# Managing the distribution grid: what's the limit?

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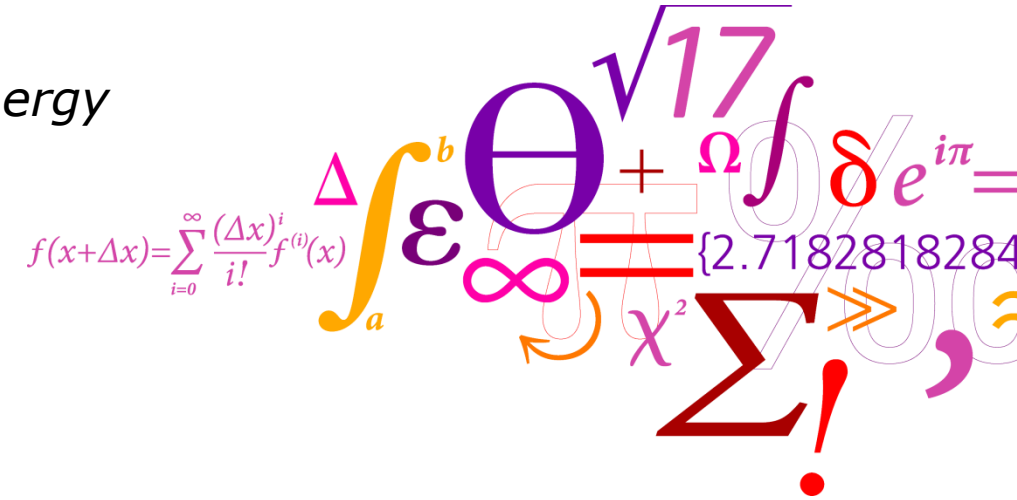



DTU Electrical Engineering
Department of Electrical Engineering

# Outline

- Introduction
- Study cases – LV grids
- Electric vehicle (EV) charging pattern model
- Technical analysis and results
- Economic analysis and results
- Conclusions and future work

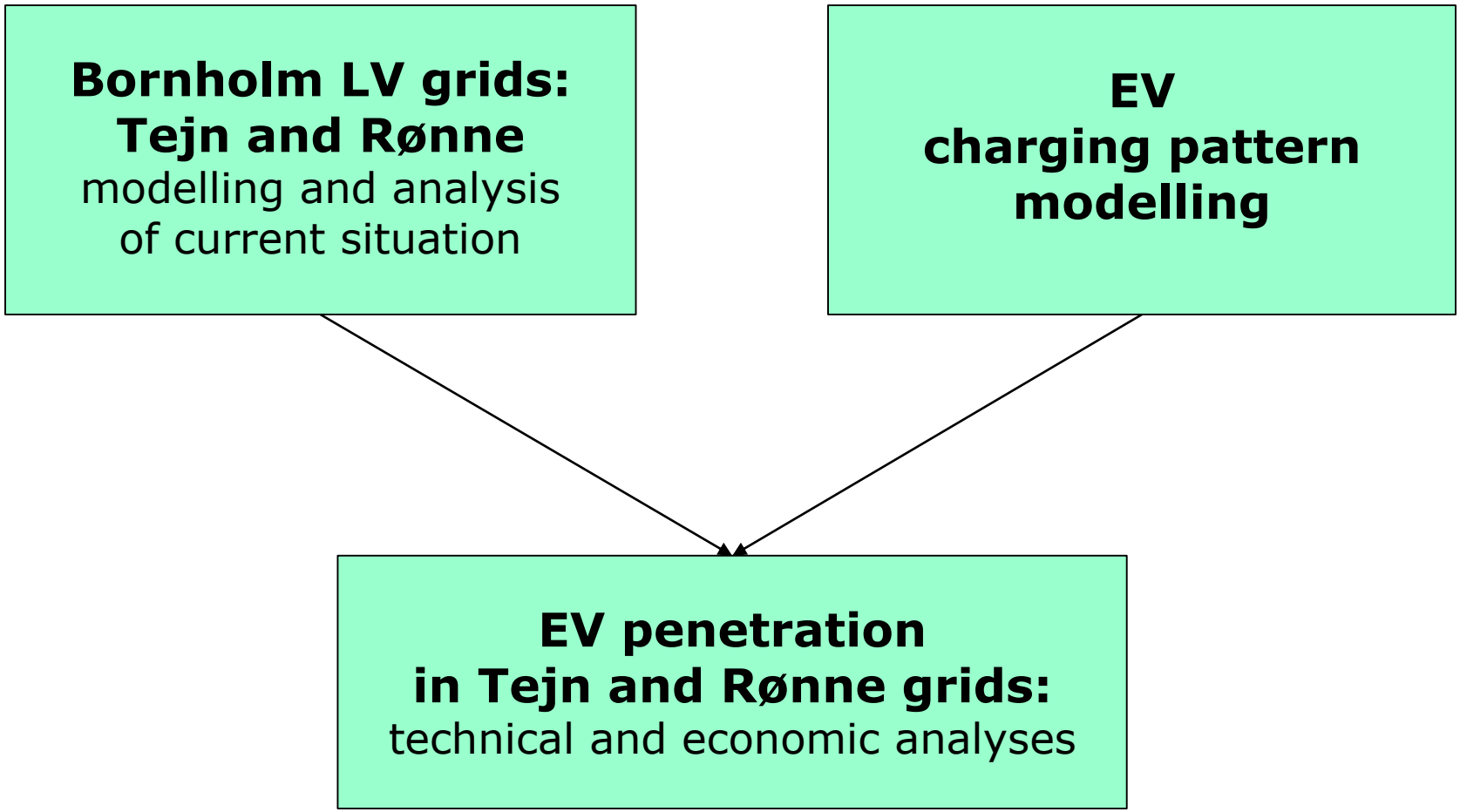
# Introduction

The electric vehicle (EV) market is growing

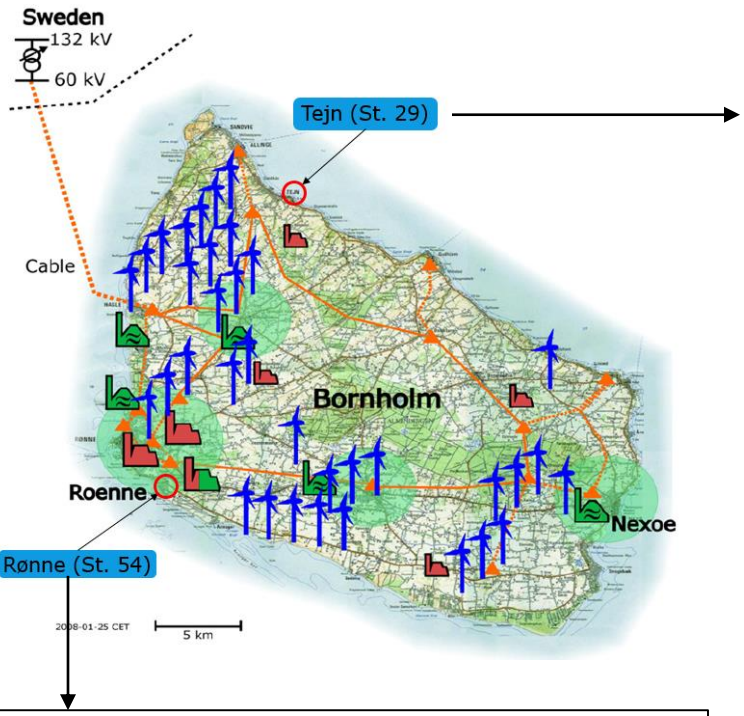
DSO concern regarding grid operation:
- Loading issues
- Voltage issues

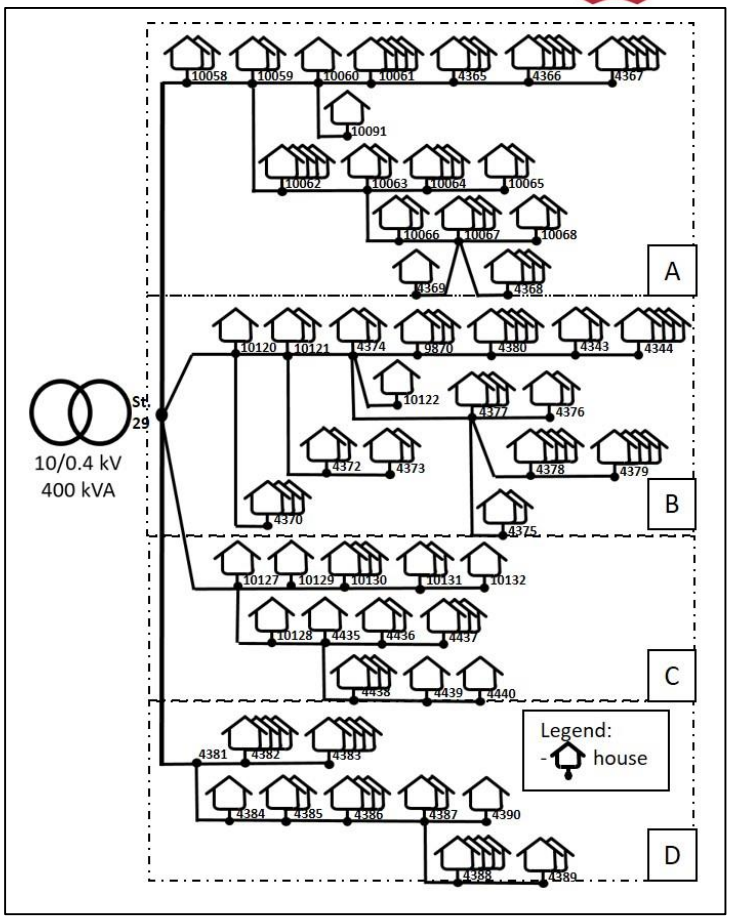
How can EVs be actively integrated in the electrical power distribution network maximizing the benefits for system, aggregator and user?

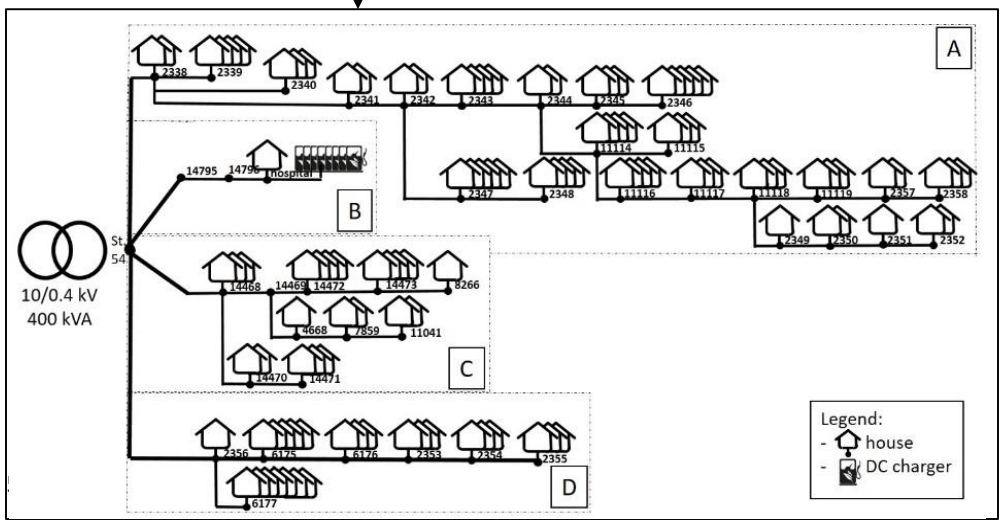
# Method


**Bornholm LV grids: Tejn and Rønne**
modelling and analysis of current situation
**EV charging pattern modelling**
**EV penetration in Tejn and Rønne grids:**
technical and economic analyses

# Study cases: LV grids




Based on the island consumption, Tejn and Rønne have characteristics, representative of the distribution grids in Bornholm.

# No EVs – base case scenario

## *Transformer/cable loading:*

No transformer/cable overloading

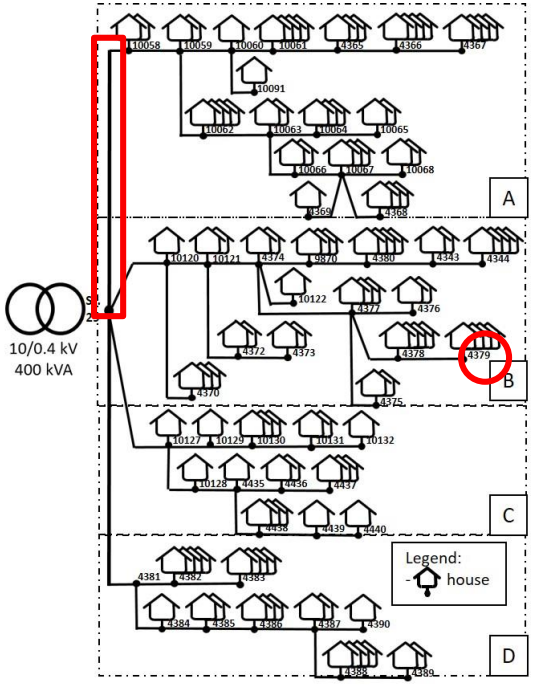
Most loaded cables:
- Tejn: cable ”St-10058”
- Rønne: cable ”St-2332”

## *Voltage analysis:*

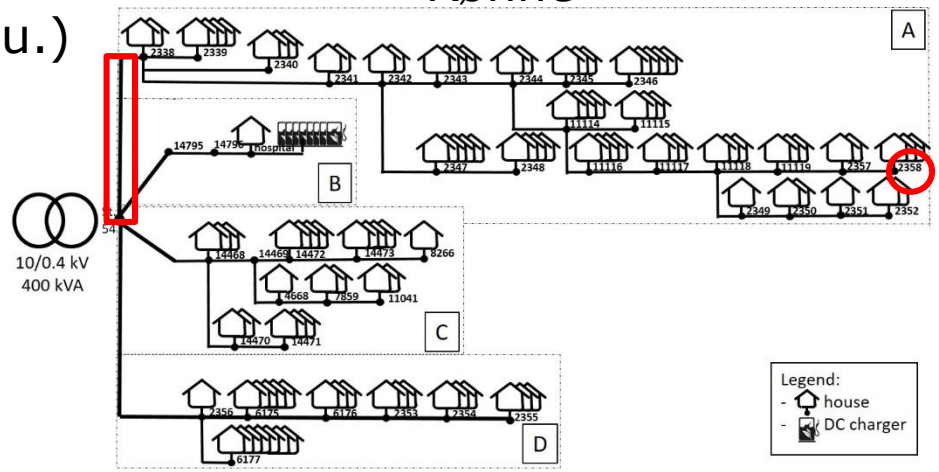
No under-voltage values (<0.9 p.u.)

Most critical terminals:
- Tejn: terminal 4379
- Rønne: terminal 2352

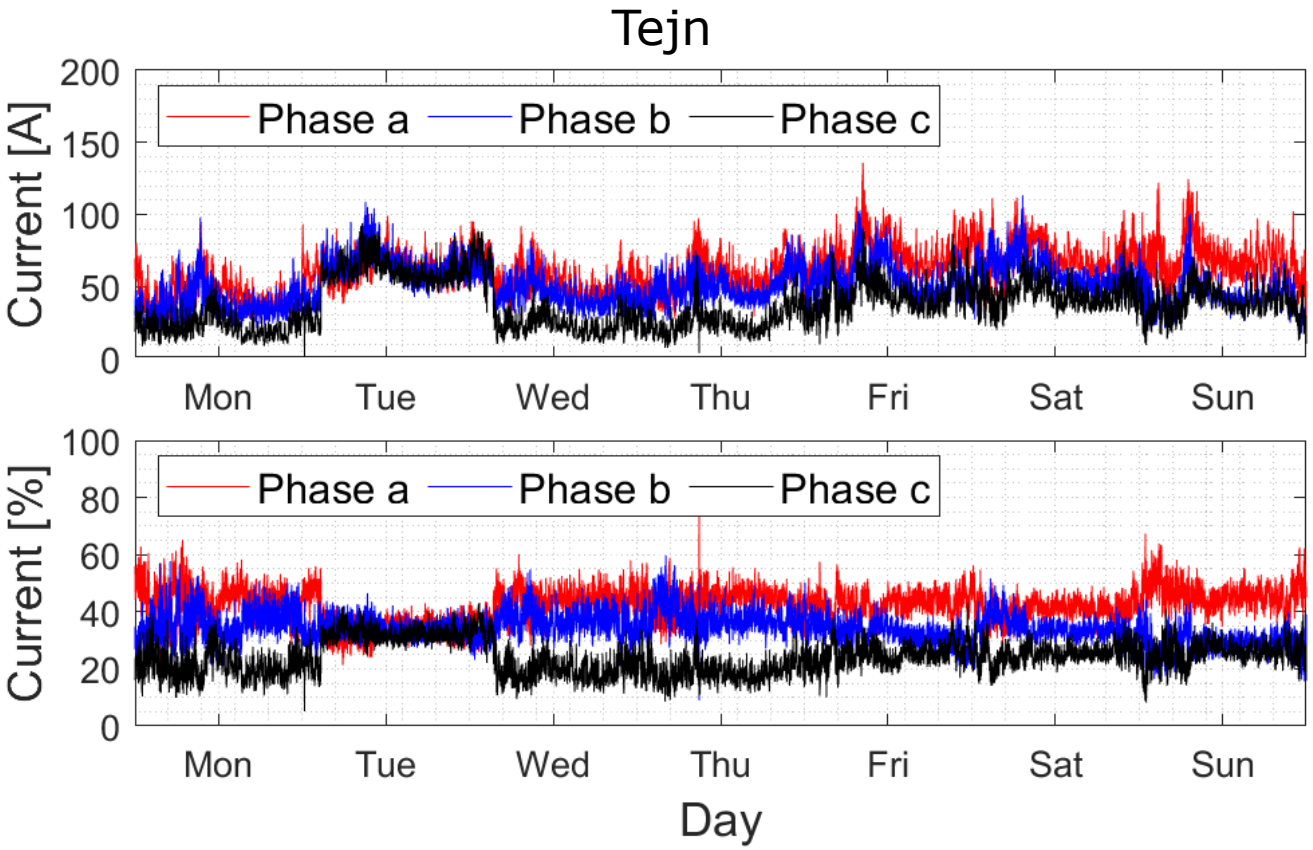
Tejn




Rønne



# Unbalanced grid




Mean distribution: 42% phase a, 33% phase b, 25% phase c.

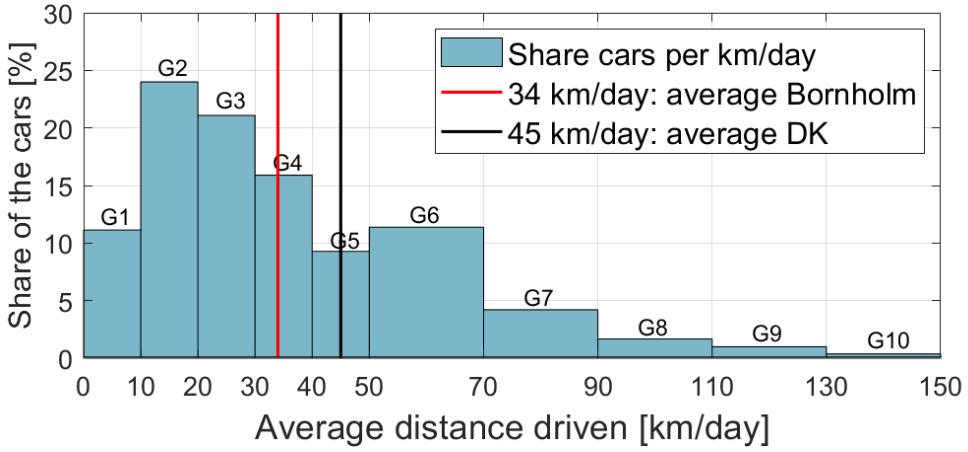
Rønne feeder has similar characteristics.

→ Assumed load: 40% in phase a, 30% in phase b, 30% in phase c.

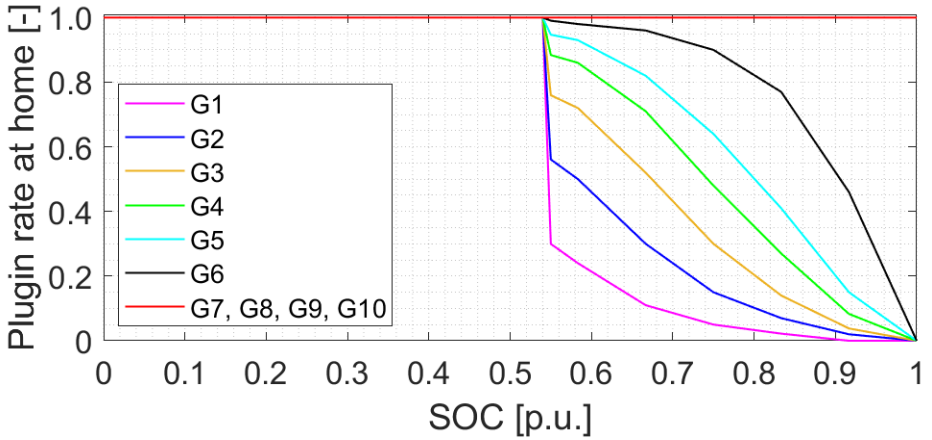
# EV charging pattern based on:

- historical driving characteristics of private conventional vehicles from Denmark

| Group | Distance x [km/day] |
|---|---|
| G1 | $0 < x \leq 10$ |
| G2 | $10 < x \leq 20$ |
| G3 | $20 < x \leq 30$ |
| G4 | $30 < x \leq 40$ |
| G5 | $40 < x \leq 50$ |
| G6 | $50 < x \leq 70$ |
| G7 | $70 < x \leq 90$ |
| G8 | $90 < x \leq 110$ |
| G9 | $110 < x \leq 130$ |
| G10 | $130 < x \leq 150$ |




- home plug-in behavior of EVs from Japan

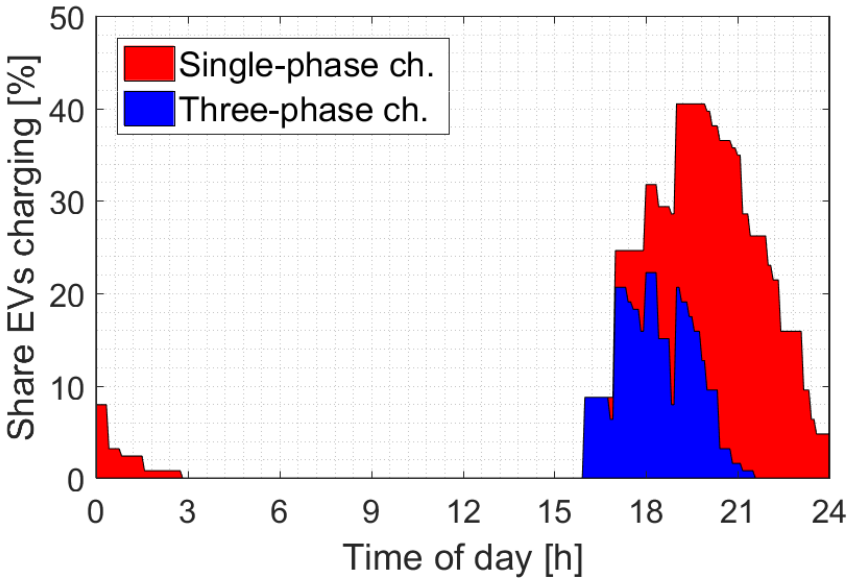


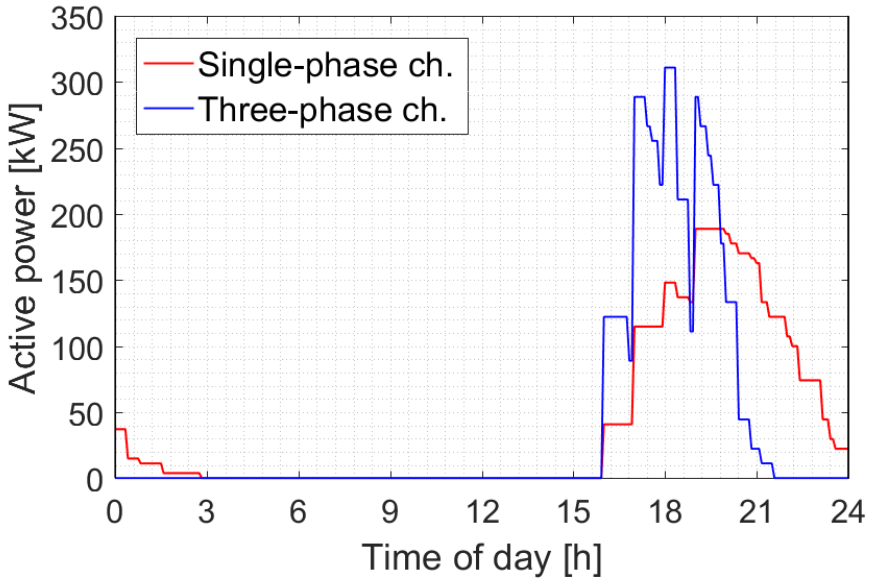

Evs: 40 kWh battery capacity

# EV charging pattern result

- Single-phase chargers (3.7 kW): max 40-45% EVs charging together
- Three-phase chargers (11.1 kW): max 20-25% EVs charging together
- Higher rated power of the chargers → less EVs charging at same time, but higher peak consumption.

Example with 127 EVs (127 households in Tejn → 100% EV penetration):

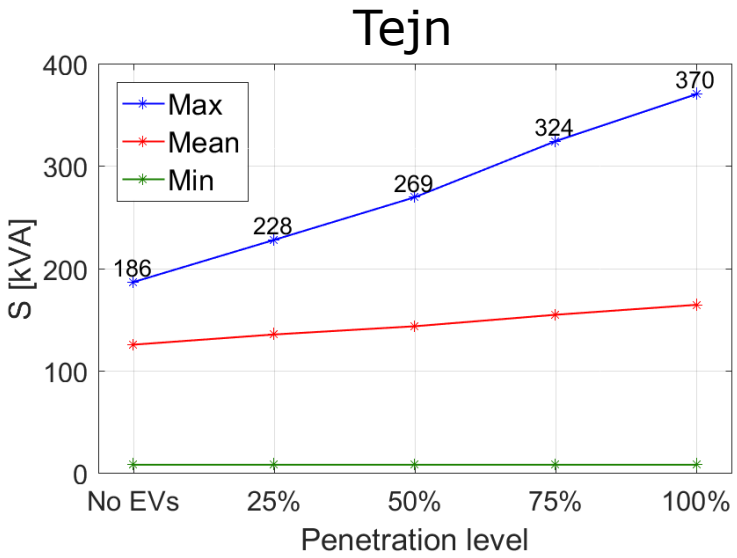


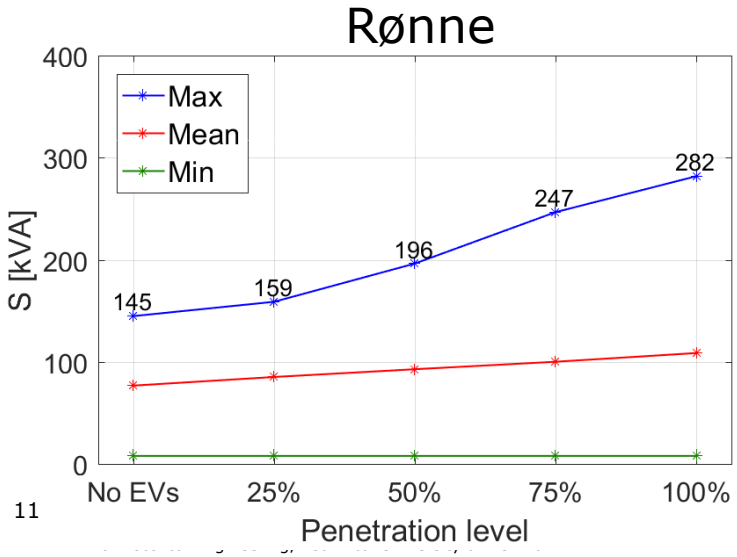



What are the impacts of
different penetration levels of EVs on the
distribution networks of Bornholm?

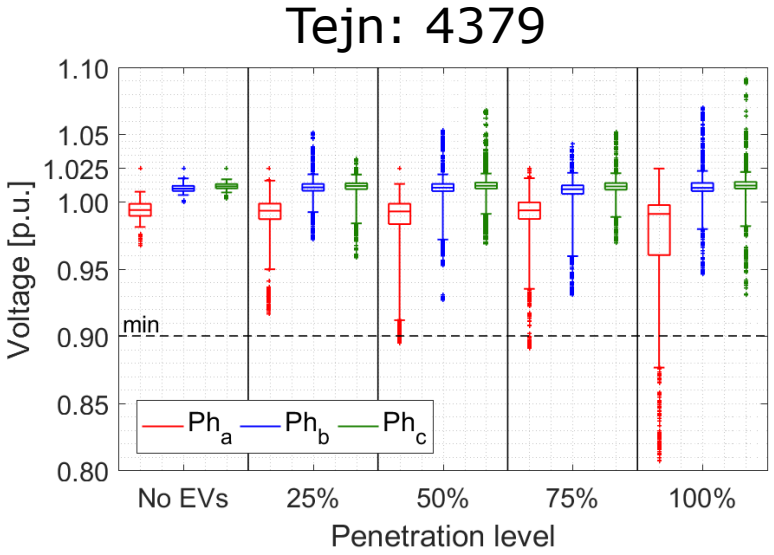
# Single-phase chargers

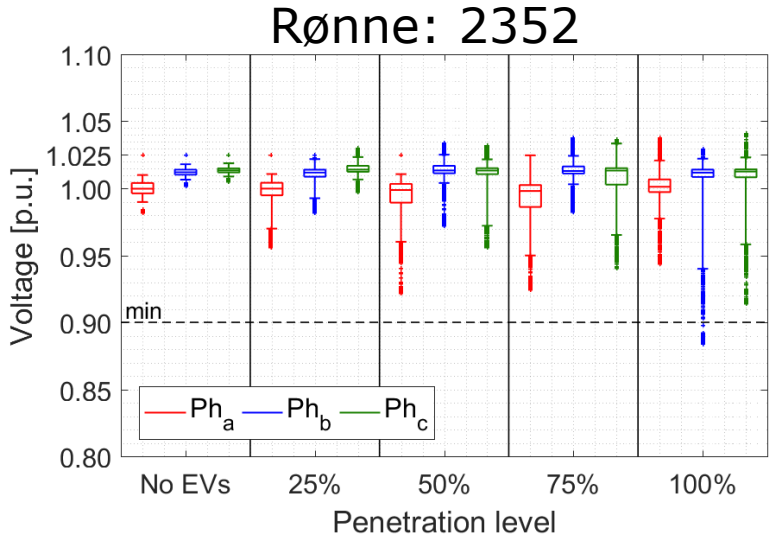
## *Transformer loading:*




## *Voltage analysis:*



# 100% EV penetration:
## - single-phase chargers (Ch-1ph)
## - three-phase chargers (Ch-3ph)

### *Transformer loading:*

| | *Transformer loading* | | | |
|---|---|---|---|---|
| | *Tejn* | | *Rønne* | |
| | mean [%] | max [%] | mean [%] | max [%] |
| *Ch-1ph* | 41.4 | 93.5 | 27.2 | 70.5 |
| *Ch-3ph* | 40.8 | 120 | 28.0 | 99.5 |

9.25 h

### *Cable loading:*

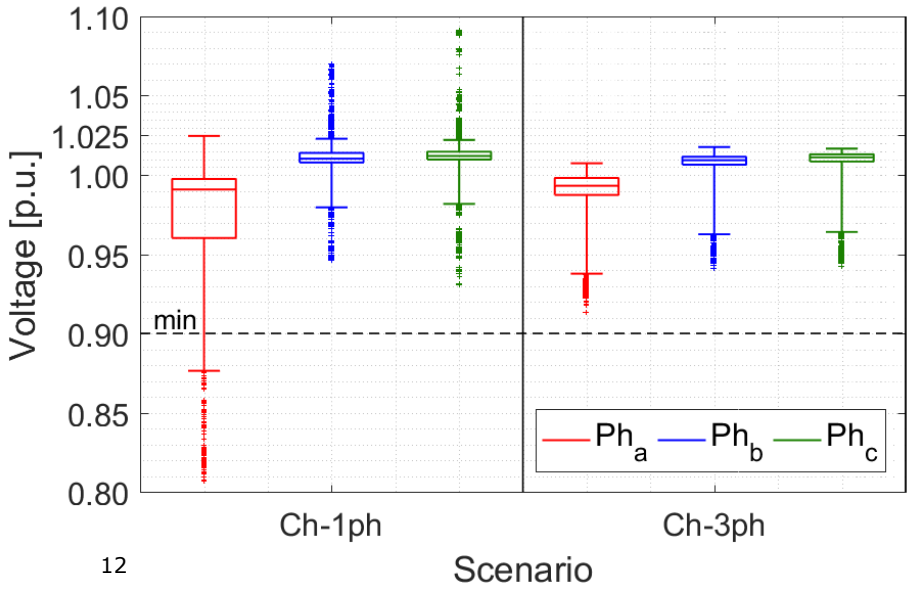
| | *Cable loading* | | | |
|---|---|---|---|---|
| | *Tejn: St-10058* | | *Rønne: St-2338* | |
| | mean [%] | max [%] | mean [%] | max [%] |
| *Ch-1ph* | 36.0 | 91.6 | 27.4 | 79.6 |
| *Ch-3ph* | 34.7 | 116 | 28.3 | 102 |

2 h

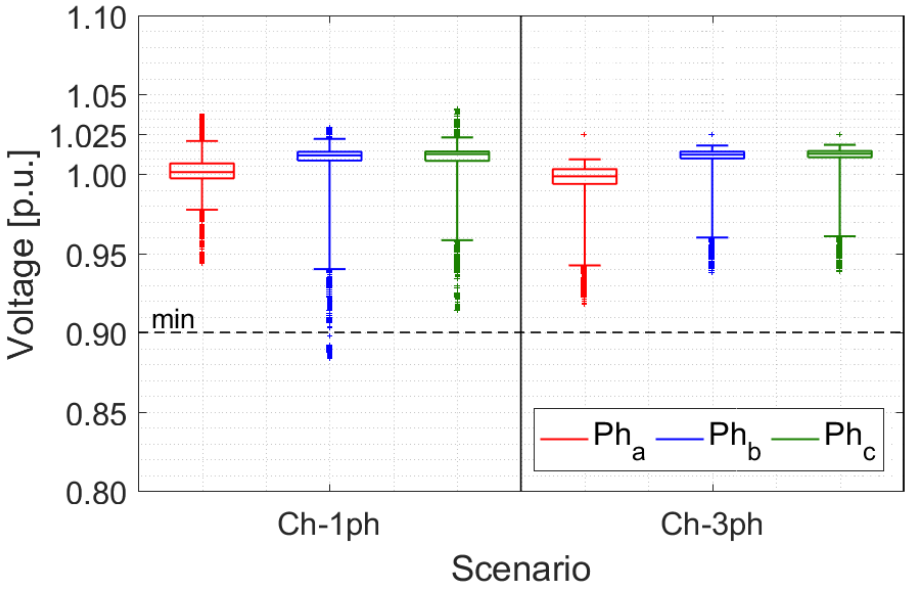
0.2 h (11 min)

### *Voltage analysis:*

Tejn: 4379




Rønne: 2352



Which value can the EVs, as a flexible active component of the distribution system network, create for the system? How should it be remunerated?

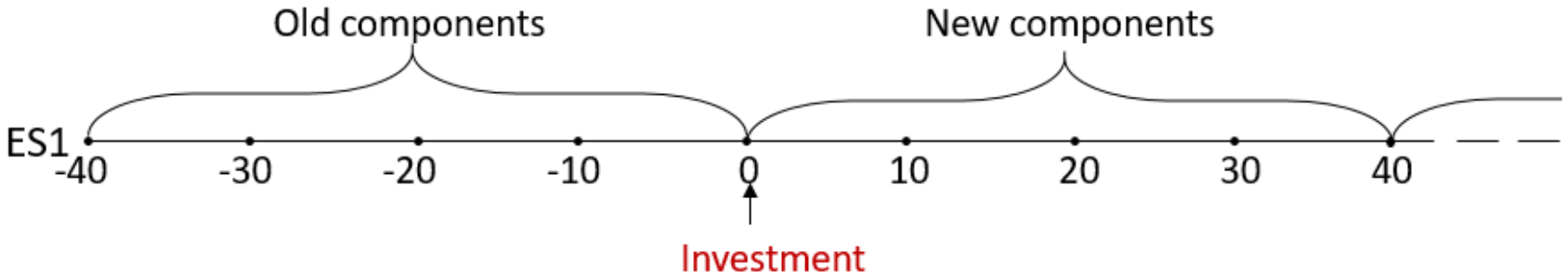
Voltage issues → EV active power modulation

Congestion issues:

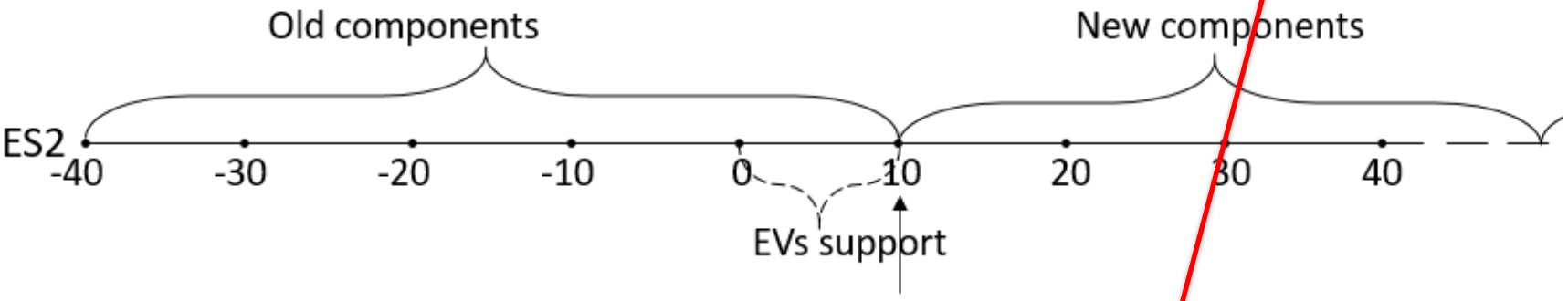
→ ES1: DSO approach to transformer/cables overloading → **new upgraded transformer/cables**

→ ES2: new approach to transformer/cables overloading → **EV support service:** DSO is allowed by the EV owners to change the active power consumption

# Economic scenario comparison



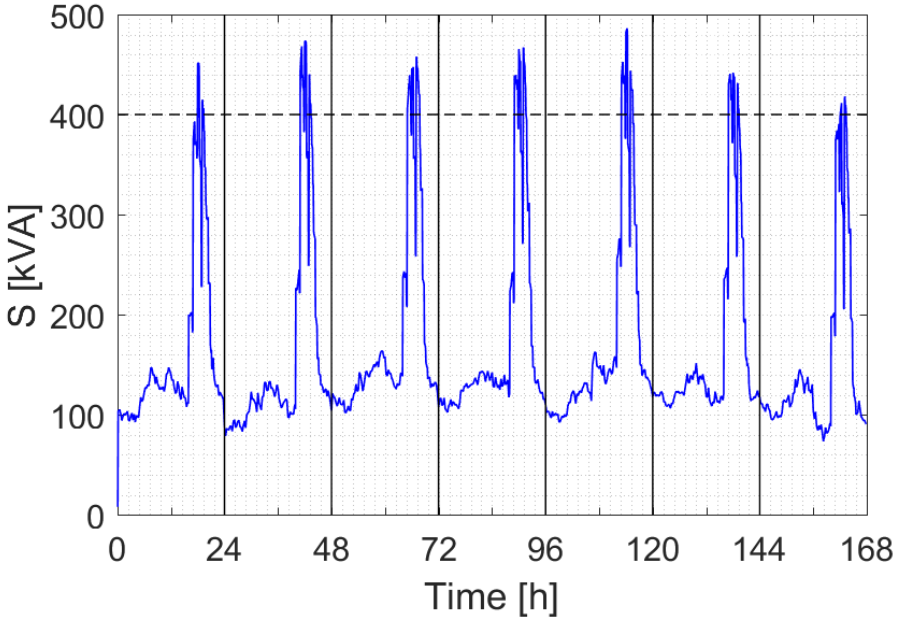

Replacement/upgrade transformer (400→630) and two cables:
Total investment: $CAPEX = 319500\ DKK + 69218\ DKK = 388718\ DKK$



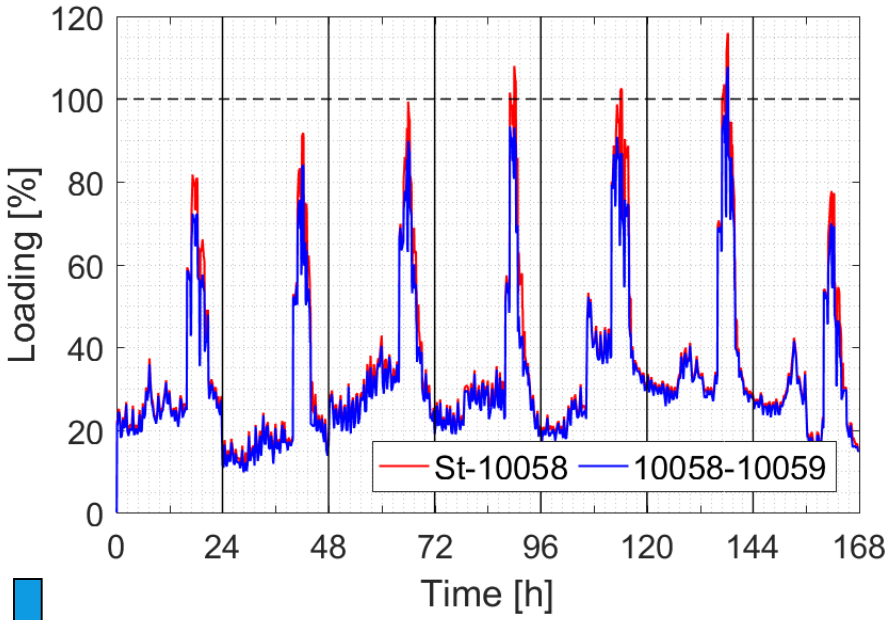

| *ES2* | |
|---|---|
| Money available for 10 years | 97180 DKK |
| Money available per year | 9718.0 DKK |
| Money available per week | 186.9 DKK |

# Economic scenario: Tejn

Transformer




Cables




| Scenario: | Ch-3ph |
|---|---|
| Moved energy during one week | 393 kWh |
| Maximum payment per kWh | 0.48 DKK/kWh |

~ 77 DKK/year per customer

# Conclusions

- Tejn and Rønne, representative distribution grids of Bornholm, without EVs do not present congestion and voltage issues

- EV charging pattern model:
  - single-phase chargers → 40-45% EVs charge together
  - three-phase chargers → 20-25% EVs charge together
  → max active power consumption is higher with three-phase

- EVs connected with single-phase chargers:
  → under-voltage values, issues only with 100% penetration
  → solution: EV active power modulation

# Conclusions

- EVs connected with three-phase chargers:

  → congestion issues with 100% penetration

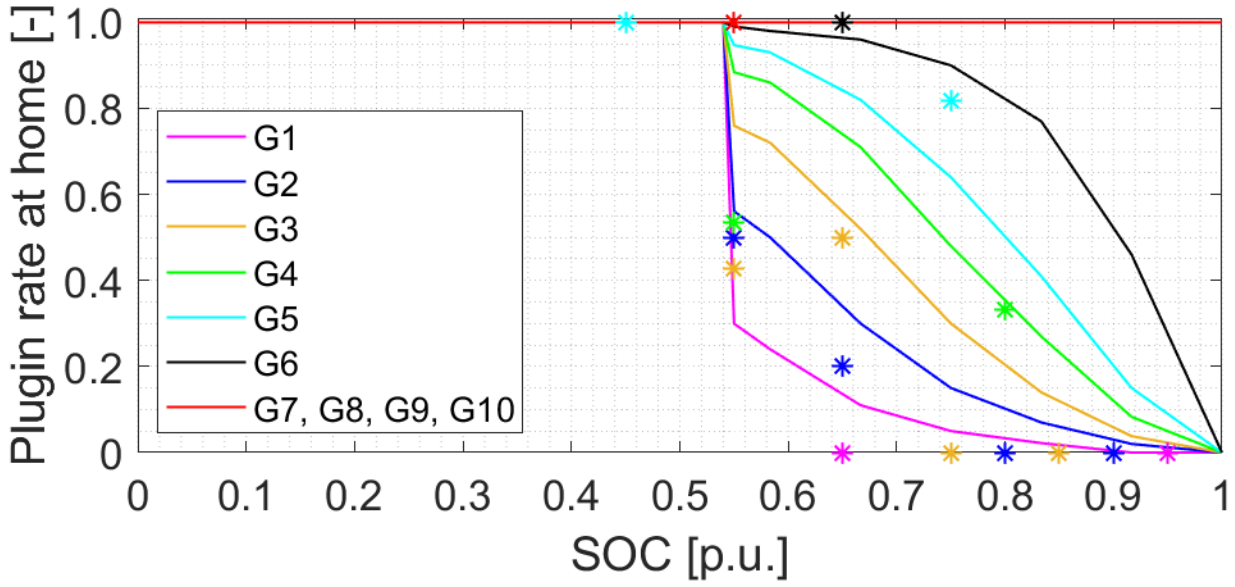
  → solution: 1. components upgrade → investment: 388718 DKK
  → cost-effective with many and long overloading periods

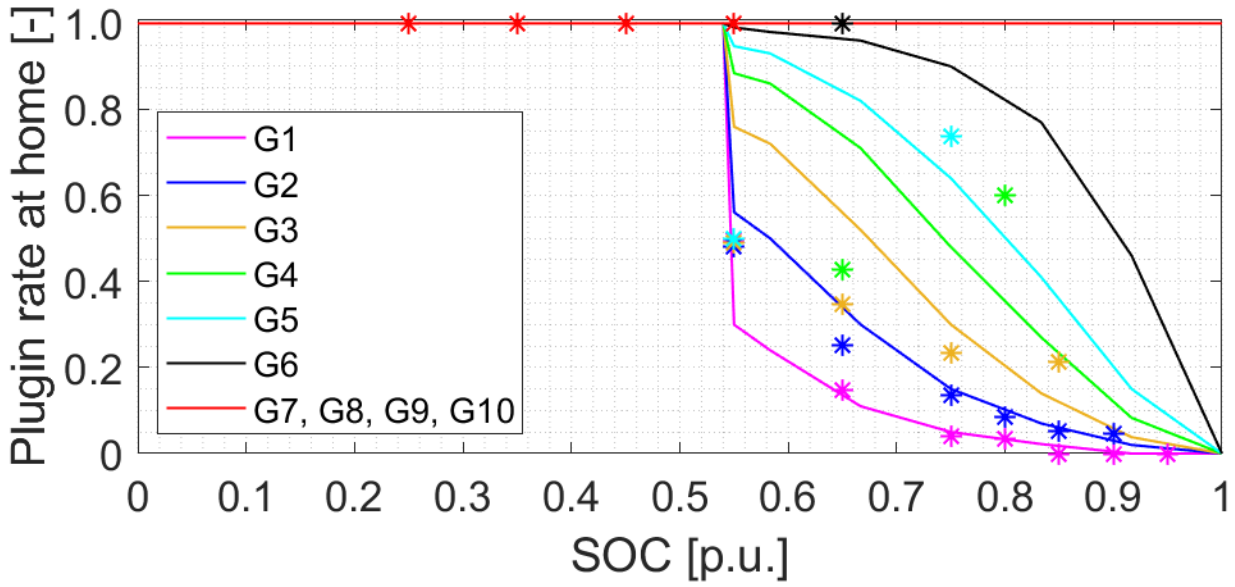
  2. EV support service → available ~190 DKK/week
  → ~77 DKK/y per customer
  → preferable with few and short overloading periods
  → less need of EV support means higher remuneration

# Future work

- Loading impact of V2G
- Plug-in rate at workplace
- Impact of fast chargers

# Thanks for your attention!

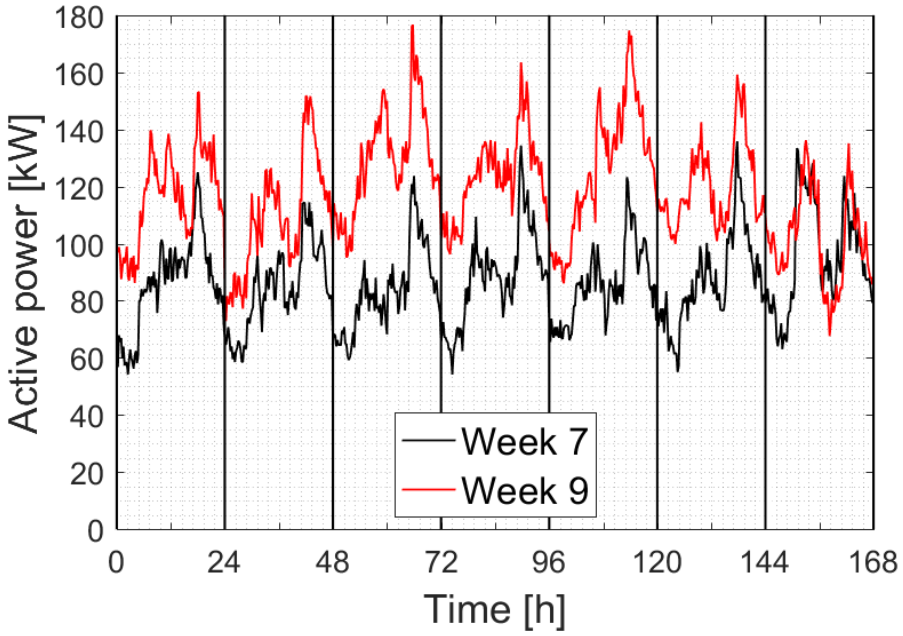

Plugin rate at home [-]
1.0
0.8
0.6
0.4
0.2
0
G1
G2
G3
G4
G5
G6
G7, G8, G9, G10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
SOC [p.u.]


Plugin rate at home [-]
1.0
0.8
0.6
0.4
0.2
0
G1
G2
G3
G4
G5
G6
G7, G8, G9, G10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
SOC [p.u.]

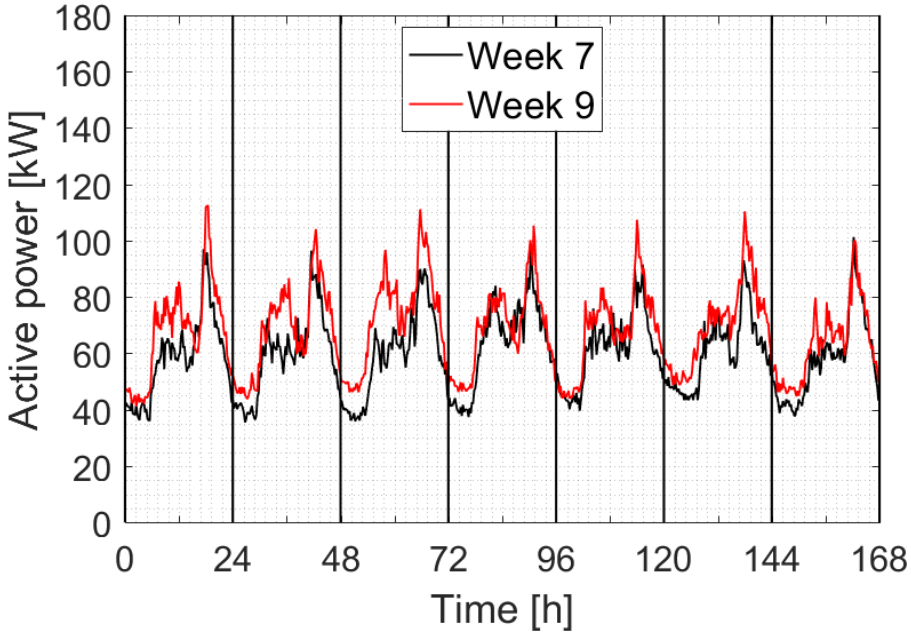
# Household consumption analysis

Analyzed weeks:
- Week 7: 12th to 18th February → normal winter week
- Week 9: 26th February to 4th March → the "Siberian cold"

Tejn



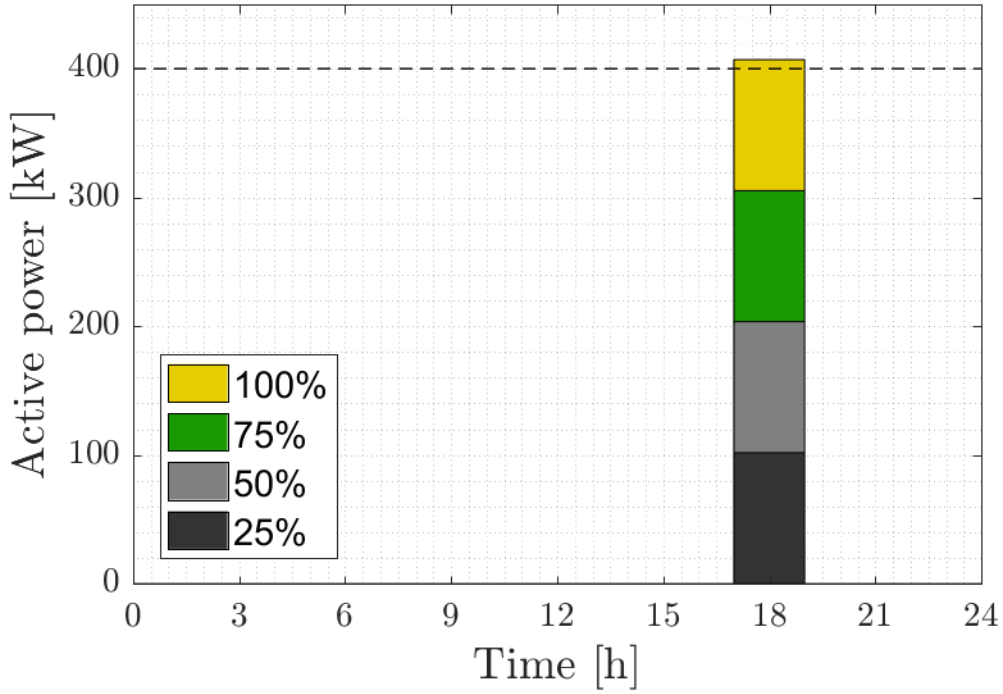

Rønne




The following analysis considers **week 9** assuming:
- cos(Φ) = 0.966 (derived from Ecogrid data)
- Load split on the 3 phases: 40%-30%-30% (derived from SGU data).

# Simple approach example

- LV distribution grid with 400 kVA MV/LV transformer
- 110 householders
- EVs penetration levels: 25%-50%-75%-100% → 110 EVs with 100% penetration
- Plug-in time 17:00 for all EVs
- Average of 35 km/day

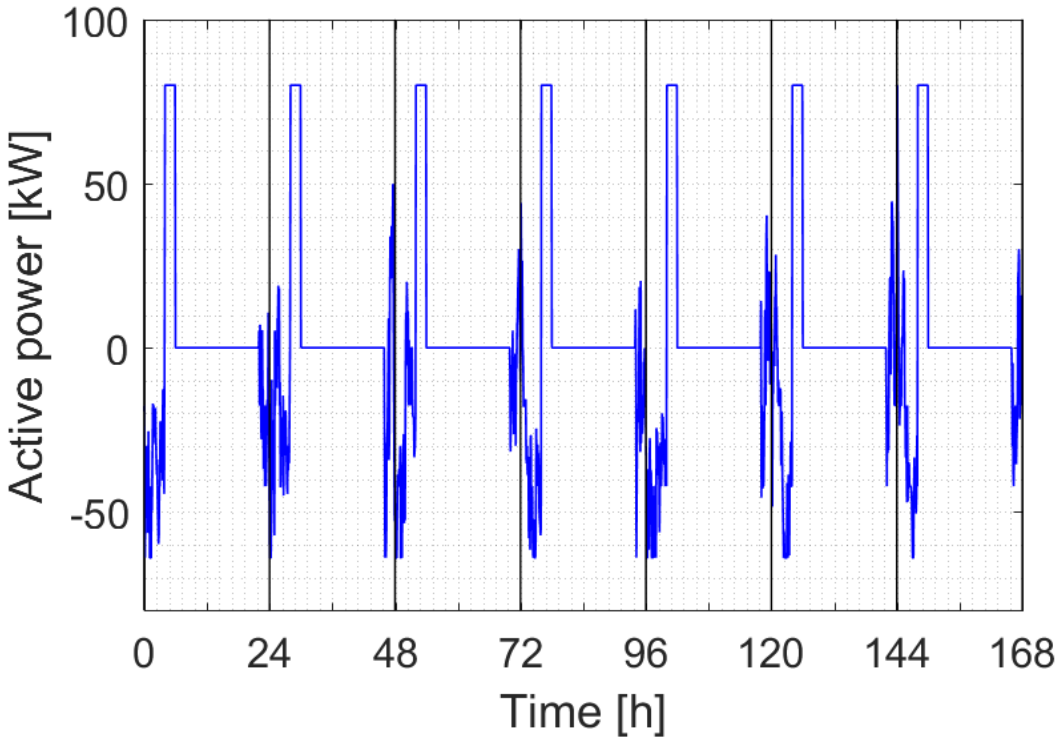


# Fast chargers

Unknown consumption week 9.

Charging pattern is designed as follows:

- 10 pm - 4 am: Evs are used for frequency regulation
- 4 am - 6 am: EVs are charged → - average driven distance 80 km/day
  - 6 am Evs have to be fully charged
- 6 am - 10 pm: EVs are driven → power equal to zero.



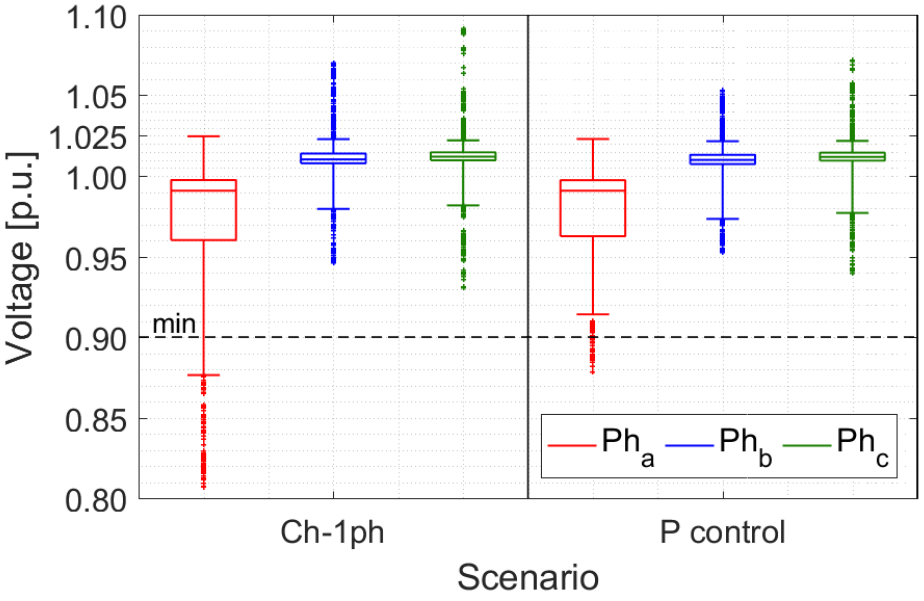
# Ch-1ph: no control/P control

*Transformer loading:*

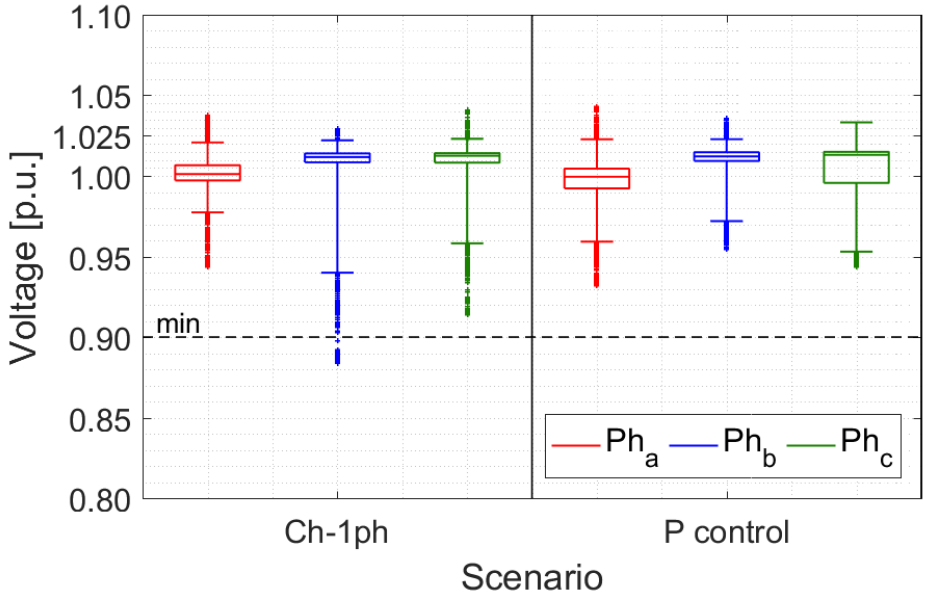
| | *Transformer loading* | | | |
|---|---|---|---|---|
| | *Tejn* | | *Rønne* | |
| | mean [%] | max [%] | mean [%] | max [%] |
| *Ch-1ph* | 41.4 | 93.5 | 27.2 | 70.5 |
| *P control* | 40.8 | 88.6 | 27.0 | 68.8 |

*Voltage analysis:*

Tejn




Rønne



# Ch-1ph: balanced/unbalanced

## *Transformer loading:*

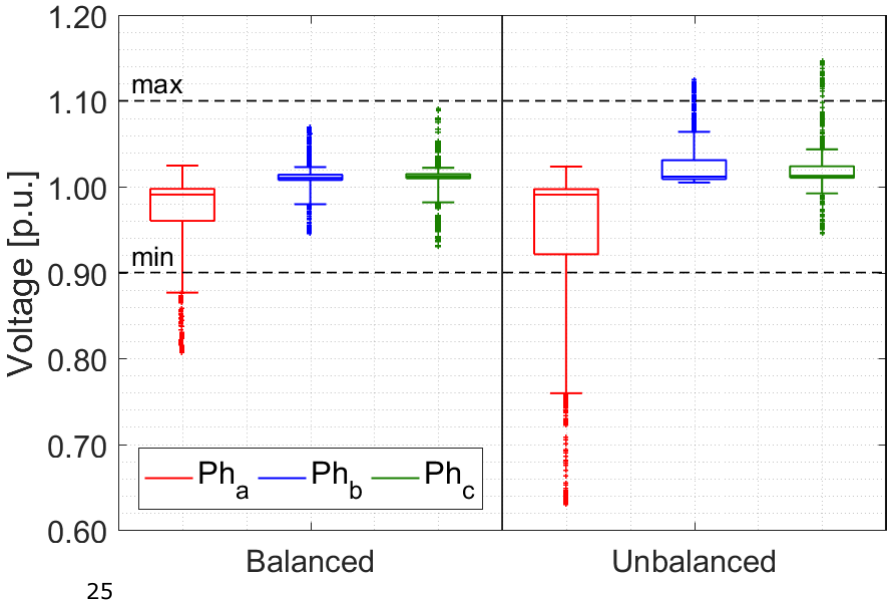
| | ***Tejn*** | ***Ronne*** |
|---|---|---|
| | $\mathbf{S_{max}}$ [%] | $\mathbf{S_{max}}$ [%] |
| *Balanced* | 93.4 | 70.5 |
| *Unbalanced* | 94.7 | 68.7 |

## *Cable loading:*

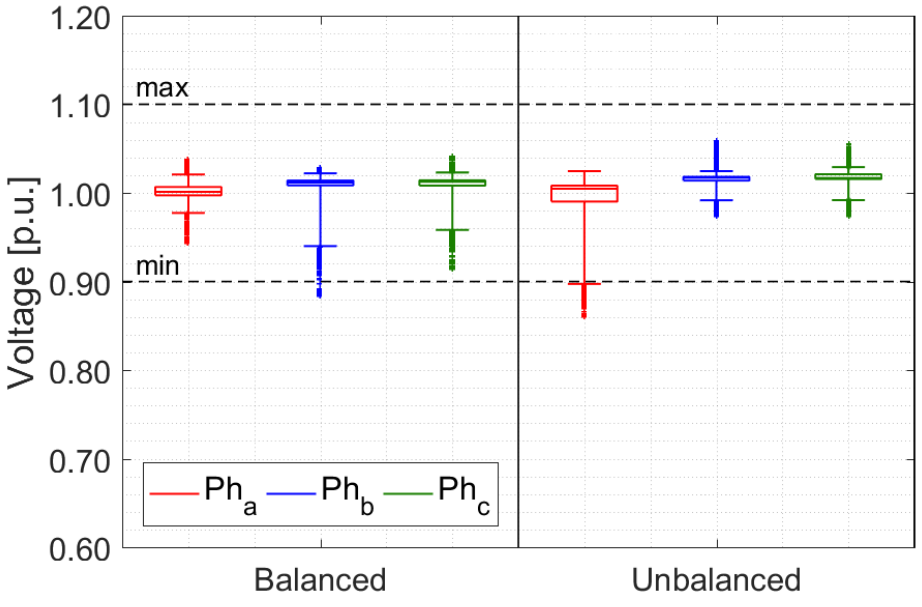
| | ***Cable loading*** | | | | | |
|---|---|---|---|---|---|---|
| | ***Tejn: St-10058*** | | ***Tejn: St-10120*** | | ***Rønne: St-2338*** | |
| | **mean** [%] | **max** [%] | **mean** [%] | **max** [%] | **mean** [%] | **max** [%] |
| *Balanced* | 36.0 | 91.6 | 24.5 | 68.0 | 27.4 | 79.6 |
| *Unalanced* | 36.1 | 84.8 | 31.2 | 113 | 29.5 | 93.5 |

## *Voltage analysis:*

Tejn




Rønne



# Effect of the ToU tariffs: plug-in time all EVs at 20

EV owners perspective: 0.5 DKK/kWh less if charging after 20

→ Total savings per year approx. 310-550 DKK…

## *Transformer loading:*

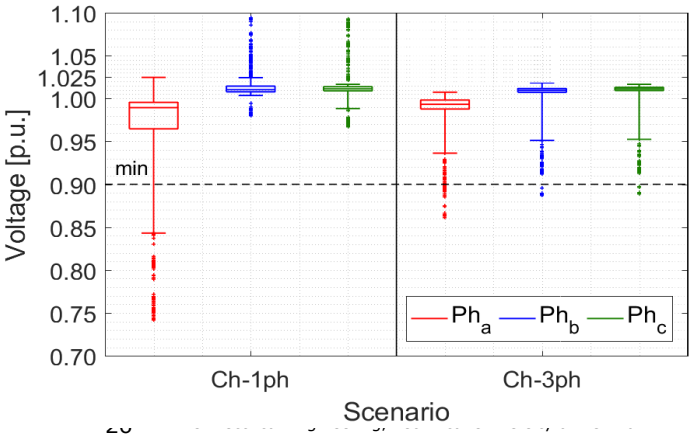
| | *Transformer loading* | | | |
|---|---|---|---|---|
| | *Tejn* | | *Ronne* | |
| | max [%] | time [h] | max [%] | time [h] |
| *Ch-1ph* | 93.4 | 0 | 73 | 0 |
| *Ch-3ph* | 201 | 10.8 | 162 | 9.83 |

## *Cable loading:*

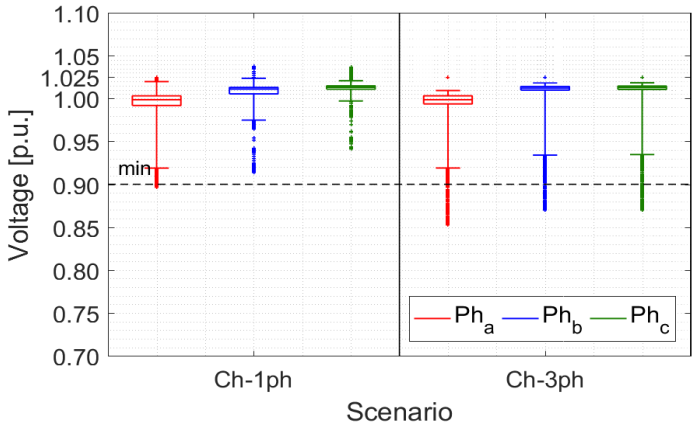
| | *Cable loading* | | | |
|---|---|---|---|---|
| | *Tejn: St-10058* | | *Ronne: St-2338* | |
| | max [%] | time [h] | max [%] | time [h] |
| *Ch-1ph* | 106 | 2 | 85.9 | 0 |
| *Ch-3ph* | 199 | 9.75 | 161 | 9.82 |

## *Voltage analysis:*

Tejn




Rønne




…**DSO** perspective
→ Congestion, low-voltage values