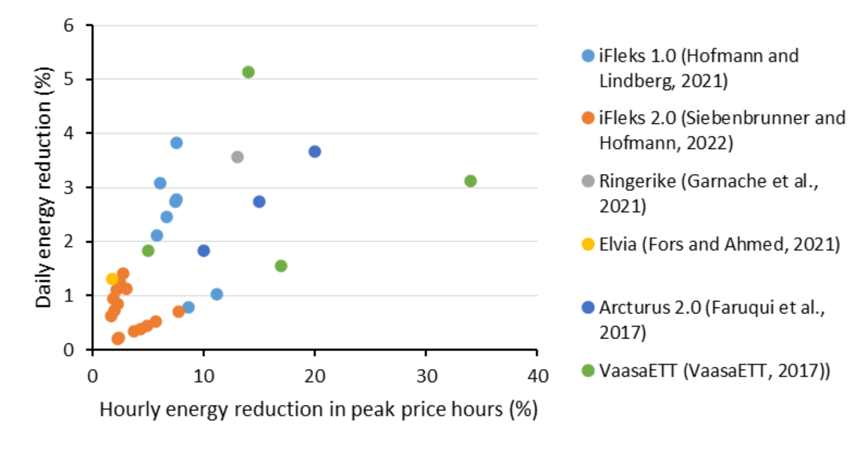
- 3608 consumers
- Nov 2020 – Oct 2021
  - Highest peak demand in Norway (ever!)
- Base case assumes that..
  - All consumers subject to same tariff and all are flexible
  - Load reduction
- Sensitivities on…
  - Load reduction versus load shifting
  - Size of flexible demand (power & energy)
  - Grid tariff design parameters



Consumer flexibility

- All consumers have flexibility (but adjusted to an average)
- Assumptions:
  - 2.5 % of the daily consumption is flexible
  - 25 % of hourly consumption is flexible





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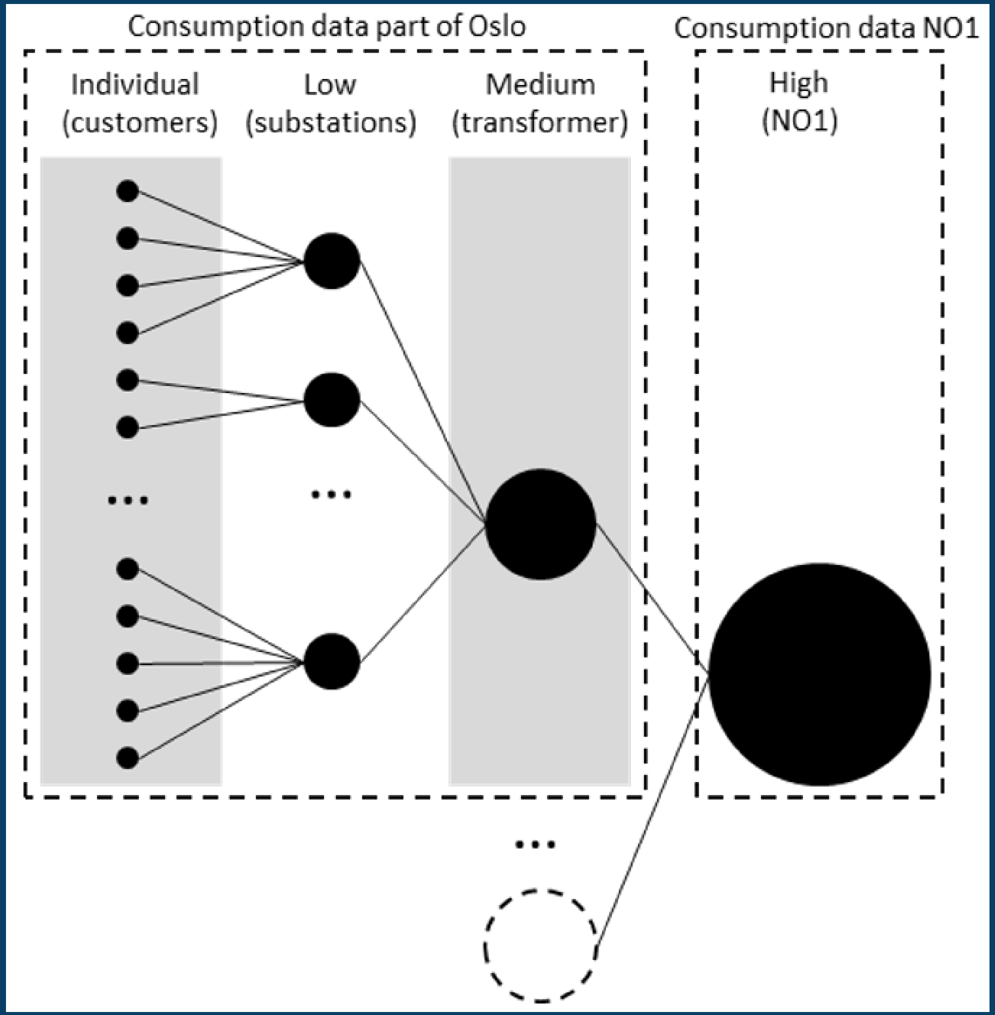
Case study

- Consumers are aggregated on four different levels
  - Consumer level (individual)
  - Substation level (LV)
  - Transformer level (MV)
  - NO1 (HV)



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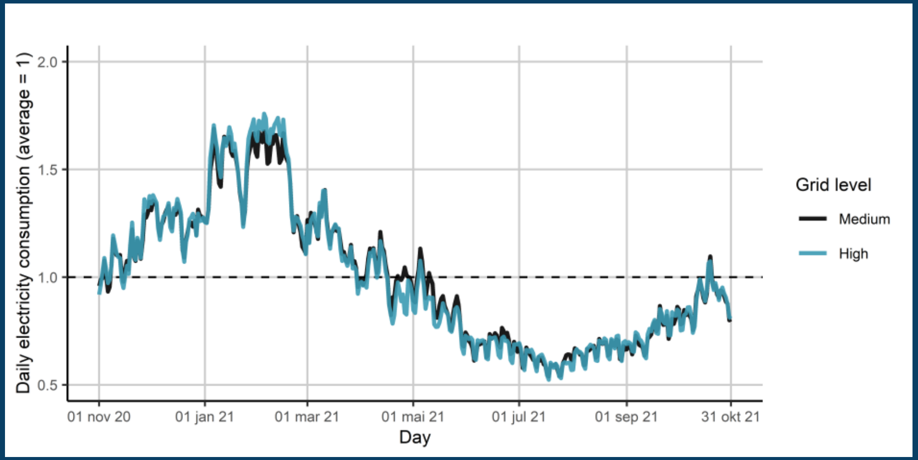
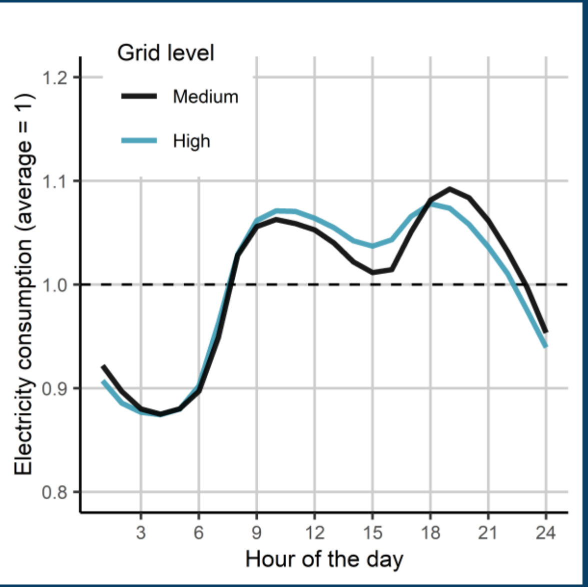
Case study

- Demand data at this transformer appear to be extrapolatable to NO1
- We therefore assume that these results can be transferred to NO1





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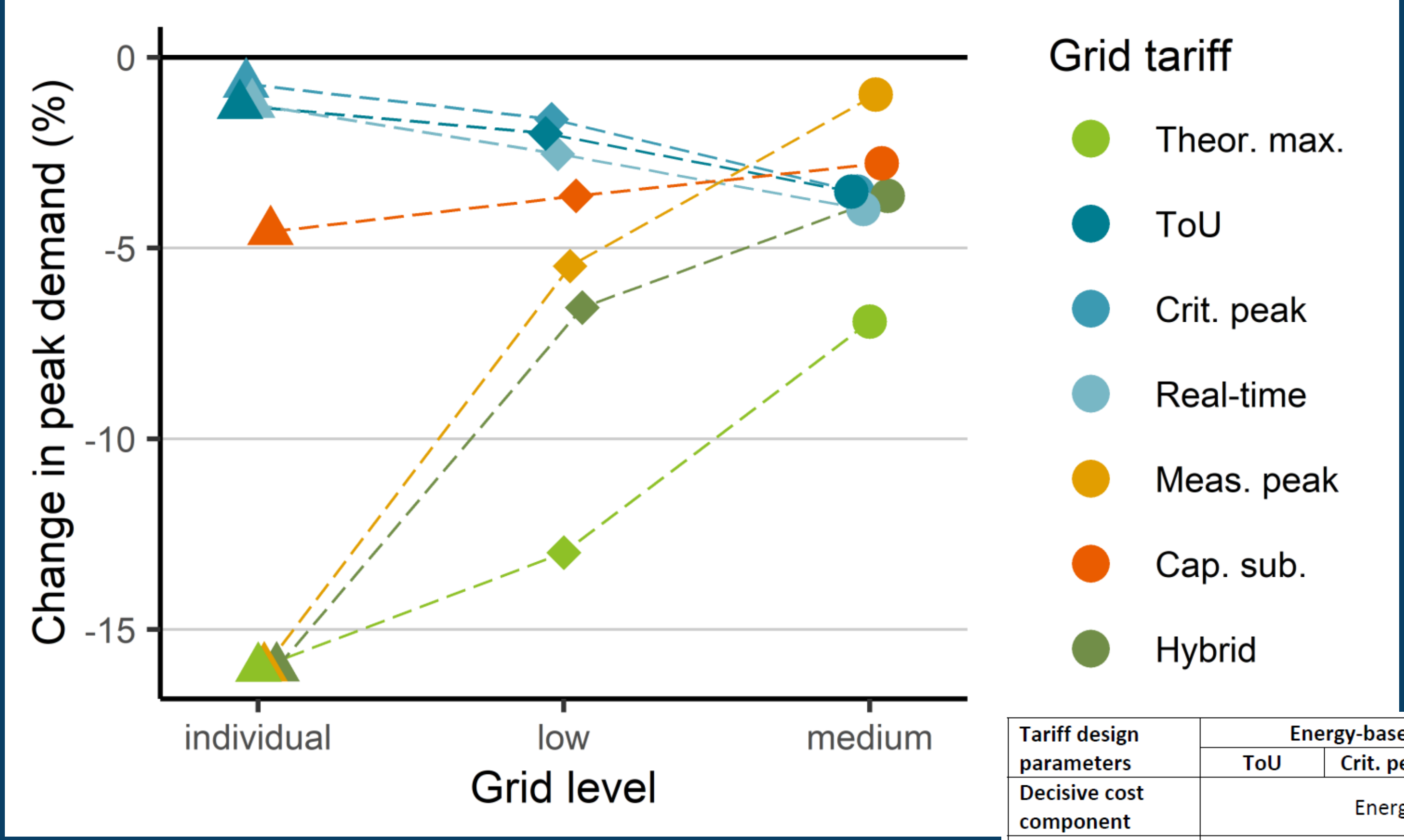
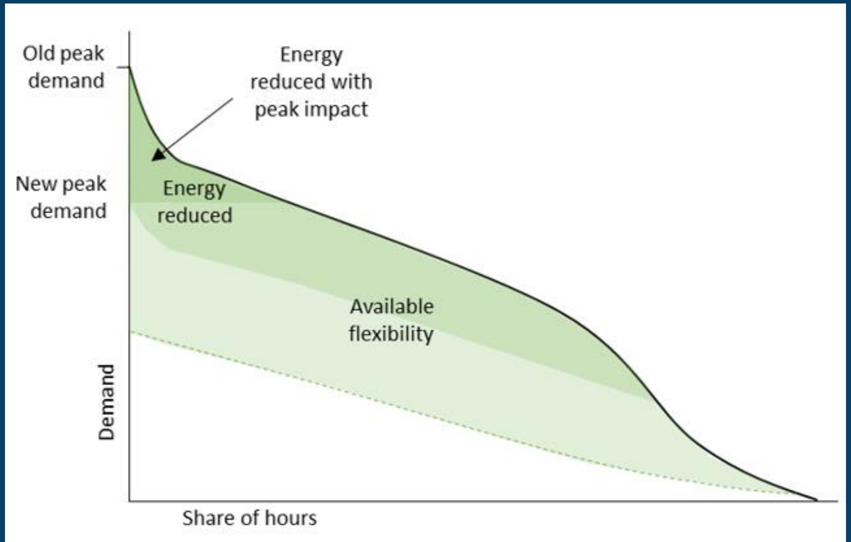
Main results – base case



Tariff design parameters	Energy-based tariffs			Capacity-based tariffs		Hybrid
	ToU	Crit. peak	Real-time	Cap. sub.	Meas. peak	
Decisive cost component	Energy			Capacity		Both
Peak basis	Grid			Individual		Both
Peak rate period setting	Ex-ante			Ex-post		Both

Main results – efficiency parameters

- Energy-based and hybrid tariffs perform the best peak demand reduction
- Critical peak pricing is the most efficient (most precise)
- All tariffs are imprecise and trigger ineffective flexibility



	Theor. max	ToU	Crit. peak	Real-time	Meas. peak	Cap. sub.	Hybrid
Change in peak demand	-6.9 %	-3.5 %	-3.5 %	-4.0 %	-1.0 %	-2.8 %	-3.6 %
Used flexibility	2.3 %	37.9 %	9.0 %	20.9 %	13.6 %	36.2 %	45.7 %
Effective flexibility	100.0 %	0.7 %	3.1 %	1.9 %	0.2 %	0.4 %	0.7 %

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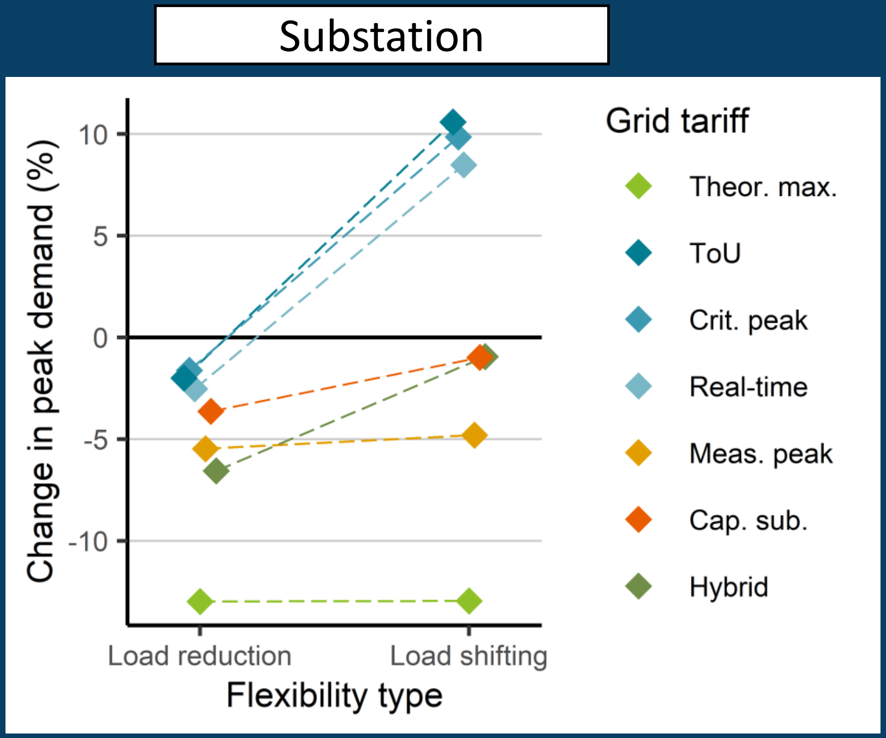
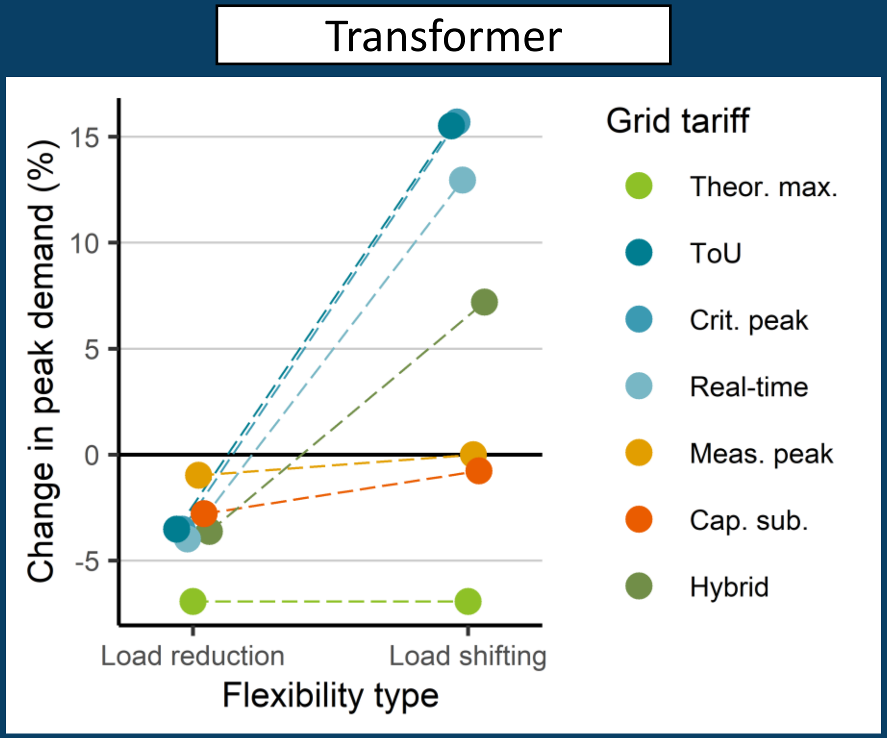
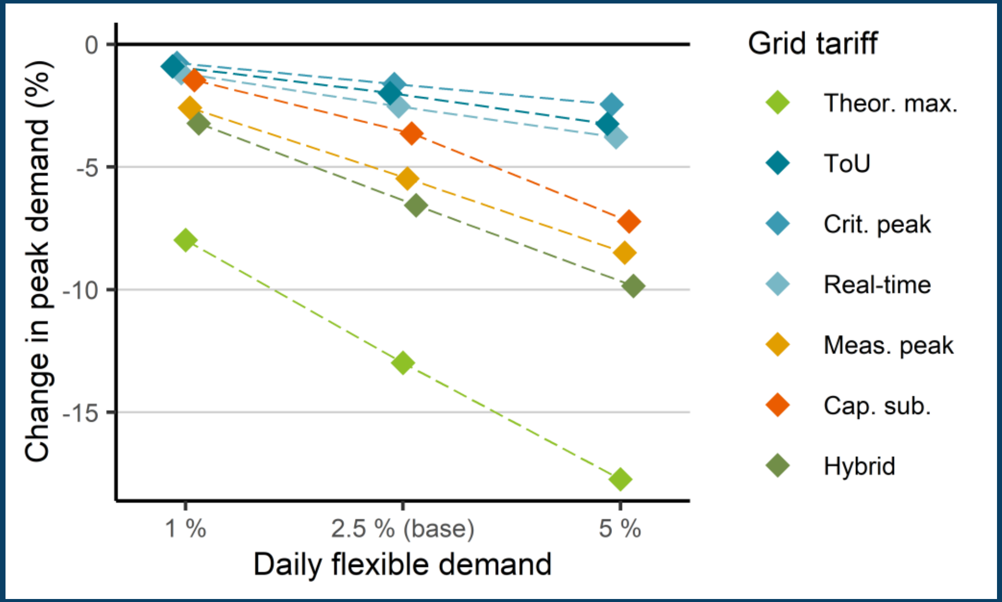
Sensitivity – reduction versus shifting



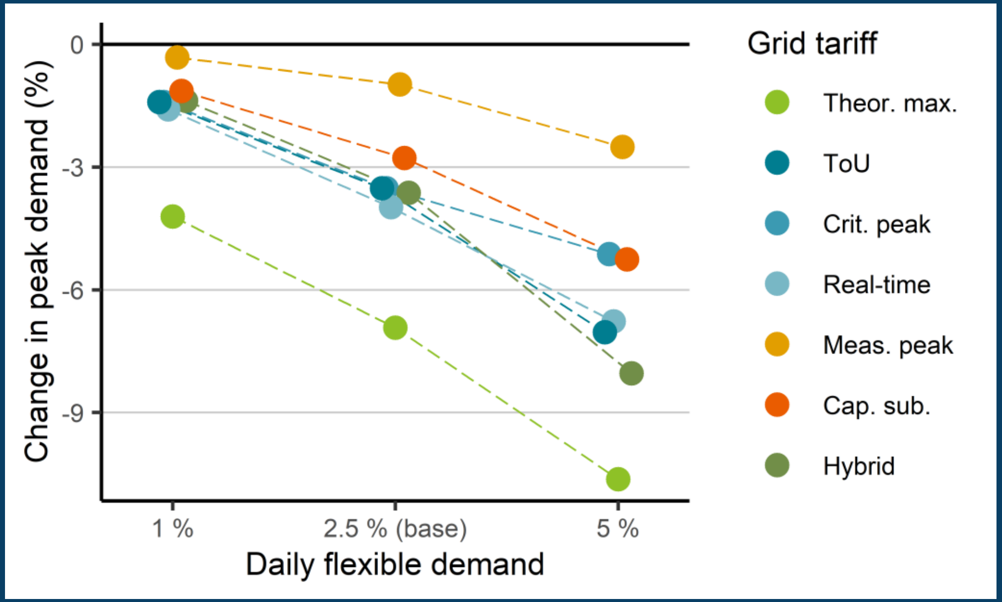


Sensitivity – level of **daily** flexible demand

Substation



Transformer



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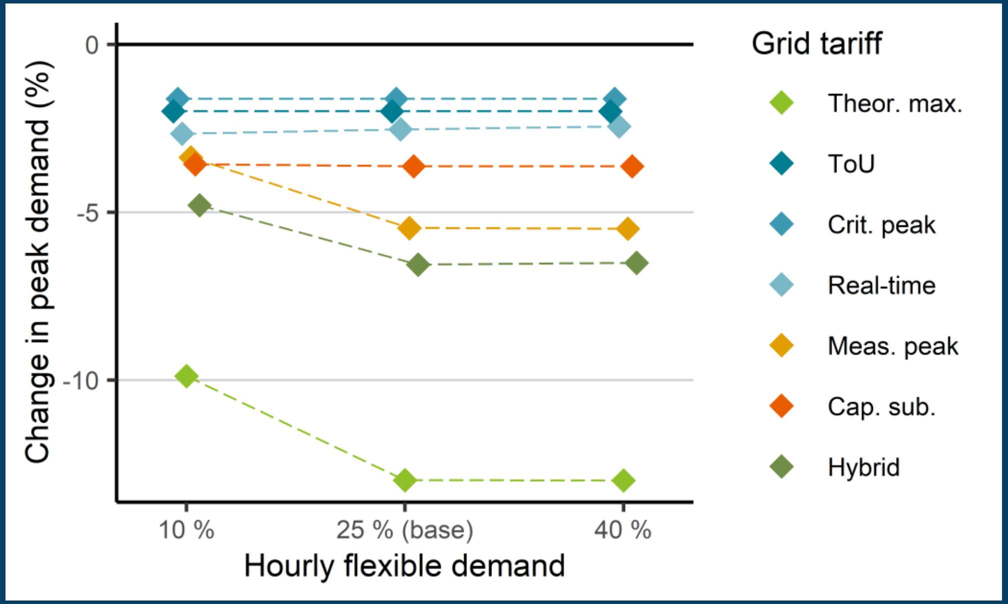
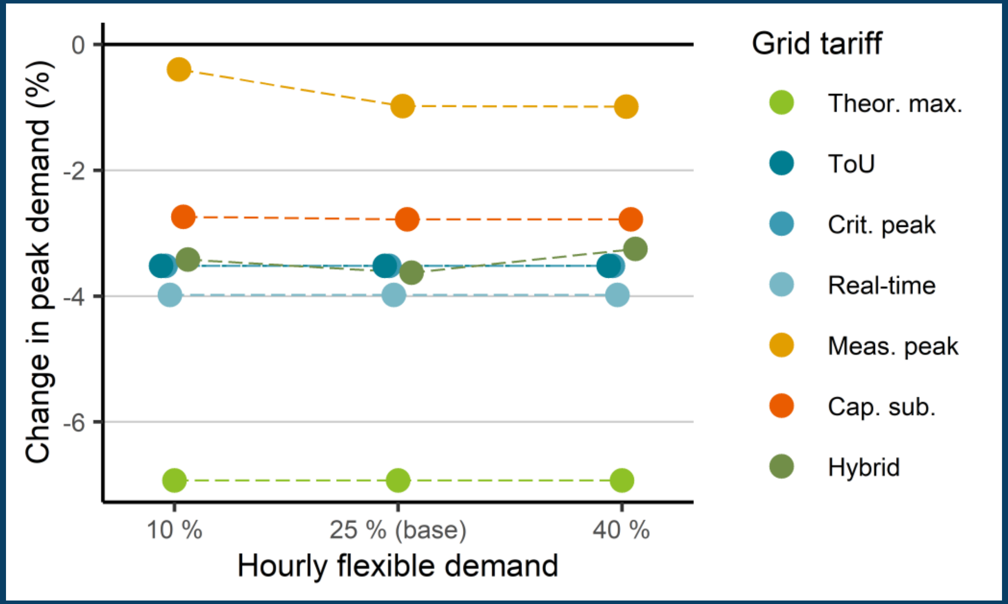
Sensitivity – level of **hourly** flexible demand

Substation



Transformer



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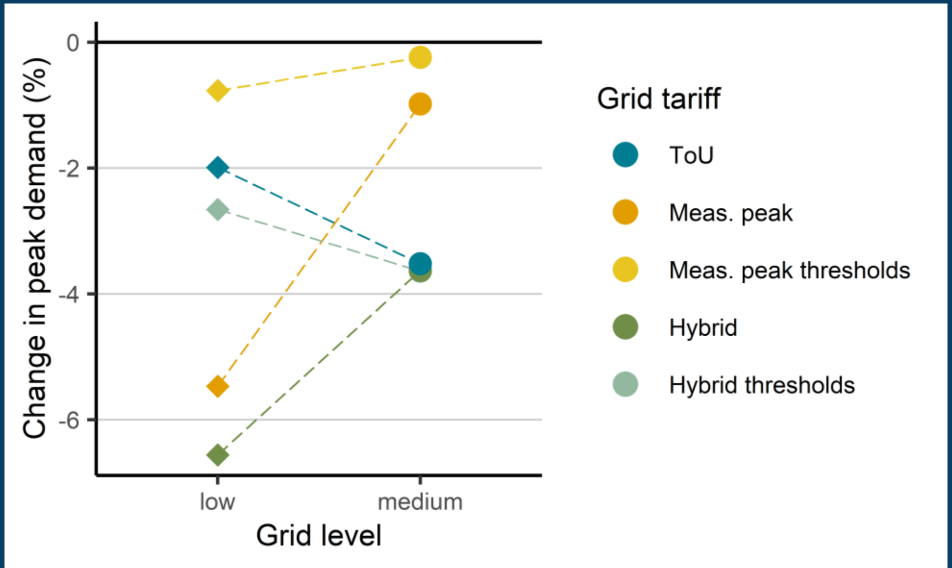
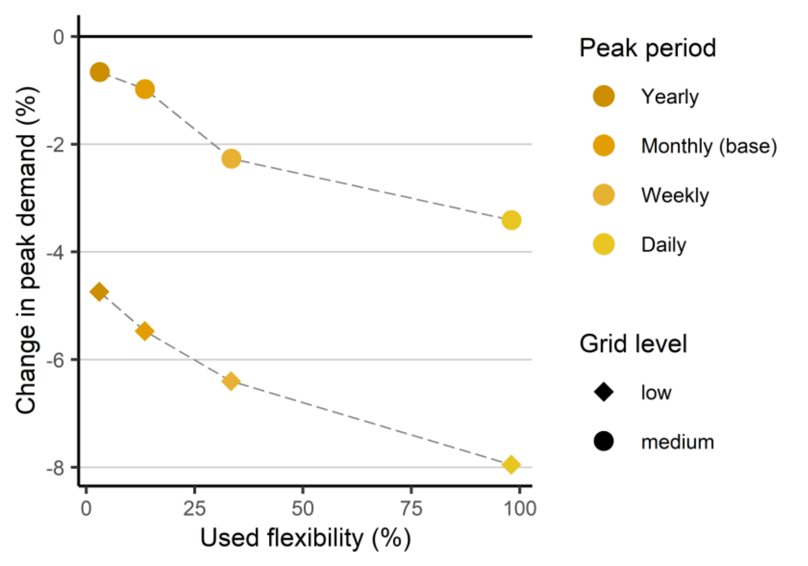
Measured peak demand: steps and peak period

- Adding steps reduces peak load reduction capability
  - The hybrid tariff is now essentially a time-of-use tariff
- Short peak period times increase peak demand reduction, but requires more response





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What happens when the spot price increases?

- **RQ4**: Aiming to reduce peak demand, is there a price signal conflict between electricity spot prices and grid tariffs?

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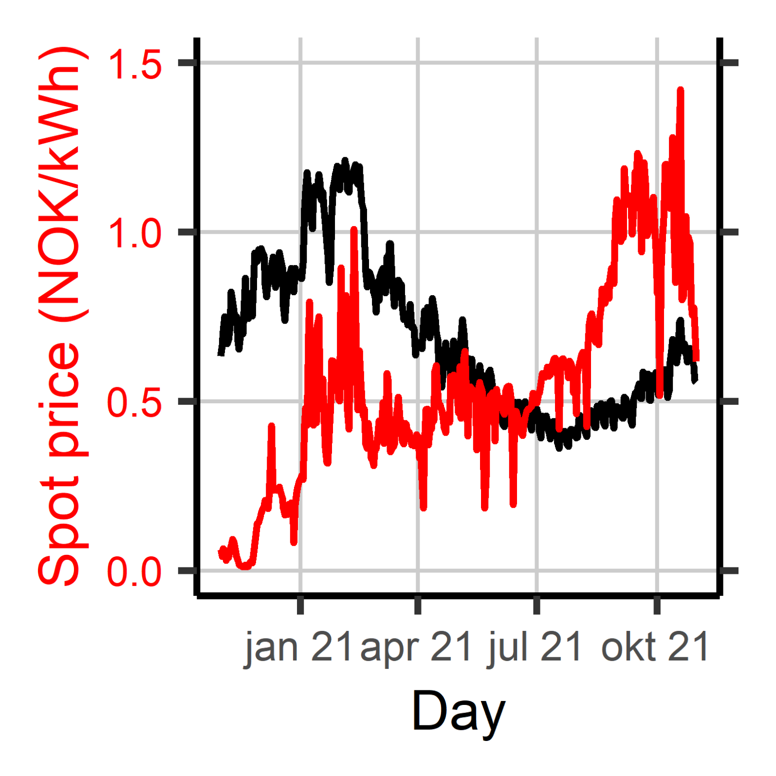
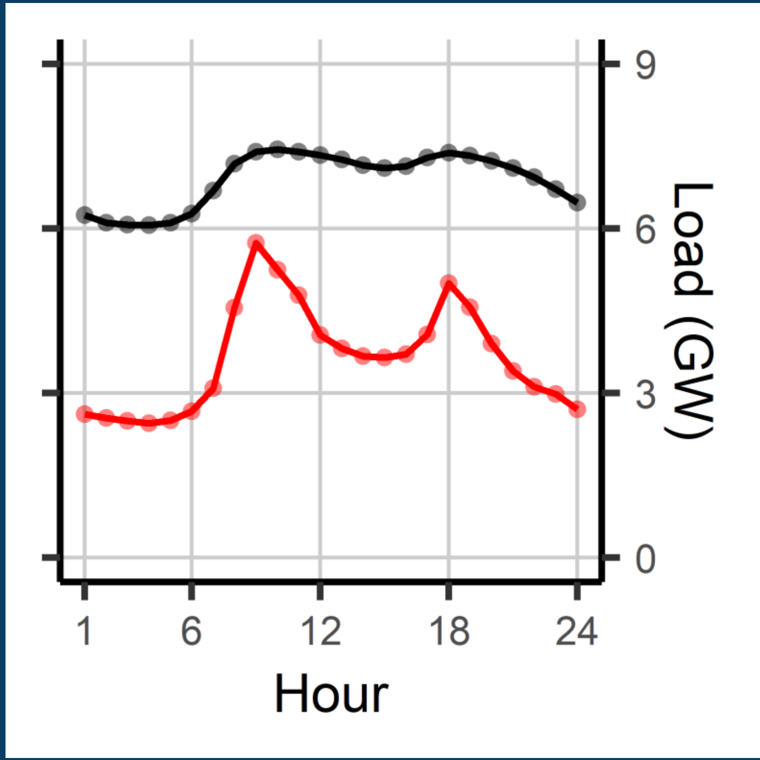
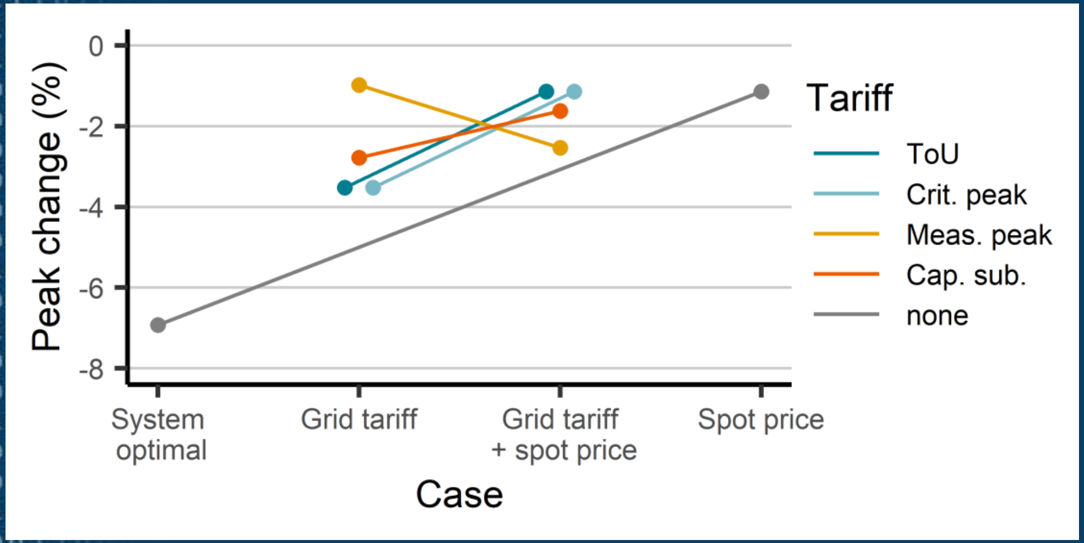
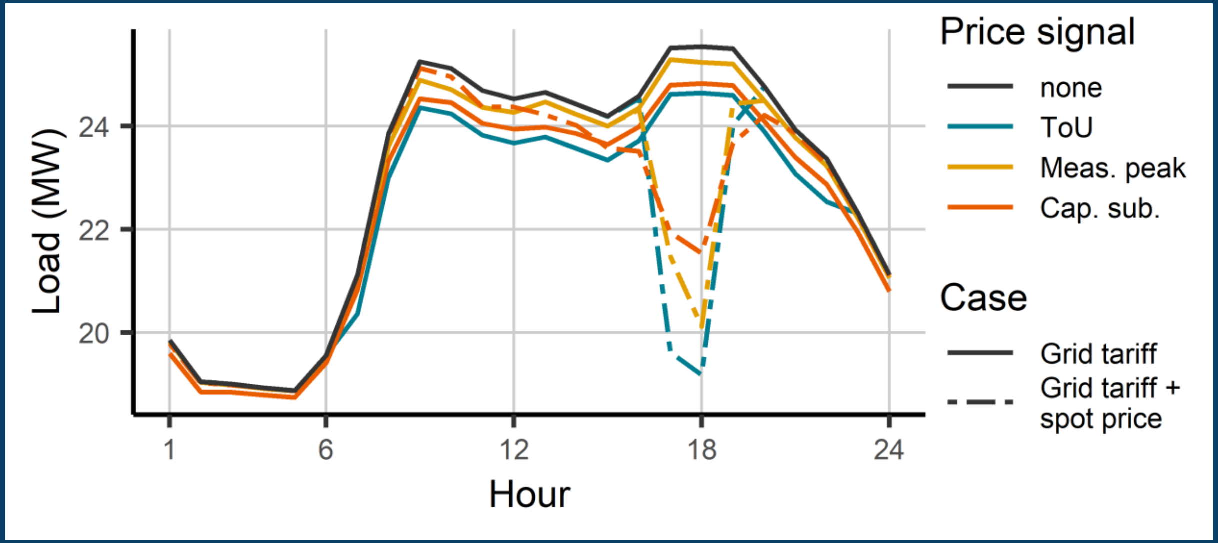
Spot prices correlate with peak demand on daily basis, but not on seasonal basis





Spot prices conflict with the price signal from grid tariffs





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Agenda

Introduction & research questions

Grid tariff design

Local electricity market design

Main findings

Take-aways

Take-aways & conclusions

- Research questions:

RQ1: How well do capacity-based grid tariffs and local electricity markets synergize in order to incentivize consumers to reduce peak demand?

Very well! Deals with coincidence factors, reduces peak demand and avoids cross-subsidies.

RQ2: How well do capacity subscription tariffs perform in terms of cost reflectivity, cost recovery and fairness?

Much better than existing tariffs, but have their own drawbacks.

RQ3: Which grid tariffs designs are the most cost reflective and efficient at reducing peak demand at different grid levels?

Hybrid and energy-based tariffs are more efficient on higher grid levels, capacity-based tariffs on lower grid levels.

RQ4: Aiming to reduce peak demand, is there a price signal conflict between electricity spot prices and grid tariffs?

Yes! Problematic for automatic demand response.

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Future work

- Consider dynamic subscription tariffs, especially for large consumers
  - Risk aspects
  - Cost reflectivity
- Local electricity markets and grid implications – grid should not be forgotten
- Consider more extensive cost redistribution and fairness aspects when designing grid tariffs
  - Determine cross-subsidies, industry ← → consumers, prosumers←→consumers

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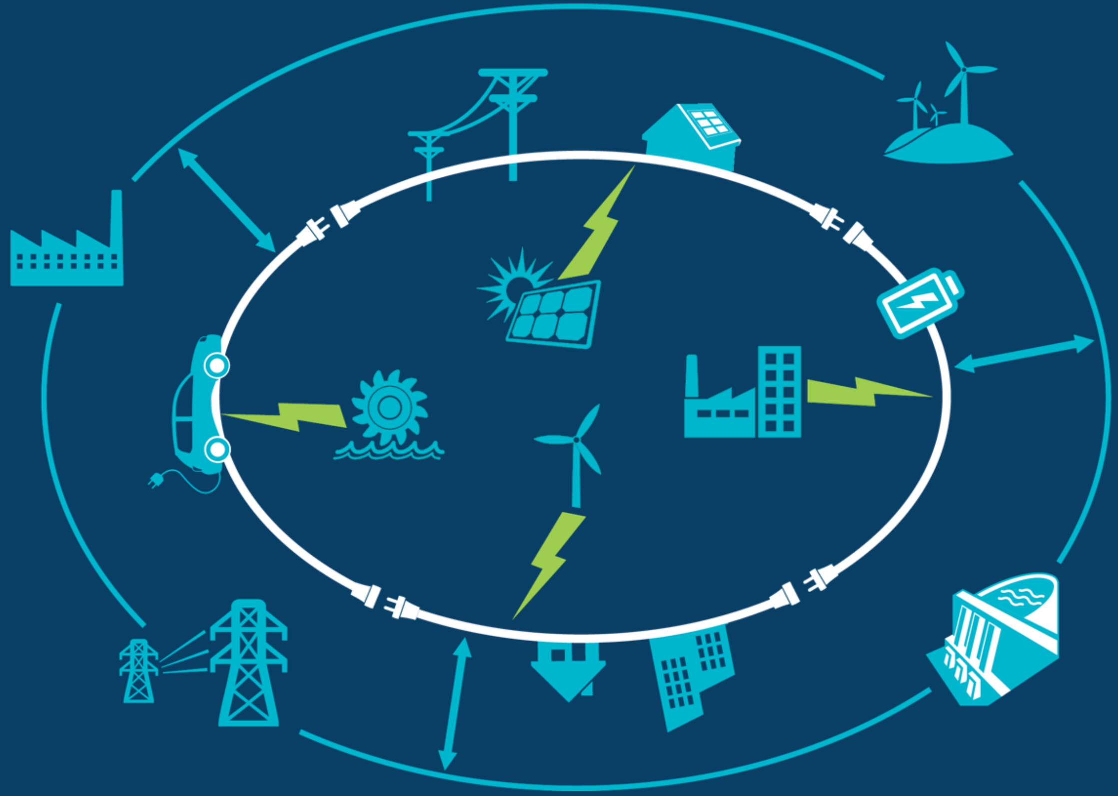
- to empower the future Smart Grid

Digital Economy (DigEco)

Norwegian Centre for Environment-friendly Energy Research



Thank you for your attention!

Questions?

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