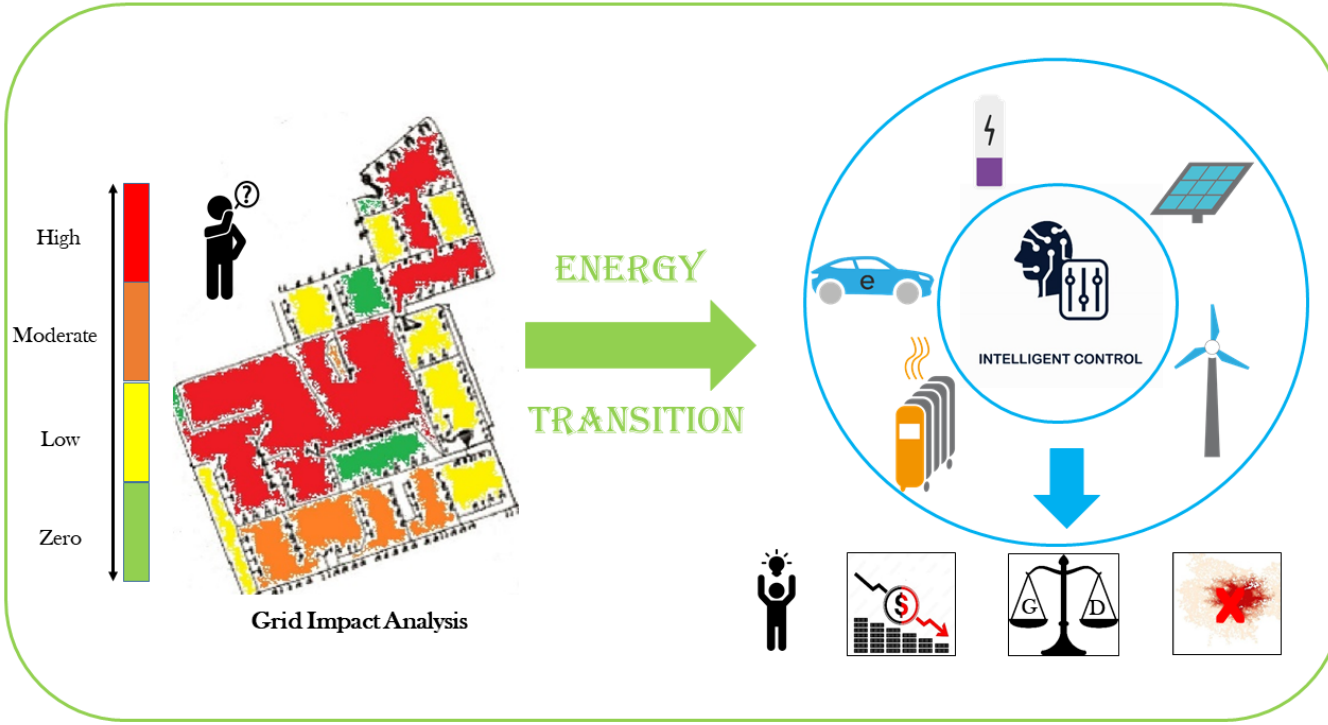
Grid Impact of Energy Transition and its mitigation with Coordinated Power Control



Damianakis Nikolaos

In cooperation with the ongoing research project NEON (New Energy and Mobility Outlook of the Netherlands)

"Accelerating the Transition to Sustainable Energy and Mobility"

with project number 17628 of the research program Crossover, which is (partly) financed by the Dutch Research Council (NWO)

Promotor: Prof Dr. Eng. Pavol Bauer

Daily Supervisor: Dr. Ir. Gautham R.C. Mouli

Electrical Sustainable Energy Department
DC Systems, Energy Conversion & Storage
Delft University of Technology, February 2023

Presentation Overview

- **Research Overview**
  - State-of-the-art, Motivation & Scientific Gaps
  - Contributions & Challenges

- **Work & Results**
  - Part 1: Grid Impact of Energy Transition
    - Methodology & Results
  - Part 2: Management of Grid Impact with Coordinated Control
    - Methodology & Results

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Research Overview

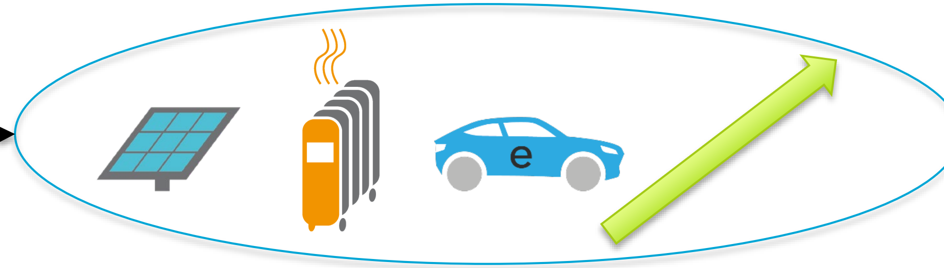
Part 1: Grid Impact of Energy Transition

Part 2: Management of Energy Transition’s Grid Impact with Coordinated Control

State-of-the-art & Motivation

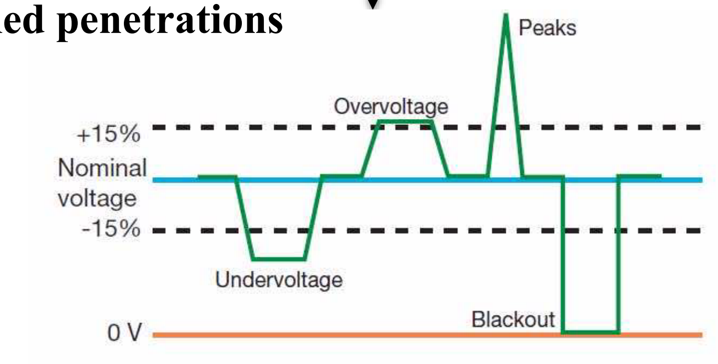
Future Grid Impact & Management

Energy Transition



Abrupt increase of electric demand & generation

Uncontrolled penetrations



Several grid impact issues

Impact must be identified!

Scientific Gap

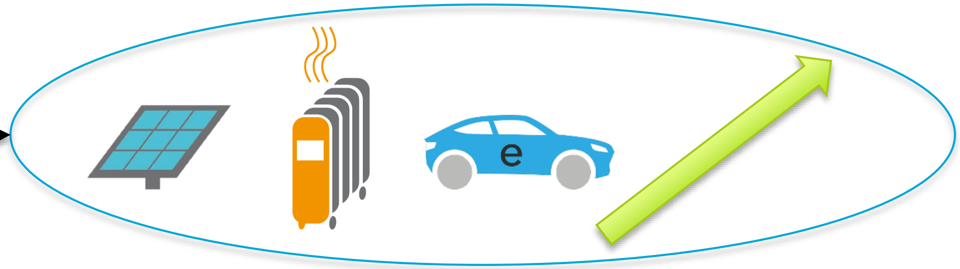
A number of works related with grid impact exist **but:**

- Only very few integrate all 3: PVs, HPs, EVs
- We focus on modelling the physical operation of components (bottom-up approach)

State-of-the-art & Motivation

Future Grid Impact & Management

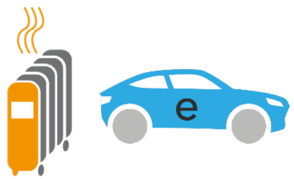
Energy Transition



Abrupt increase of electric demand & generation

If control is implemented in EMS:

- grid impact, congestions minimization
- Reduce consumption, peaks
- Increase penetrations
- <u>With flexibility of “Smart Loads”</u>
- <u>With Energy Storage Systems (ESSs)</u>



and/or

Impact must be controlled!

Scientific Gap

A number of works related with control exist **but:**

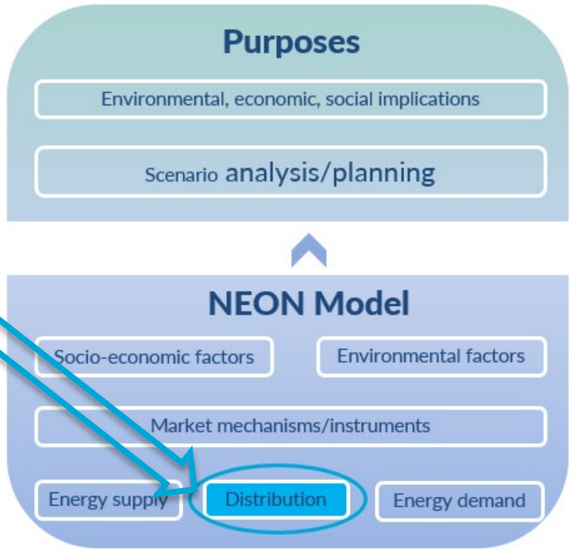
- <u>Few works integrate all EVs, PVs, HPs (and ESS)</u>
- <u>Consider detailed component physical operation (degradation)</u>
- <u>Compare importance of Smart Loads & ESSs</u>

Research Goal Statement

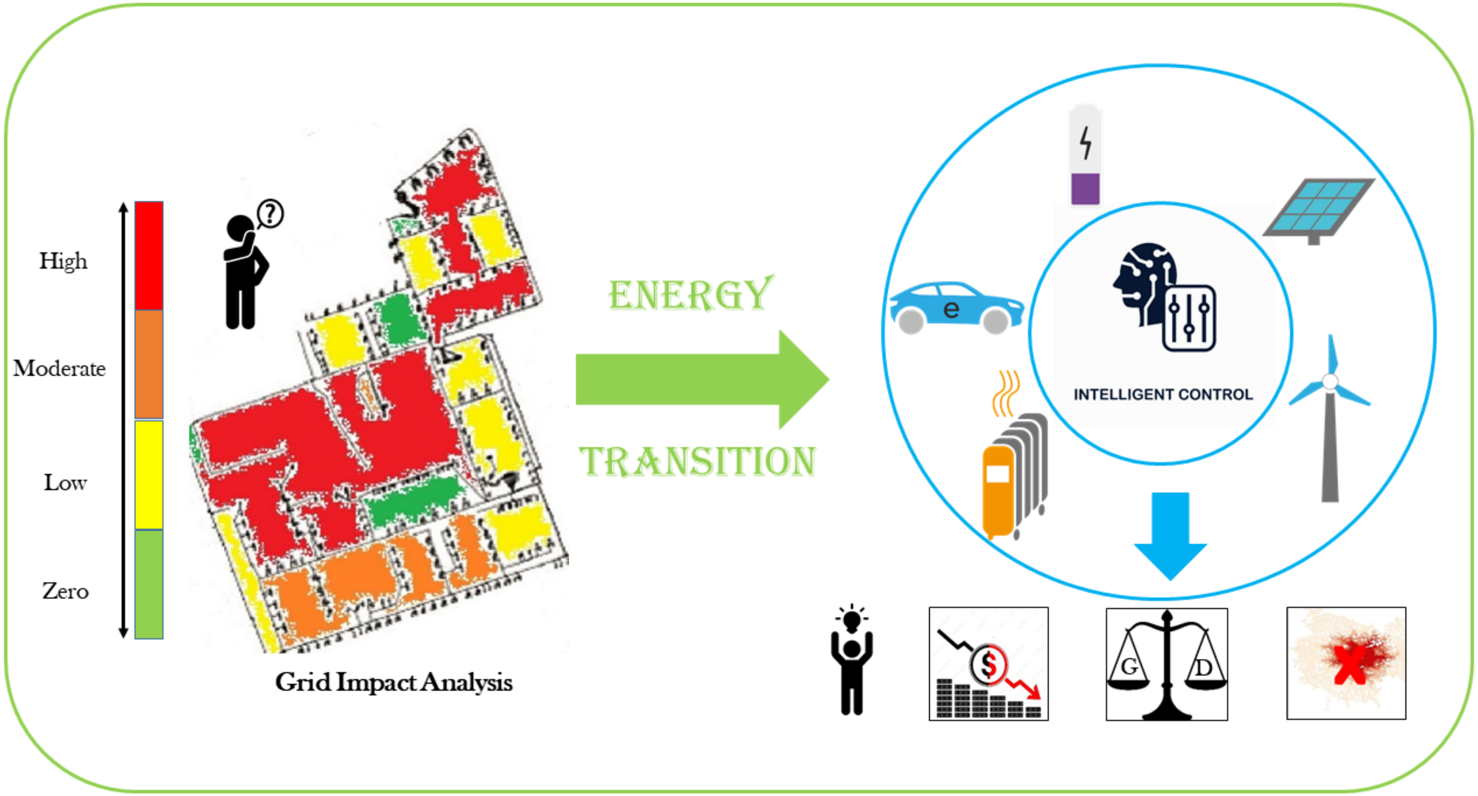
"How can Renewable Energy Sources (RES), Energy Storage Systems (ESS), Electrified Mobility & Heating be intelligently managed in future Distribution with the goals of minimum grid impact and maximum cost savings?"

"New Energy and mobility Outlook for the Netherlands"

Location in NEON Research

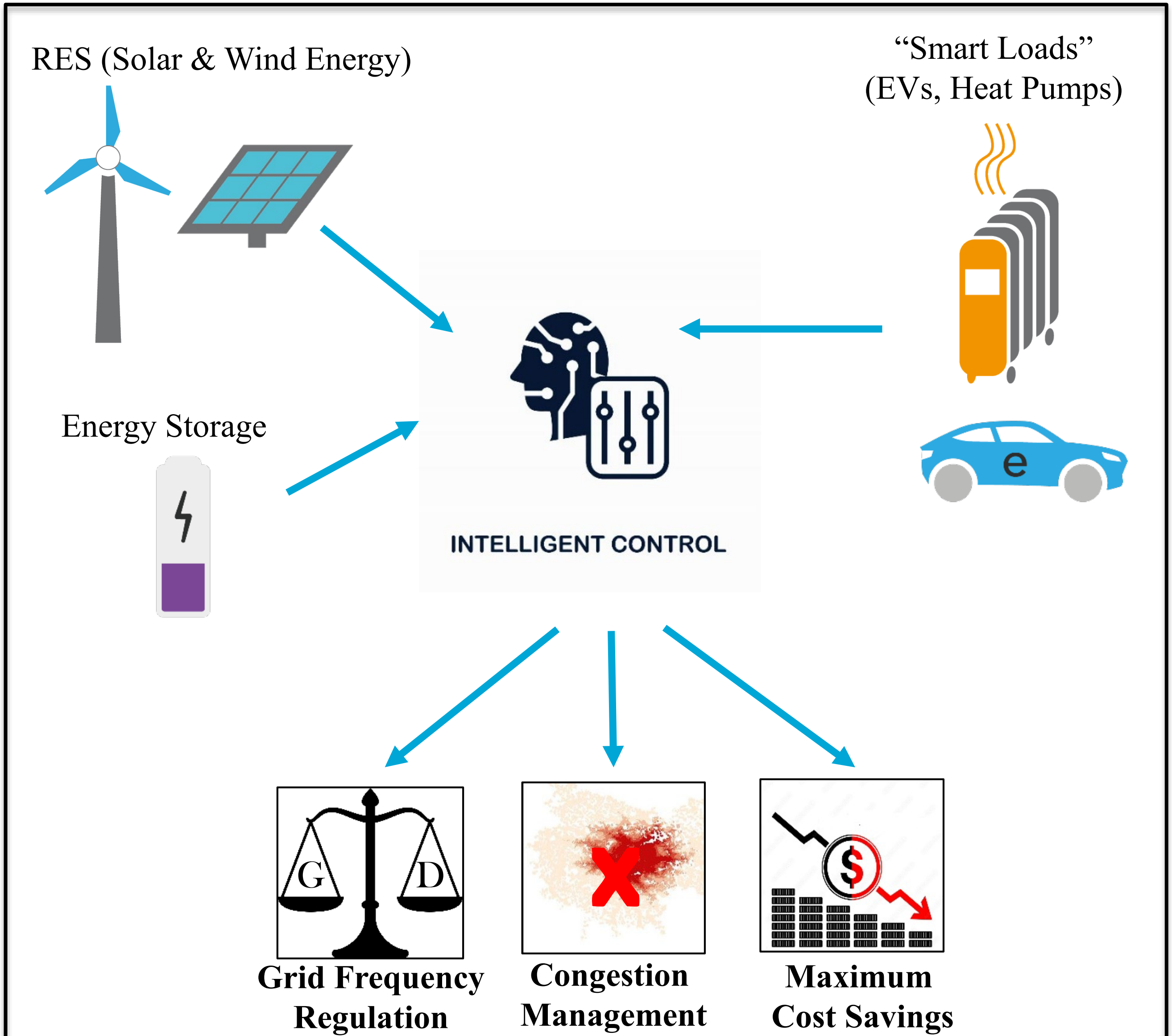


NEON Work Package 2: Energy Transport



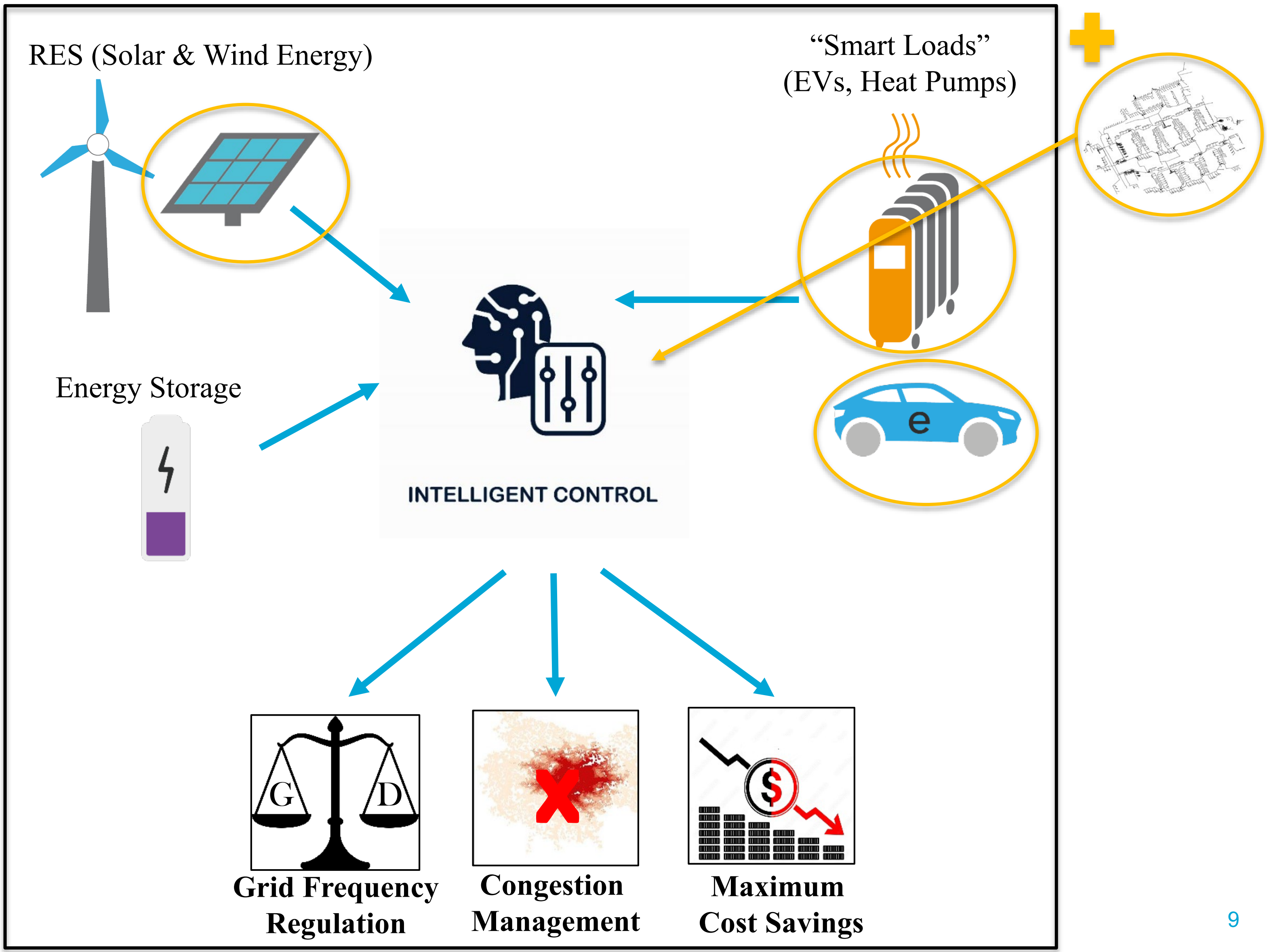
FROM GRID IMPACT TO COORDINATED CONTROL !

Concept of Coordinated Control & Contributions



Concept of Coordinated Control & Contributions

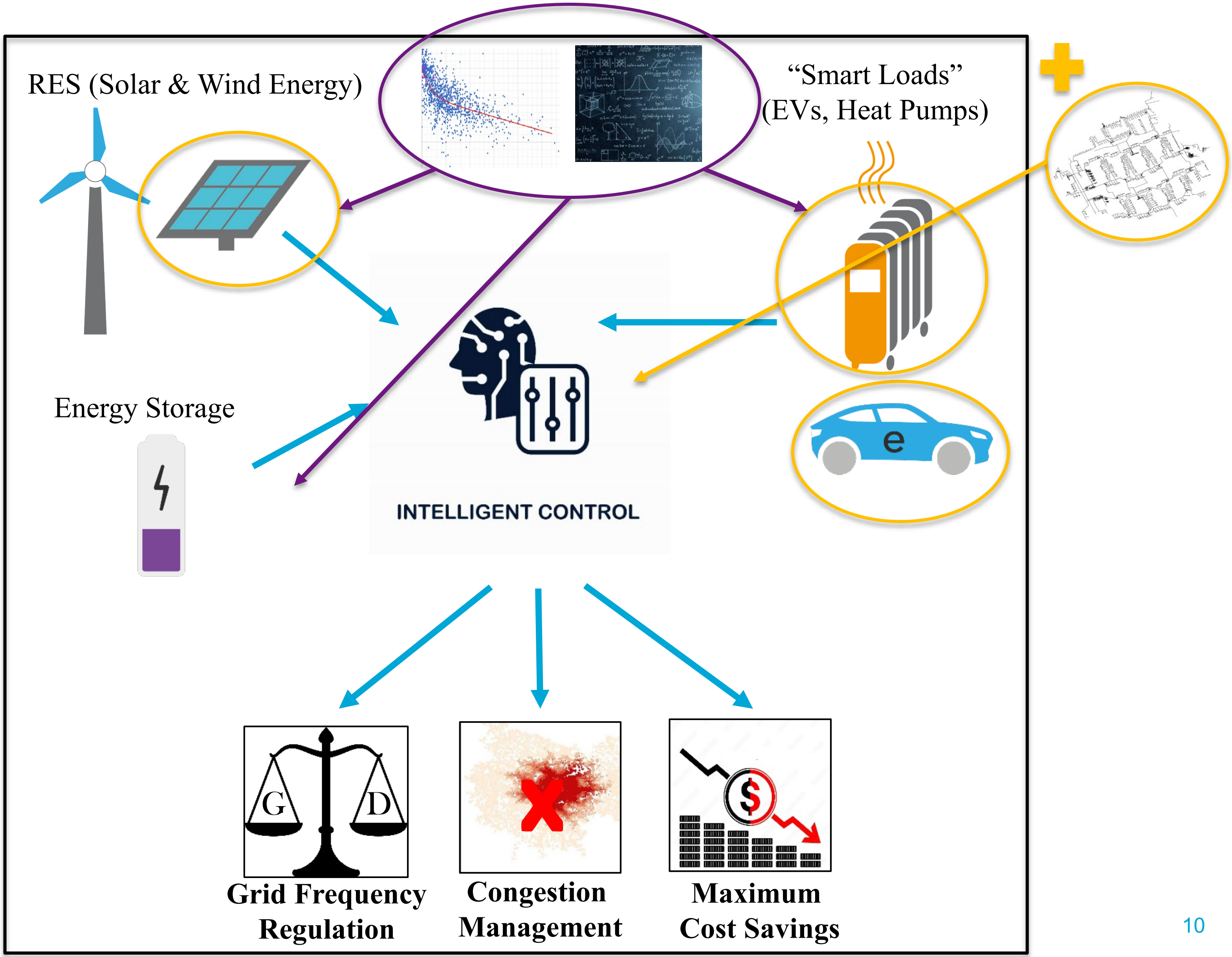
1. grid-level control with PVs, EVs, & HPs



Concept of Coordinated Control & Contributions

1. grid-level control with PVs, EVs, & HPs

2. Degradation and physical operation of components

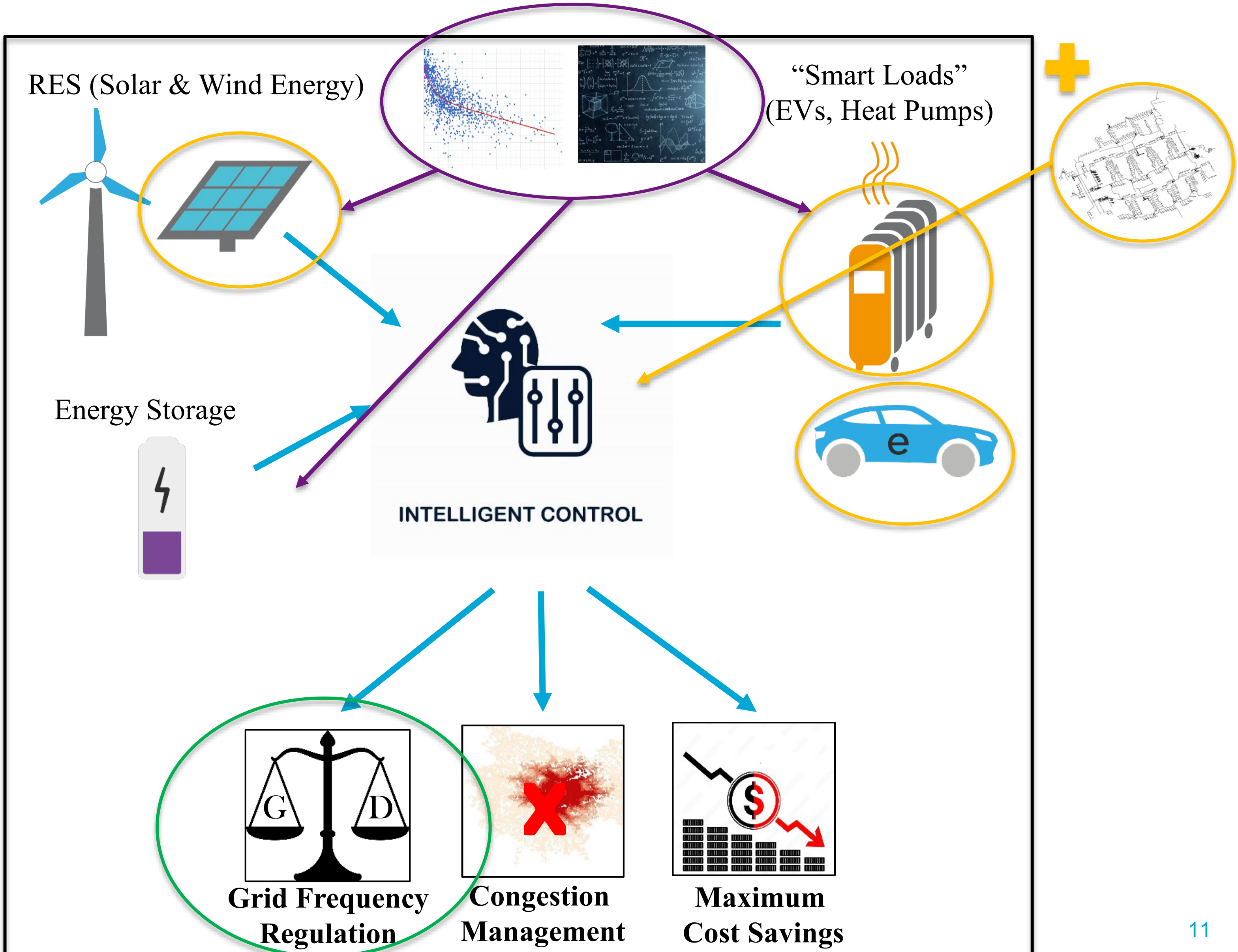


Concept of Coordinated Control & Contributions

1. grid-level control with PVs, EVs, & HPs

2. Degradation and physical operation of components

3. Efficient bidding strategy & all types of f regulation



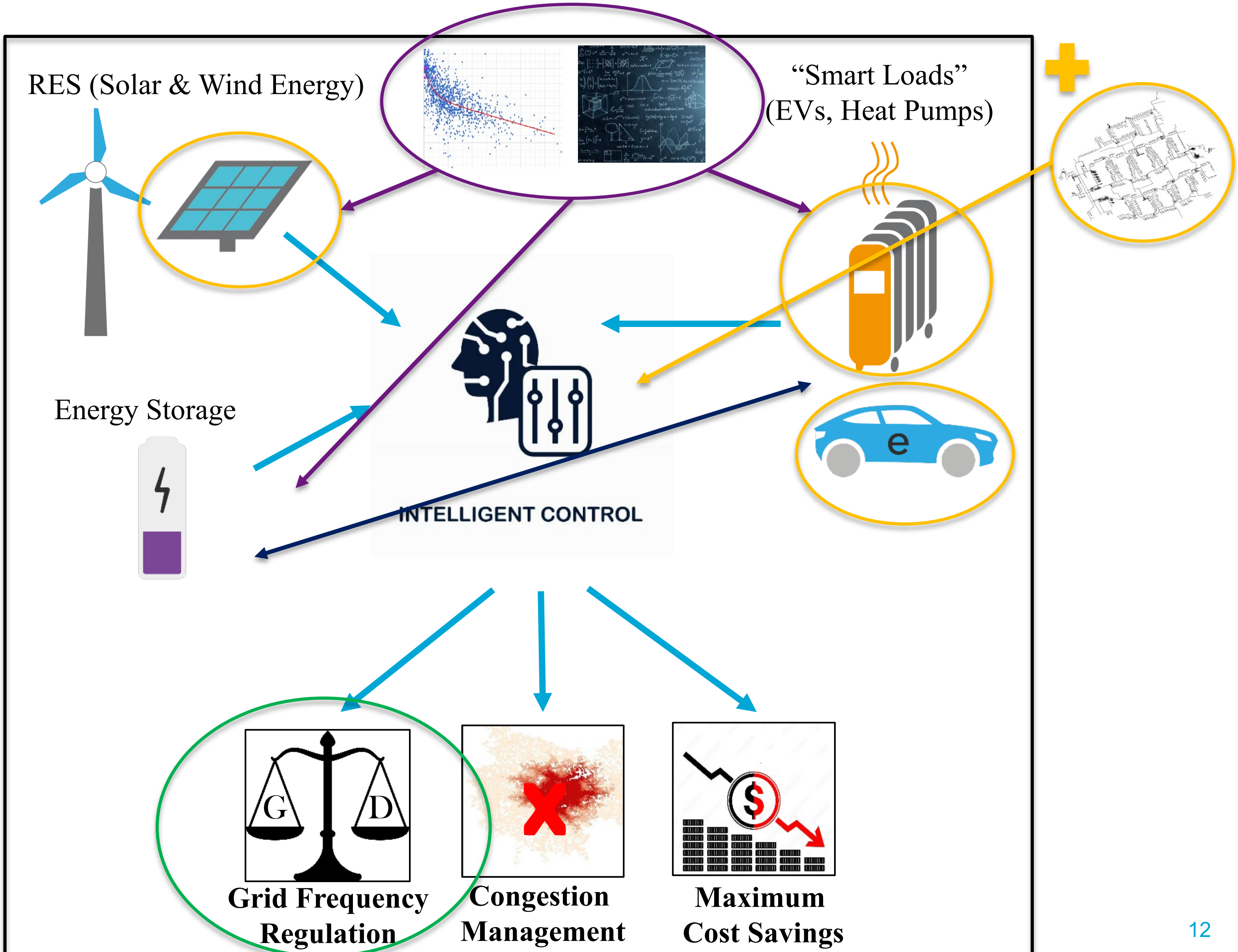
Concept of Coordinated Control & Contributions

1. grid-level control with PVs, EVs, & HPs

2. Degradation and physical operation of components

3. Efficient bidding strategy & all types of f regulation

4. Comparison between storage and smart loads



Concept of Coordinated Control & Contributions

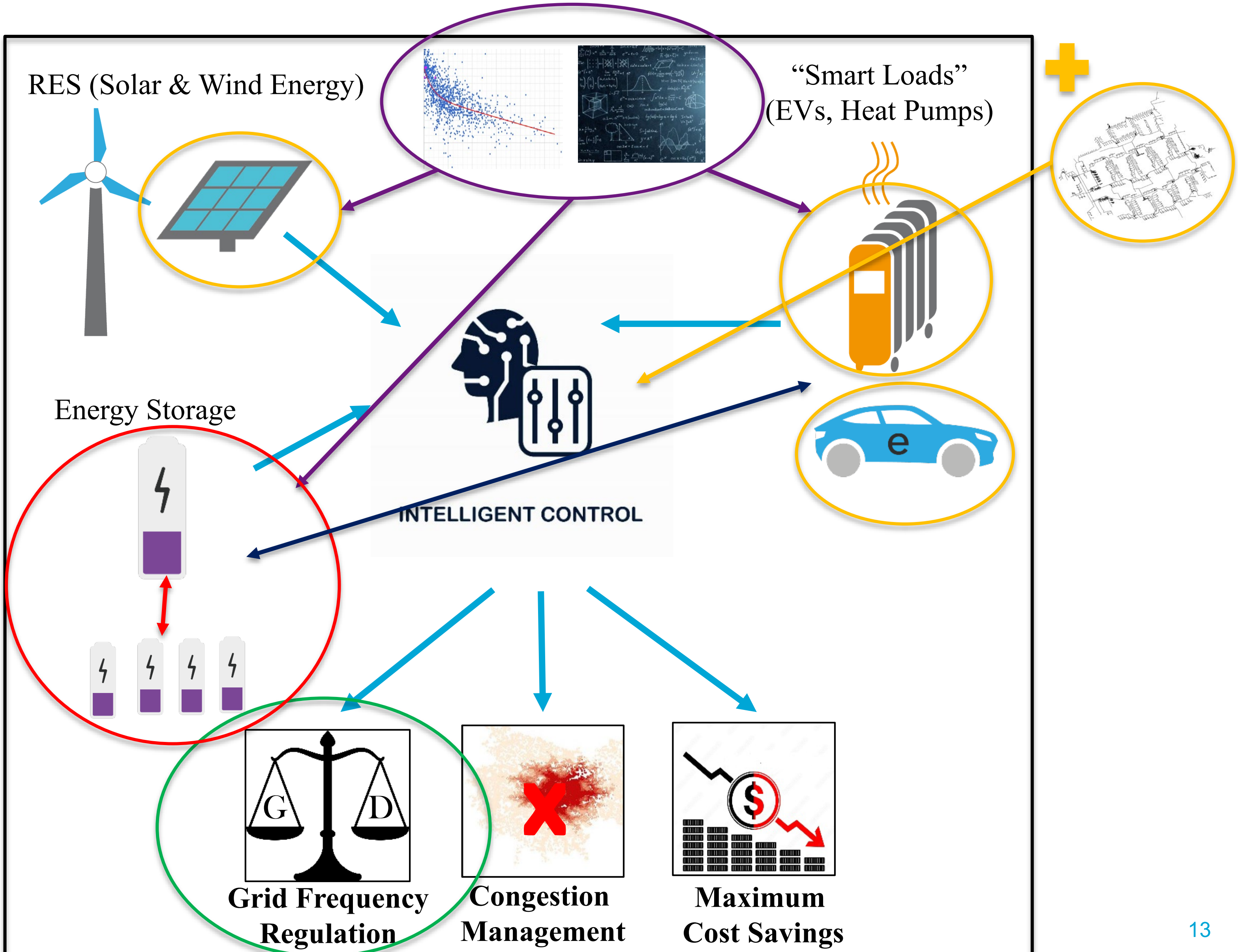
1. grid-level control with PVs, EVs, & HPs

2. Degradation and physical operation of components

3. Efficient bidding strategy & all types of f regulation

4. Comparison between storage and smart loads

5. Comparison between shared storage and distributed storages



Concept of Coordinated Control & Challenges

Data-Driven or Physical Modeling?

Selection of optimization method is crucial !

Pros

Cons

MI(N)LP:

- inner-system knowledge
- interpretability of results
- Less dependence on data

BUT

- usually slow and computationally expensive
- convergence hazards
- Uncertainty management with additional implementations

Machine Learning:

- good trade-off between accuracy-time
- inherently manages uncertainties

BUT

- data-dependence
- black-box representation

What about combination ?

1. Task Division

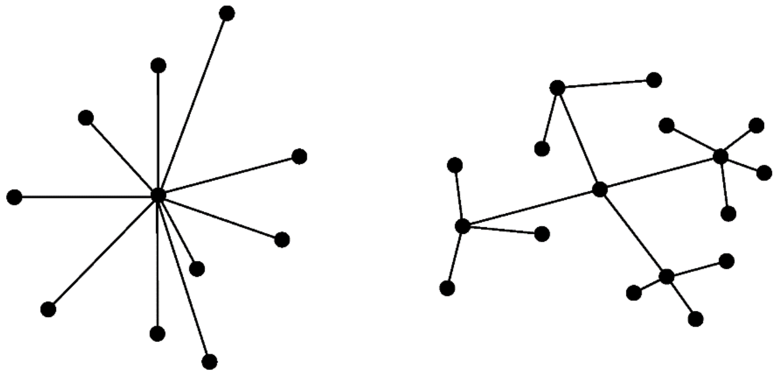
2. Use of the one to deal with the defects of the other

!

Concept of Coordinated Control & Challenges

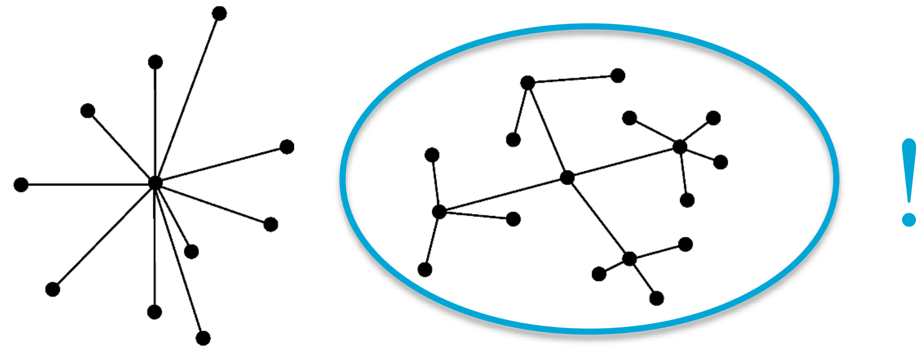
Data-Driven or Physical Modeling?

Concept of Coordinated Control & Challenges



Centralized or Decentralized?

Data-Driven or Physical Modeling?



- **Centralized**:
  - globally optimized results
  - one point-of-view

  but
  - computationally expensive
  - hardly scalable
  - what about reality? (privacy issues, vast use of smart-meters, communication equipment)

Pros **Cons**

- **De-centralized**:
  - Scalable
  - computationally lighter (in-parallel optimizations)
  - more "real" (consumers may not want to give control)

  but
  - only near-to-optimal results
  - many points-of-view, many actors with different objectives

Pros **Cons**

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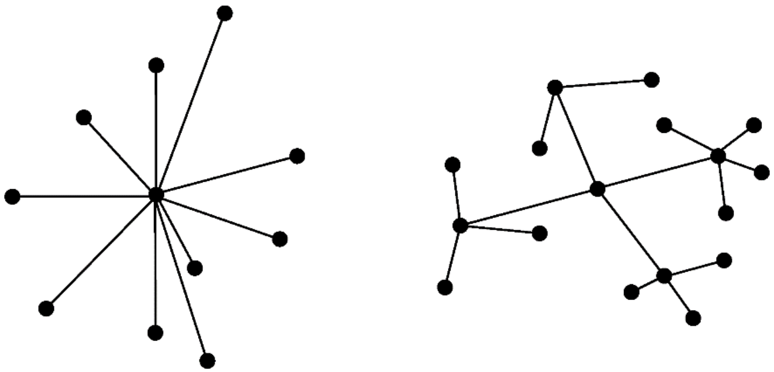
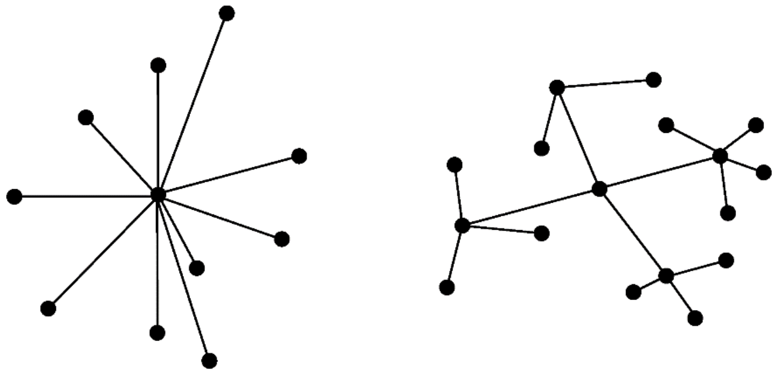
Concept of Coordinated Control & Challenges



Centralized or Decentralized?

Data-Driven or Physical Modeling?

Concept of Coordinated Control & Challenges



Centralized or Decentralized?

Energy Storage

Power Dispatch

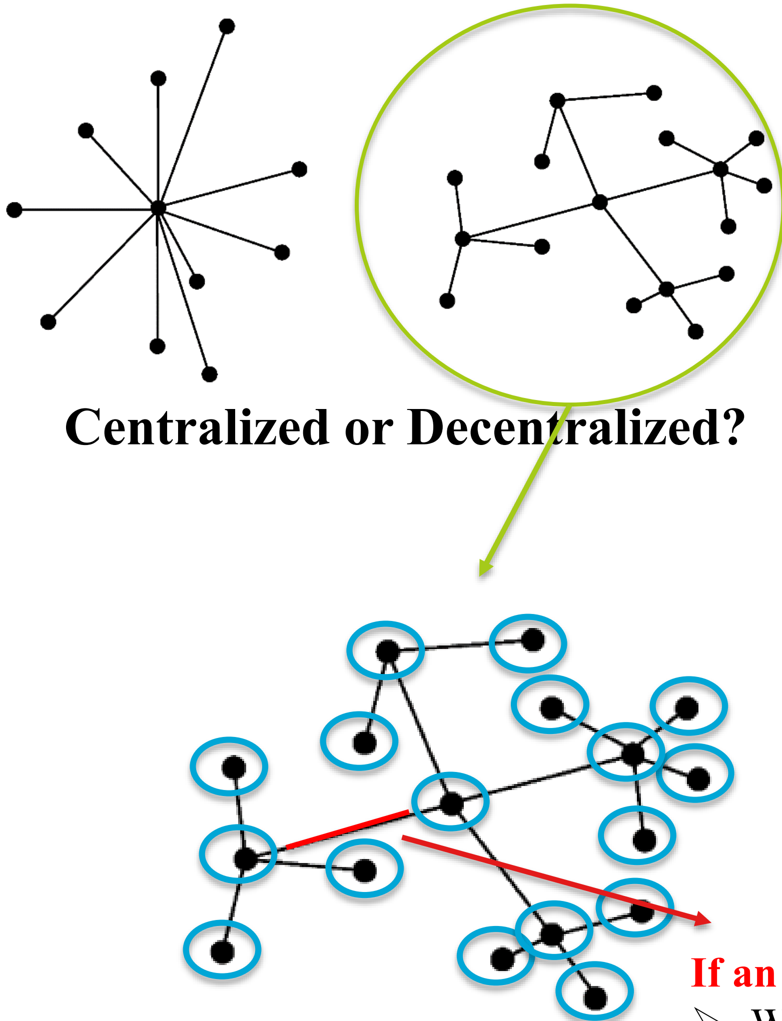
Optimization

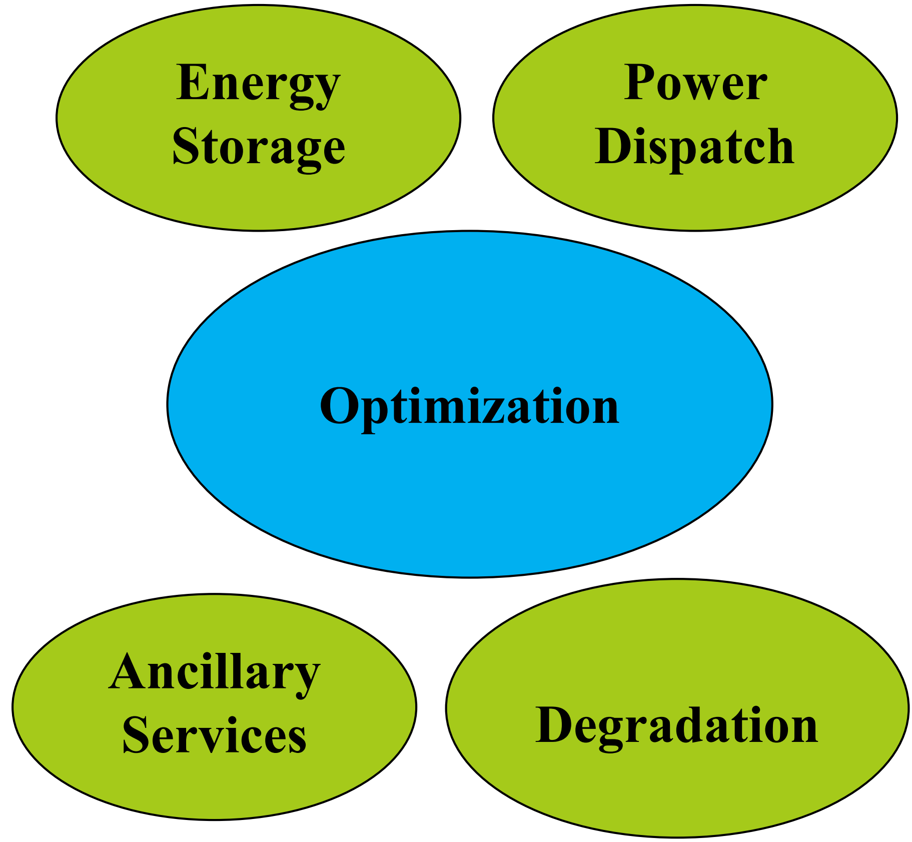
Ancillary Services

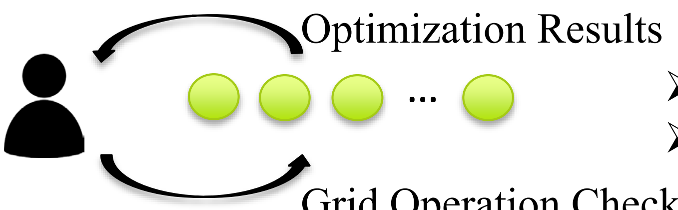
Degradation

Data-Driven or Physical Modeling?

Concept of Coordinated Control & Challenges







If an issue occurs:

- Who helps congestion management?
- With what flexibility?
- If a load must be curtailed, what priority?

Data-Driven or Physical Modeling?

Methodology & Results

Part 1: Grid Impact of Energy Transition

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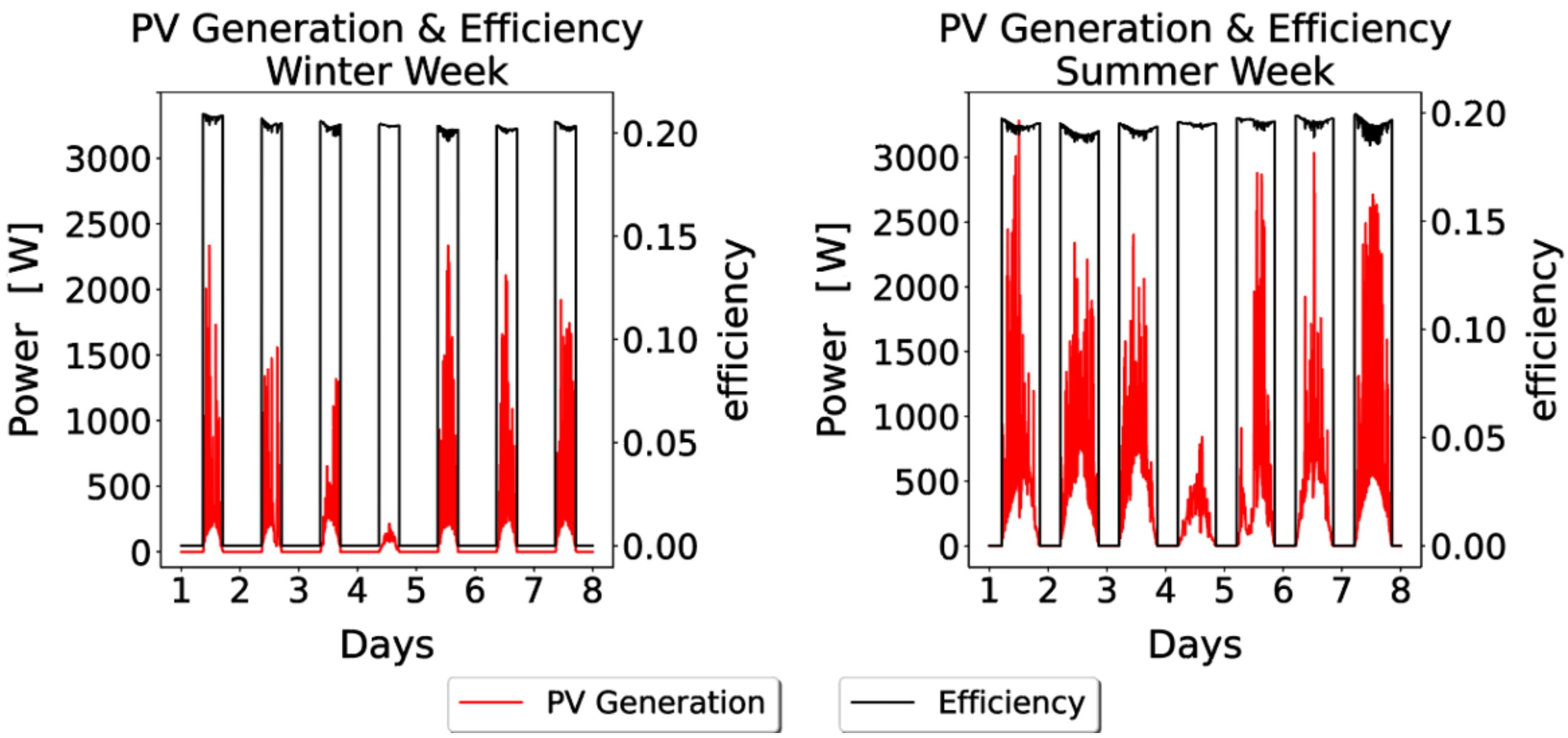
PV, EV, Building & HP Models

PV Generation

- Inputs
  - Weather Data from Meteonorm database
    - Irradiation, ambient Temperature, Wind speed
  - Panasonic HIT PV Module Specifications
    - Size
    - MPP Characteristics
    - STC Characteristics
    - NOCT Characteristics
- Module Temperature calculated by Duffie-Beckman model
- Module Temperature impact on efficiency
- Irradiation impact on efficiency
- 90 random 3kW rated PV Power Profiles generated by Monte-Carlo Simulation

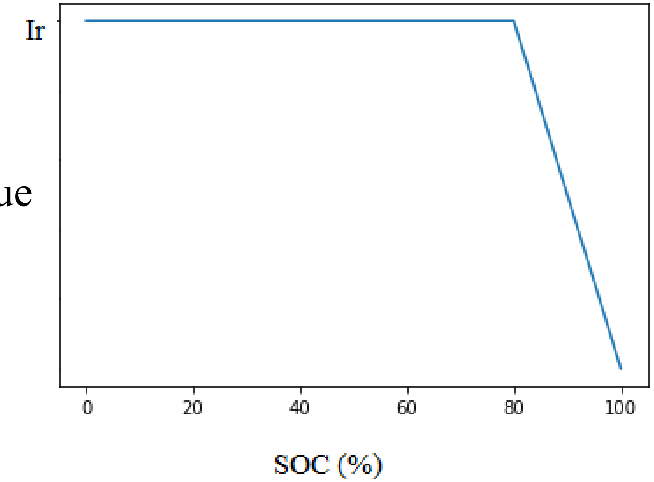
PV Generation



EV Consumption

- Inputs (Elaad Open Database)
  - Arrival and Departure SOCs
  - Requested Energy
  - Arrival and Departure Times
- Inputs (considered various EVs)
  - Rated current I_{rat}
  - Battery Capacity C_{bat}
- 30% higher EV consumption during Winter due to heating
- EV Constant Current – Constant Voltage Charging (CC-CV) Behavior

Linearized representation of CC-CV EV charging



- 200 weekly datasets for Home, Semi-Public & Public Chargers generated by MCS

<u>The above work is part of the PhD project of student Yunhe Yu, who works on OSCD project</u>

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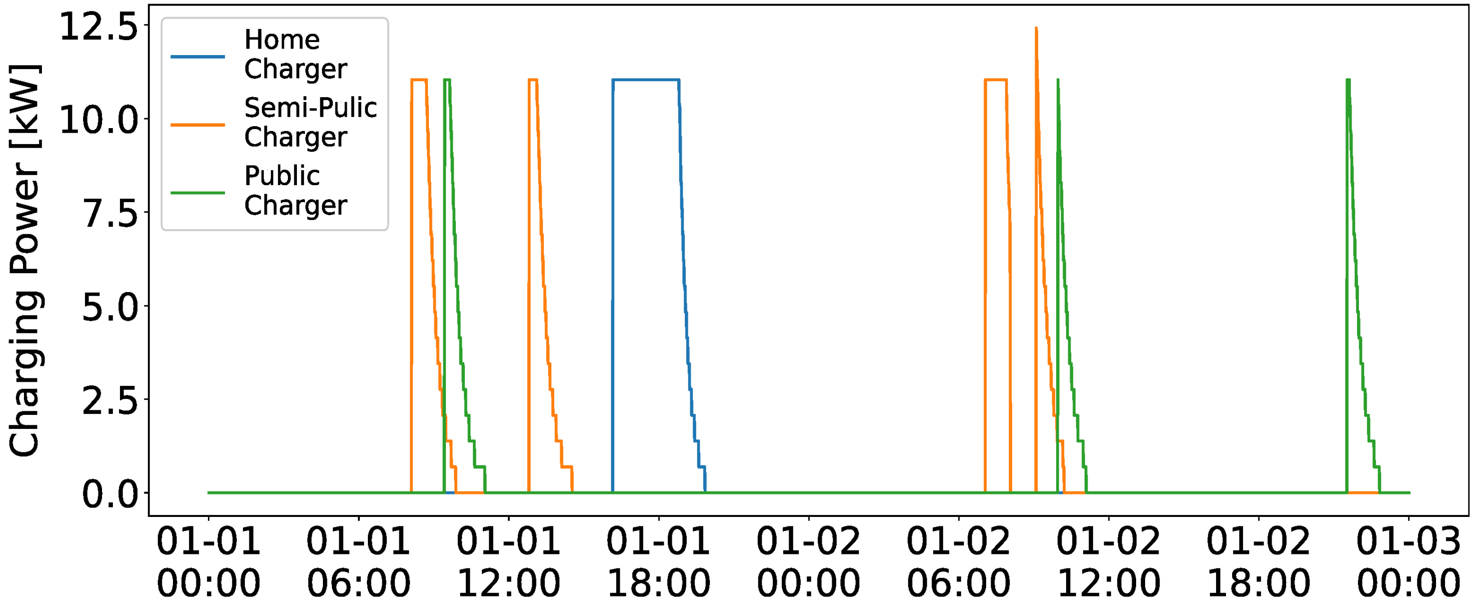
EV Consumption



Home, Semi-Public & Public Chargers' Behavior during 2-days time period

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Building & HP Models

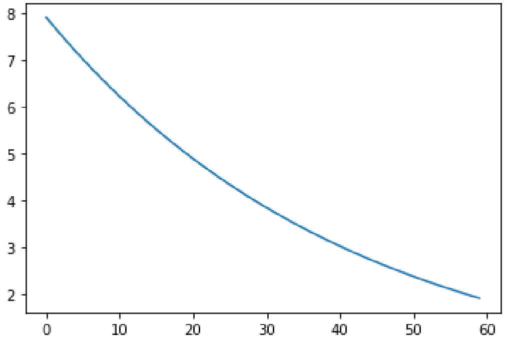
- Typical Dutch Terraced House

- New Conductivity Norms & Insulation Analysis

Required Conductivity U-values for new buildings:

- $U_{wall} < 0.3\ W/m^2K$
- $U_{roof} < 0.18\ W/m^2K$
- $U_{floor} < 0.22\ W/m^2K$

- HP Specifications (e.g Output Capacity) from reversible LIK 8MER HP Module
- ON-OFF Air-Sourced Heat Pumps, Floor-heating
- Space-heating and DHW
- No Thermal Storage for Grid Impact Analysis
- COP model: estimated with regression from 10 different HP models



- Residential & Commercial Building Occupancy Profiles
- Weather Data from Meteonorm database

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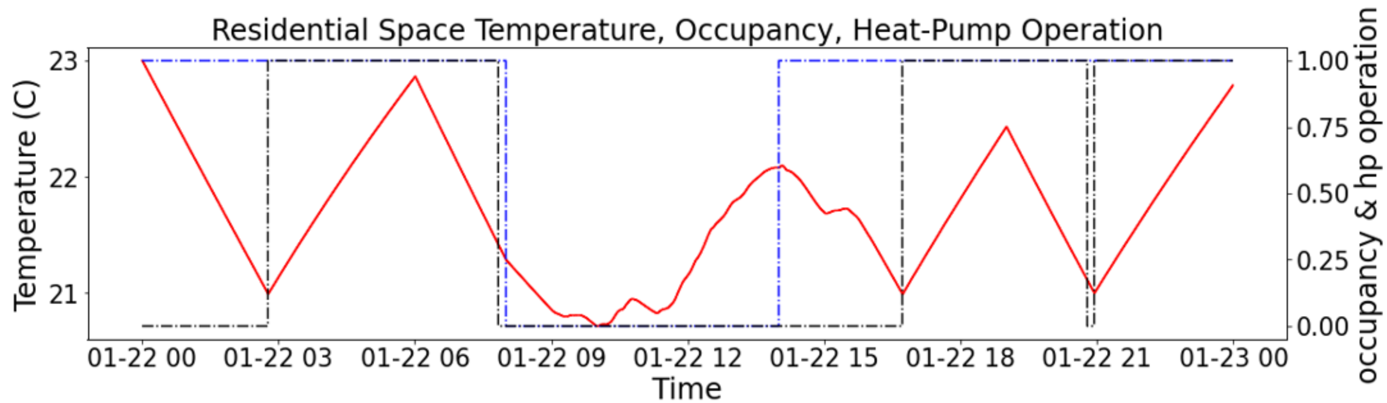
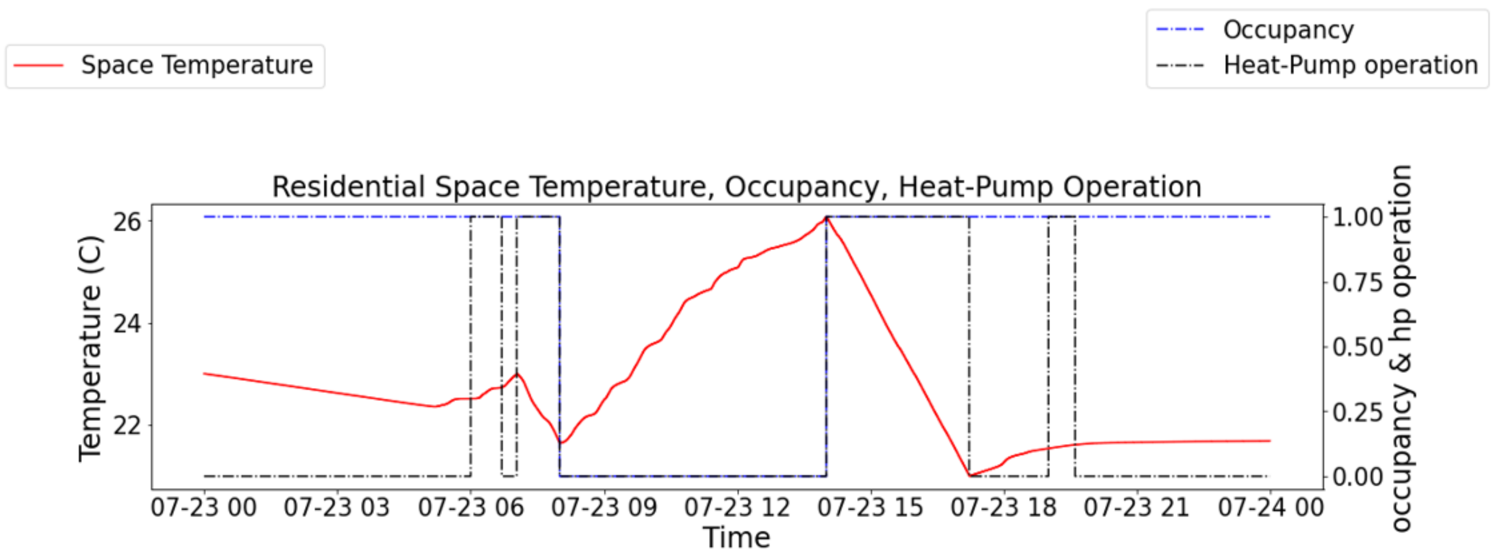
Building & HP Models



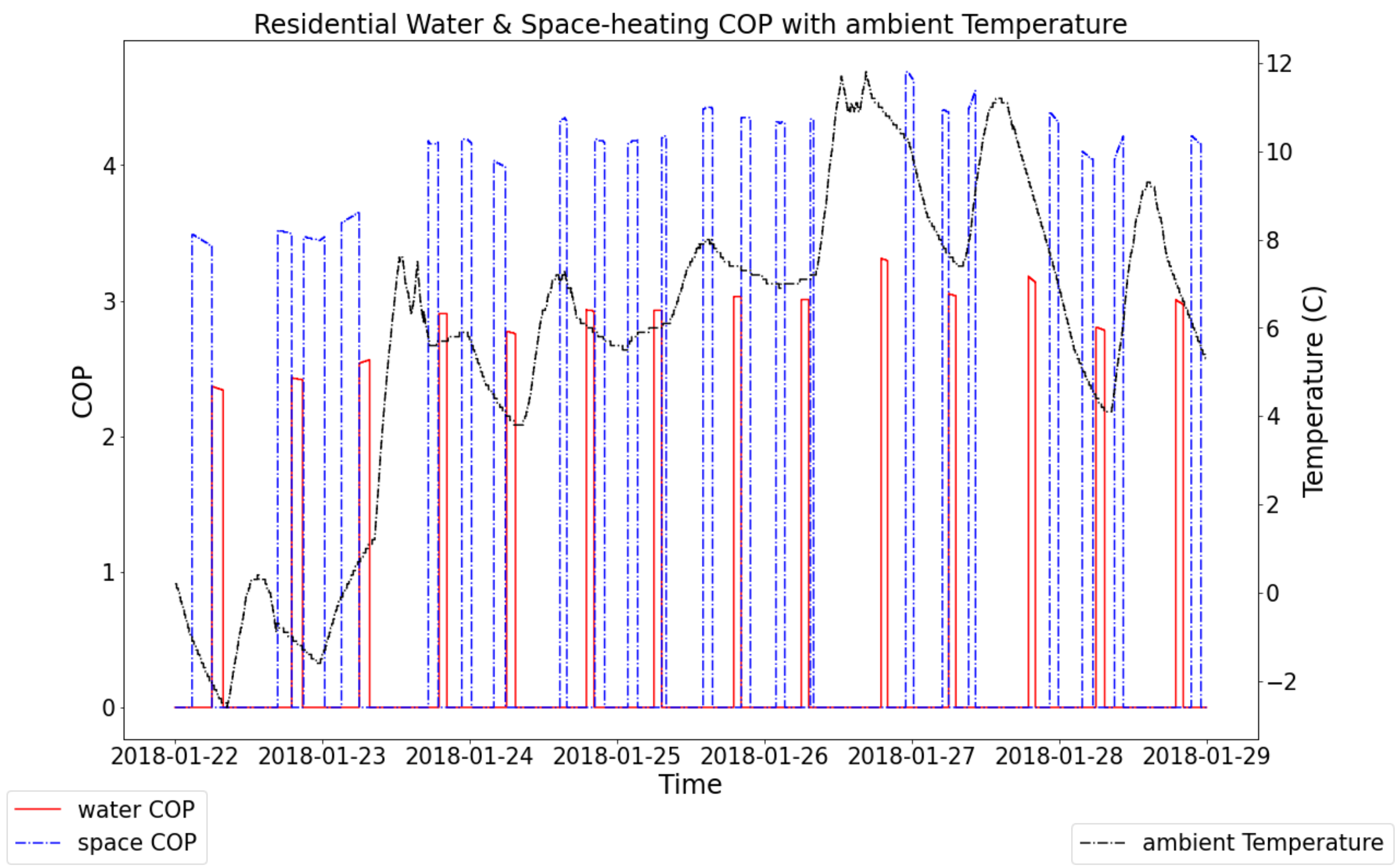
Building Temperature and ON-OFF operation (winter week)



Building Temperature and ON-OFF operation (summer week)

<u>Desired Building Temperature: 21-23 C</u>

Building & HP Models

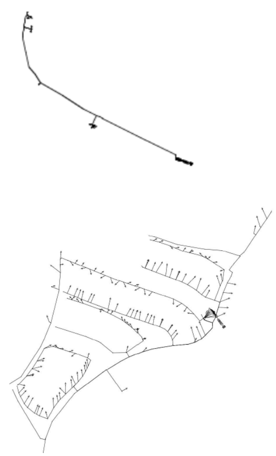


HP Heating COPs vs ambient Temperature (winter week)

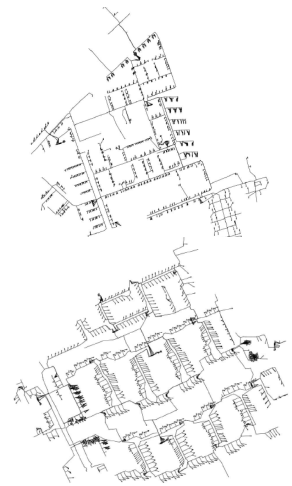
Distribution Grids, Study Cases & Objectives

Part 1: Grid Impact of Energy Transition

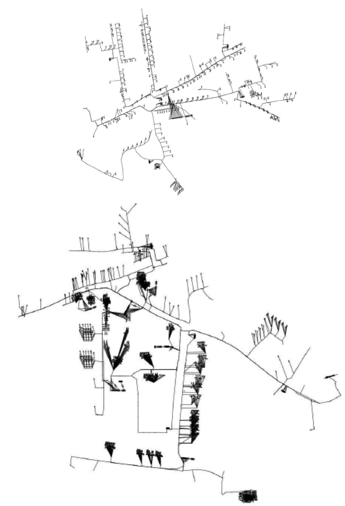
2 rural



2 suburban



2 urban



Representative light-loaded

Representative heavy-loaded

Grid type	light rural grid	heavy rural grid
No. of Nodes	23	373
Nodes with loads	3	126
No. of loads	3	138
Yearly energy demand [MWh]	97.9	486.7

Grid type	light suburban grid	heavy suburban grid
No. of Nodes	1742	1920
Nodes with loads	486	516
No. of loads	809	885
Yearly energy demand [MWh]	2353.03	2530.6

Grid type	light urban grid	heavy urban grid
No. of Nodes	1334	1322
Nodes with loads	251	155
No. of loads	349	876
Yearly energy demand [MWh]	1680.223	2745.5 6

6 Dutch Residential & Commercial grids (Enexis)

Part 1: Grid Impact of Energy Transition

Grid Impact Issues:
- Transformer Overloading
- Lines Overloading
- Nodes Voltage Deviations (under- and over-voltage)

Study Cases:
- 6 different distributional areas
- 3 different load conditions: PVs-HPs, PVs-EVs, PVs-HPs-EVs
- 4 different LCT penetrations: 0, 50, 80, 100%
- 1 week of 2 different seasons
- 2 different ways of approach: top-down & bottom-up

Grid impact metrics
- Overall maximum issue magnitude
- Overall issue duration
- Overall times of issue appearance
- Magnitude & duration per issue time
- (Magnitude)x(duration) per issue time
- number of simultaneous issue locations within the grid

Objectives:
- the most vulnerable distributional area
- the most crucial grid impact issue
- the most ”heavy” LCT considering different penetrations
- the most ”heavy” season
- the overall grid impact of all LCTs
- Weekend/weekdays effects

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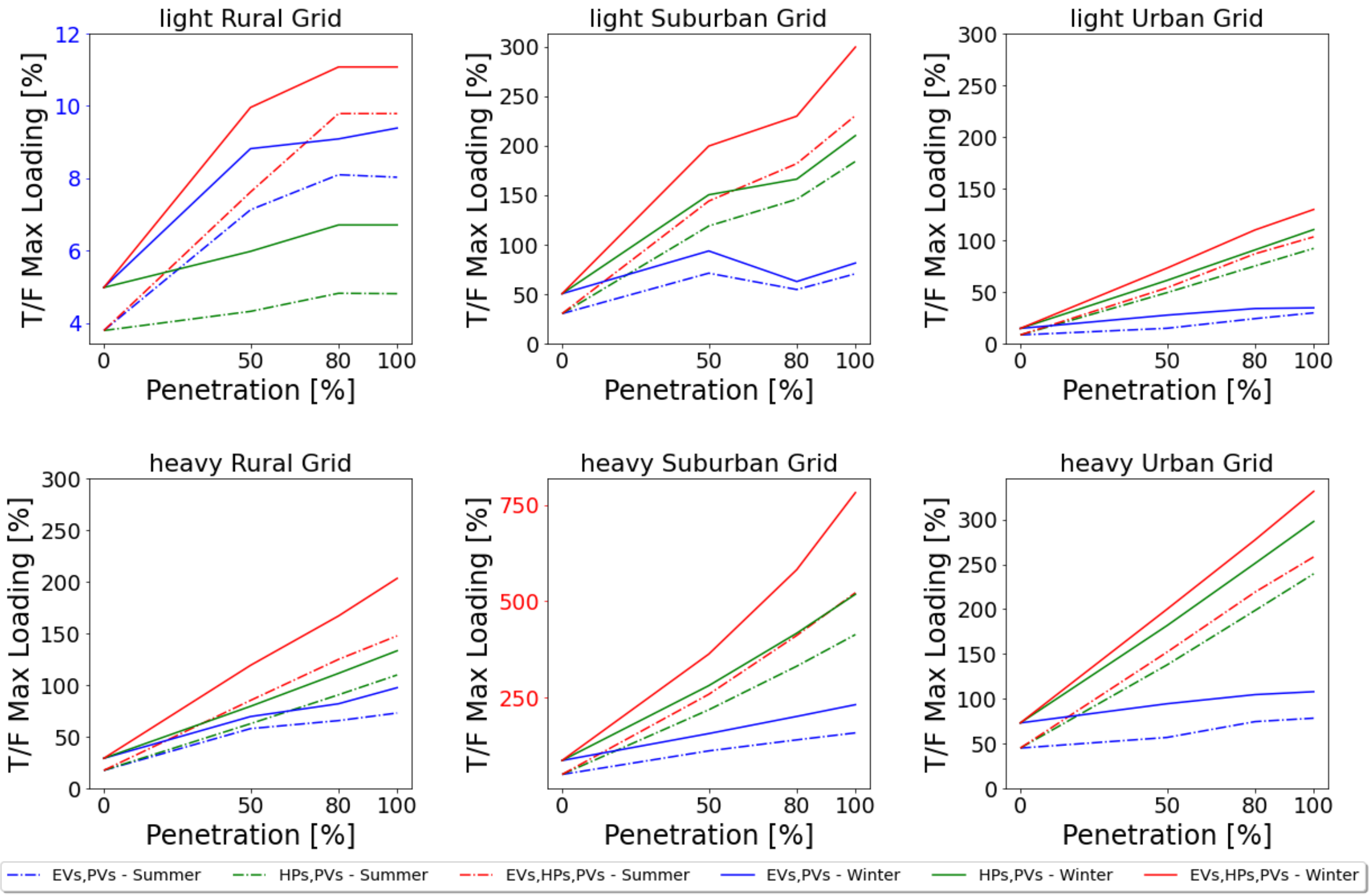
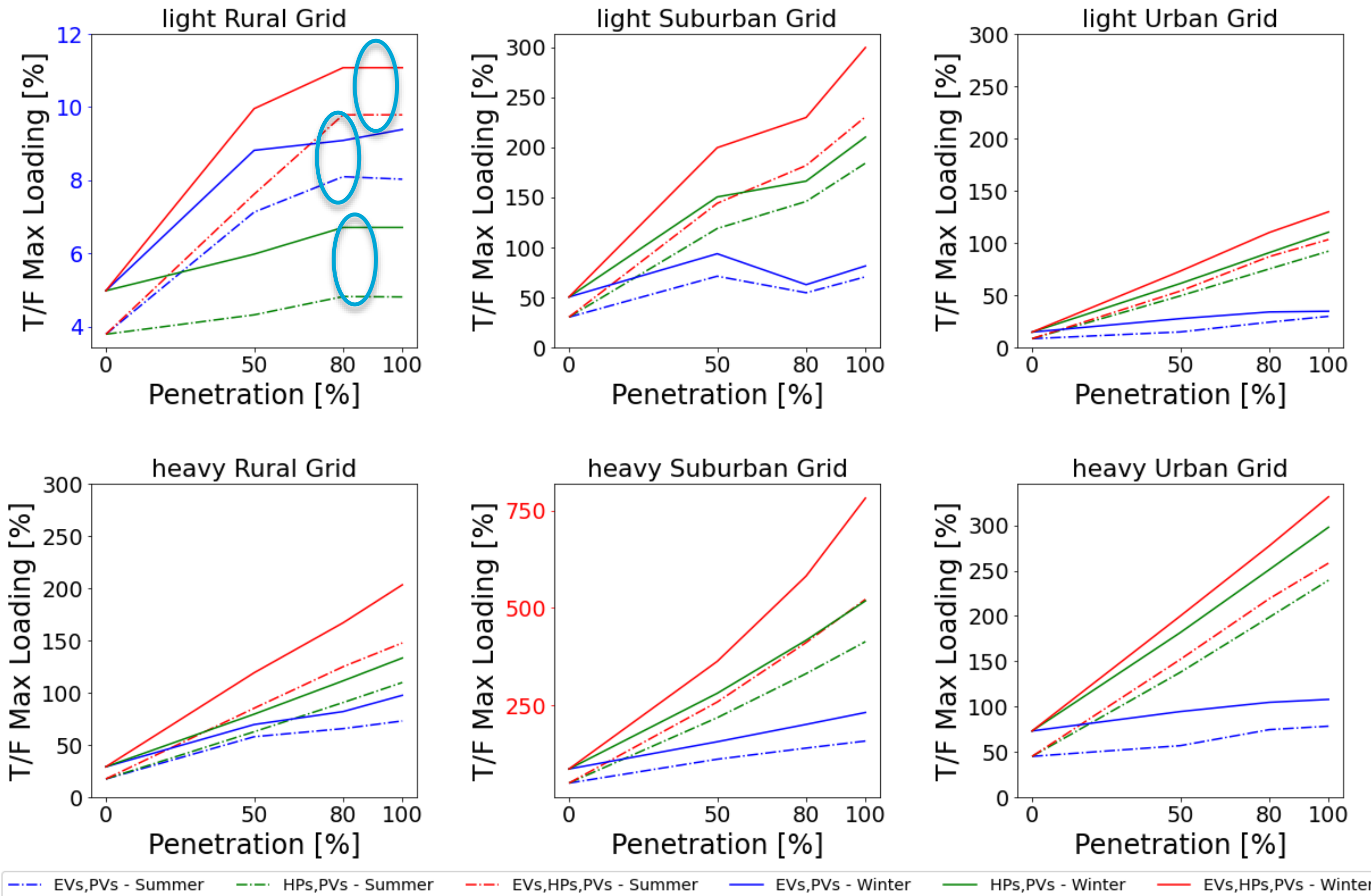
Transformer Loading (1)



Transformer Maximum Loading at 0, 50, 80 & 100% penetrations of EVs, HPs & EVs-HPs during Summer & Winter per Distribution Grid

Transformer Loading (1)

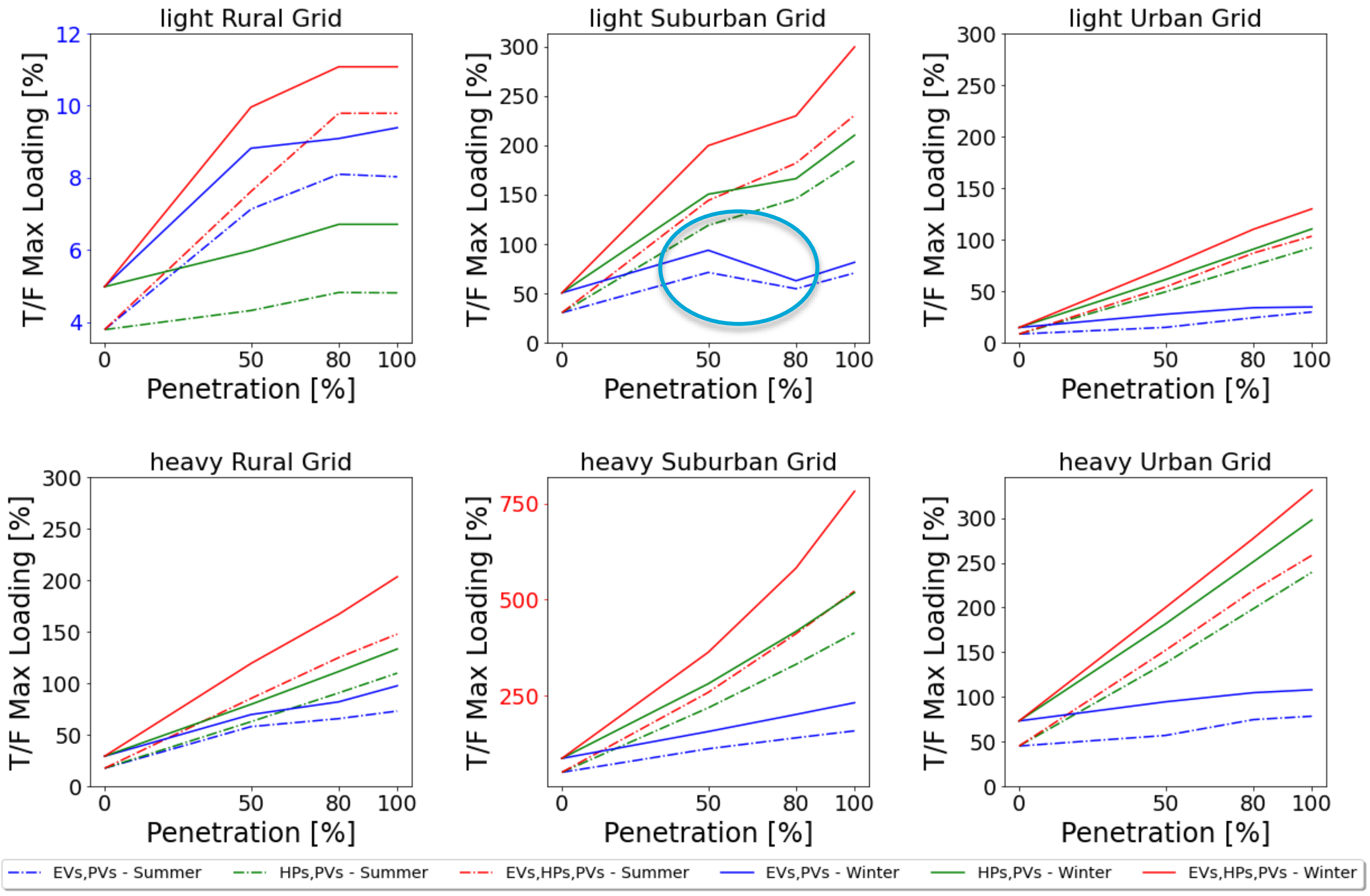


Transformer Maximum Loading at 0, 50, 80 & 100% penetrations of EVs, HPs & EVs-HPs during Summer & Winter per Distribution Grid

- Winter heavier Season than Summer in all cases

Interesting Insights

Transformer Loading (1)

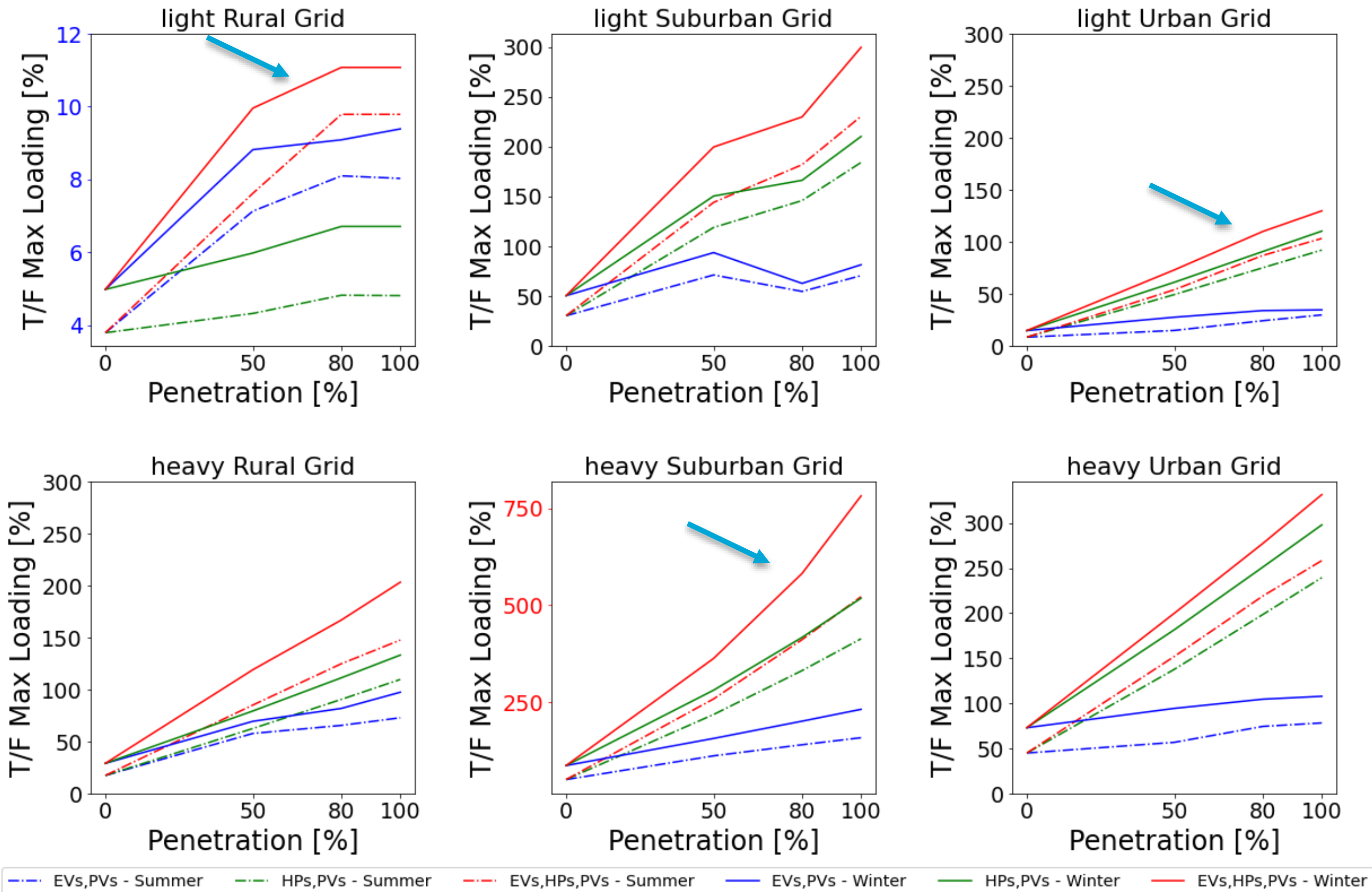


Transformer Maximum Loading at 0, 50, 80 & 100% penetrations of EVs, HPs & EVs-HPs during Summer & Winter per Distribution Grid

- Winter heavier Season than Summer in all cases
- Mitigation of PV issues with Evs can be seen but not by HPs

Interesting Insights

Transformer Loading (1)

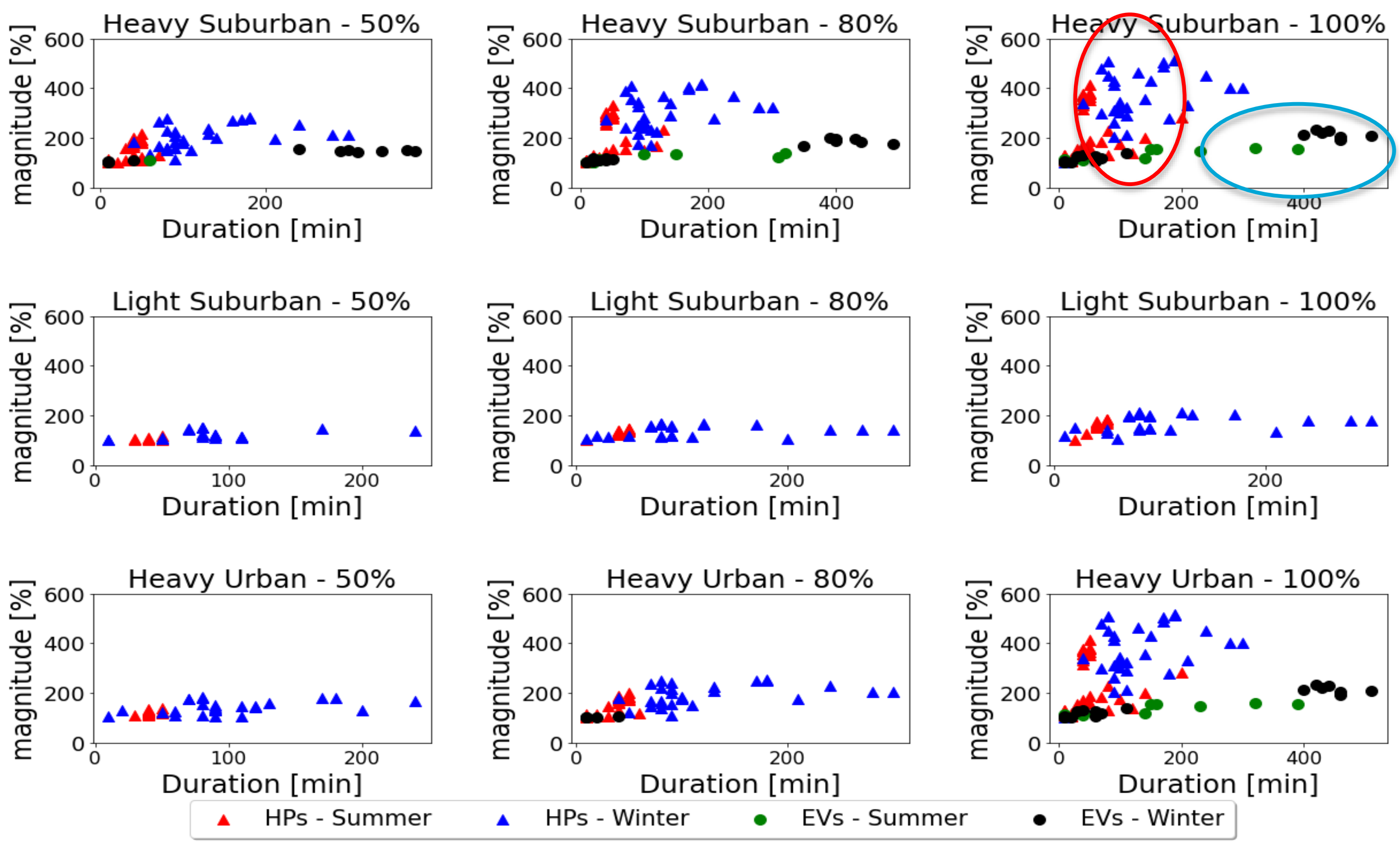


Transformer Maximum Loading at 0, 50, 80 & 100% penetrations of EVs, HPs & EVs-HPs during Summer & Winter per Distribution Grid

- Winter heavier Season than Summer in all cases
- Mitigation of PV issues with Evs can be seen but not by HPs
- Different slopes for T/F loading increase in different grids

Interesting Insights

Transformer Loading (2)



Magnitude & Duration of Violations during Summer & Winter at 50, 80 & 100% penetrations of HPs & EVsat 3 most vulnerable Distribution Grids

- Suburban Area most vulnerable in all cases
- HPs heavier LCT than Evs (both in magnitude & duration & violation times
- However, Evs have generally high violation durations
- Over-voltage less likely to appear than Under-voltage

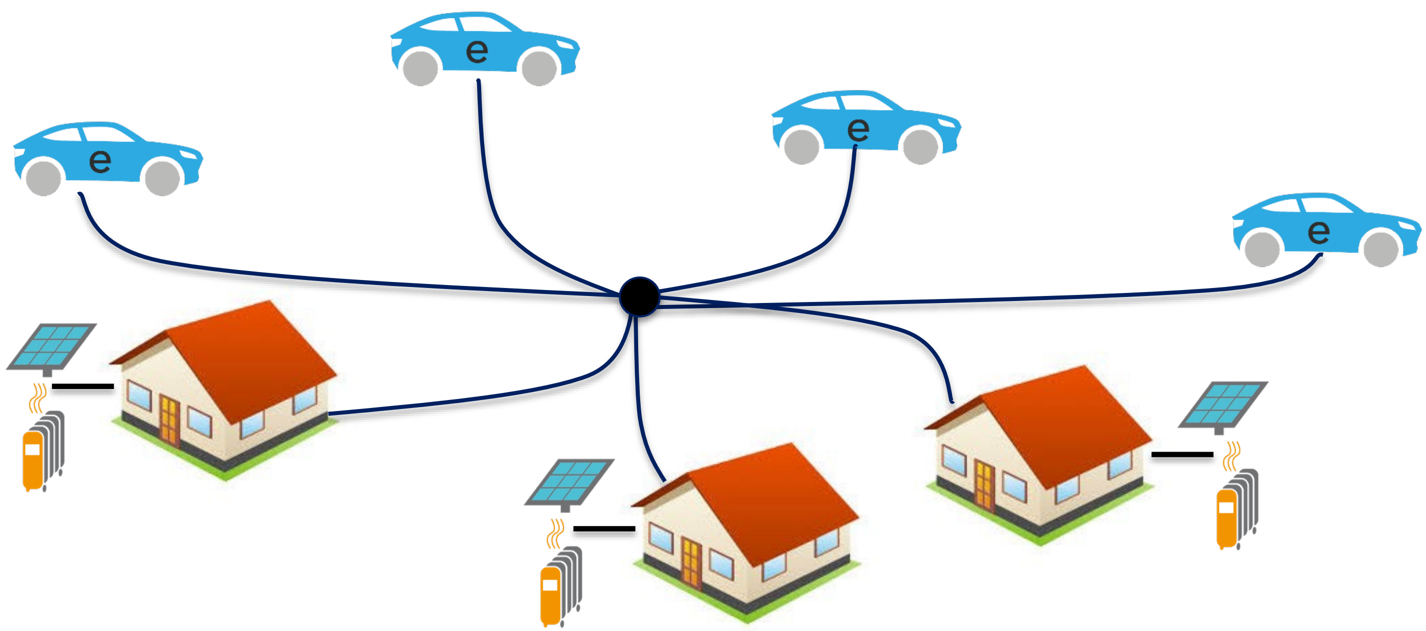
Interesting Insights

Methodology & Results

Part 2: Management of Grid Impact with Coordinated Control

Part 2: Management of Grid Impact with Coordinated Control

- **Initial Stage:**
  - Only Power Dispatch, MILP Rolling-Horizon Optimization
  - Only 1 node (3 Buildings, 4 Chargers)
  - Simplifications need yet to be solved



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Part 2: Management of Grid Impact with Coordinated Control

- **Objectives**:
  - EVs all charged upon departure (EV penalty)
  - All Buildings thermal comfort [21, 23] respected (HP penalty)
  - No PV curtailment (PV penalty)
  - Min grid exchange power cost

- **Constraints**:
  - Node Power Balance
  - Grid, Chargers, EVs, PV, HP Limits
  - Buildings Thermal Balance
  - SOCs, Buildings Temperature Dynamics

- **Simplifications to be addressed:**
  - No Domestic Hot Water, only space heating
  - Non-linearities are avoided, to be addressed with AI
  - Re-optimization only upon new EV arrivals

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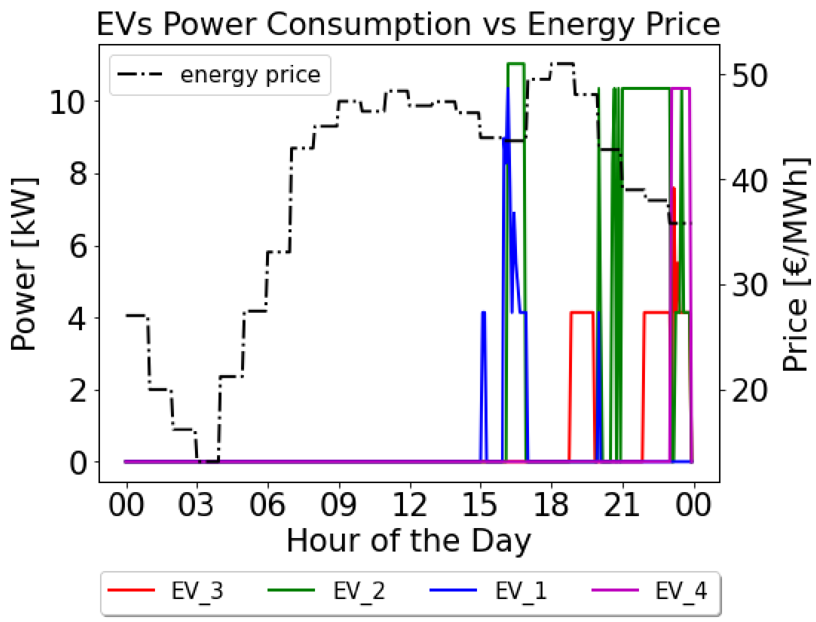
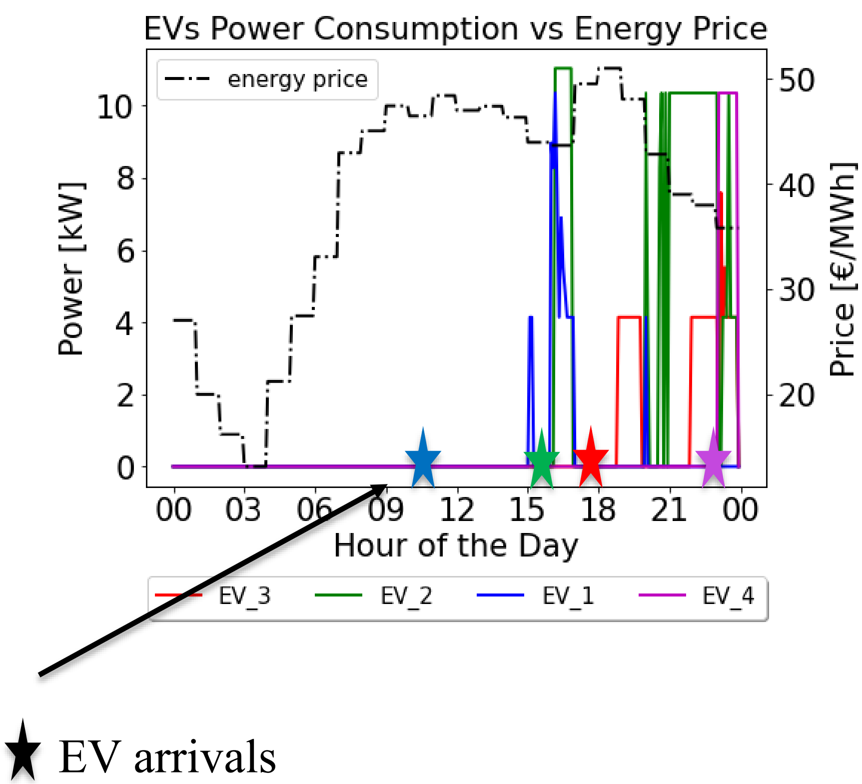
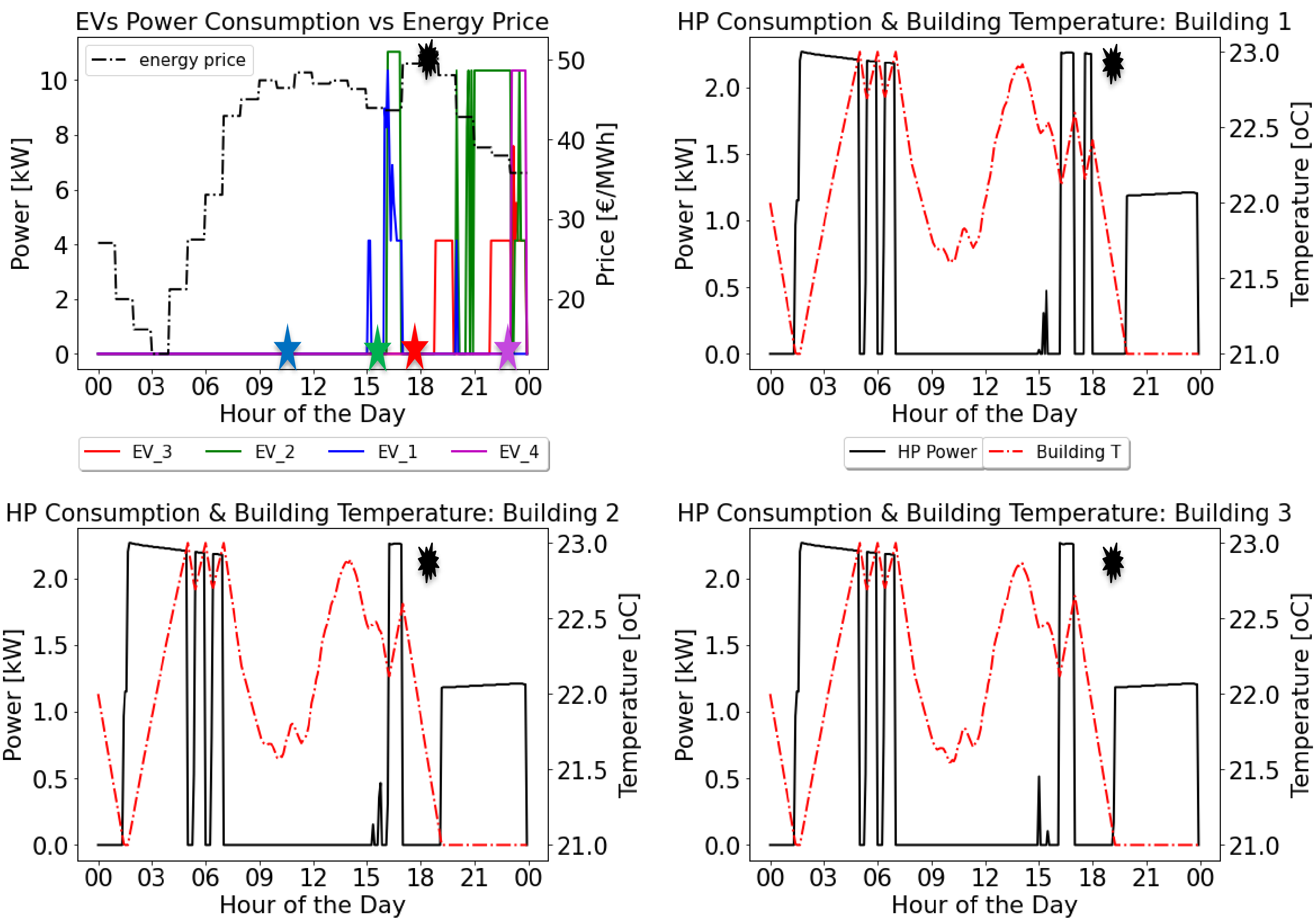
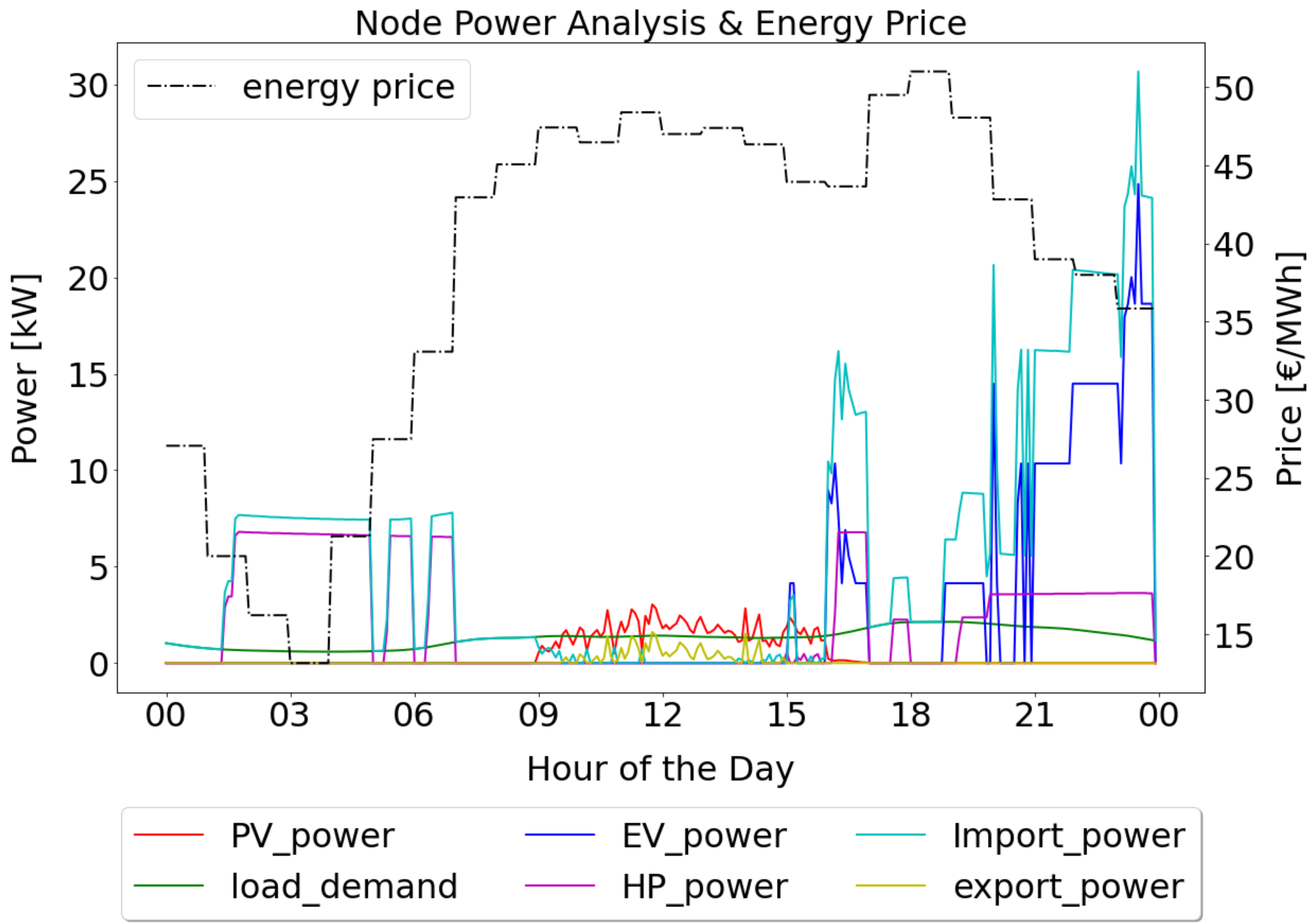
Coordinated Control Results



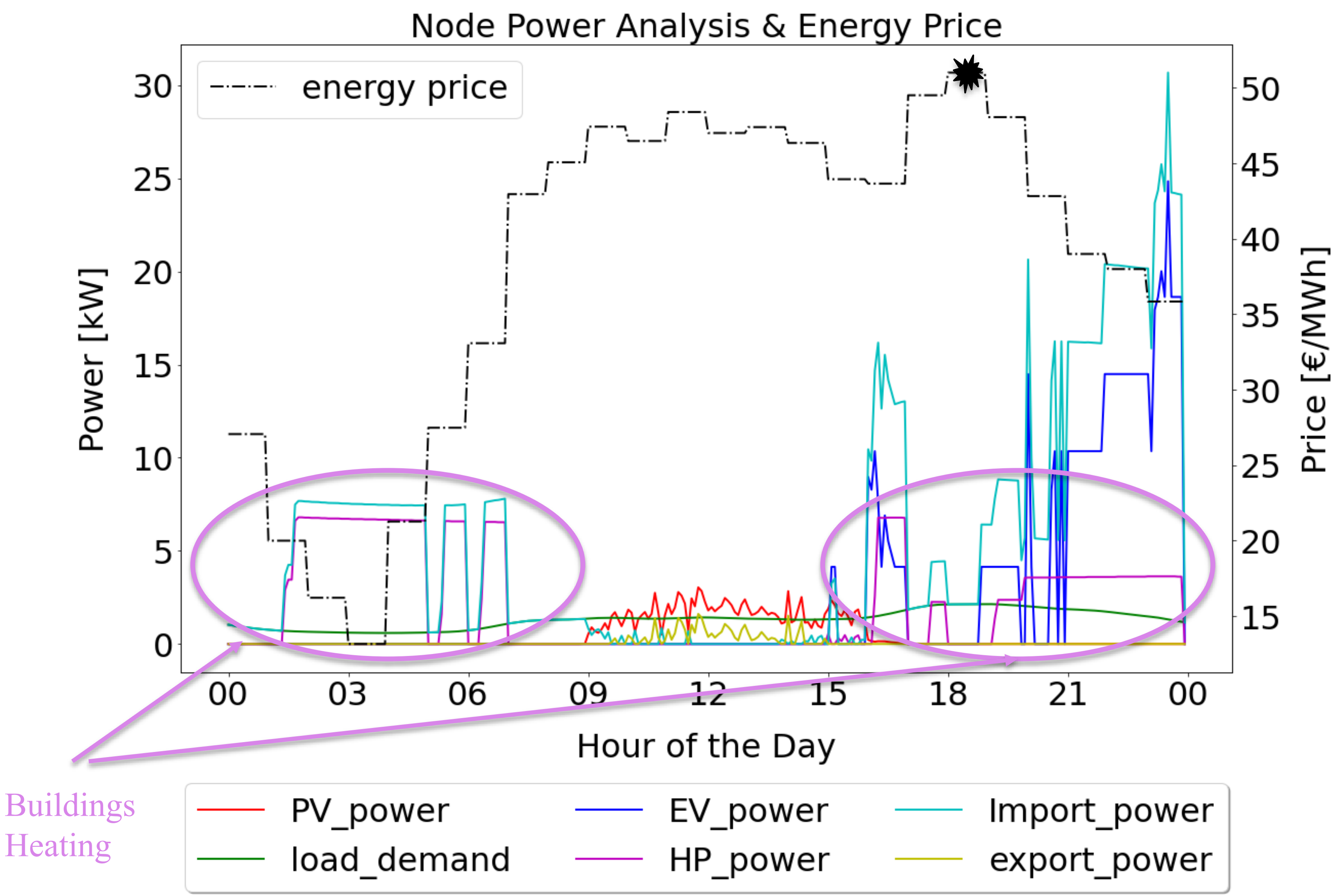
EVs Power Consumption vs Energy Price
energy price
Power [kW]
Price [€/MWh]
Hour of the Day
0
2
4
6
8
10
20
30
40
50
00
03
06
09
12
15
18
21
00
EV_3
EV_2
EV_1
EV_4

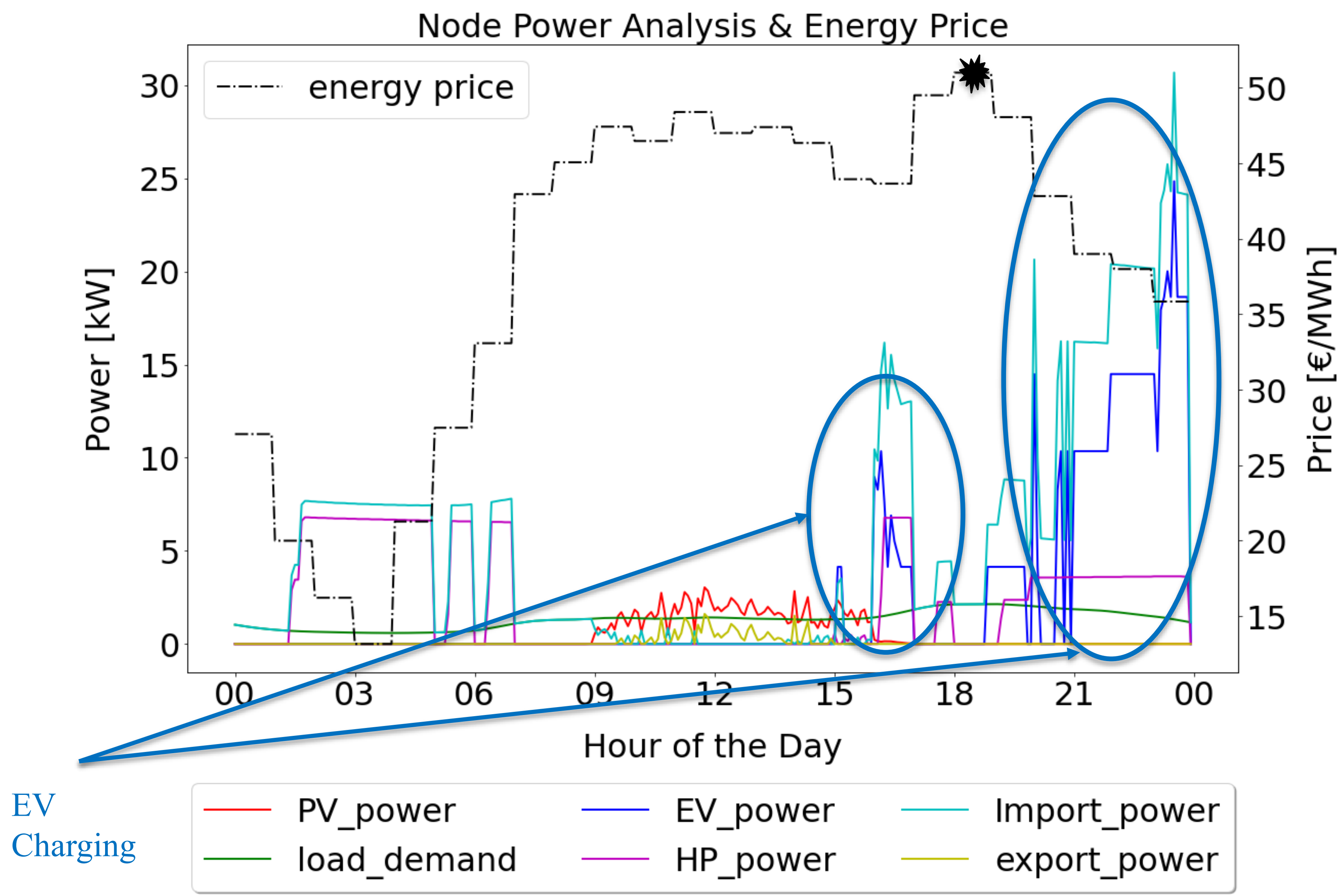

EVs Power Consumption vs Energy Price
energy price
Power [kW]
Price [€/MWh]
Hour of the Day
EV_3
EV_2
EV_1
EV_4
EV arrivals

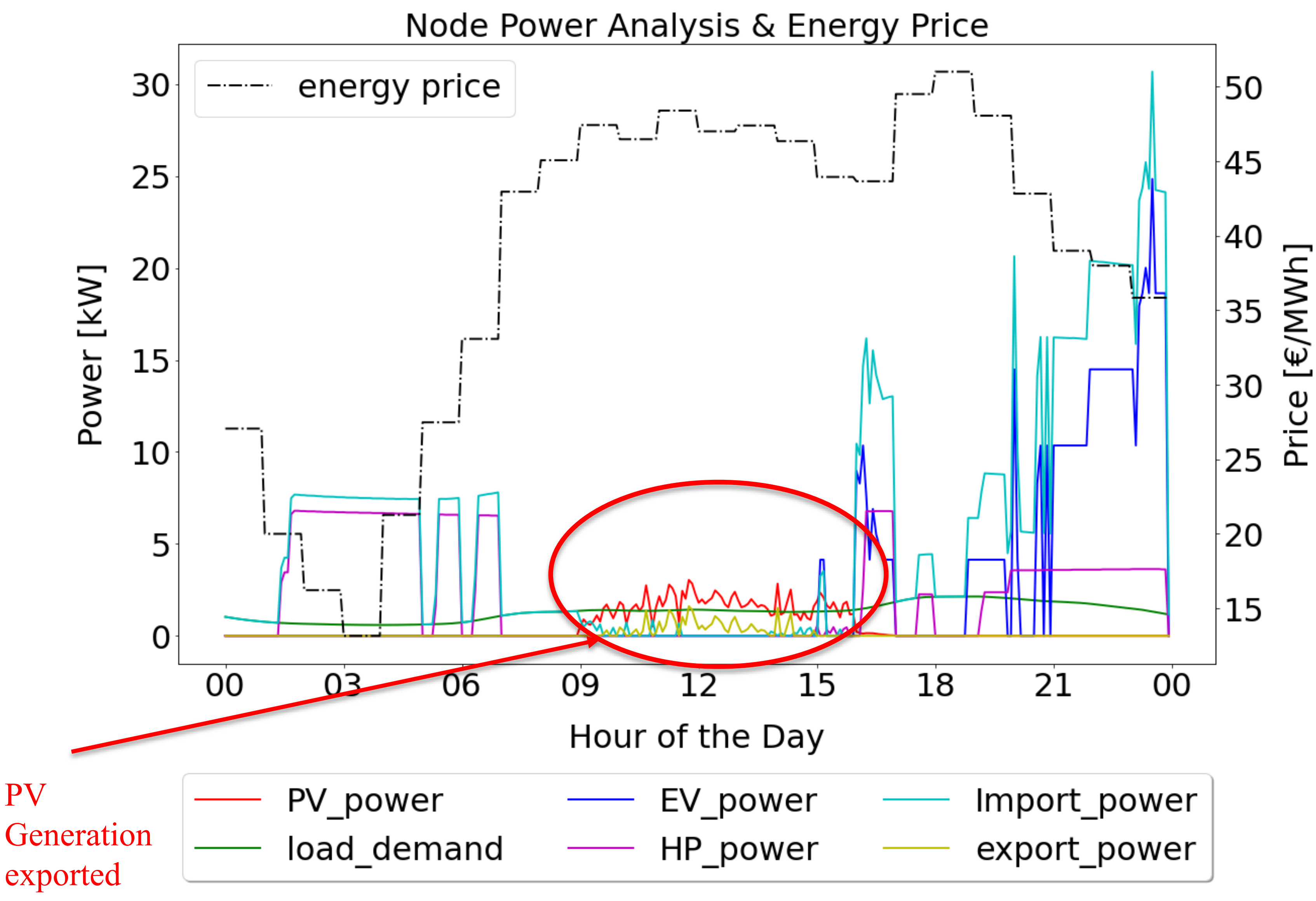

EVs Power Consumption vs Energy Price
energy price
Power [kW]
Price [€/MWh]
Hour of the Day
EV_3
EV_2
EV_1
EV_4
HP Consumption & Building Temperature: Building 1
Power [kW]
Temperature [oC]
Hour of the Day
HP Power
Building T
HP Consumption & Building Temperature: Building 2
Power [kW]
Temperature [oC]
Hour of the Day
HP Consumption & Building Temperature: Building 3
Power [kW]
Temperature [oC]
Hour of the Day



Node Power Analysis & Energy Price
energy price
Power [kW]
Price [€/MWh]
30
25
20
15
10
5
0
50
45
40
35
30
25
20
15
00
03
06
09
12
15
18
21
00
Hour of the Day
PV_power
EV_power
Import_power
load_demand
HP_power
export_power


Node Power Analysis & Energy Price
energy price
Power [kW]
Price [€/MWh]
Hour of the Day
30
25
20
15
10
5
0
50
45
40
35
30
25
20
15
00
03
06
09
12
15
18
21
00
Buildings
Heating
PV_power
load_demand
EV_power
HP_power
Import_power
export_power


Node Power Analysis & Energy Price
energy price
Power [kW]
Price [€/MWh]
Hour of the Day
00
03
06
09
12
15
18
21
00
0
5
10
15
20
25
30
15
20
25
30
35
40
45
50
EV
Charging
PV_power
load_demand
EV_power
HP_power
Import_power
export_power


Node Power Analysis & Energy Price
energy price
Power [kW]
Price [€/MWh]
Hour of the Day
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45
50
PV_power
load_demand
EV_power
HP_power
Import_power
export_power
PV Generation exported

Thank you for your attention!!!

Questions?

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Acknowledgements

Special Thanks…

- To my promotor Prof. P. Bauer, my supervisor dr. G.R.C Mouli & the DCE&S Group for their valuable guidance

- To NEON Colleagues & Partners for their contribution to the important ongoing research of NEON Project

- To ElaadNL and Enexis Partners & PhD Student Yunhe Yu for their crucial inputs for this PhD Research

- To Green Village for the realization of today's event!

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Appendix A: Developed Models in-detail

PV Generation Model

PV Generation (1)

Module orientation = [0, 360), step = 20

Monte Carlo Simulation

90 PV 3kW rated power profiles
Randomly distributed
12 Panels x 245W

Tilt angle = [10, 50], step = 10

$$\textbf{Generation}: G_{AOI} = G_M{}^{direct} + G_M{}^{diffuse} + G_M{}^{albedo}$$

$$G_M{}^{direct} = DNI(\sin\theta_M \cos\alpha_s \cos(A_M - A_s) + \cos\theta_M \sin\alpha_s$$

$$G_M{}^{diffuse} = DHI\left(\frac{1+\cos\theta_M}{2}\right): Isotropic\ Sky\ Model$$

$$G_M{}^{albedo} = GHI * a * \left(1 - \frac{1+\cos\theta_M}{2}\right)$$

Module Temperature: Duffie-Beckman model

$$T_M = T_{air} + \frac{G_{AOI}}{G_{NOCT}}(NOCT - 20C) * \frac{9.5}{5.7 + 3.8 * w}(1 - \frac{\eta_{STC}}{ta{\sim}0.9})$$

- Inputs (Meteonorm):
  - DNI (Direct Normal Irradiance)
  - DHI (Diffuse Horizontal Irradiance)
  - GHI (Global Horizontal Irradiance)
  - T_{air}, wind speed: w
- Inputs (PV module): IT PV module, see appendix
  - A_{module}
  - $V_{MPP}, I_{MPP}, P_{MPP}$
  - $\eta_{STC} = \frac{P_{MPP}}{G_{STC} * A_{module}}$, G_{STC}
  - $V_{OC_{STC}}, I_{SC_{stc}}, P_{MPP_{STC}}$: Standard Test Conditions
  - $Coef_{V_{OC}}, Coef_{I_{SC}}, Coef_{P_{MPP}}$: Temperature Coefficients
  - NOCT, G_{NOCT}
- Assumptions
  - Tilt angle: θ_M
  - Module Orientation: A_M
  - Effective transmittance – absorptivity τα ~ 0.9
  - Albedo α (ground reflectivity of roofs)
  - Inverter efficiency: η_{inv}

calculation

$$\textbf{Final PV Generation}: P = \eta_{real} * A_{module} * G_{AOI} * \eta_{inv}$$

PV Generation (2)

$$\boldsymbol{\eta_{real} = \eta(T, G)}$$

<u>Efficiency: Temperature dependent</u>

$$V_{OC}(\mathrm{T_M}, G_{STC}) = V_{OC_{STC}} + Coef_{V_{OC}}(\mathrm{T_M} - \mathrm{T_{STC}})$$

$$I_{SC}(\mathrm{T_M}, G_{STC}) = I_{SC_{STC}} + Coef_{I_{SC}}(\mathrm{T_M} - \mathrm{T_{STC}})$$

$$P_{MPP}(\mathrm{T_M}, G_{STC}) = P_{MPP_{STC}} + Coef_{P_{MPP}}(\mathrm{T_M} - \mathrm{T_{STC}})$$

$$\eta(\mathrm{T_M}, G_{STC}) = \frac{P_{MPP}(\mathrm{T_M}, G_{STC})}{A_{module} * G_{STC}}$$

$$\eta_{coef} = \frac{\eta(\mathrm{T_M}, G_{STC}) - \eta_{STC}}{\mathrm{T_M} - \mathrm{T_{STC}})}$$

<u>Efficiency: Irradiance dependent</u>

$$V_{OC}(25C, G_{AOI}) = V_{OC_{STC}} + \frac{nk_BT}{q}\ln\left(\frac{G_{AOI}}{G_{STC}}\right) * N$$

$$I_{SC}(25C, G_{AOI}) = I_{SC_{STC}} * \frac{G_{AOI}}{G_{STC}}$$

$$P_{MPP}(25C, G_{AOI}) = FF * V_{OC}(25C, G_{AOI}) * I_{SC}(25C, G_{AOI}),$$

$$where\ Fill\ Factor\ FF = \frac{\eta_{STC} * G_{STC} * A_{module}}{P_{MPP_{STC}}}$$

$$\eta(25C, G_{AOI}) = \frac{P_{MPP}(25C, G_{AOI})}{A_{module} * G_{AOI}}$$

$$\eta_{real} = \eta(\mathrm{T_M}, G_{AOI}) = \eta(25C, G_{AOI}) * [1 + \frac{\eta_{coef}}{\eta_{STC}} * (T_{\mathrm{M}} - 25C)]$$

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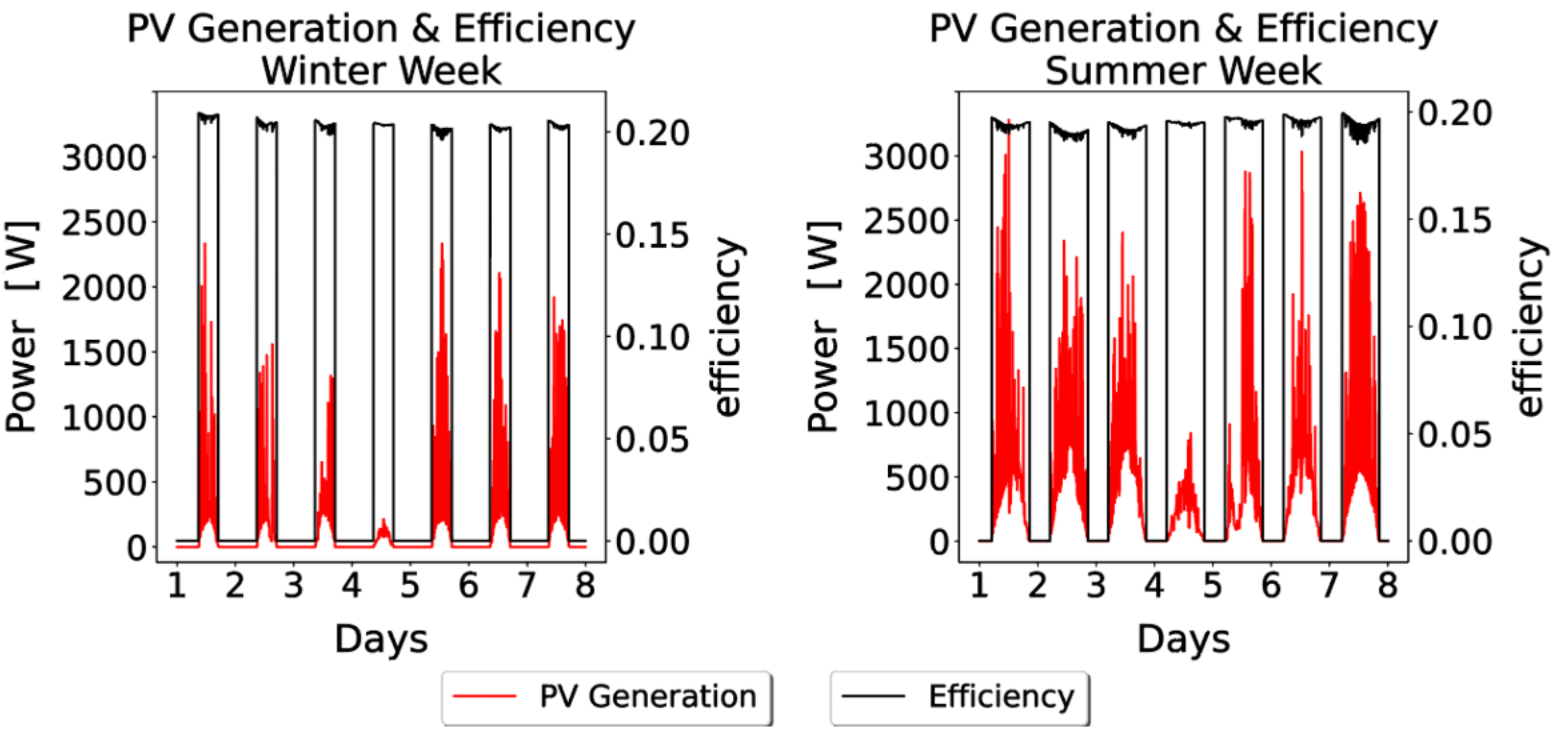
PV Generation (3)
Results



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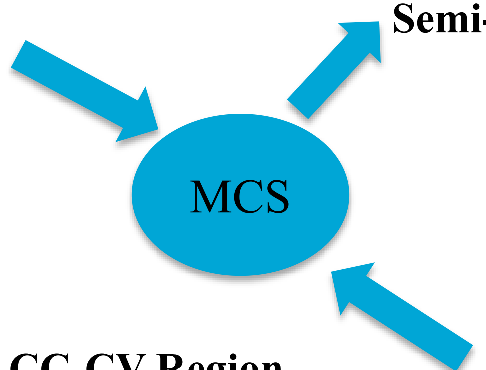
EV Model

EV Consumption (1)

- Inputs (Elaad Open Database)
  - Arrival and Departure SOCs
  - Requested Energy
  - Arrival and Departure Times
- Inputs (considered various EVs)
  - Rated current I_{rat}
  - Battery Capacity C_{bat}

200 weekly datasets for Home, Semi-Public & Public Chargers



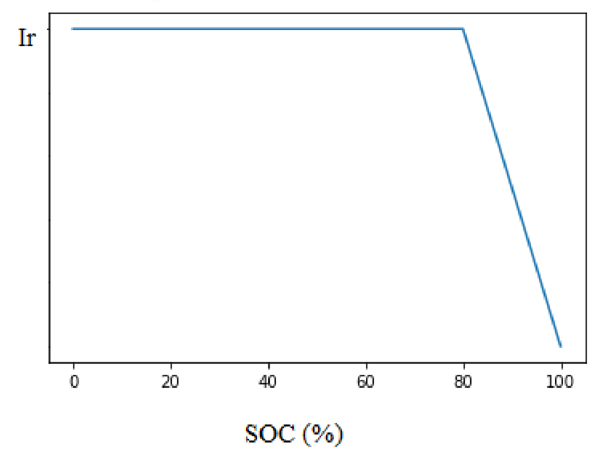
CC-CV Region

- 0-80% Constant Current Region
- 80-100% Constant Voltage Region

$$I_{cv}(t) = 5 * \left(1 - SOC(t)\right) * I_{rat}(t)$$

$$I_{charg}(t) = \min(I_{rat}(t), I_{cv}(t))$$

$$SOC(t) < 80\%: I_{charg}(t) = I_{rat}(t)$$
$$SOC(t) > 80\%: I_{charg}(t) = I_{cv}(t)$$



Linearized representation of CC-CV EV charging

<u>The above work is part of the PhD project of student Yunhe Yu, who works on OSCD project</u>

EV Consumption (2)

30% Higher Consumption during Winter

SOC_{arr} Summer SOC_{dep}

$$E_{drive} = (SOC_{dep} - SOC_{arr})Capacity$$

SOC'_{arr} Winter SOC'_{dep}

$$E'_{drive} = (SOC'_{dep} - SOC'_{arr})Capacity$$

$$If\ \frac{E'_{drive}}{E_{drive}} = 130\%$$

& → …

Assuming that $SOC'_{dep} = SOC_{dep}$

$$SOC'_{arr} = 1.3SOC_{arr} - 0.3SOC_{dep}$$

&

$$E'_{requested} = (SOC'_{dep} - SOC'_{arr})Capacity$$

The increased consumption during winter has been assessed in terms of arrival SOC & requested energy, keeping number of charging sessions steady

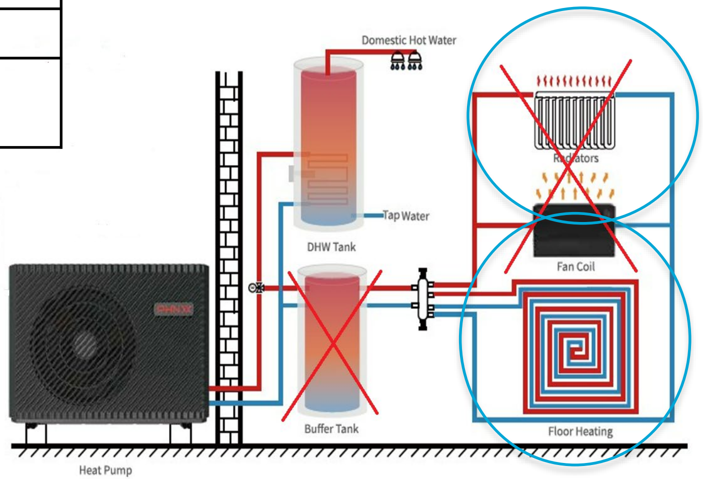
Building & Heating Models

Considered Building Model Approach

Surface	Material	Dimensions (m2)	Thickness (m)	Conductivity (W/mK)
Floor	Wood	90	0.03	0.18
Front/Back Walls	Brick	15x5	0.23	1
Side Walls	Brick	6x8	0.23	1
Roof	`Clay	15x4.25	0.015	0.72
Windows/ Door	-	-	-	-

Building Characteristics

Typical Dutch Terraced House



Heat Pump Lay-out

- Simulated as 1-zone space
- Total Building Volume:

$$A_{floor} * Height_{frontwall} + A_{floor} * \frac{H_{frontwall} - H_{sidewall}}{2}$$

- Total Building Area:

$\sum(all\ areas)\ , where\ roof\ considered\ twice$

Improvement of building insulation

$$\textbf{Insulation equation}: U_{desired} = \frac{1}{\frac{thickness_{material}}{U - value_{material}} + \frac{thickness_{insulation}}{U - value_{insulation}}}$$

Required U-values for new buildings:

- $U_{wall} < 0.3\ W/m^2K$
- $U_{roof} < 0.18\ W/m^2K$
- $U_{floor} < 0.22\ W/m^2K$

Insulation Materials:

- EPS (Expanded Polystyrene): 0.024 W/mK
- PIR board (Celotex): 0.019W/mK

Walls + 80mm EPS → 0.28 W/m^2K
Roof + 110mm Celotex → 0.17 W/m^2K

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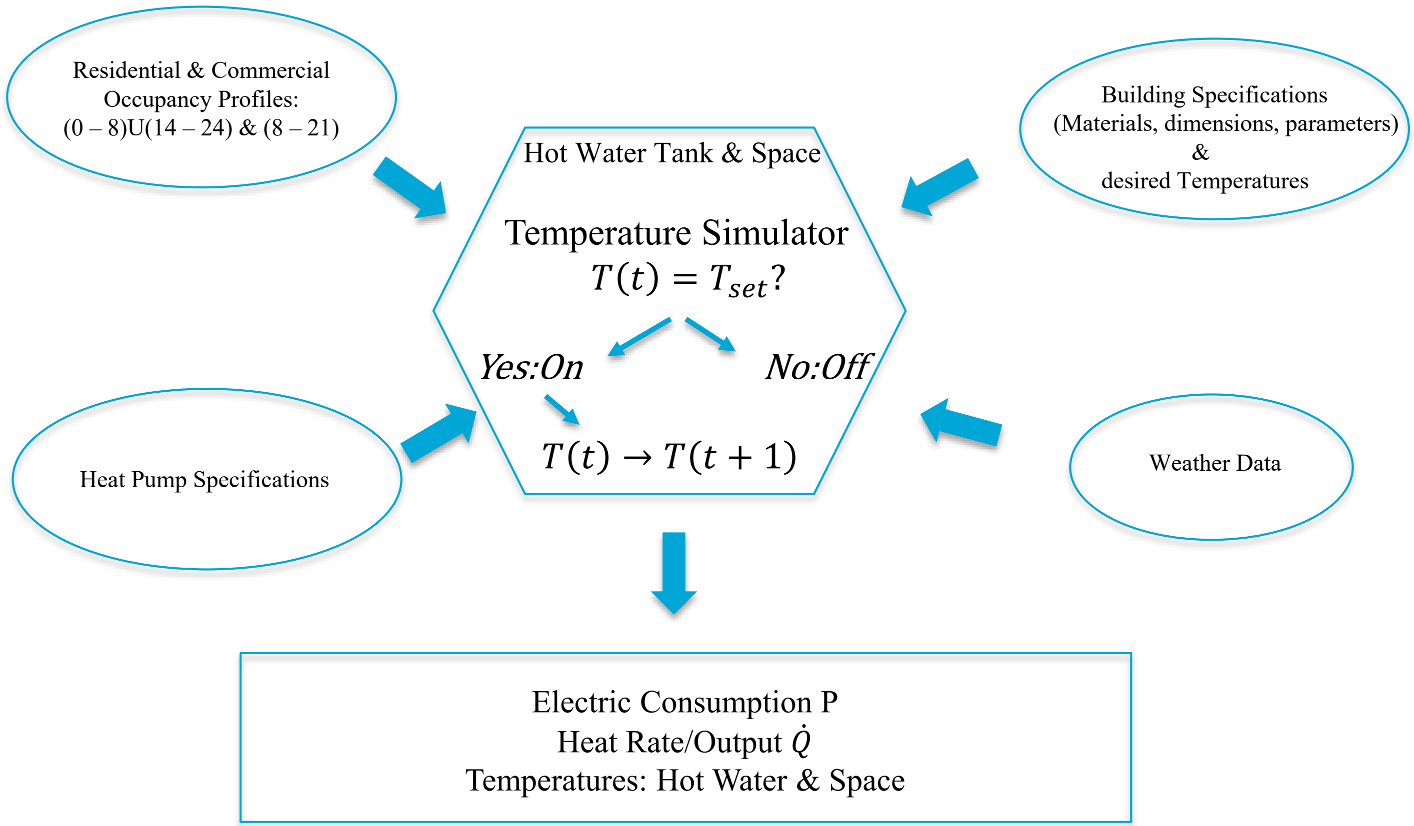
Concept of Heating Model



Note: Heat Pump cannot heat tank and space simultaneously: twice per day (morning 06:00 & evening 19:00) hot water is heated and is given priority

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Heating Model

Space Heating ($T_{supply} = 35$)

$$T_{house}(t+1) = \frac{\dot{Q}_{house} = \dot{Q}_{hp} + \dot{Q}_{irrad} - \dot{Q}_{loss}}{C_{m_{building}} + V_{house} * C_{p_{air}} * \rho_{air}} * \Delta t + T_{house}(t)$$

$$\dot{Q}_{irrad} = (Irradiance\ incident\ on\ building) * WWR * SHGC$$

WWR: Window-to-wall ratio (30%) & SHGC: solar heat gain coefficient (20%)

$$\dot{Q}_{loss} = Q_{conduc} + Q_{ventil} = \sum (U_{area} * A_{area}) * (T_{house} - T_a) + C_{air} * \rho_{air} * ACH_{house} * (T_{house} - T_a), where\ ACH = 0.35h^{-1}$$

$$\dot{Q}_{hp}(t) = \dot{m}_w * C_w * (T_{supply} - T_{return}(t))$$

$$P_{con}(t) = \dot{Q}_{hp}(t)/COP(t)$$

$\dot{Q}_{irrad}$

$$C * \frac{\Delta T_{house}}{\Delta t}$$

$\dot{Q}_{loss}$

$$\dot{Q}_{hp}(t) = U_{floor} * A_{floor}(T_f - T_{house}(t))$$

Stored heat in the floor neglected for steady state

$\dot{m}_w * C_w * T_{supply}$

$\dot{m}_w * C_w * T_{return(t)}$

Hot Water Tank Heating ($T_{supply} = 50$)

$$T_{tank}(t+1) = \frac{\dot{Q}_{tank} = \dot{Q}_{stored} = \dot{Q}_{hp} - \dot{Q}_{loss}}{C_{m_{tank}} = V_{tank} * C_{p_{water}} * \rho_{water}} * \Delta t + T_{house}(t)$$

$$\dot{Q}_{loss} = U_{tank} * A_{tank} * (T_{water} - T_a)$$

$$\dot{Q}_{hp}(t) = \dot{m}_w * C_w * (T_{supply} - T_{return}(t))$$

$$P_{con}(t) = \dot{Q}_{hp}(t)/COP(t)$$

$\dot{Q}_{loss}$

$$C_{tank} * \frac{\Delta T_{tank}}{\Delta t}$$

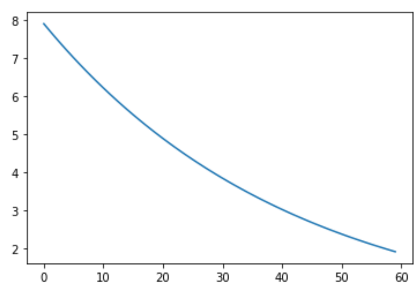
$\dot{Q}_{hp}$

$$V_{tank} = 1.25 * 65 * (N_{people})^{0.7}$$

$$A_{tank} = 2 * pi * R * H + 2 * pi * R^2$$

$$R_{tank} = 0.23m, H_{tank} = 1.3m$$

$$U_{tank} = 5.98 * 10^{-4} kW/(Km^2)$$



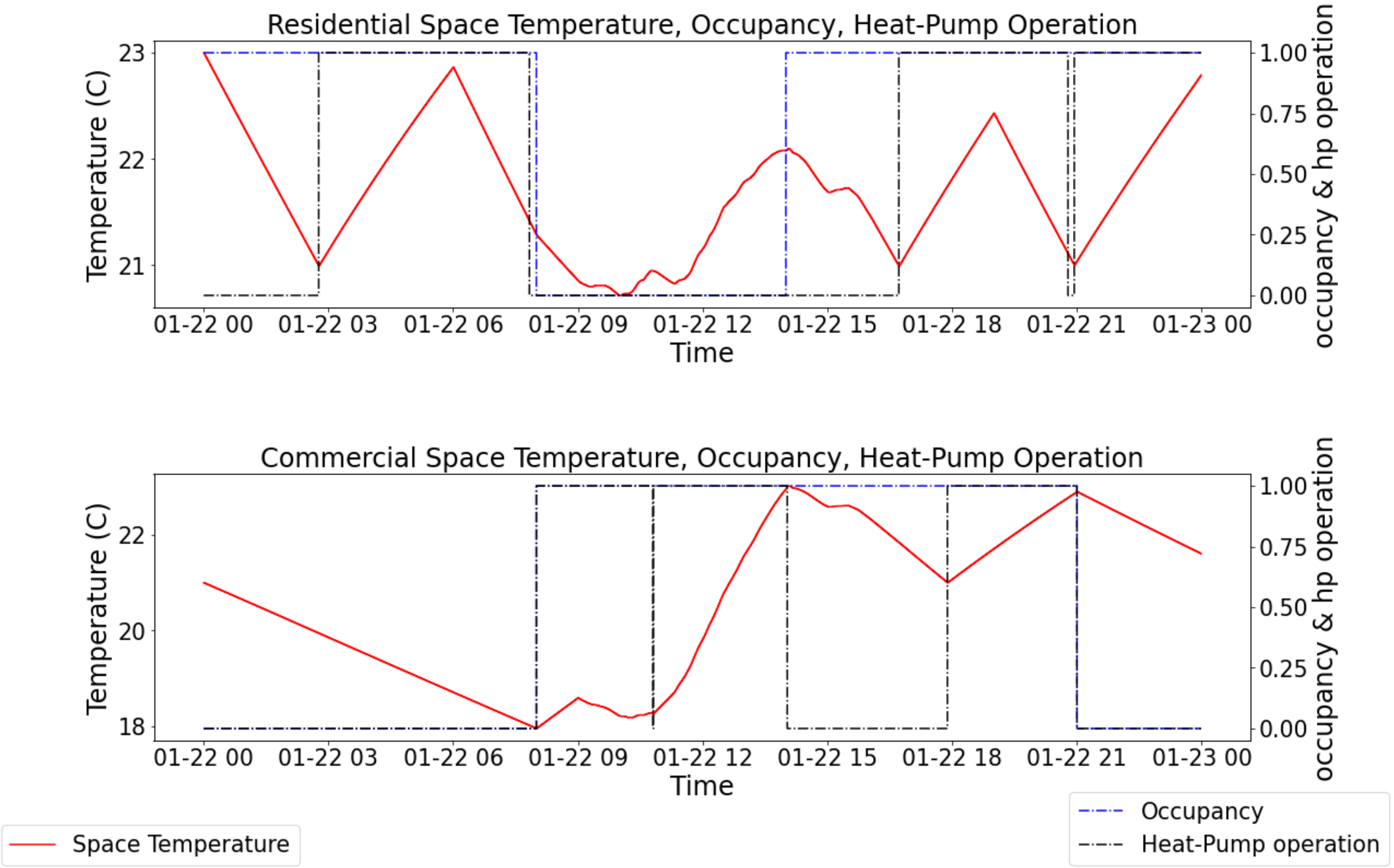
$$COP(t) = 7.90471 * e^{-0.024*(T_{ret}(t) - T_a)}$$

Estimated with regression from 10 different HP models "Cooling & Heating COP"

- Desired $Ton_{house} = 21$ & $Toff_{house} = 23$
- Mass Flow Rate of Water: $\dot{m}_{ASHP} = 0.5kg/s$
- **Every timestep: T_{supply}, T_a → $\dot{Q}_{hp}(t)$ (HP specs), $\dot{Q}_{loss}(t)$, $\dot{Q}_{irrad}(t)$ → $T_{house}(t)$ & $T_{return}(t)$ → $COP(t)$ → $P_{con}(t)$**

Heating Model Results

Occupancy, HP ON-OFF Temperature & Building Temperature



Building Temperature and ON-OFF operation (winter week)

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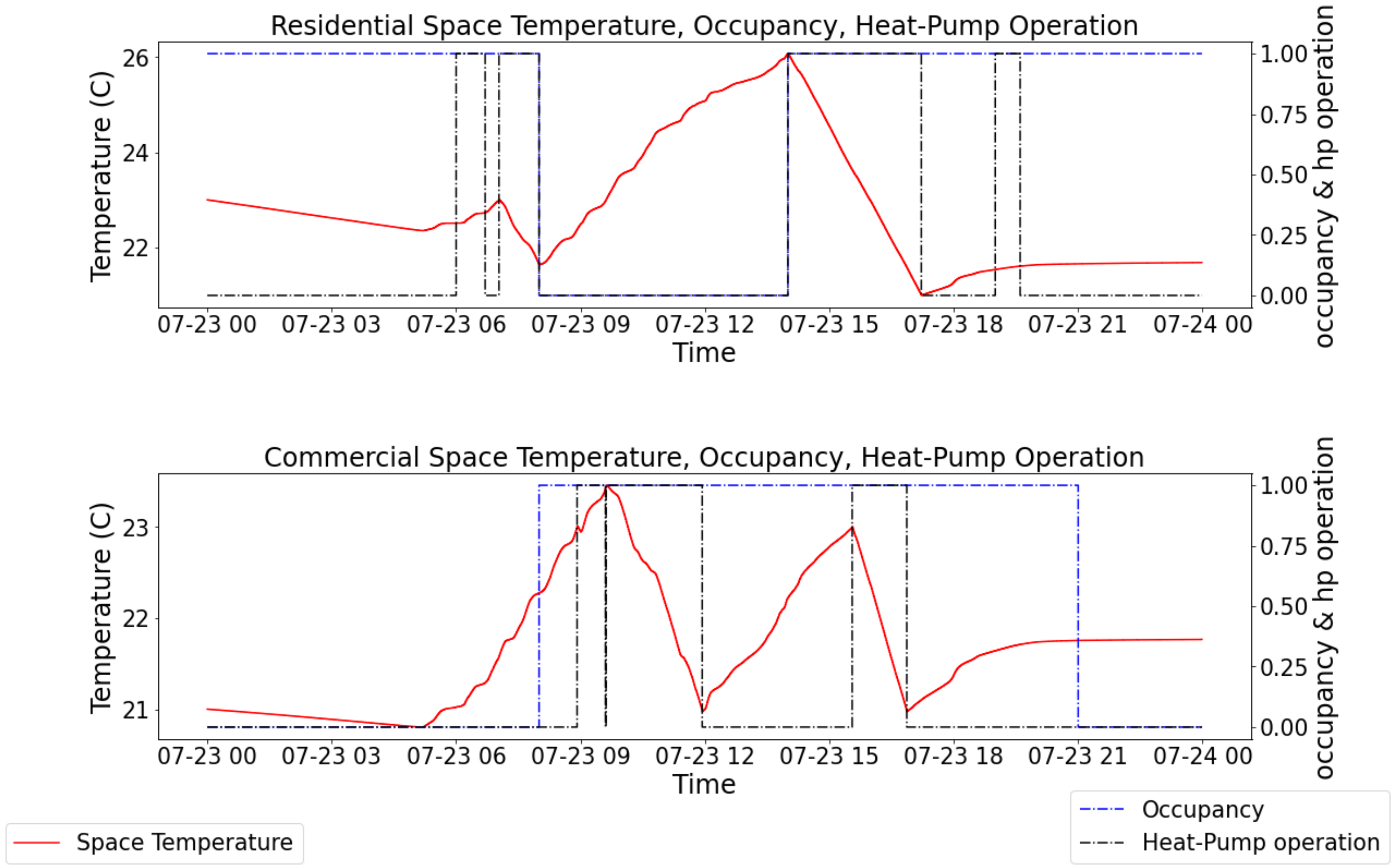
Heating Model Results

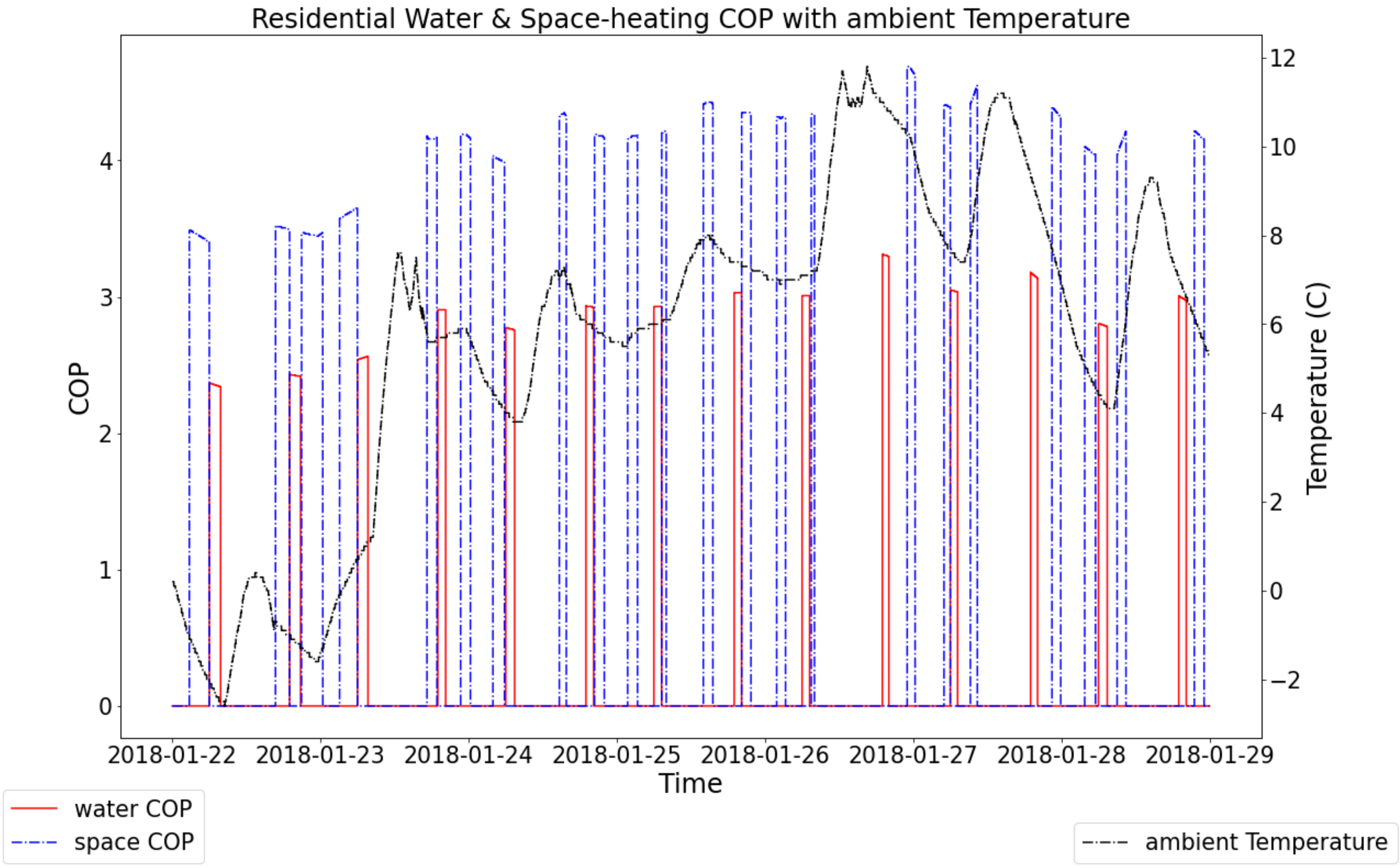
Occupancy, HP ON-OFF Temperature & Building Temperature



Building Temperature and ON-OFF operation (summer week)

Heating Model Results

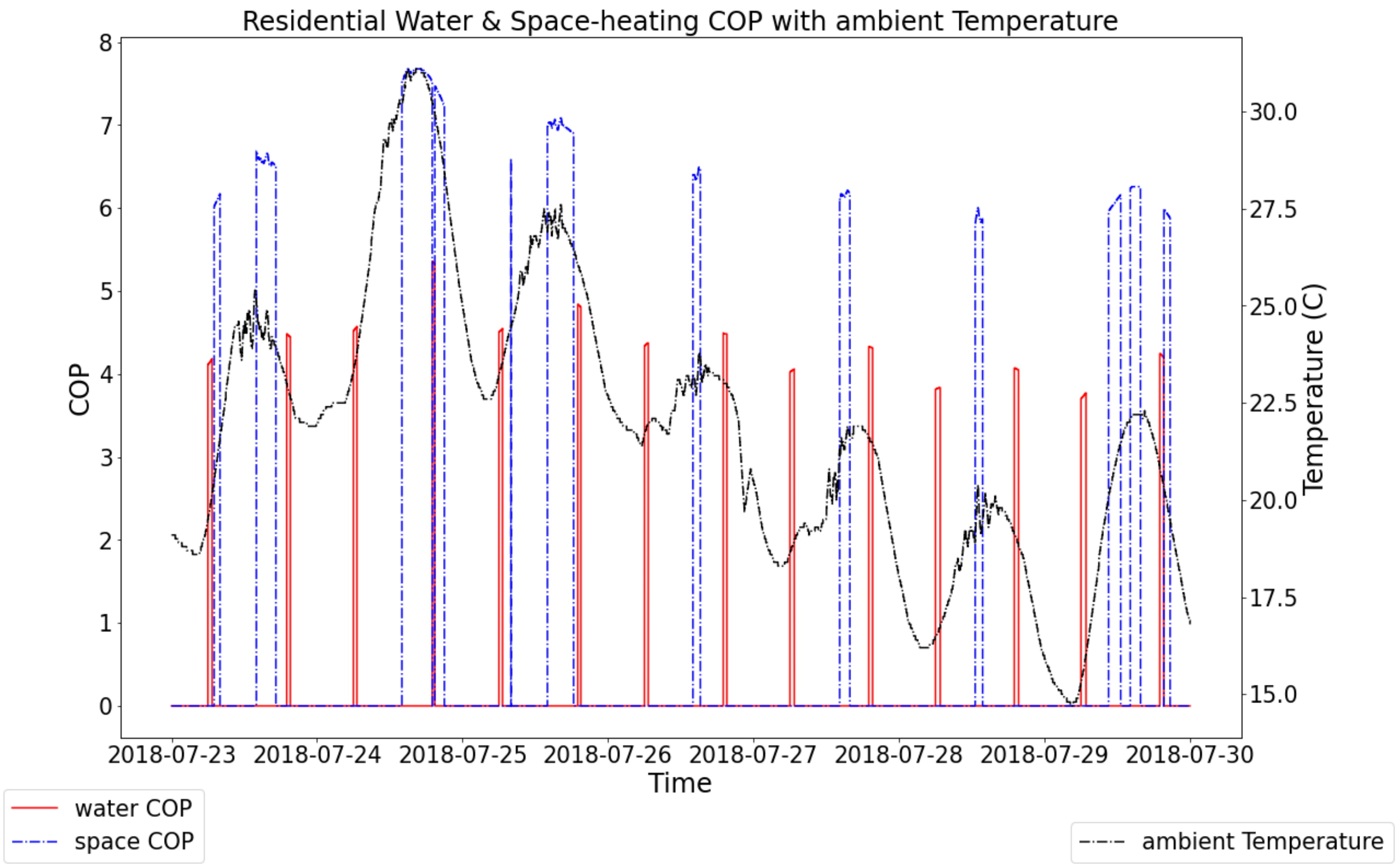
Weekly water & space-heating COP vs ambient Temperature



HP Heating COPs vs ambient Temperature (winter week)

Heating Model Results

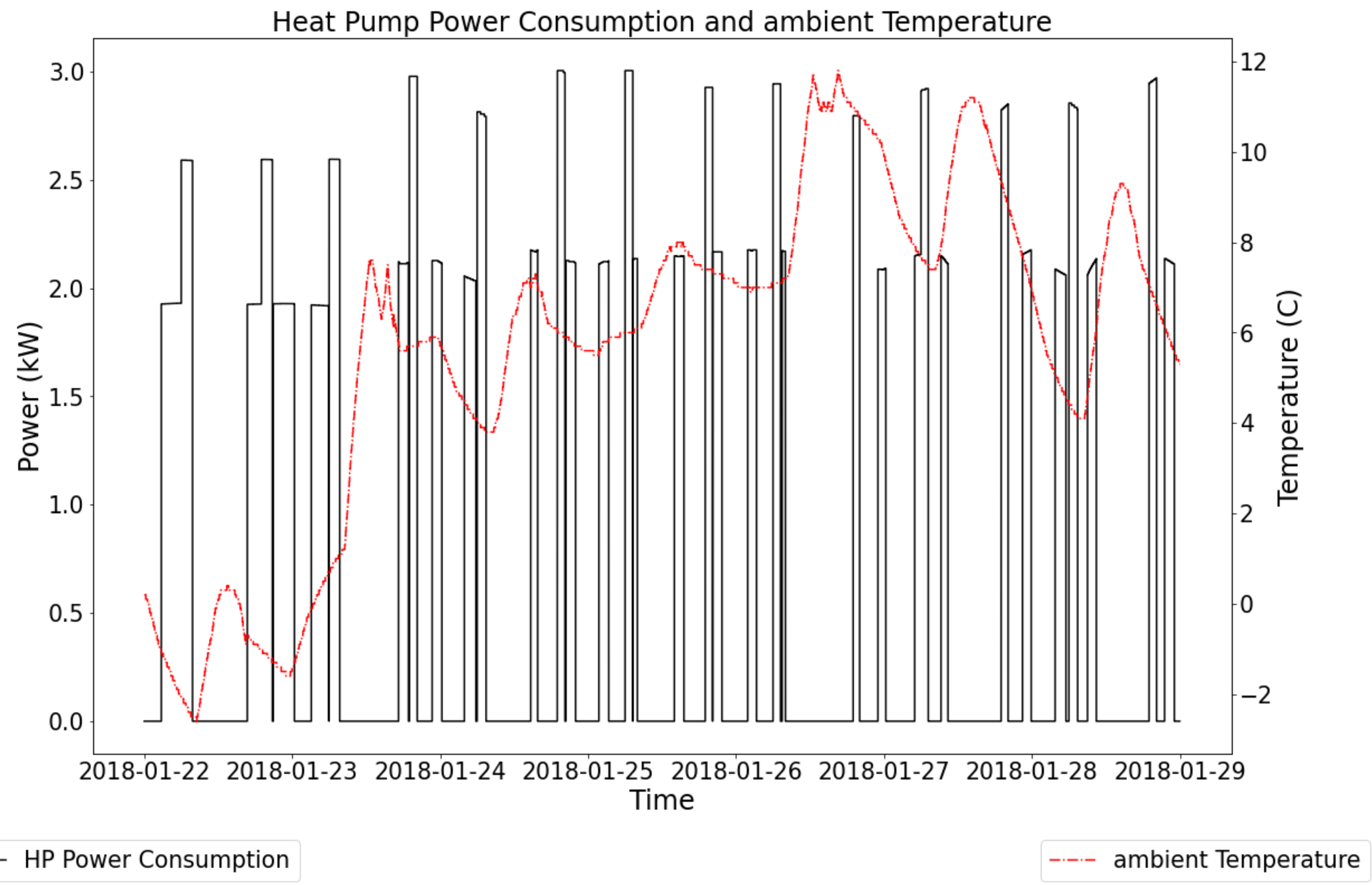
Weekly water & space-heating COP vs ambient Temperature



HP Cooling COPs vs ambient Temperature (summer week)

Heating Model Results

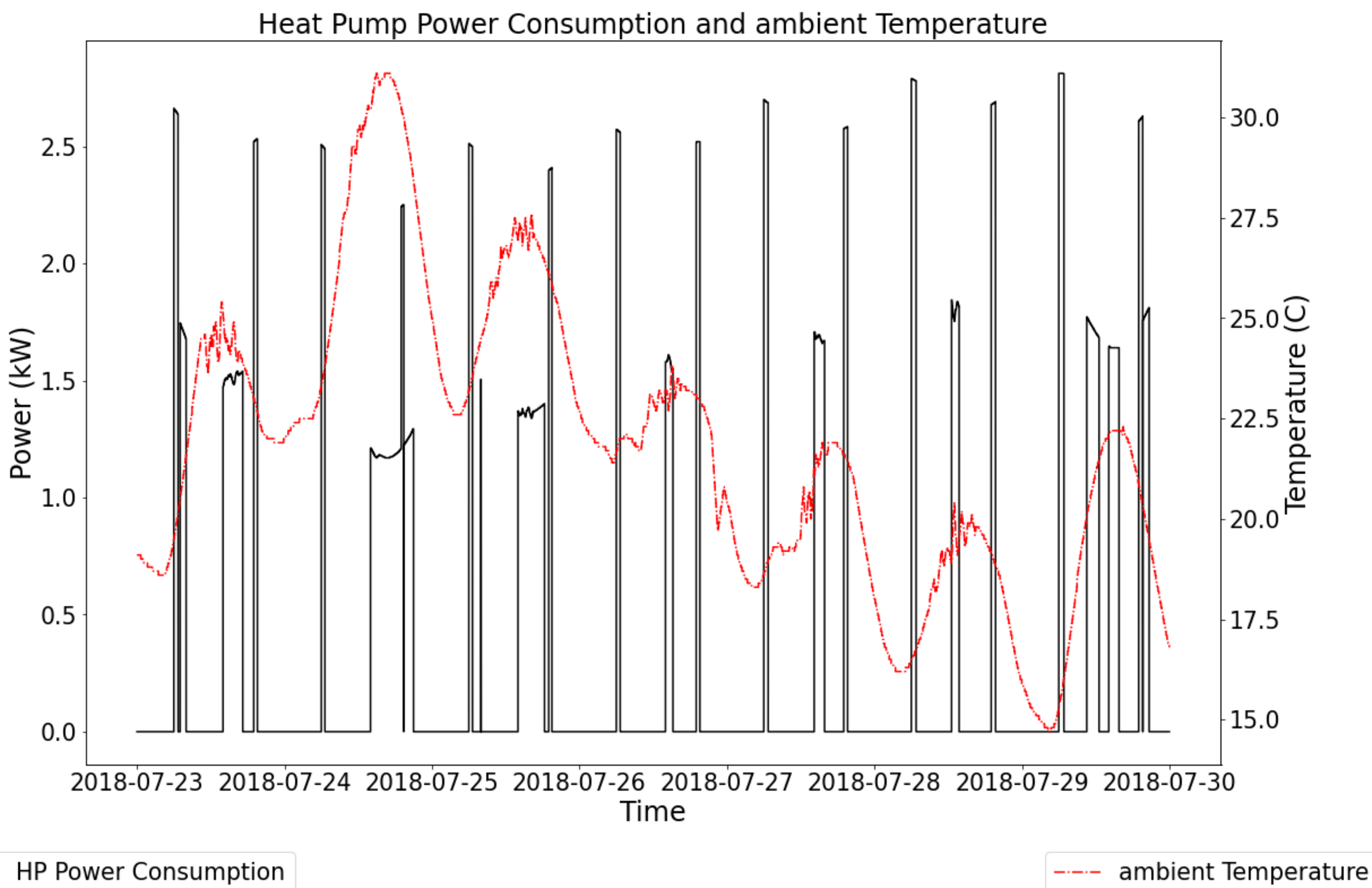
HP Power Consumption vs ambient Temperature



HP Heating Consumption vs ambient Temperature (winter week)

Heating Model Cooling Results

HP Power Consumption vs ambient Temperature



HP Cooling Consumption vs ambient Temperature (summer week)

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Appendix B: Some more Grid Impact Results

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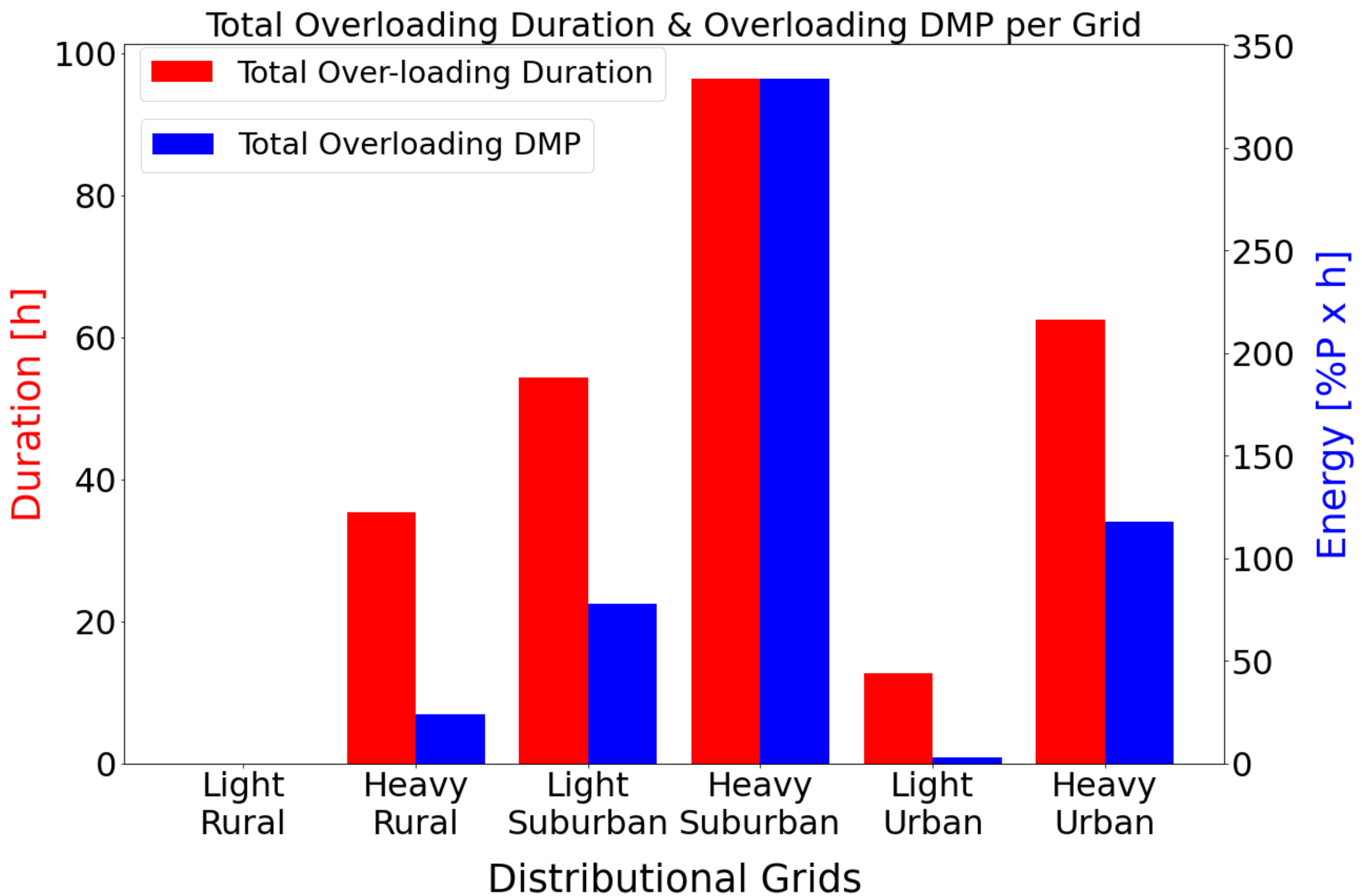
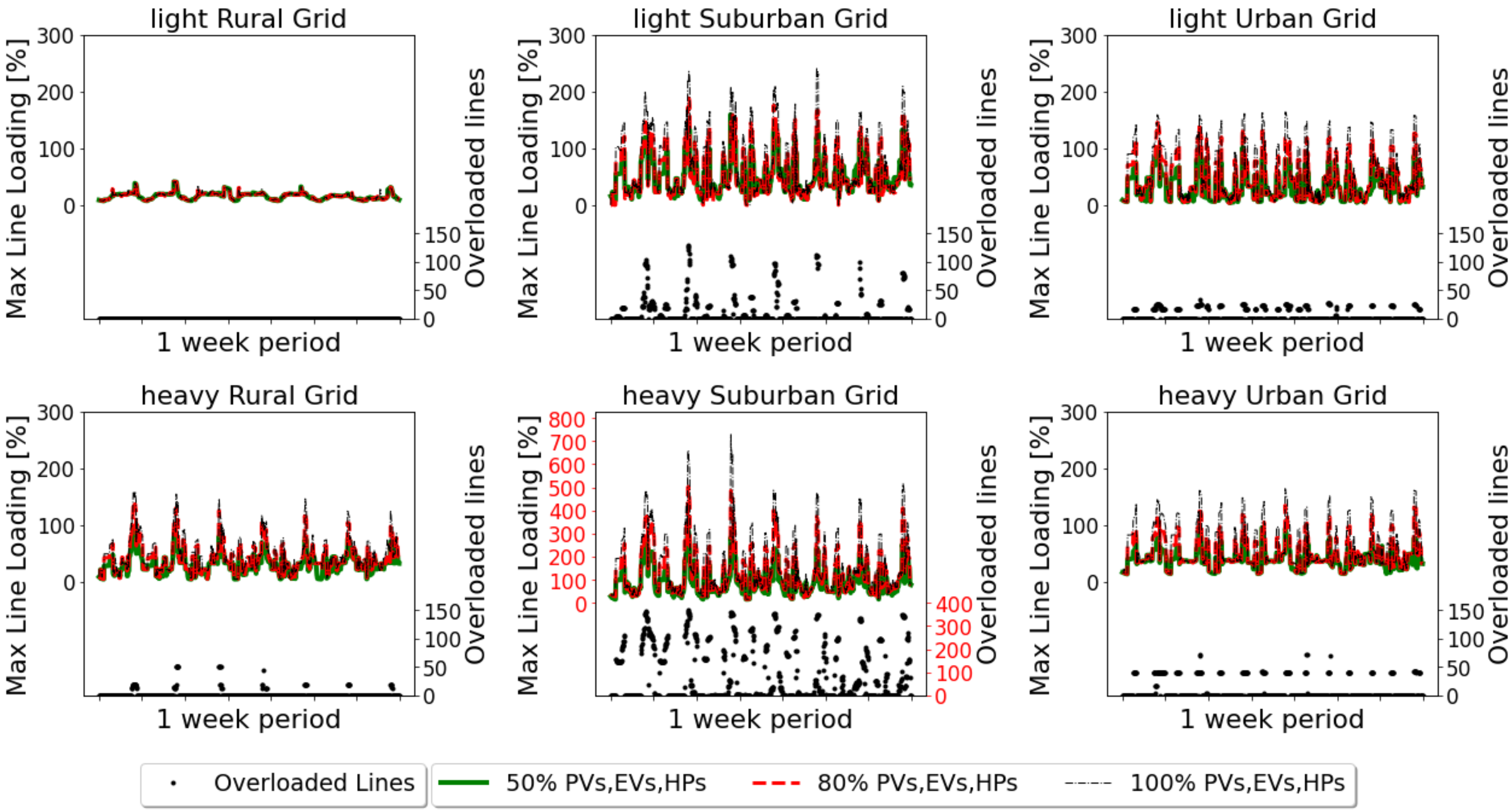
Transformer Loading (3)



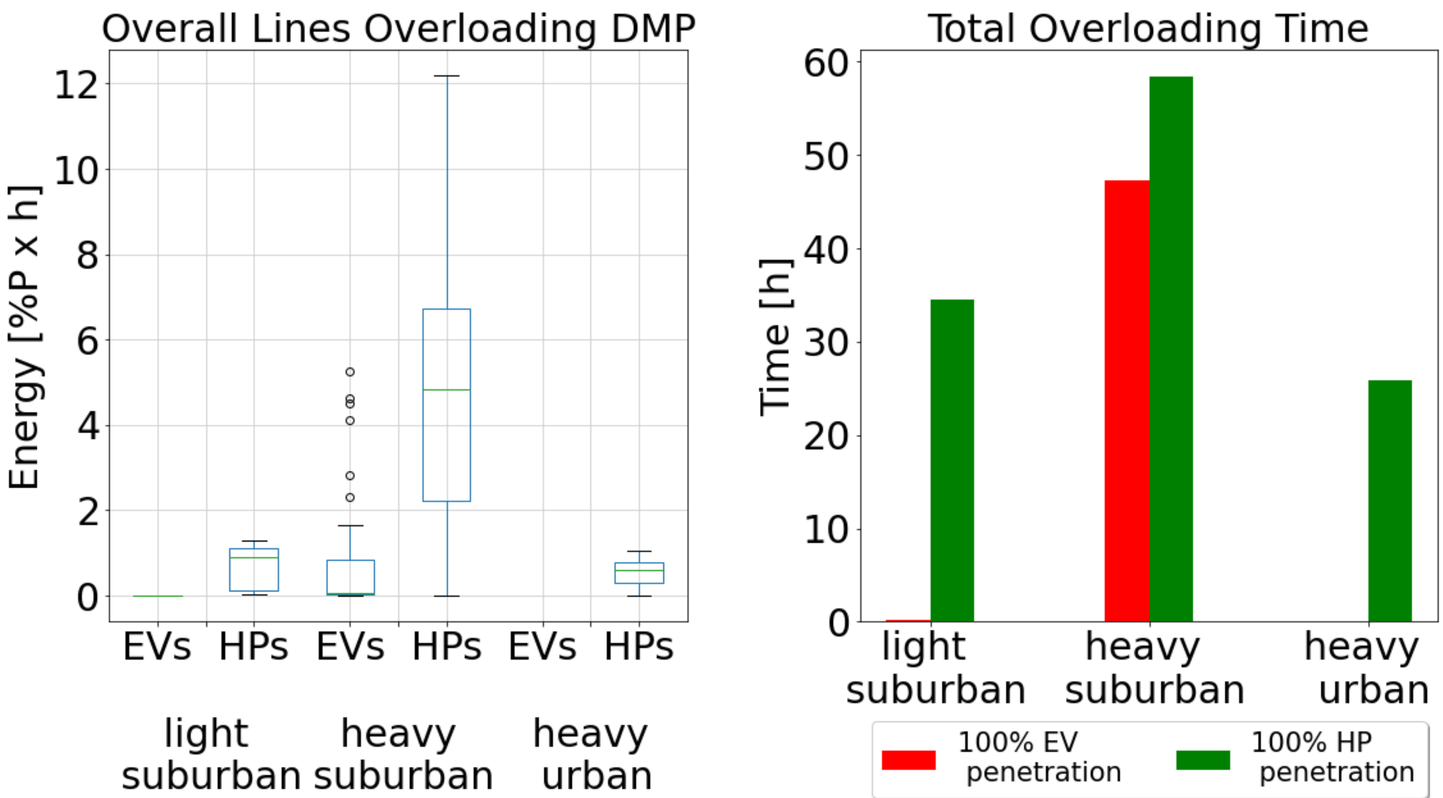
Total Overloading Duration & Overloading DMP at 100% combined LCT Penetrations per Distribution Grid

Lines Loading (1)



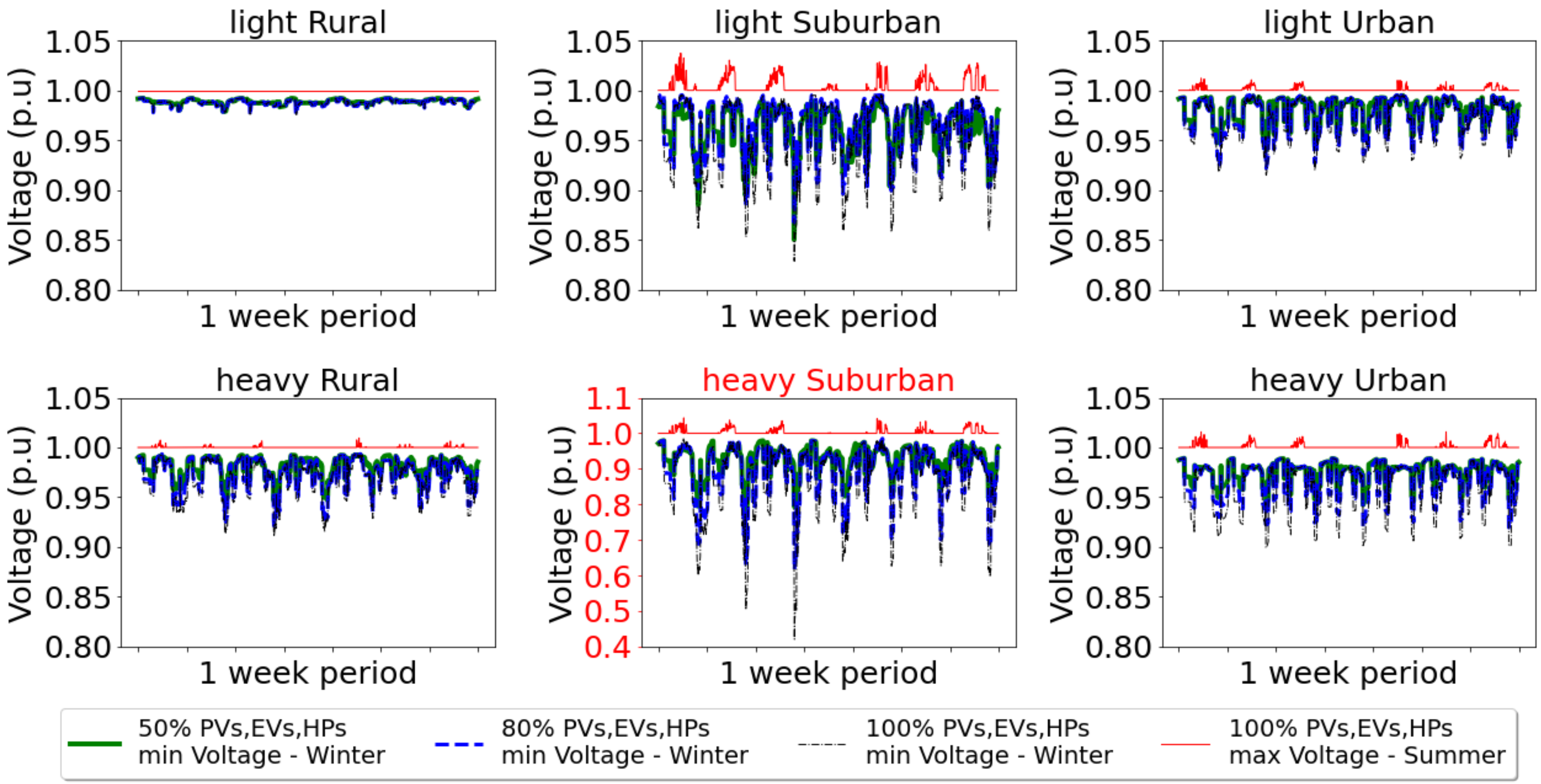
Lines Maximum Loading at 50, 80 & 100% combined LCTs penetrations
And number of over-loaded Lines at 100% per Distribution Grid

Lines Loading (2)



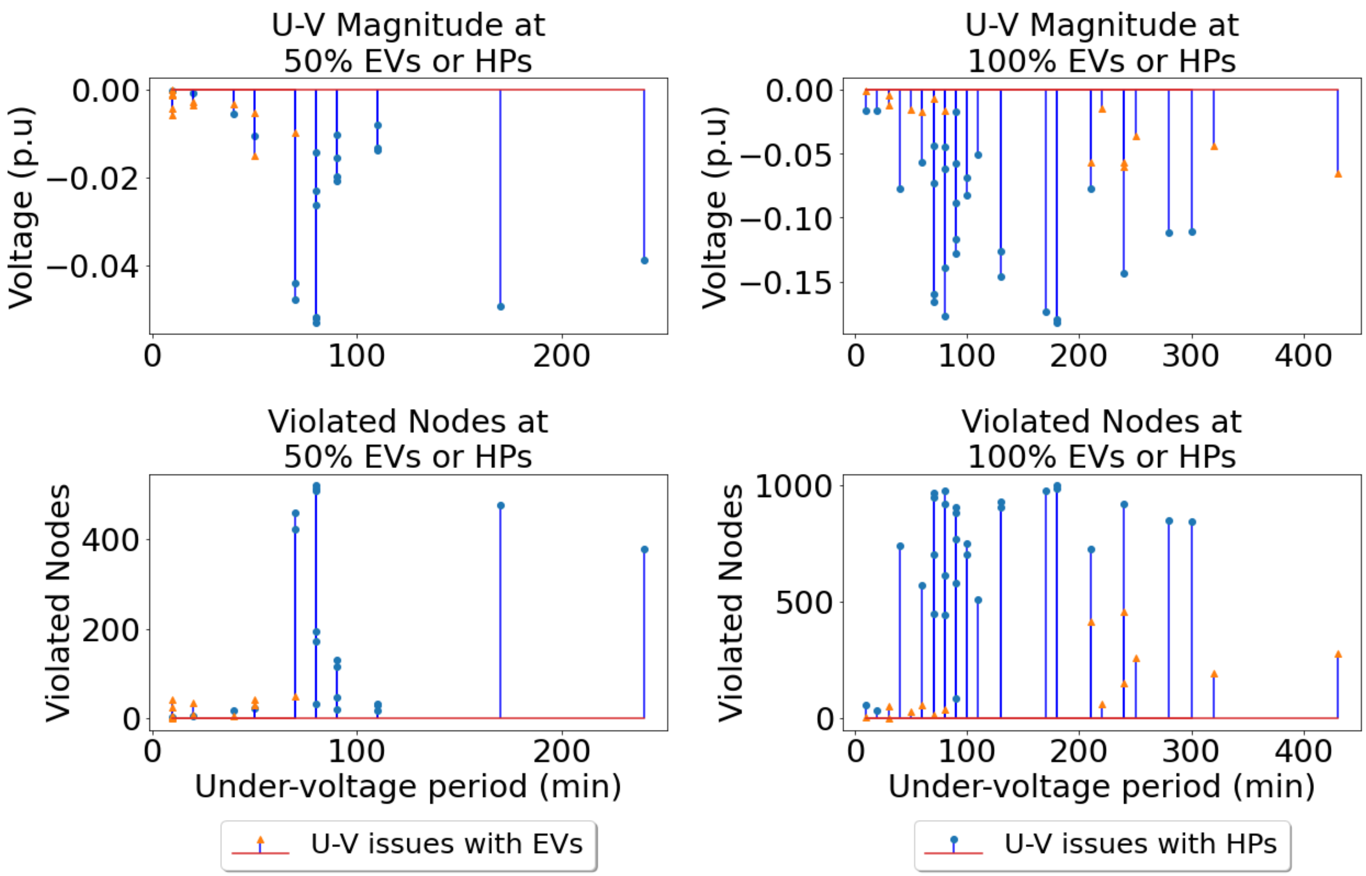
Overall Lines Over-loading DMP and Time at 100% HP & EV penetration at the 3 most vulnerable Distribution Grids

Nodes Voltage Deviation (1)



Nodes min Winter Undervoltage & max Summer Overvoltage at 50, 80 & 100% combined LCTs penetrations And number of violated Nodes at 100% per Distribution Grid

Nodes Voltage Deviation (2)



Under-Voltage Magnitude and Number of Violated Nodes at 50% & 100% HP and EV penetrations