# Introduction – Chris Develder

- Professor at Ghent University since Oct. 2007
  - *Research Interests*: **smart grids** (data analytics; optimization/scheduling algorithms for DSM/DR), **information extraction** (e.g., knowledge base population, relations in news archives); **optical networks** (dimensioning, resilience schemes, ILP)
  - Visiting researcher at UC Davis, CA, USA, Jul-Oct. 2007 (optical grids)
  - Visiting researcher at Columbia Univ., NY, USA, 2013-14 (IE)
- Industry Experience: network planning/design tools
  - OPNET Technologies (now part of Riverbed), 2004-05
- PhD, Ghent University, 2003
  - "Design and analysis of optical packet switching networks"
- More info: [http://users.atlantis.ugent.be/cdvelder](http://users.atlantis.ugent.be/cdvelder)

# Algorithms and communications for smart grids: Knowing and controlling power consumption


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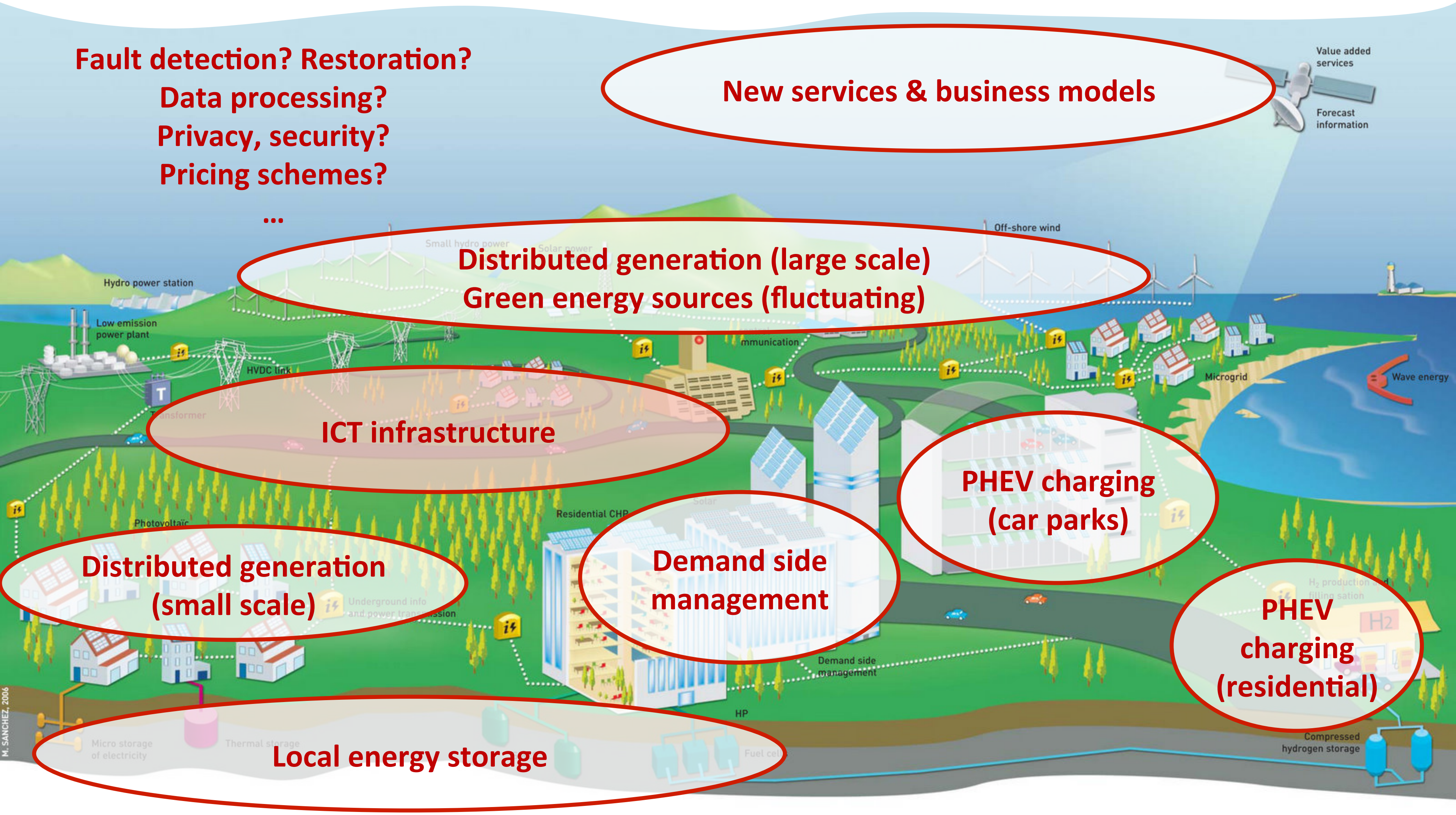
# Smart Grids

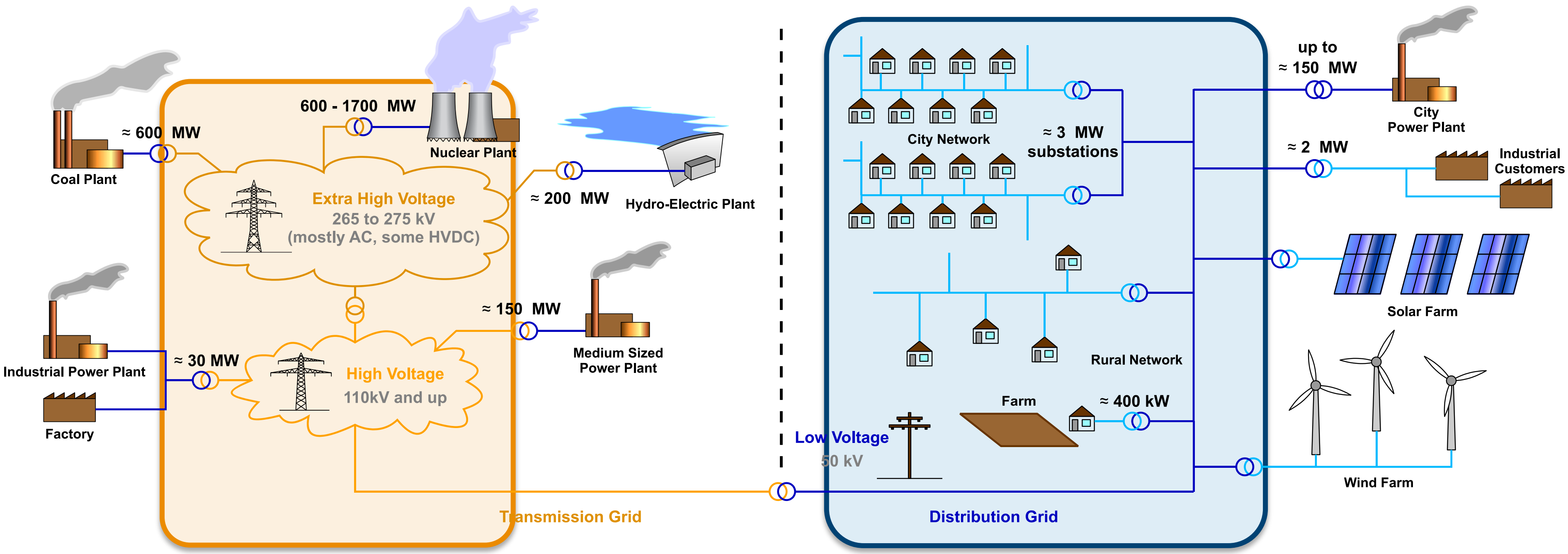


Fault detection? Restoration?
Data processing?
Privacy, security?
Pricing schemes?
…
New services & business models
Value added services
Forecast information
Distributed generation (large scale)
Green energy sources (fluctuating)
Small hydro power
Solar power
Off-shore wind
Hydro power station
Low emission power plant
HVDC link
Transformer
ICT infrastructure
Microgrid
Wave energy
PHEV charging (car parks)
Residential CHP
Photovoltaïc
Demand side management
Distributed generation (small scale)
Underground info and power transmission
Demand side management
PHEV charging (residential)
$H_2$ production and filling station
HP
Local energy storage
Micro storage of electricity
Thermal storage
Fuel cell
Compressed hydrogen storage
M. SANCHEZ, 2006

# Power grid structure

## Transmission network (operated by TSO)

## Distribution network (operated by DSO)

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# Outline

1. Introduction

**Part I: Algorithms for DSM/DR**

2. Example 1: Peak shaving
3. Example 2: Wind balancing

**Part II: Data analytics**

5. Clustering smart metering data
6. EV usage analysis

**Part III: Communication middleware**

7. C-DAX: A cyber-secure data and control cloud for power grids

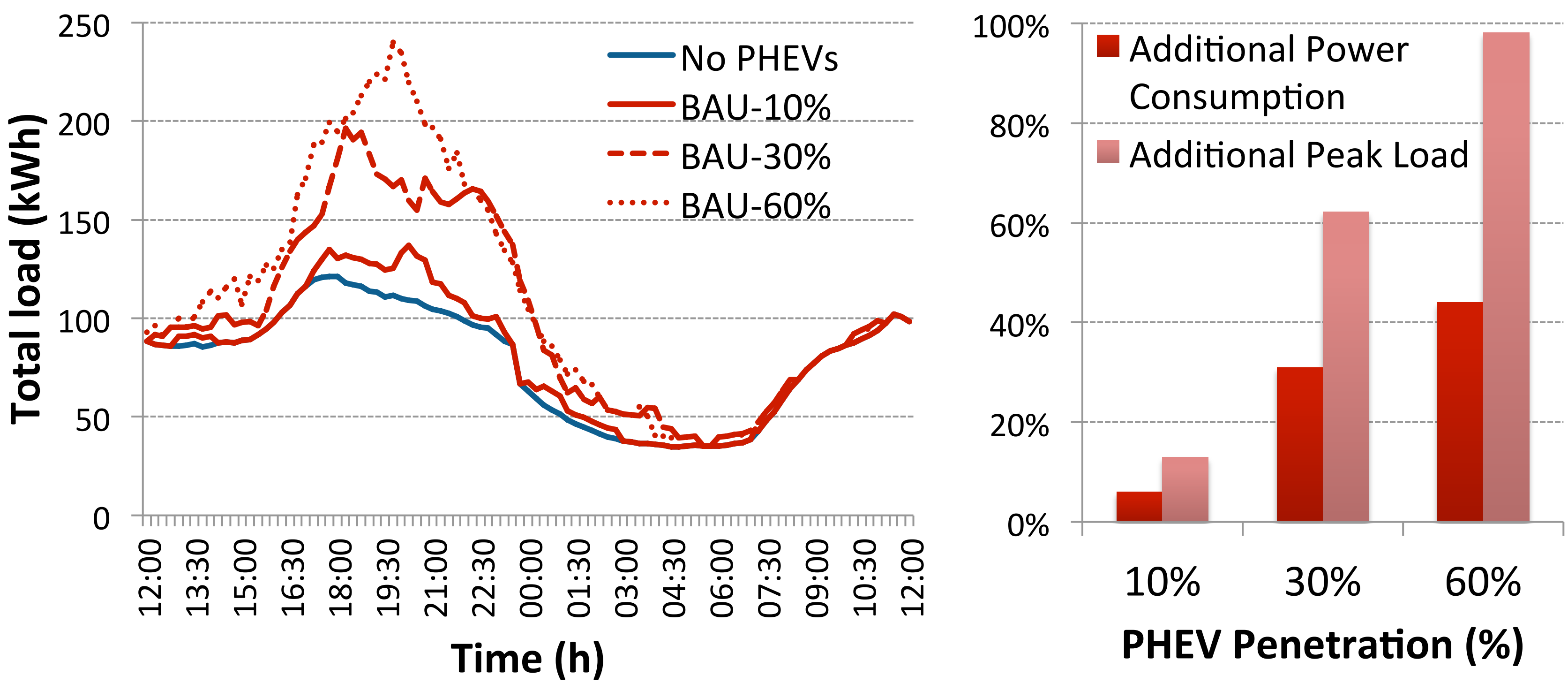
*K. Mets, R. D'Hulst and C. Develder, **"Comparison of intelligent charging algorithms for electric vehicles to reduce peak load and demand variability in a distribution grid"**, J. Commun. Netw., Vol. 14, No. 6, Dec. 2012, pp. 672-681. doi:10.1109/JCN.2012.00033*

# Example case study: EV charging

- Research questions:
  1. Impact of (uncontrolled) EV charging in a residential environment?
  2. Minimal impact on load peaks we could theoretically achieve?
  3. How can we minimize the impact of EV charging in practice?

# Impact of EV charging

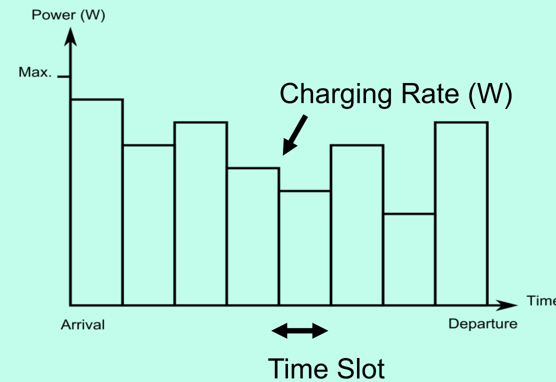
- Sample analysis for 150 homes, x% of them own a PHEV
- BAU = maximally charge upon arrival at home

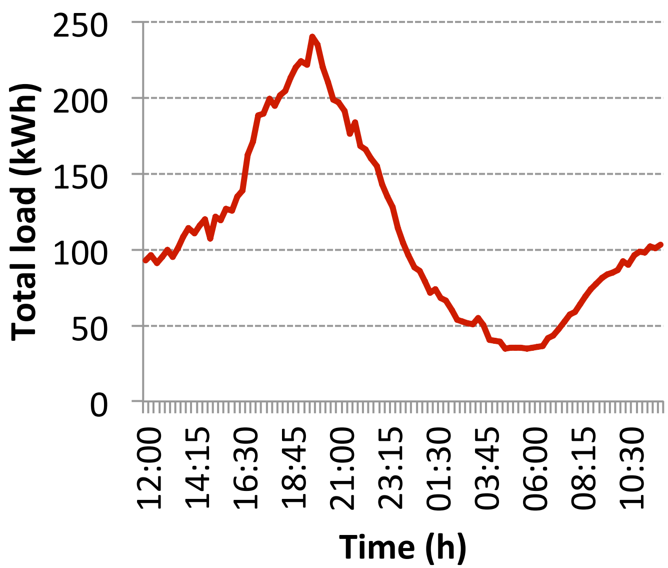


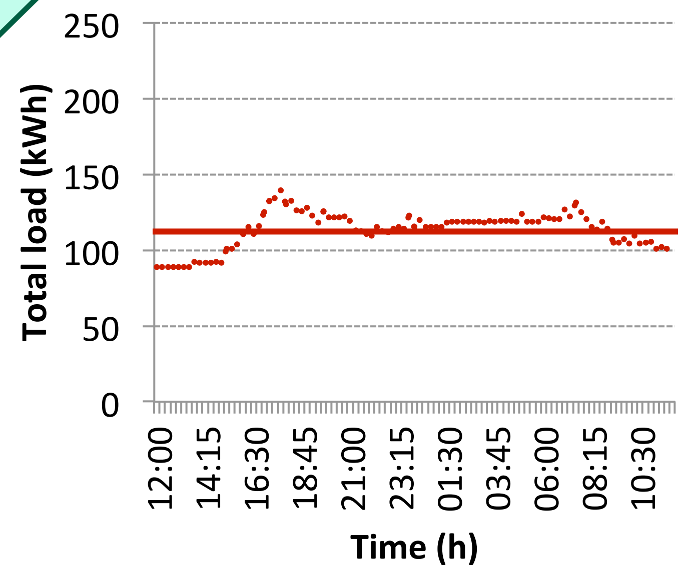
# Controlling EV charging?

- Objectives:
  - Reduce peak load
  - Flatten (total) load profile
    (= reduce time-variability)
  - Avoid voltage violations

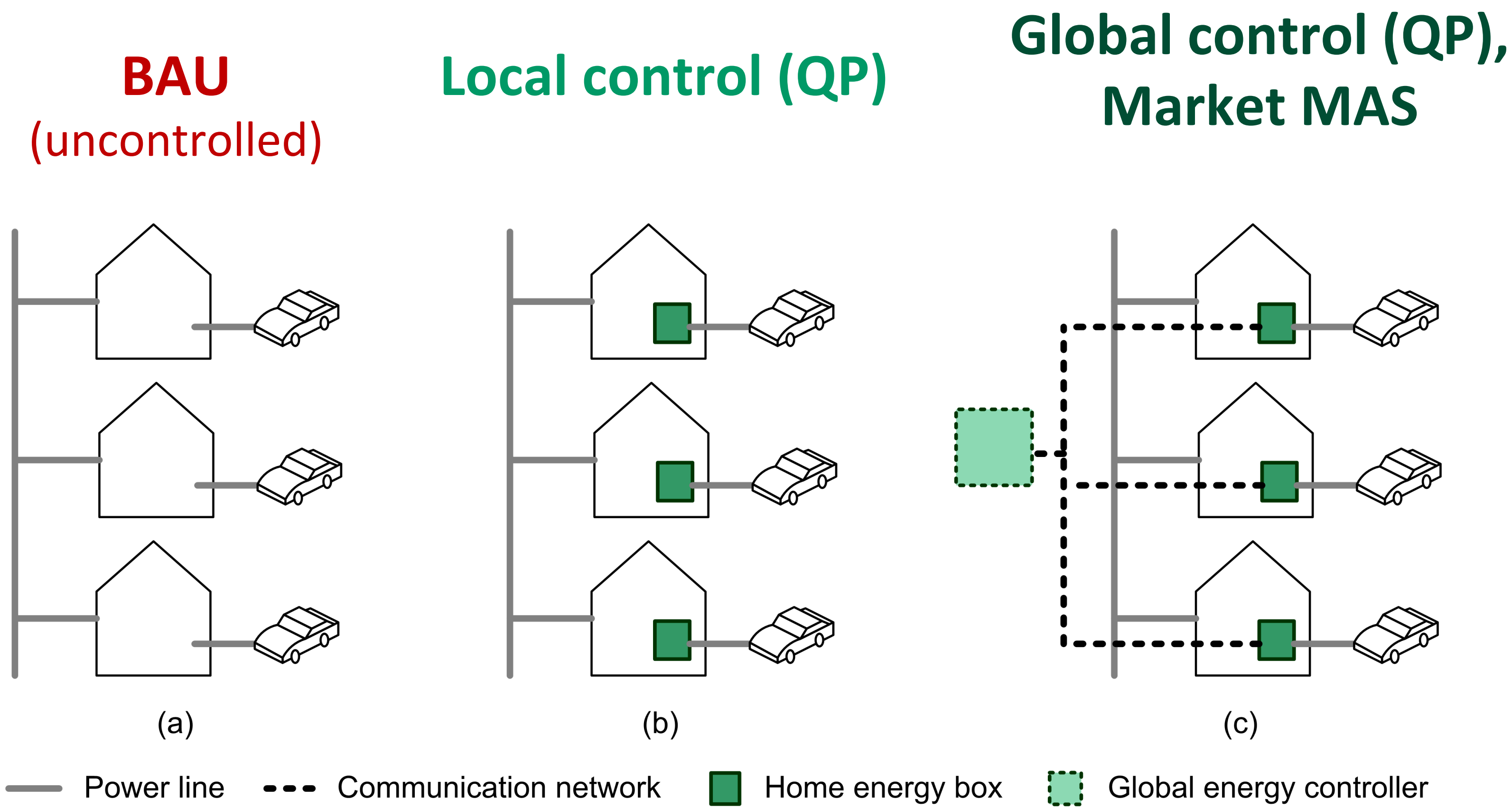
## Charging schedule



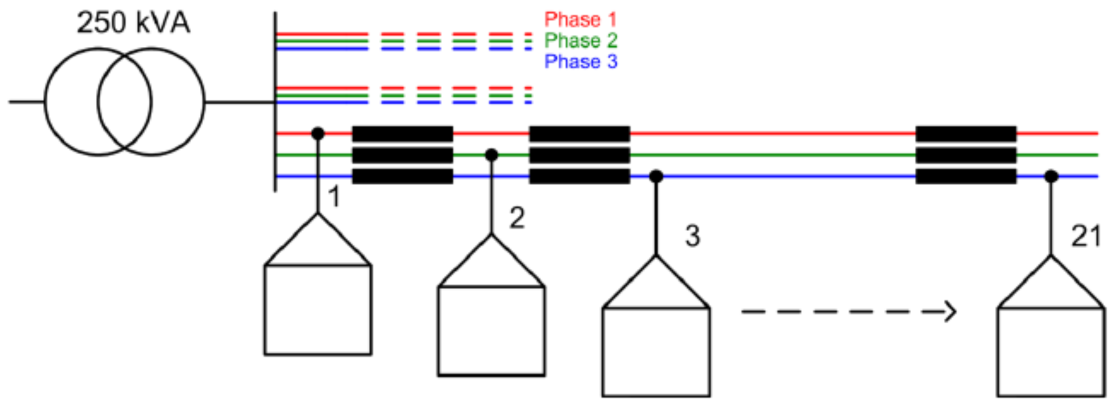



# Smart charging: QP



# Case study

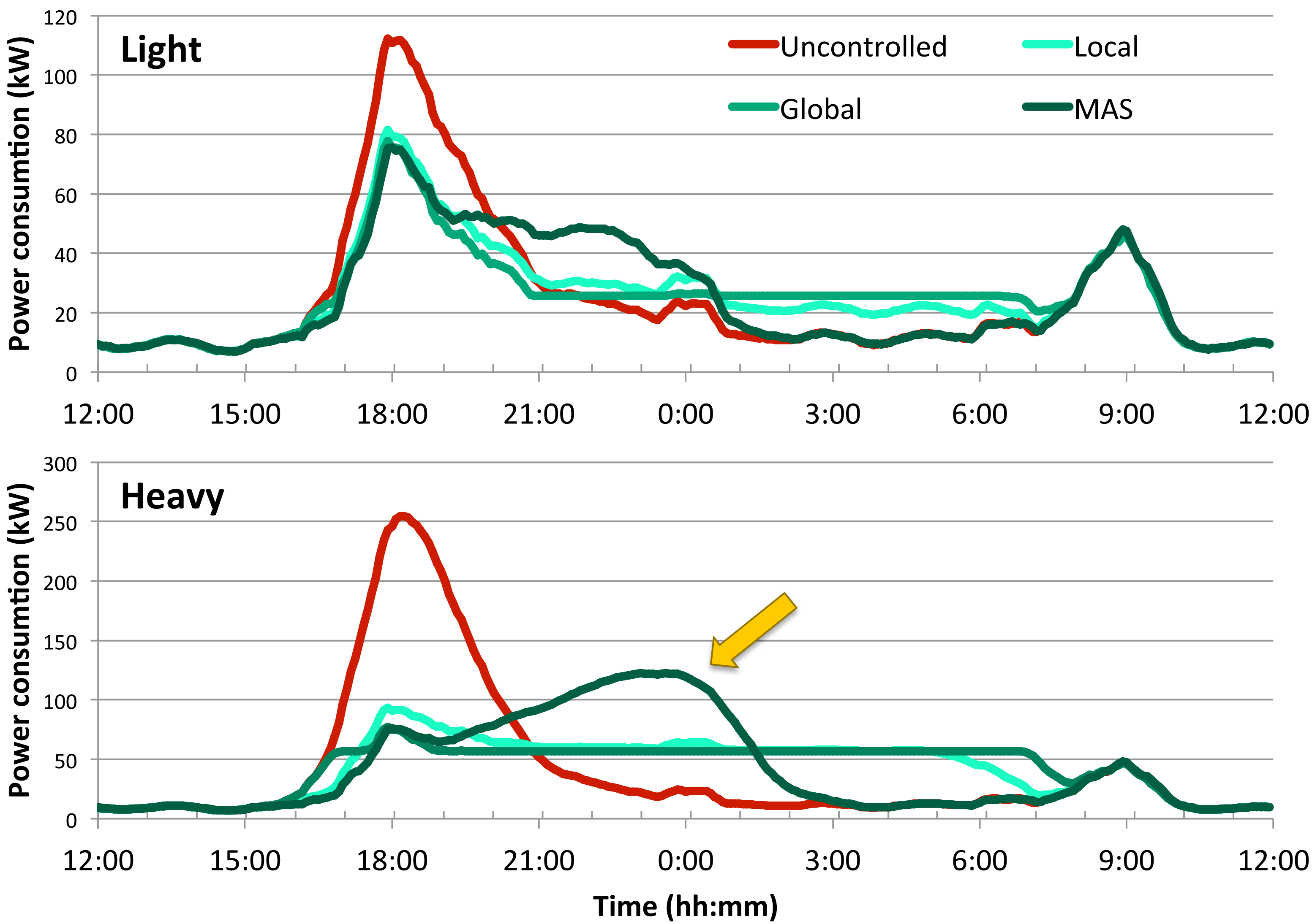
- 63 Households
  - Randomly distributed over 3 phases
  - Spread over 3 feeders




- Electrical vehicles
  - PHEV: 15 kWh battery
  - Full EV: 25 kWh battery
  - Randomized arrivals (~5pm) and departures (~6am)

| Scenario | PHEV 3.6 kW | PHEV 7.4 kW | EV 3.6 kW | EV 7.4 kW |
|---|---|---|---|---|
| Light | 4 | 3 | 2 | 1 |
| Medium | 10 | 10 | 5 | 4 |
| Heavy | 17 | 16 | 7 | 7 |

# Results (1) – Load profiles



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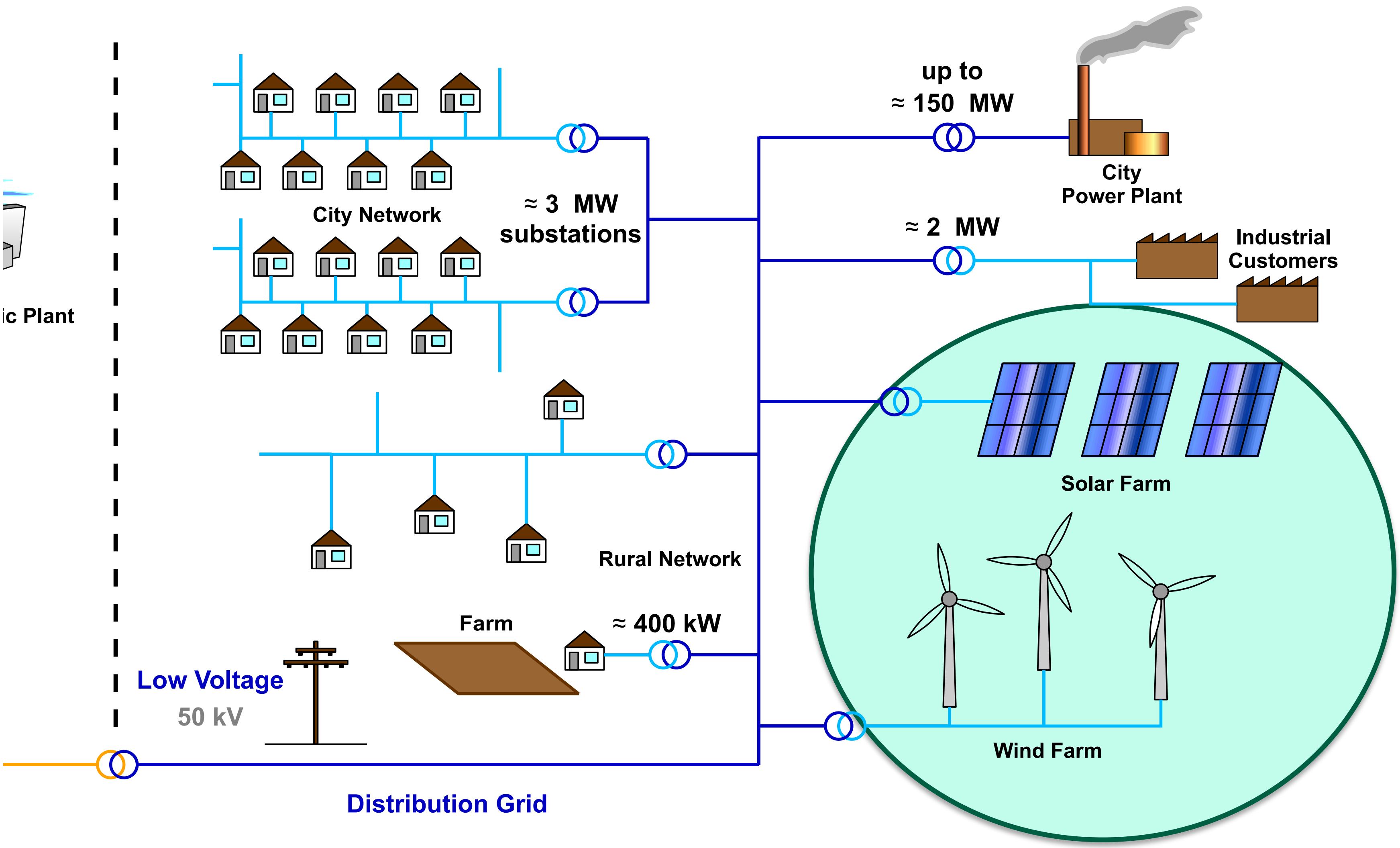
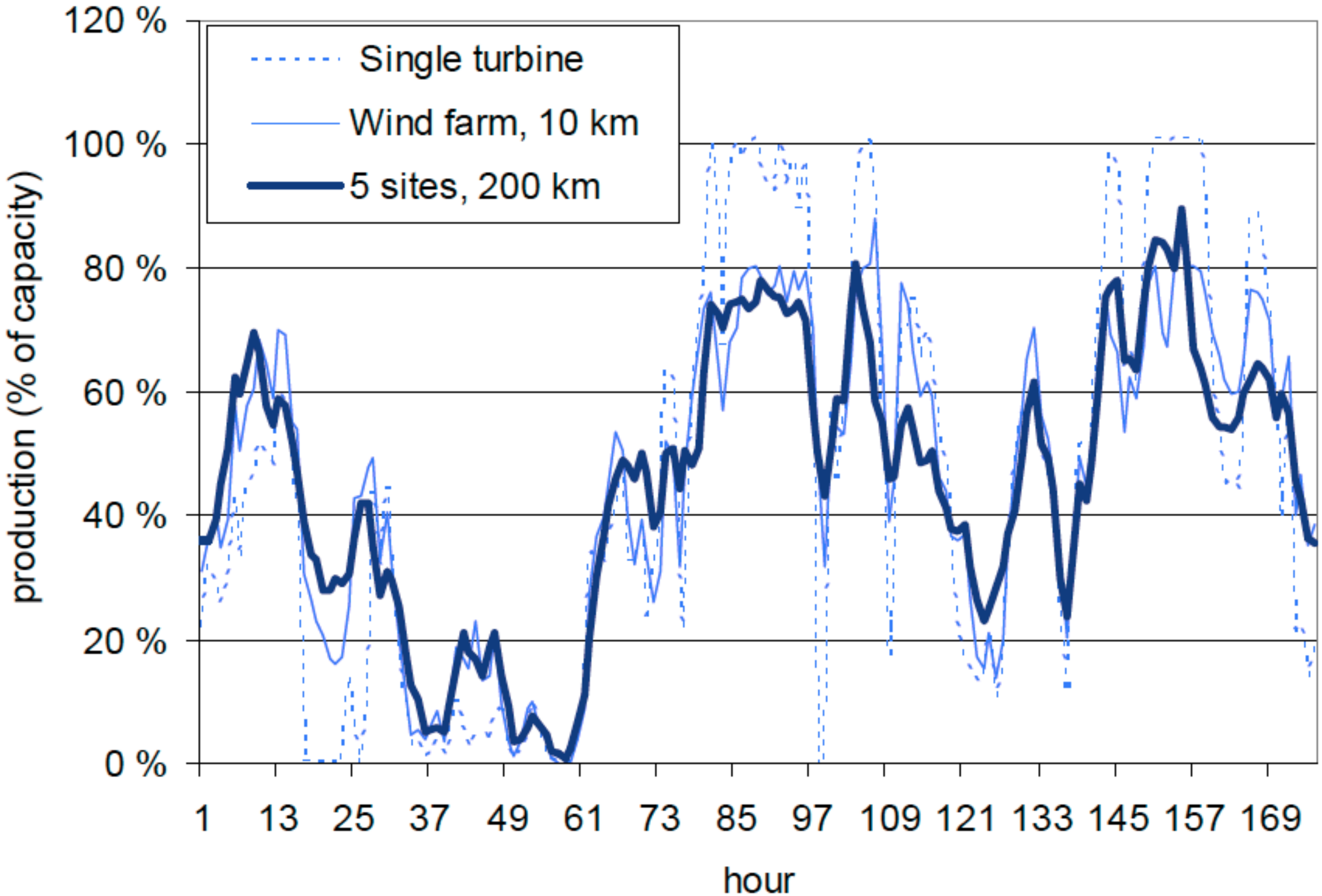
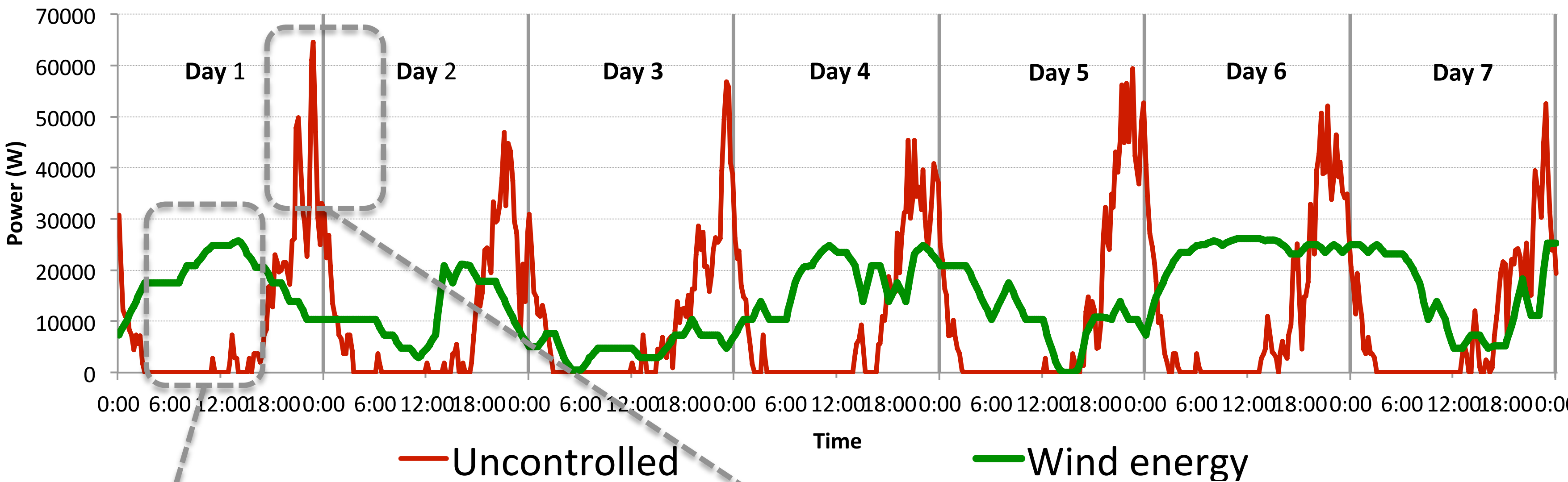
# Distributed generation (DG)



# A typical wind profile



# Wind balancing with EV charging

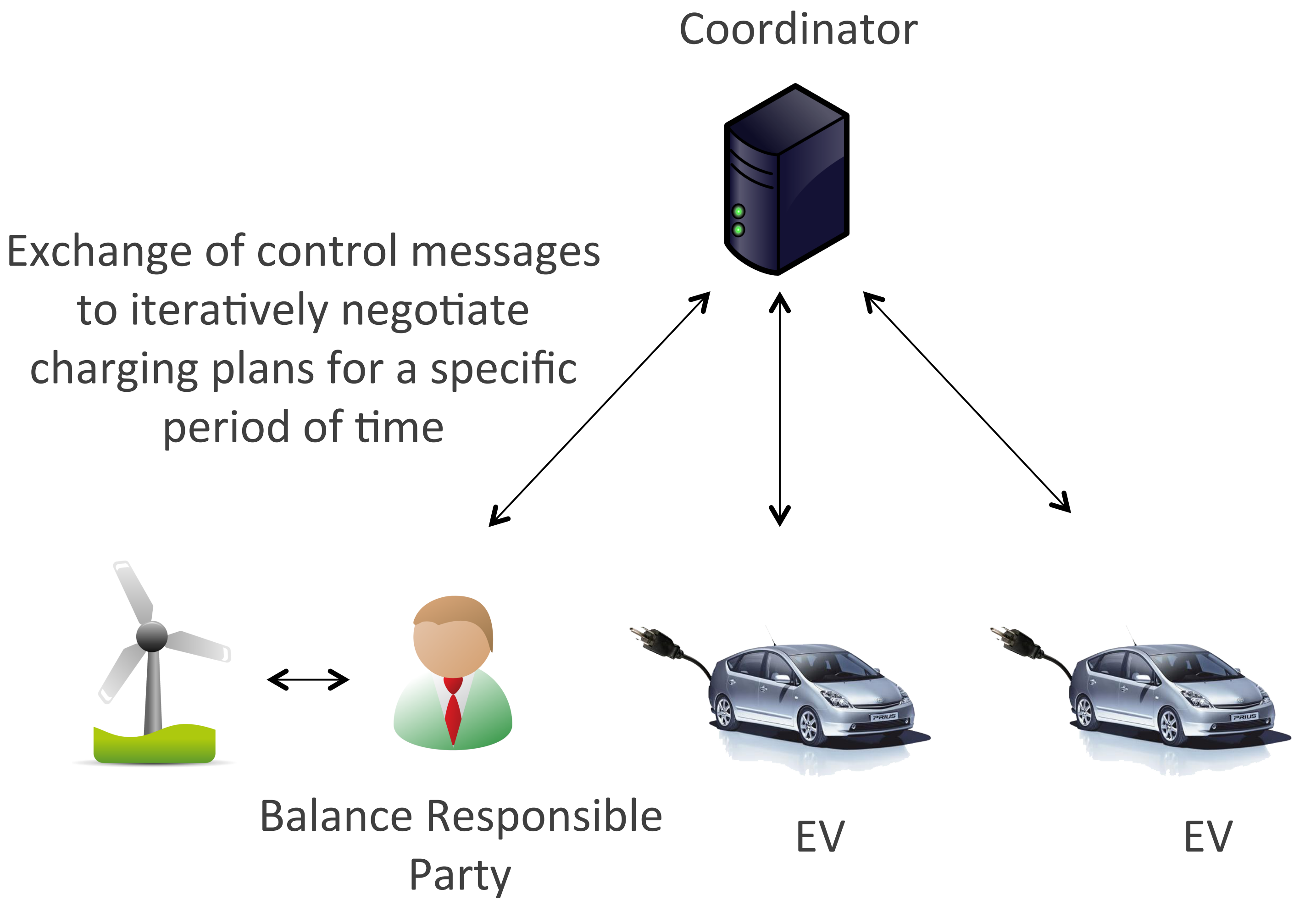



**Supply/demand imbalance & High peak loads**

- Inefficient use of RES
- Imbalance costs
- High peak loads

Undesirable!

# Distributed control



# Centralized Optimization Model

- Based on social welfare maximization
  - **Minimize imbalance costs *C***
  - **Minimize user disutility *D***
- Objective: $$\min_{d_t, x_t} \sum_{t=1}^{T} C(d_t) + \sum_{k=1}^{K} \sum_{t=1}^{T} D_t^k(x_t^k)$$
- Global constraints:

$$d_t = \sum_{k=1}^{K} x_t^k, \forall t \in \{1, 2, .., T\}$$

- Local constraints:
  - BRP: supply < limit
  - EV: energy & time constraints

Drawbacks:
***1) Privacy***: sharing of cost & disutility functions, arrival/departure info, …
***2) Scalability***

# Distributed optimization model

- Move demand-supply constraint into objective, w/ Lagrange multiplier $\lambda_t$

$$\underbrace{\sum_{t=1}^{T} C\left(d_t\right) + \sum_{k=1}^{K}\sum_{t=1}^{T}\left(D_t^k\left(x_t^k\right)\right.}_{\textit{original objective}} + \underbrace{\left.\lambda_t\left(x_k^t - d_t\right)\right)}_{\textit{constraint}}$$

- Notice: Objective function is separable into *K*+1 problems that can be solved in parallel *(assuming $\lambda_t$ are given)*

1 BRP problem

$$\boxed{\sum_{t=1}^{T}\left(C\left(d_t\right) - \lambda_t d_t\right)} + \boxed{\sum_{k=1}^{K}\sum_{t=1}^{T}\left(D_t^k(x_t^k) + \lambda_t x_t^k\right)}$$

$K$ subscriber problems

- Iteratively update pricing vector $\lambda_t$ …

# Distributed optimization model scheme:

1. Coordinator distributes virtual prices
2. **BRP** solves local problem
3. **Subscribers** solve local problem

*in parallel*

4. Coordinator collects schedules:
   - **BRP**: $d^i = [d_1^i, d_2^i, ..., d_T^i]$
   - **EVs**: $x^{k,i} = [x_1^{k,i}, x_2^{k,i}, ..., x_T^{k,i}]$
5. Coordinator updates virtual prices:

$$\lambda_t^{i+1} = \lambda_t^i + \gamma \cdot \left[ \sum_{k=1}^{K} x_t^{k,i} - d_t^i \right]$$

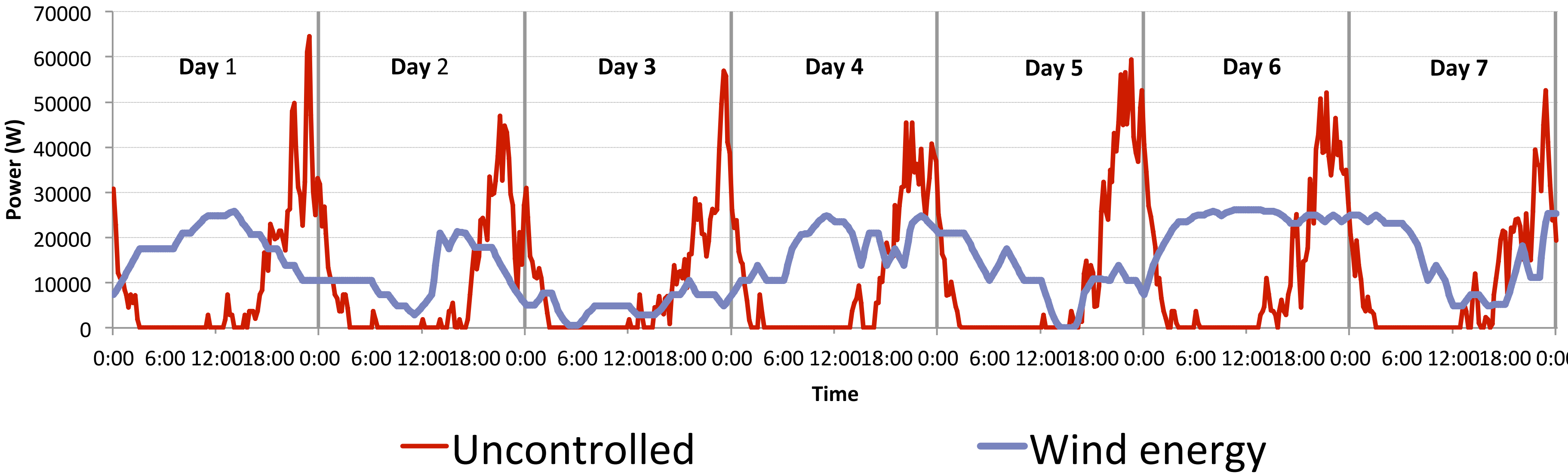
6. Repeat until demand = supply

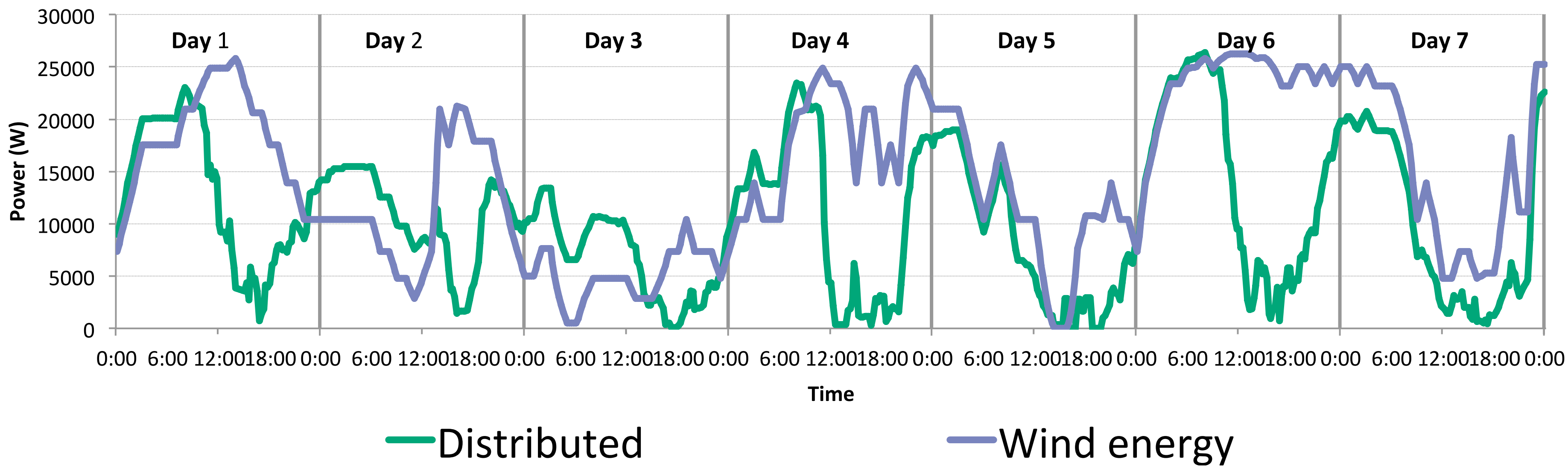
# Case study: Algorithms

- **Uncontrolled business as usual (BAU)**
  - EV starts charging upon arrival
  - EV stops charging when state-of-charge is 100%
  - No control or coordination
- **Distributed algorithm**
  - Executed at the start of each time slot
- **"Ideal world" benchmark**
  - Offline all-knowing algorithm determines schedules for ALL sessions
  - No EV disutility function → maximum flexibility
  - Objective:

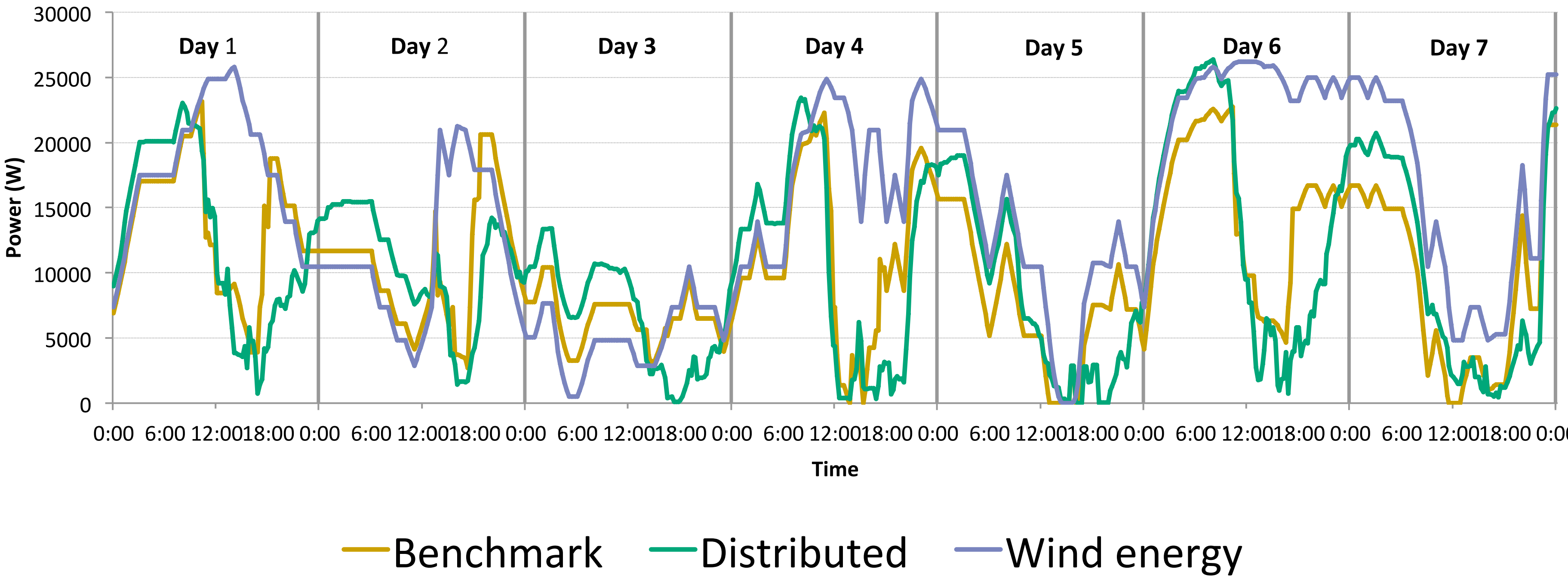
$$\min \sum_{t=1}^{S} \left( w_t - \sum_{k=1}^{K} x_t^k \right)^2$$

# Results: Uncontrolled BAU vs. Distributed

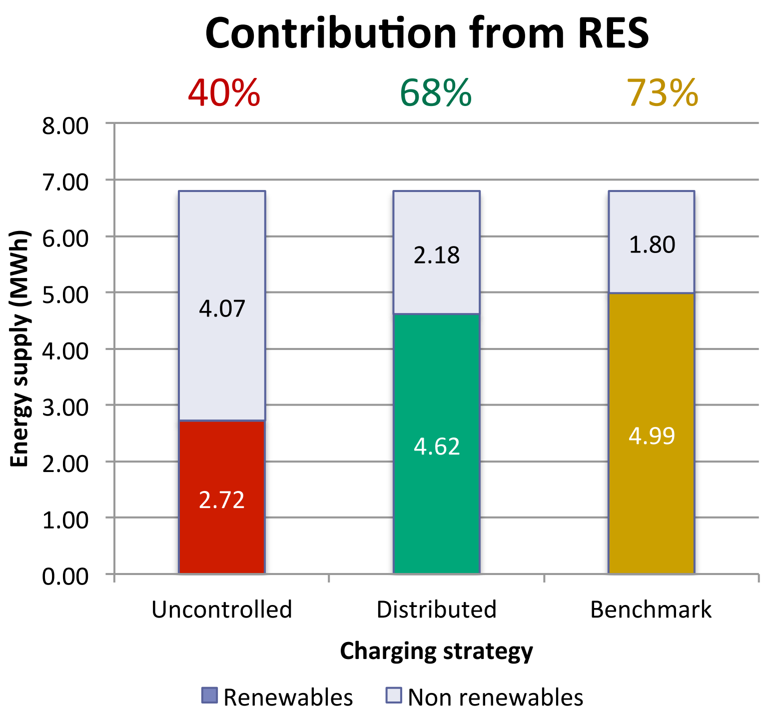


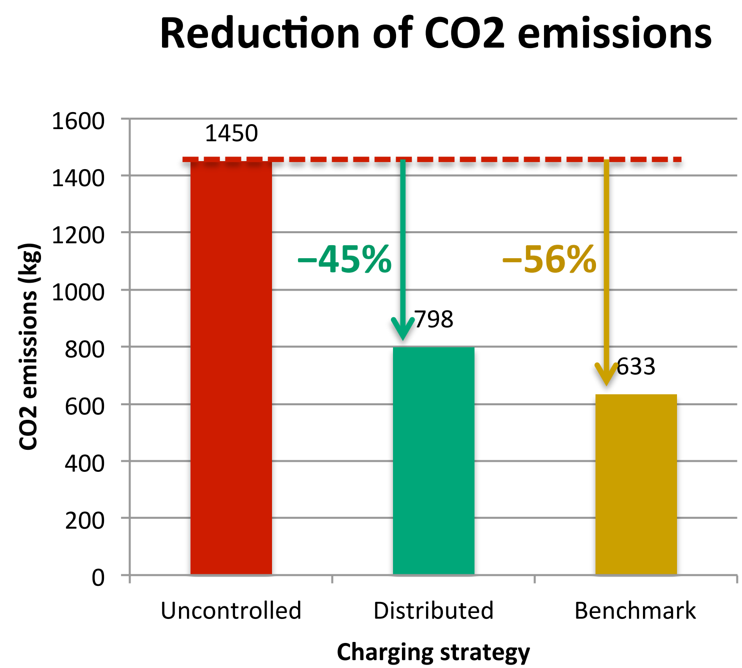



# Results: Distributed vs. Benchmark



# Results: Energy Mix




Renewables: 7.4 CO2 g/kWh
Non Renewables: 351.0 CO2 g/kWh

- Total energy consumption ≈ 6.8 MWh
- Substantial increase in the use of renewable energy
- Reduced $CO_2$ emissions

# Conclusions

- **Objective**: balance wind energy supply with electric vehicle charging demand

- **Method**: Distributed coordination algorithm where participants exchange virtual prices and energy schedules

- **Performance**: Distributed coordination significantly better than BAU, close to “ideal world” benchmark
  - Increased usage of renewable energy sources
  - Reduction of $CO_2$ emissions

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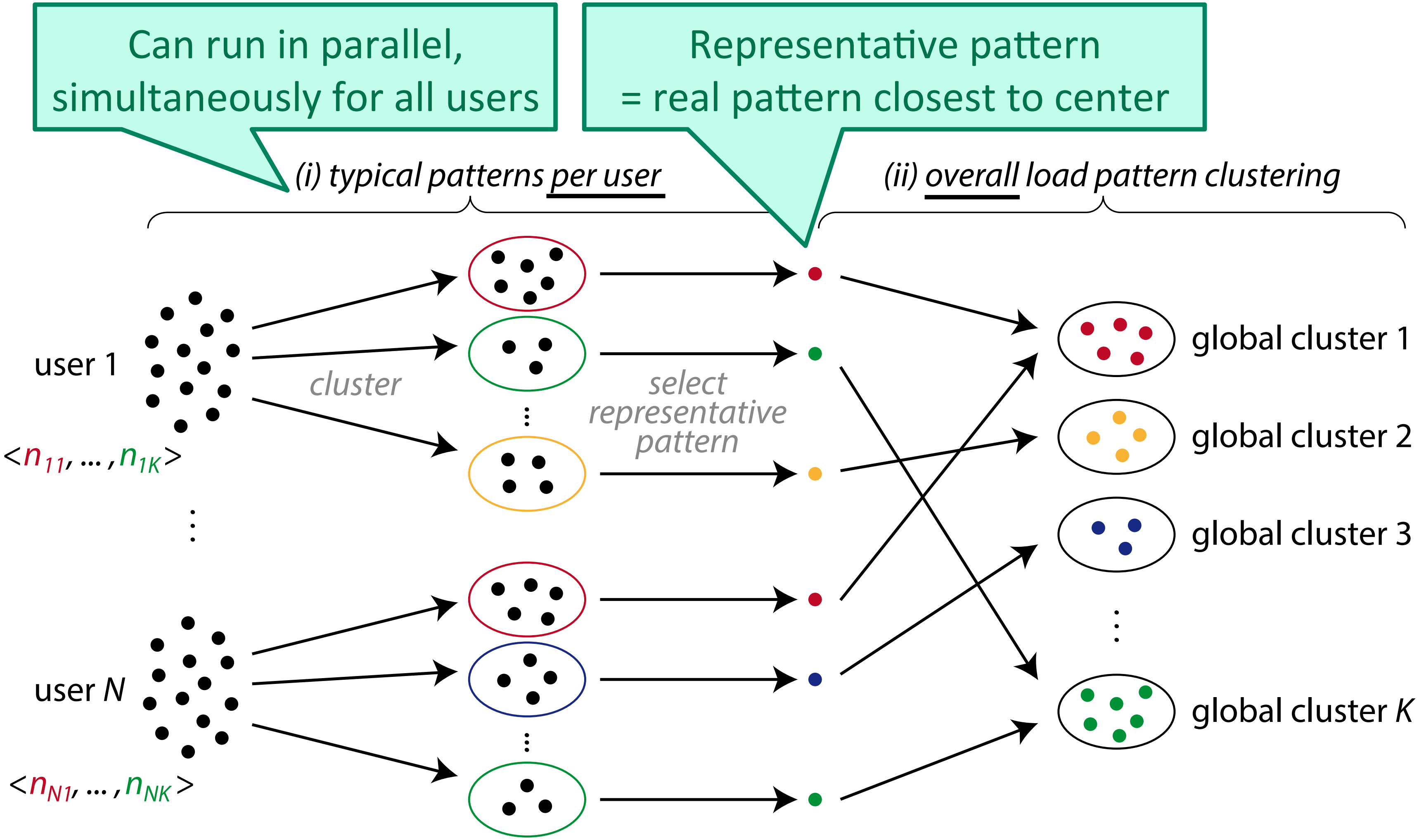
*K. Mets, F. Depuydt. and C. Develder, **"Two-stage load pattern clustering using fast wavelet transformation"**, IEEE Trans. Smart Grid, 2015. doi:10.1109/TSG.2015.2446935*

# Clustering smart metering data

- **Goal:** Identify different types of daily power consumption time series
    1. Single household: distinct types of daily load patterns?
    2. Over whole population: distinct groups of users?

- **Why?**
    - Demand analysis (nation-wide, distribution substations, … single houses)
    - Customer segmentation, tariffs, billing…
    - Power system planning
    - Load forecasting
    - Demand response programs
    - …

# Two-stage load pattern clustering



# Core ideas

- Hierarchical scheme
- Wavelet transformation:
  - Dimensionality reduction
  - Invariance/tolerance to time shifting

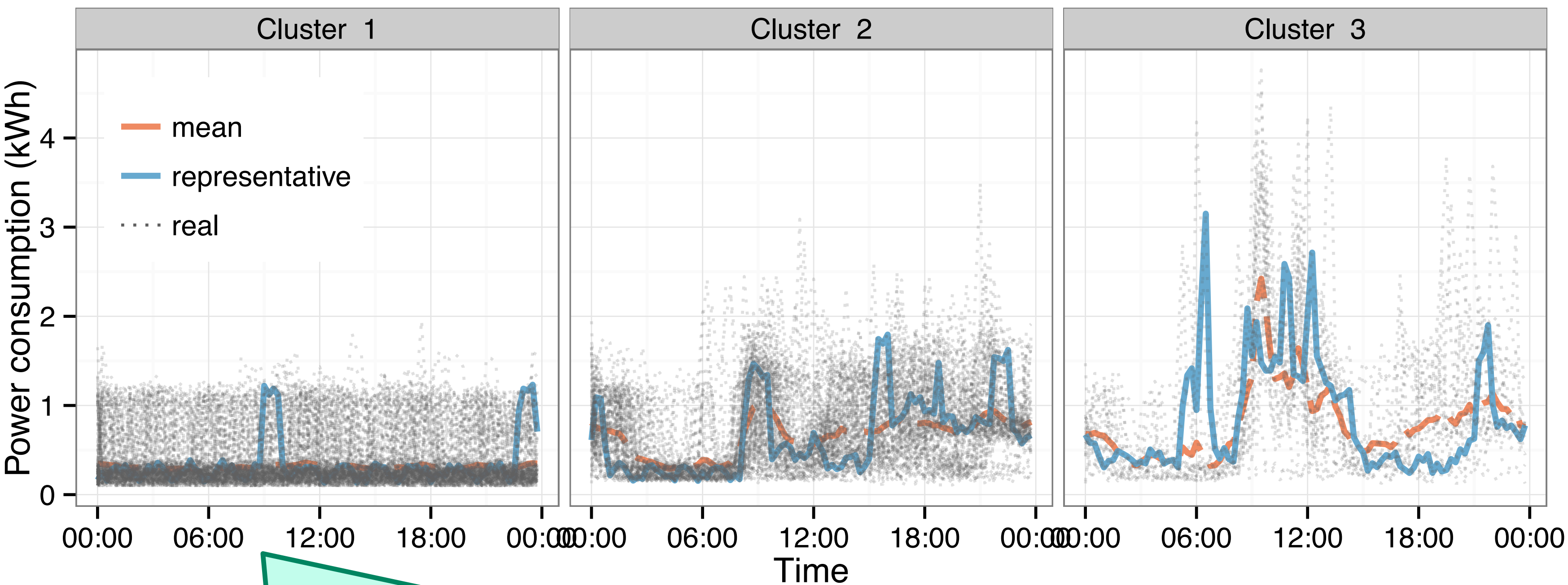

- G-means (instead of k-means) [Hamerly2003]

*G. Hamerly, C. Elkan, "Learning the k in k-means", NIPS 2003*

# Sample result: Single user

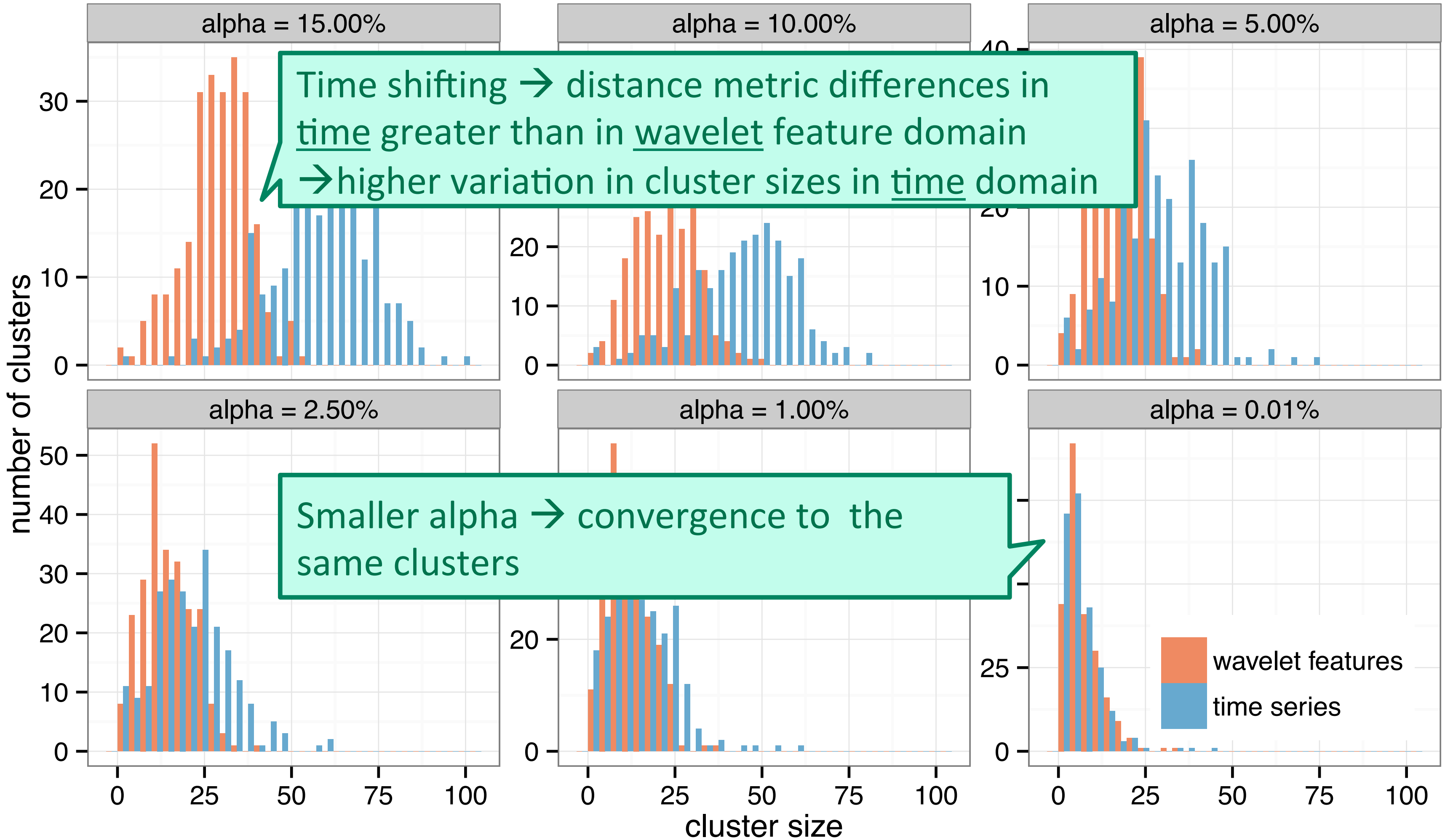
For alpha = 0.01% → low number of clusters

*Note: representative ≠ arithmetic mean*




Because of FWT: similar time shifted patterns are clustered together!

# **Time vs wavelet domain:** Number of clusters




Time shifting → distance metric differences in time greater than in wavelet feature domain →higher variation in cluster sizes in time domain

Smaller alpha → convergence to the same clusters

# Conclusions

- Totally unsupervised clustering process
  - No a priori definition of ‘typical day’, groupings into weekday/weekend …
  - Cluster size/quality controllable via parameter $\alpha$
- Note on scalability:
  - Stage 1 = executed per user (in parallel)
  - Stage 2 = number of profiles to cluster is limited, by reducing ‘representative’ profile
  - Vector space dimensionality is reduced by FWT (96 → 7 or 8 features)

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*C. Develder, N. Sadeghianpourhamami, M. Strobbe, N. Refa, **"Quantifying flexibility in EV charging as DR potential: Analysis of two real-world data sets"**, under review, 2016*

# EV charging analysis: Research questions

1. Types of user behavior?
   - Clustering
   - Generative models

2. Quantification of flexibility?
   - Sojourn vs idle time
   - Demand response potential

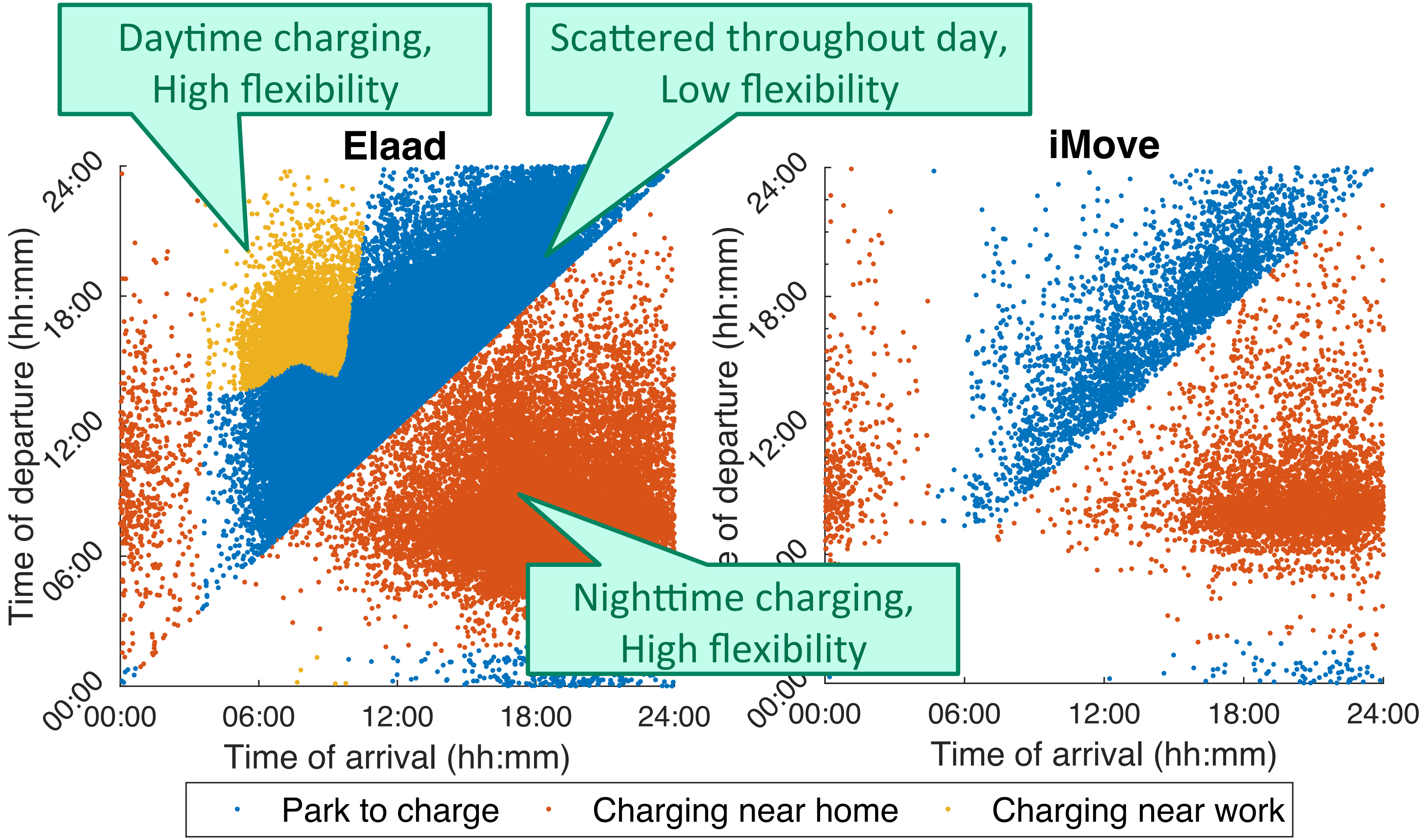
# Input: Two real-world data sets

| | iMove | ElaadNL* |
|---|---|---|
| Period | Mar 2012 – Mar 2013 | Jan 2011 – Dec 2015 |
| # Sessions | 8,520 | 1,141,849 |
| # Users† | 134 | 53k |
| Car type | Full EV | Unknown mix |
| Charge point | At home | Public |
| Trip details | Yes | No |

*: Results are based on sessions from 1 Jan 2015 – 31 Mar 2015 (N = 90,562)

†: In iMove, at any point in time, up to 50 users were active. For ElaadNL, sessions are tied to a particular charging car**d**.

# User behavior: 3 Types of behavior

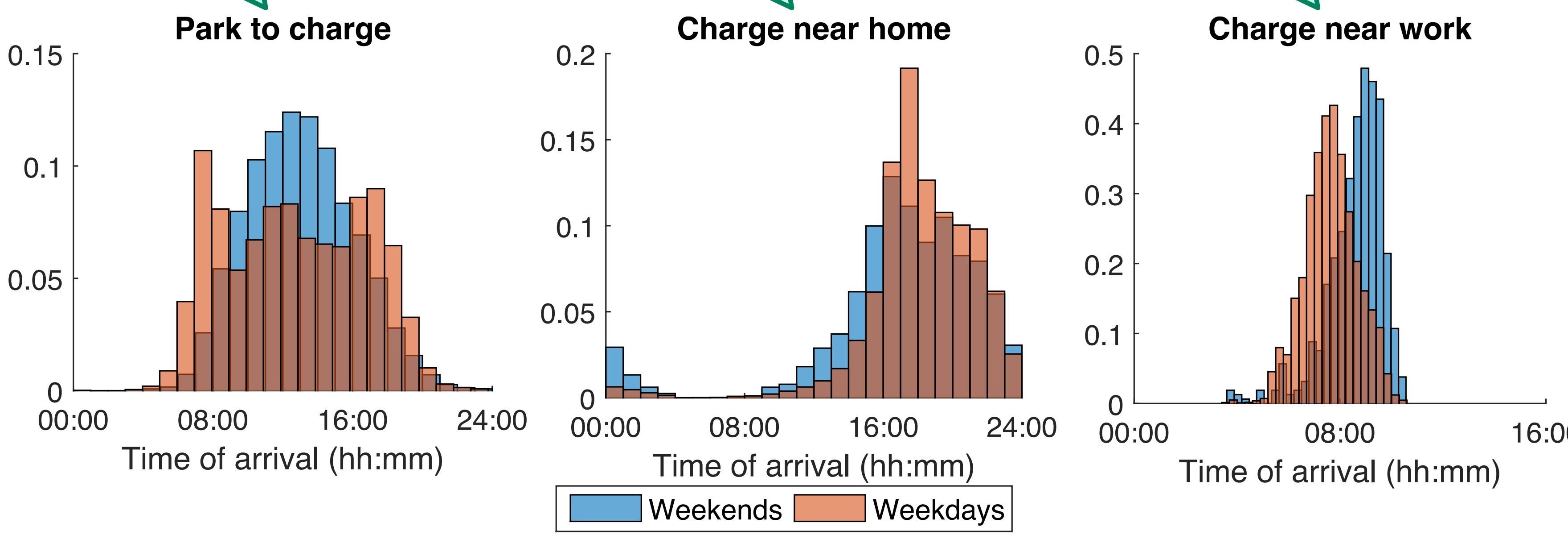


# User behavior: Distributions of *arrival times*

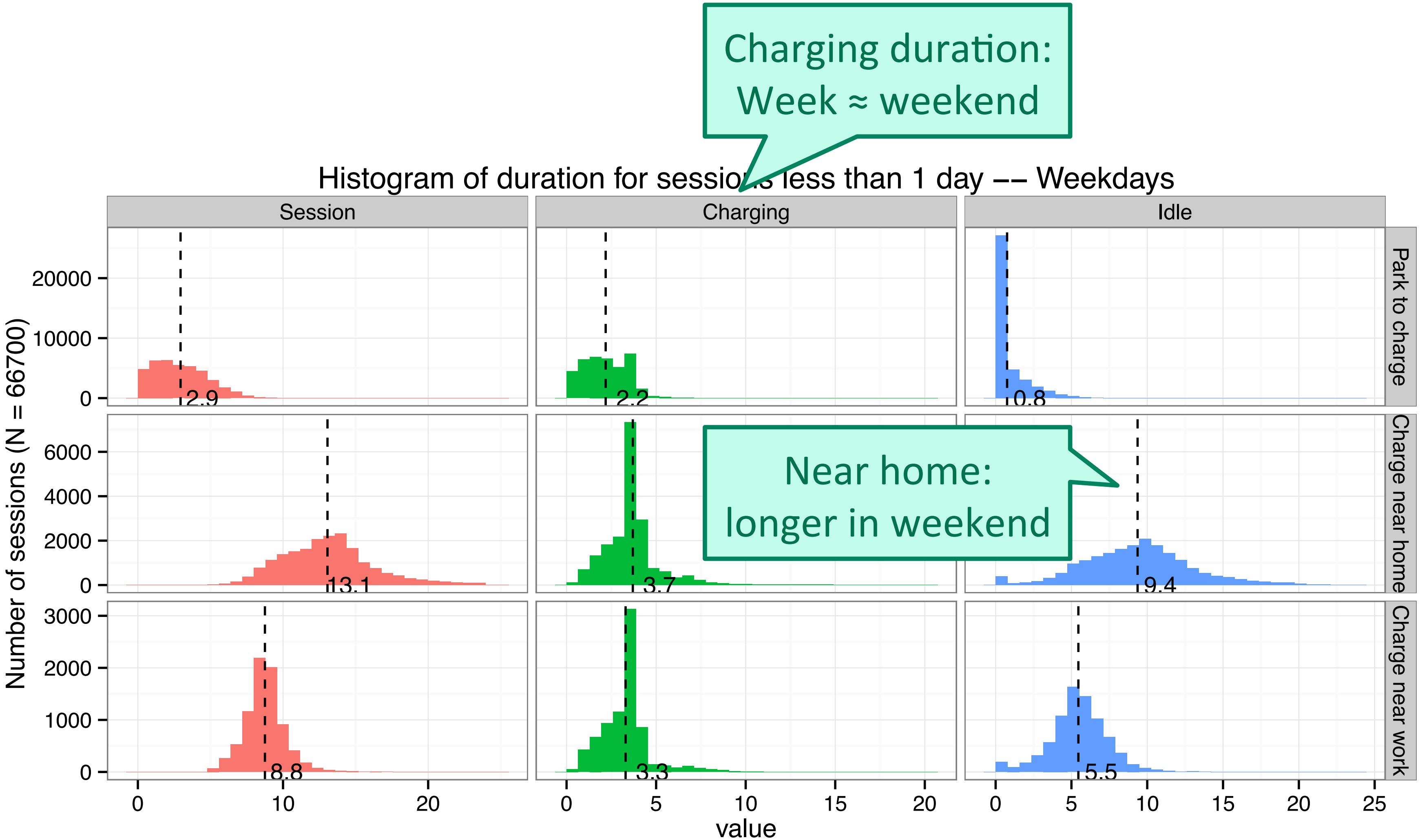
Different week vs weekend pattern

Slightly more spread in weekend

Shift to later times in weekend



# User behavior: *Session* duration – Weekdays



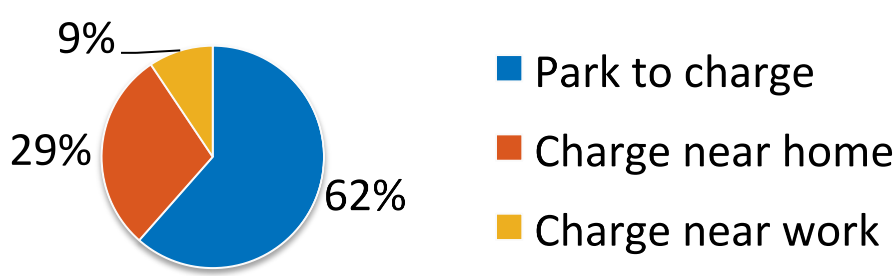
# User behavior: *Session* duration – Weekends

# User behavior: Statistical models

Table II: Fitted distributions for total sojourn and idle times

| | | | Sojourn time ($\delta^{\text{sojourn}}$) | | | Idle time ($\delta^{\text{idle}}$) | | |
|---|---|---|---|---|---|---|---|---|
| Cluster | Sub-cluster departures | Fraction | Distr. | Normalized distr. parameters* | [min, max] (hours) | Distr. | Normalized distr. parameters* | [min, max] (hours) |
| Park to charge (61.5%) | in 1st 24 h | 98.9% | Beta | $\alpha = 1.91,\ \beta = 14.22$ | $[0.02, 23.91]$ | Beta | $\alpha = 0.31,\ \beta = 10.04$ | $[0, 23.66]$ |
| | in 2nd 24 h | 0.9% | Gamma | $\alpha = 1.24,\ \beta = 6.40$ | $[24.00, 36.11]$ | Logistic | $\mu = 0.64,\ s = 0.06$ | $[5.05, 32.35]$ |
| | in 3rd 24 h | 0.1% | Gamma | $\alpha = 1.40,\ \beta = 5.01$ | $[48.01, 59.93]$ | Logistic | $\mu = 0.62,\ s = 0.08$ | $[34.21, 55.11]$ |
| Charge near home (29.1%) | in 1st 24 h | 95.4% | Logistic | $\mu = 0.56,\ s = 0.08$ | $[0.02, 23.99]$ | Normal | $\mu = 0.42,\ \sigma^2 = 0.17$ | $[0, 23.53]$ |
| | in 2nd 24 h | 3.3% | Beta | $\alpha = 2.59,\ \beta = 1.95$ | $[28.13, 47.95]$ | Normal | $\mu = 0.57,\ \sigma^2 = 0.16$ | $[19.37, 47.86]$ |
| | in 3rd 24 h | 0.8% | Beta | $\alpha = 2.44,\ \beta = 1.61$ | $[52.84, 72.00]$ | Normal | $\mu = 0.57,\ \sigma = 0.21$ | $[47.25, 70.00]$ |
| | in 4th 24 h | 0.3% | Beta | $\alpha = 2.91,\ \beta = 1.39$ | $[74.75, 95.86]$ | Normal | $\mu = 0.64,\ \sigma^2 = 0.20$ | $[69.05, 93.73]$ |
| Charge near work (9.4%) | in 1st 24 h | 99.6% | Logistic | $\mu = 0.27,\ s = 0.06$ | $[5.00, 18.52]$ | Logistic | $\mu = 0.35,\ s = 0.07$ | $[0, 15.54]$ |

* The parameters of distributions are the following: (i) *Normal*: mean $\mu$ and variance $\sigma^2$, (ii) *Beta*: shape parameters $\alpha$ and $\beta$, (iii) *Gamma*: shape $\alpha$ and rate $\beta$, (iv) *Logistic*: location parameter $\mu$ and scale parameter $s$. Note that the parameter values are reported for fits of normalized data, i.e., durations are rescaled per sub-cluster as $\delta_{\text{normalized}} = \frac{\delta - \min}{\max - \min}$.



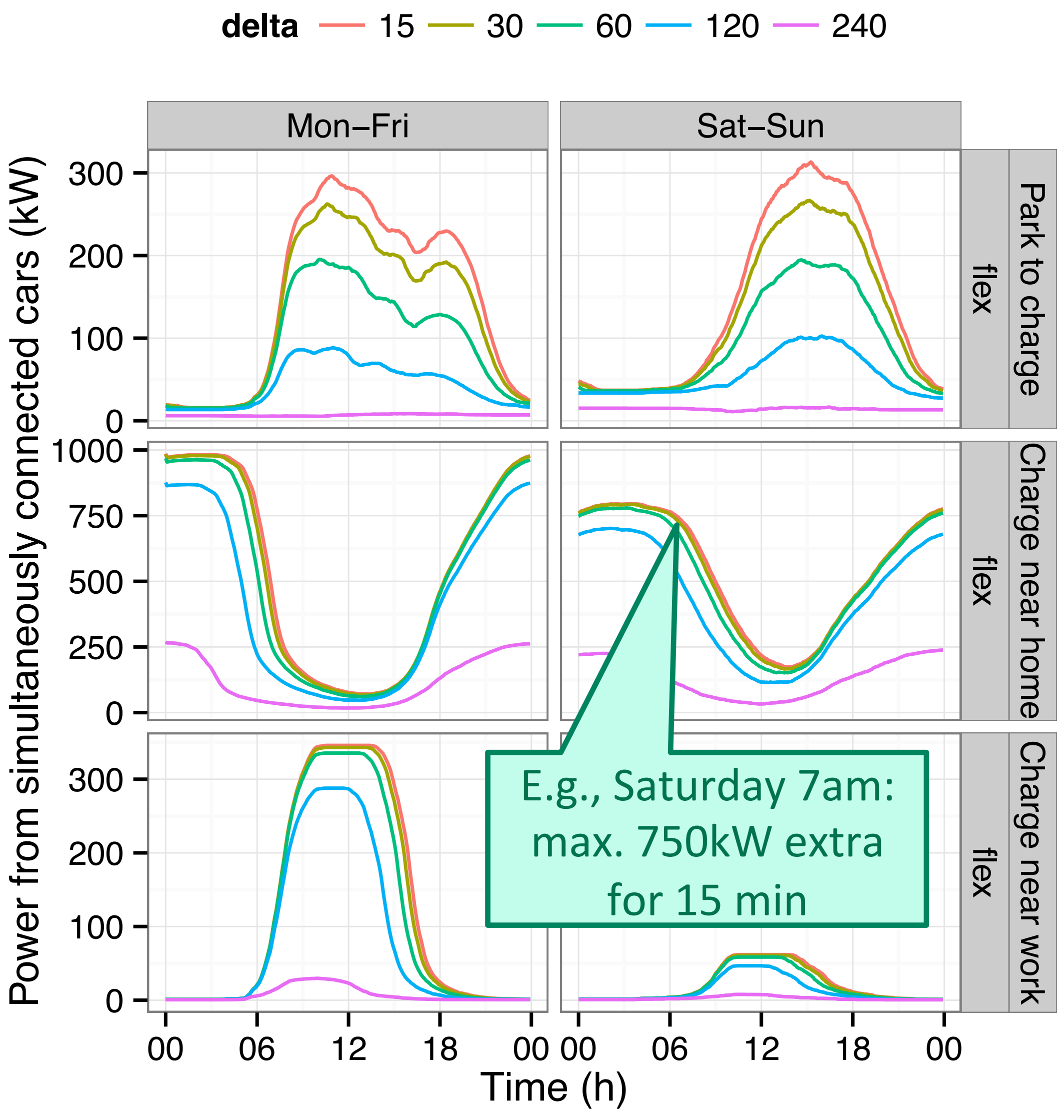
# Quantification of flexibility: Calculation

Upper bound: we disregard impact of using/ suppressing power in [*t*,*t*+Δ] on flexibility at other times *t'*

$P_{FLEX}(t, \Delta)$ = Maximal power that DR could either consume constantly, or not at all, in interval [t, t+Δ]

- Charging session has to include [t, t+Δ]
- Charging duration ≥ Δ [else we could not consume in full interval]
- Flexibility = session duration − Δ ≥ charging duration [we can move it away]

# Quantification of flexibility: Result




- Park to charge:
  - Daytime flexibility
  - Weekend: ≈ volume, but ≠ timing
- Near home:
  - Nighttime flex
  - Weekend: lower & more spread
- Near work:
  - Daytime flex
  - Low in weekend

# Conclusion on flexibility analysis EVs

- Real world data set
- Three major types of charging sessions
- Statistical models of user behavior
- Methodology to quantify flexibility

- Application?
  E.g., extrapolation of iMove data to 3% of Flemish fleet by 2020:
  - ~100k cars out of ~3.2M, noon in weekend => can have ~7MW extra for 2h

*PS: Similar analysis for household appliances in smart device trial:*

*N. Sadeghianpourhamami, T. Demeester, D.F. Benoit, M. Strobbe and C. Develder, **"Modeling and analysis of residential flexibility: Timing of white good usage"**, Appl. Energy, Jul. 2016, pp. 1-27. (Accepted for publication)*

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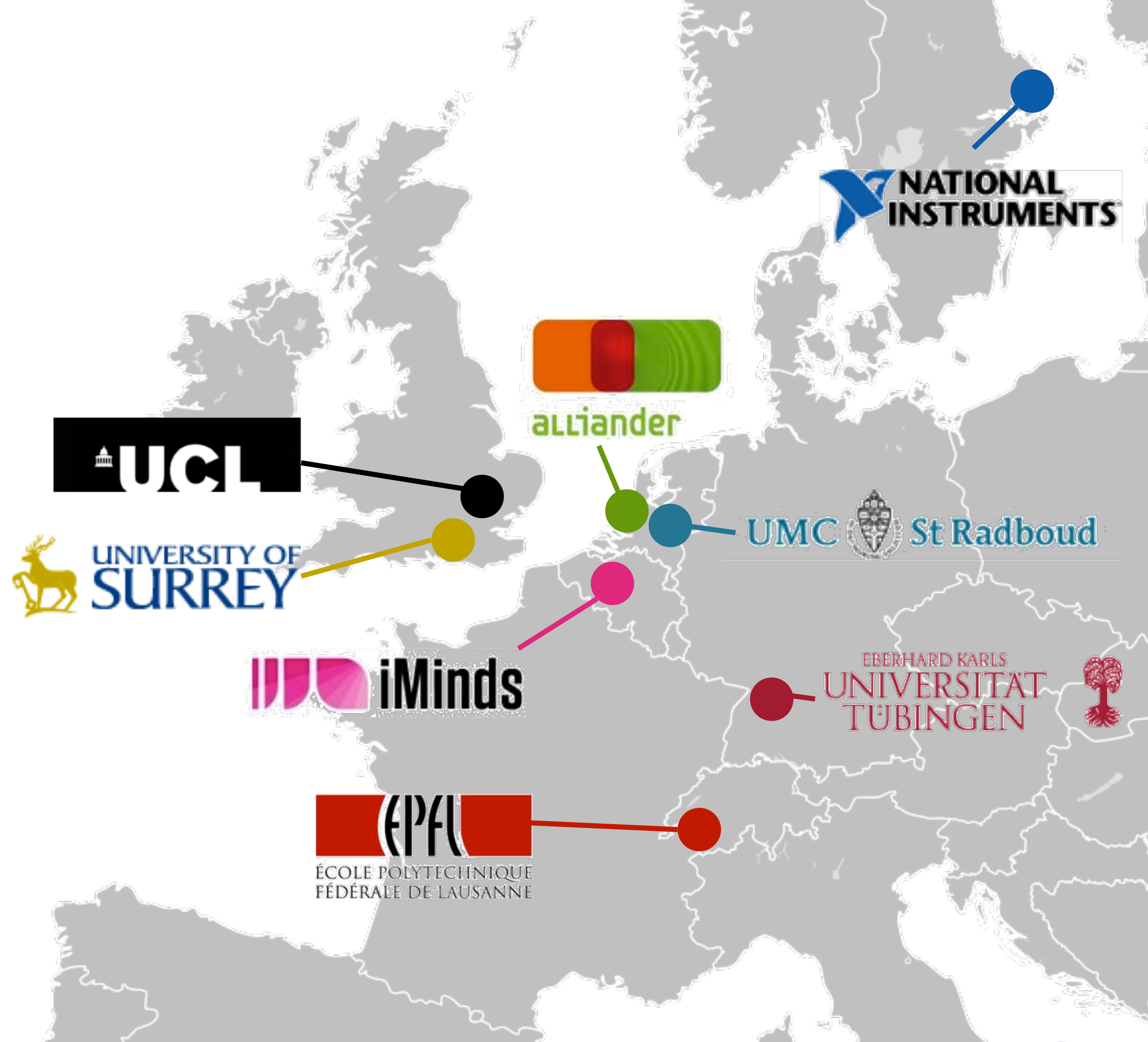
*W.K. Chai, et al., **"An information-centric communication infrastructure for real-time state estimation of active distribution networks"**, IEEE Trans. Smart Grid, Vol. 6, No. 4, Jul. 2015, pp. 2134-2146. doi:10.1109/TSG.2015.2398840*

# C-DAX: Cyber-secure Data and Control Cloud for power grids

- Project FP7-ICT-2011-8
- Oct. 1, 2012 – Feb. 19, 2016
- Budget: 4.3M EUR
  EU-funding: 2.9M EUR
- More info:
  [http://www.cdax.eu](http://www.cdax.eu)



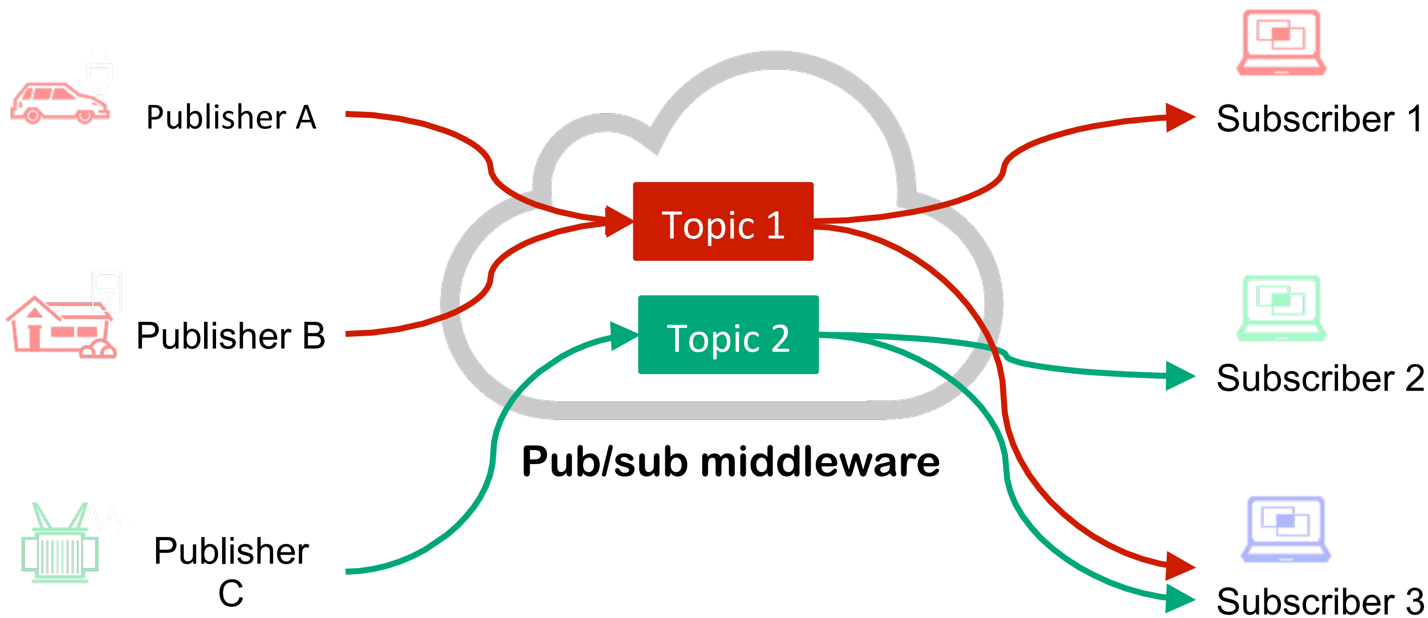
# Smart grid communication pattern variation

- **1-to-1**: e.g., control messages for specific assets
- **1-to-M**:
  - *Broadcast*: e.g., energy offers in demand response schemes
  - *Anycast*: e.g., offer for voltage regulation by any suitable subset of EVs located in a certain area
- **M-to-1**: e.g., energy consumption reports in demand response or smart metering
- **M-to-N**: e.g., multiple charging offers from different charging stations to multiple EVs
- **Asynchronous** communication in dynamic scenarios: e.g., EVs come and go, retrieve/deliver data while connected to the network

# ICN = Information Centric Networks

- Alternative for Point-to-point networks
  - Explicit point-to-point connections from producer to predefined consumers → need to know/config all IPs
- ICN paradigm = based on **topic** rather than IP address
  - Consumers "pull" or "subscribe to" the data "topics"
  - Agnostic of who produced and when/where info is stored
  - Decoupling of producers/consumers
- Advantages:
  - Inherent **security**: hosts do not know each other's locations
  - Overlay network **management**:
    - Management of IP connections, optimal placement of the data within the cloud, resilience…
    - In-network management and processing (e.g., caching, aggregation, filtering, rate adaptation, traffic engineering …)

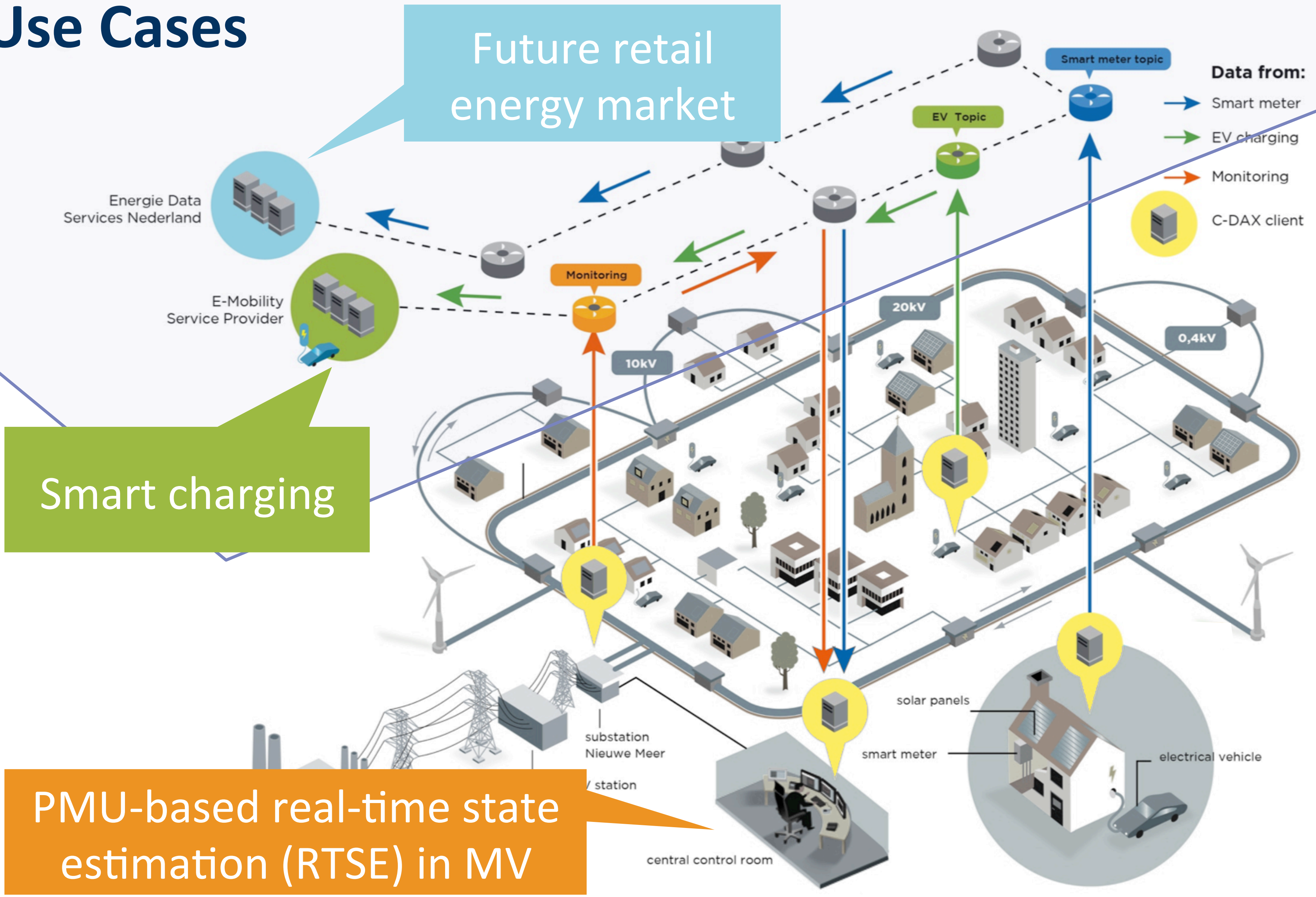
# Topic-based Communication



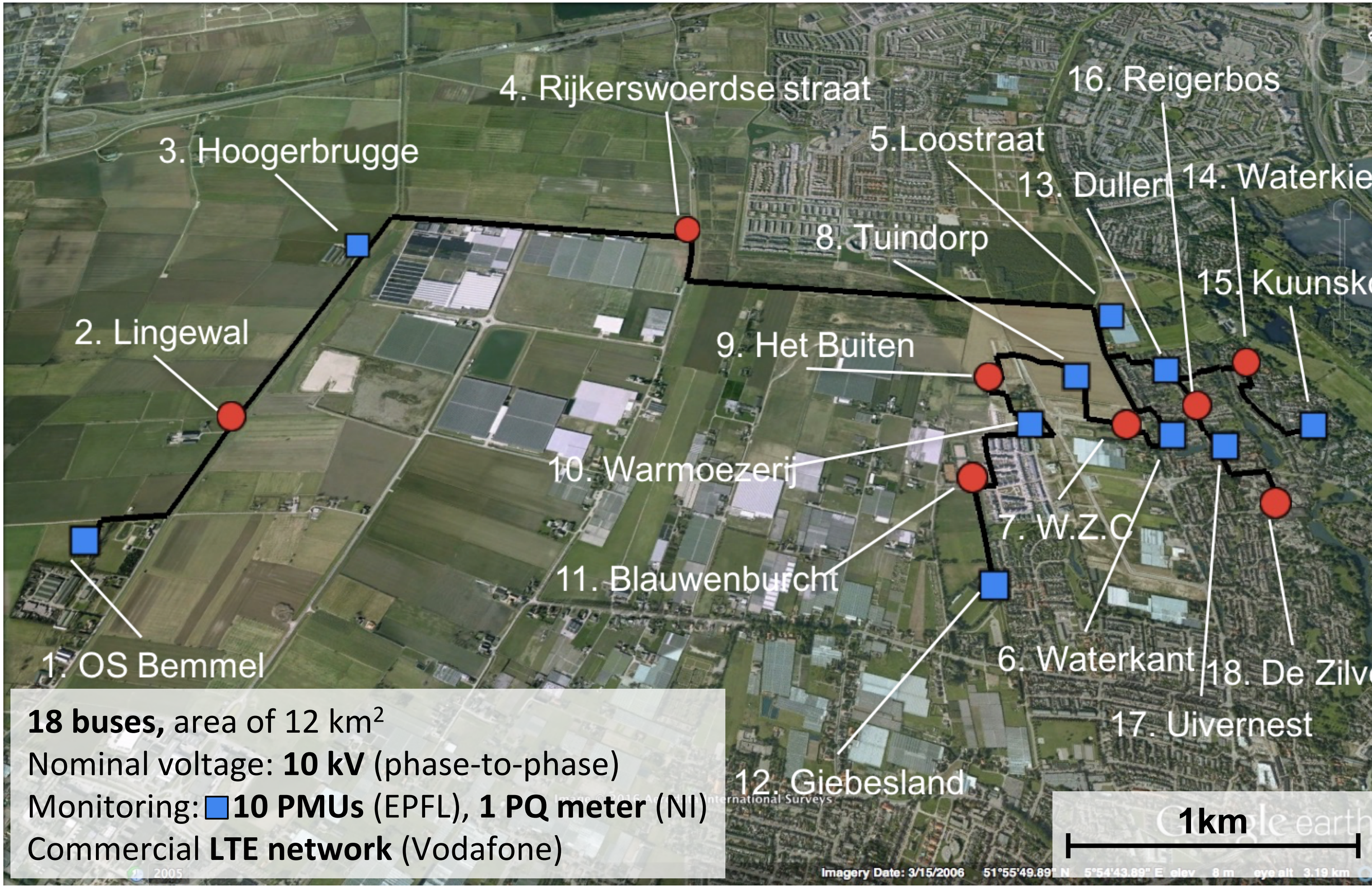

Benefits of decoupling publishers and subscribers

- Communication partners do not need to know each other
- Asynchronous communication possible
- Facilitating extensibility, management and configurability

# Use Cases

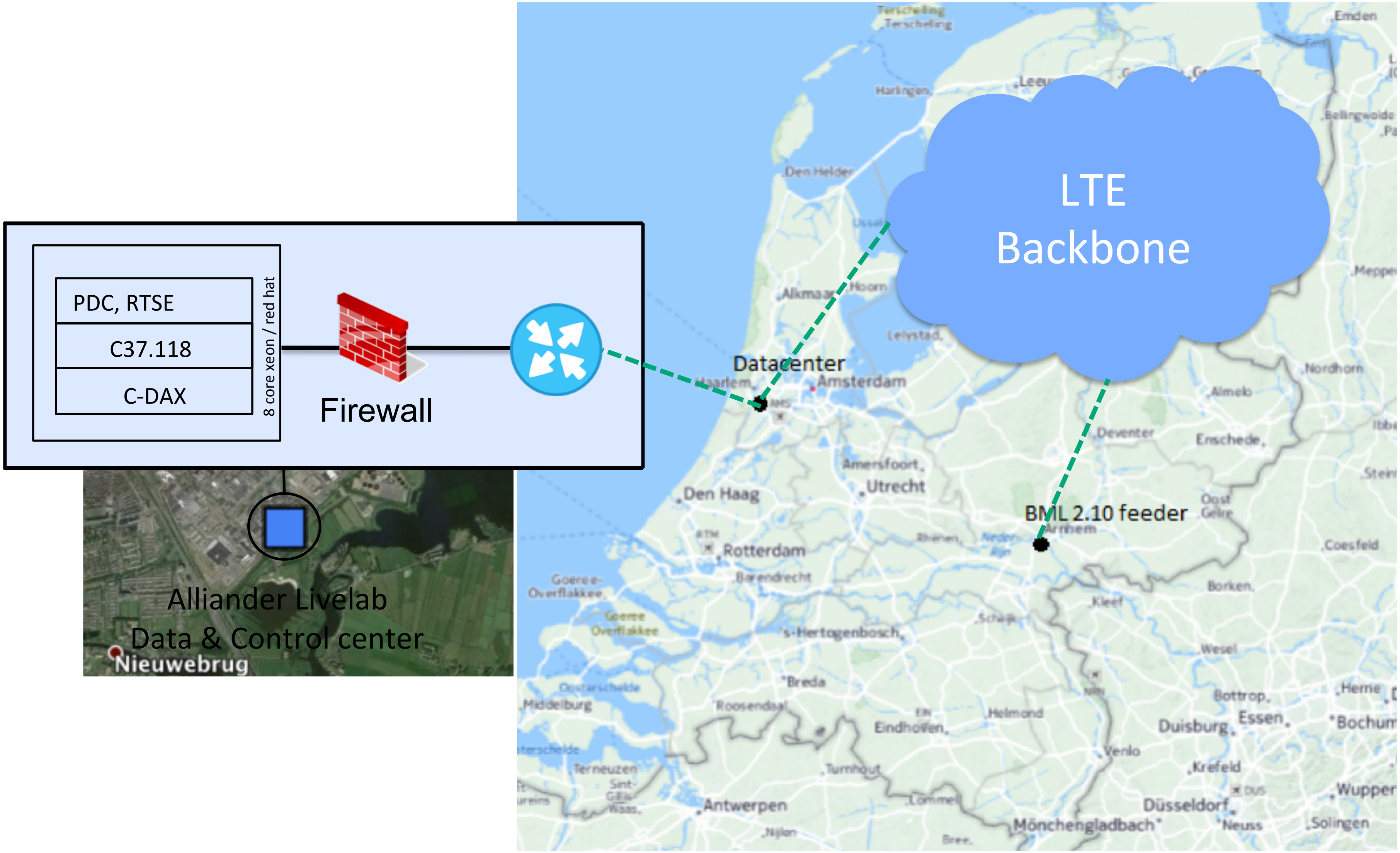

Future retail energy market
Smart charging
PMU-based real-time state estimation (RTSE) in MV
Energie Data Services Nederland
E-Mobility Service Provider
Smart meter topic
EV Topic
Monitoring
Data from:
Smart meter
EV charging
Monitoring
C-DAX client
20kV
10kV
0,4kV
solar panels
smart meter
electrical vehicle
substation Nieuwe Meer
station
central control room

# Field trial setup: Feeder of Alliander (Arnhem, NL)




**18 buses,** area of 12 km$^2$
Nominal voltage: **10 kV** (phase-to-phase)
Monitoring: **10 PMUs** (EPFL), **1 PQ meter** (NI)
Commercial **LTE network** (Vodafone)

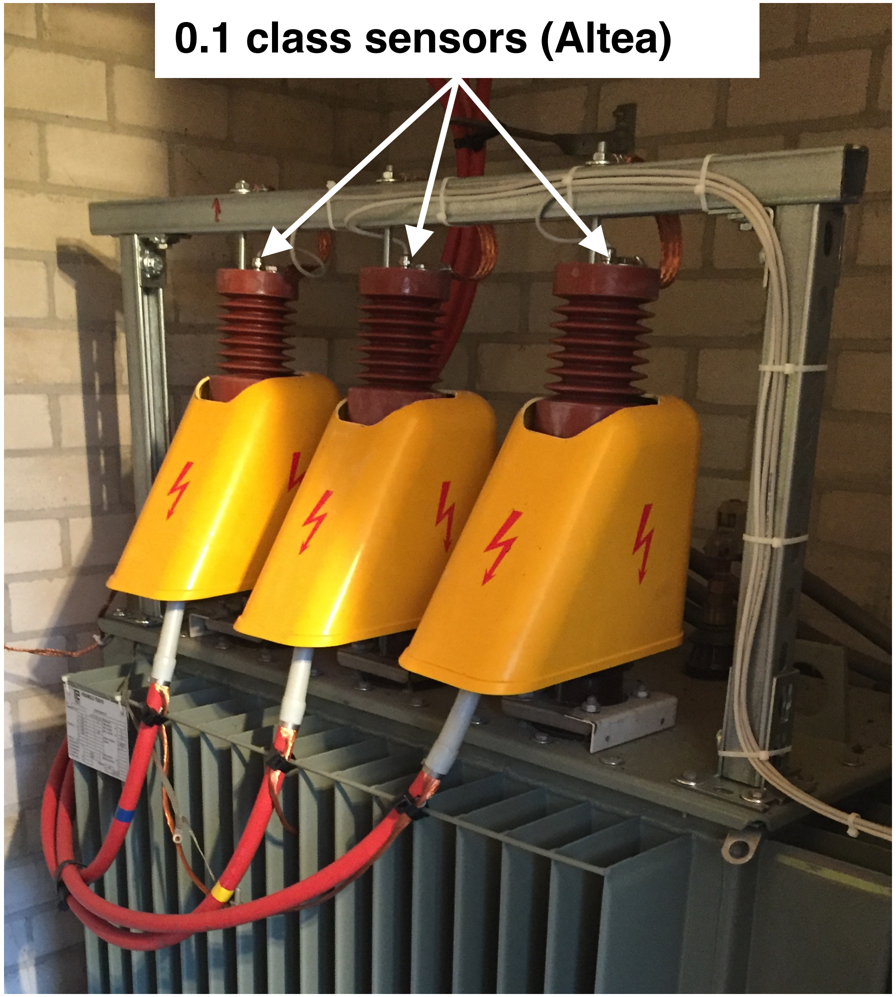
# Field trial setup: Alliander data center

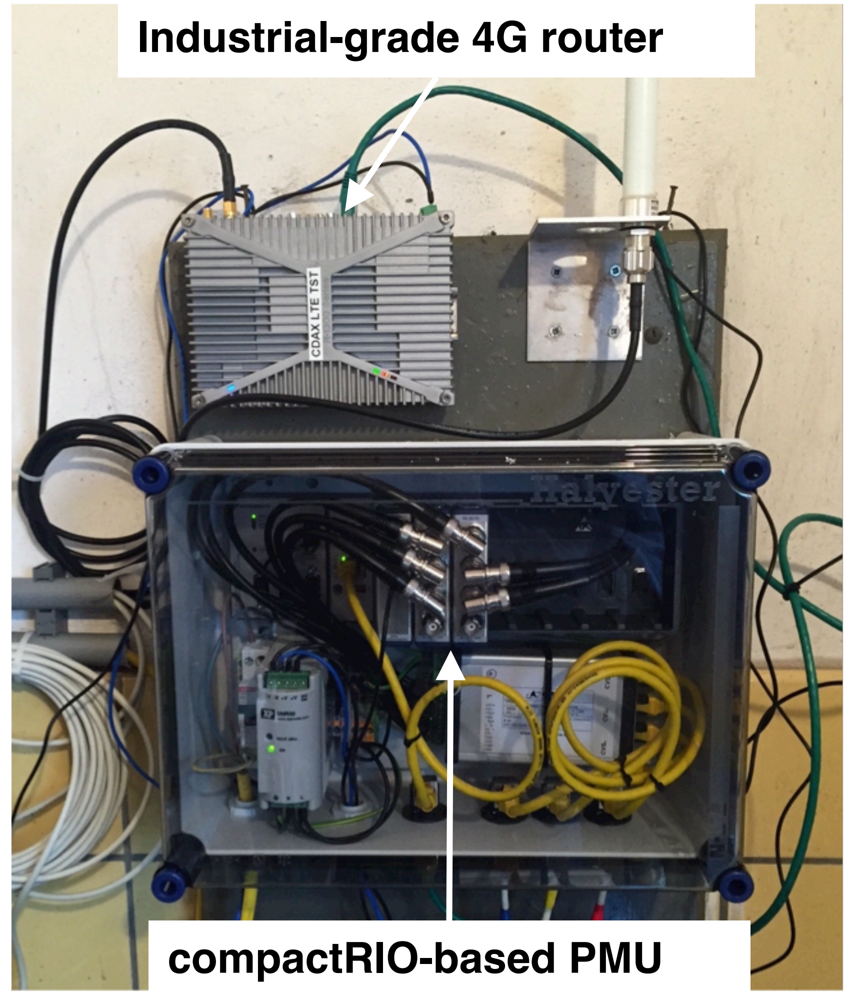


# Phasor Measurement Units – The EPFL PMU

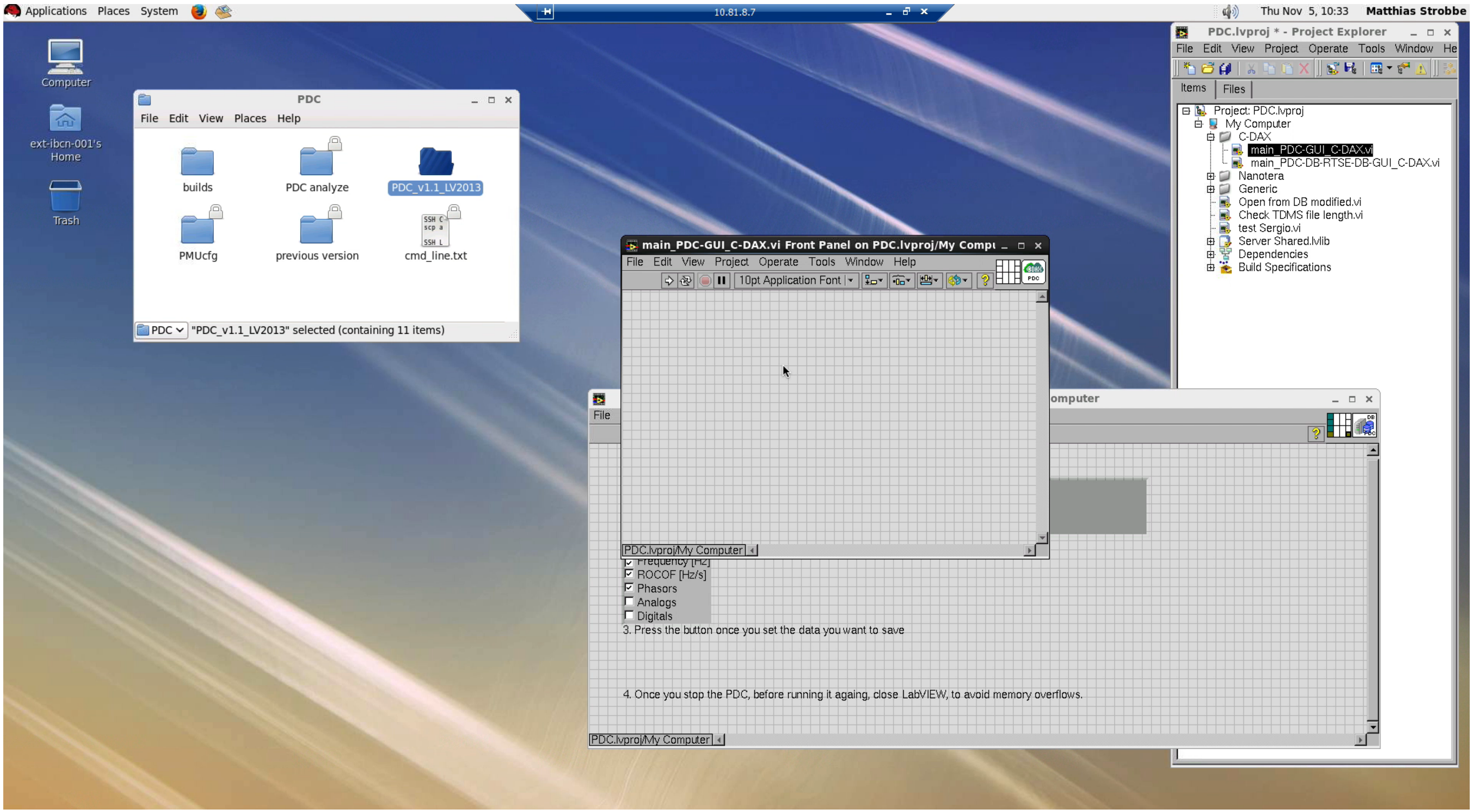
- First PMU worldwide **specifically designed for ADN** operating conditions
- Rugged and compact **NI-compactRIO** enclosure to fit in reduced spaces
- First worldwide **FPGA-based PMU** (high speed and determinism)
- Equipped with a ±100 ns (max error) stationary **GPS module**
- Metrologically characterized at **Swiss Federal Institute of Metrology** (METAS)
    - **Steady state accuracy**: 10 ppm (independently of harmonic distortion)
    - **Measurement reporting latency**: 37 ms
    - **Reporting rates**: 10-20-50-100-200 fps
    - IEEE Std. C37.118 **class-P compliant**

# Substation setup



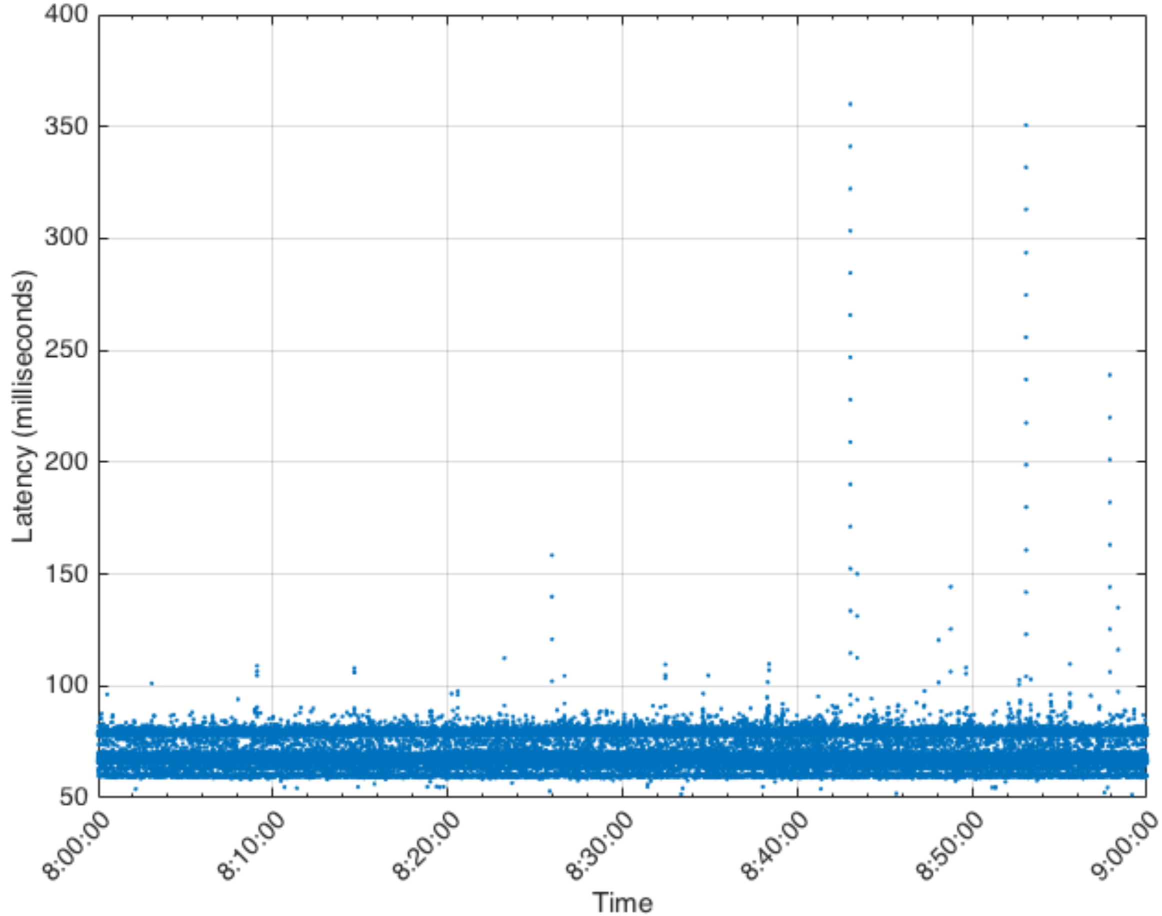



# Demo



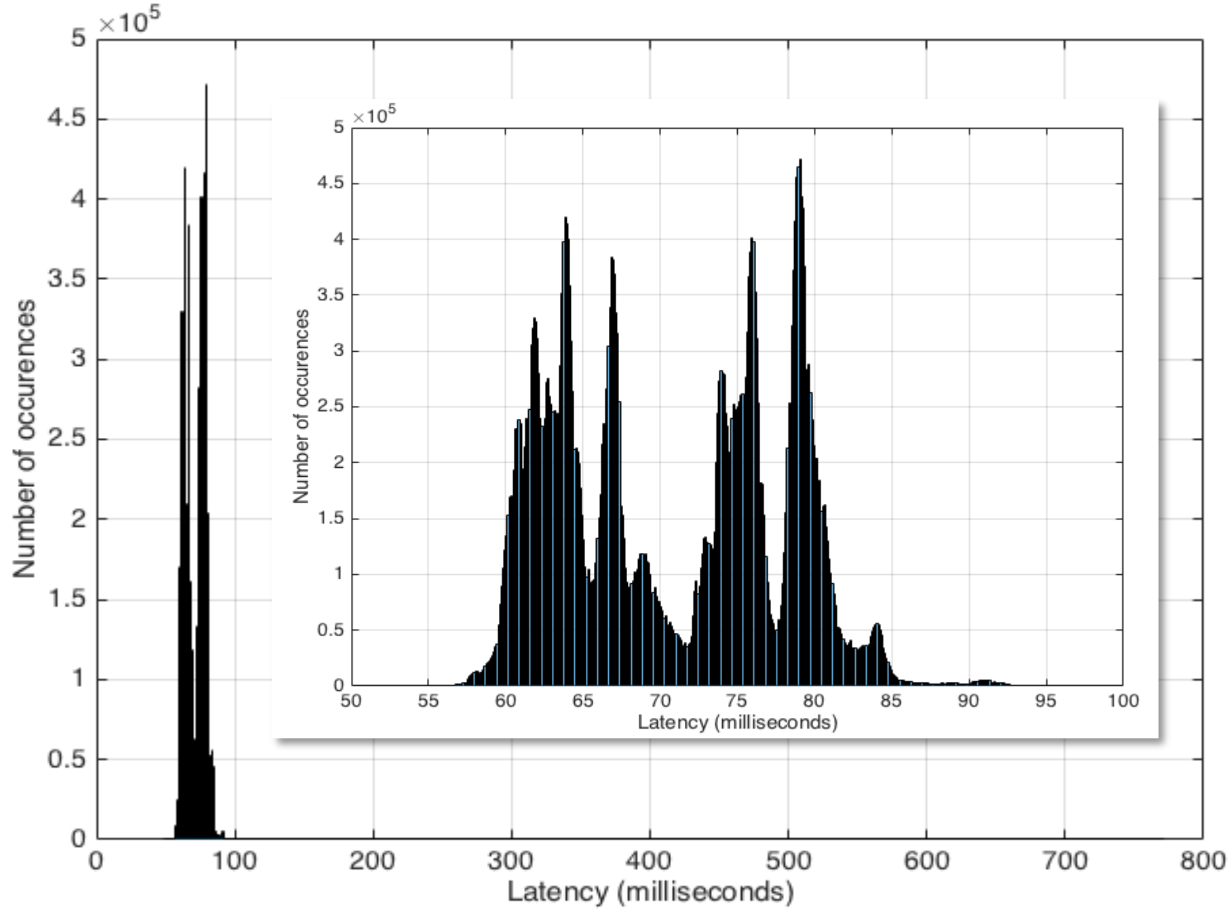
Applications Places System
10.81.8.7
Thu Nov 5, 10:33 Matthias Strobbe
Computer
ext-ibcn-001's Home
Trash
PDC
File Edit View Places Help
builds
PDC analyze
PDC_v1.1_LV2013
PMUcfg
previous version
cmd_line.txt
"PDC_v1.1_LV2013" selected (containing 11 items)
PDC.lvproj * - Project Explorer
File Edit View Project Operate Tools Window He
Items Files
Project: PDC.lvproj
My Computer
C-DAX
main_PDC-GUI_C-DAX.vi
main_PDC-DB-RTSE-DB-GUI_C-DAX.vi
Nanotera
Generic
Open from DB modified.vi
Check TDMS file length.vi
test Sergio.vi
Server Shared.lvlib
Dependencies
Build Specifications
main_PDC-GUI_C-DAX.vi Front Panel on PDC.lvproj/My Compu
File Edit View Project Operate Tools Window Help
10pt Application Font
PDC.lvproj/My Computer
ROCOF [Hz/s]
Phasors
Analogs
Digitals
3. Press the button once you set the data you want to save
4. Once you stop the PDC, before running it againg, close LabVIEW, to avoid memory overflows.

# Synchrophasor data latencies (4G network)



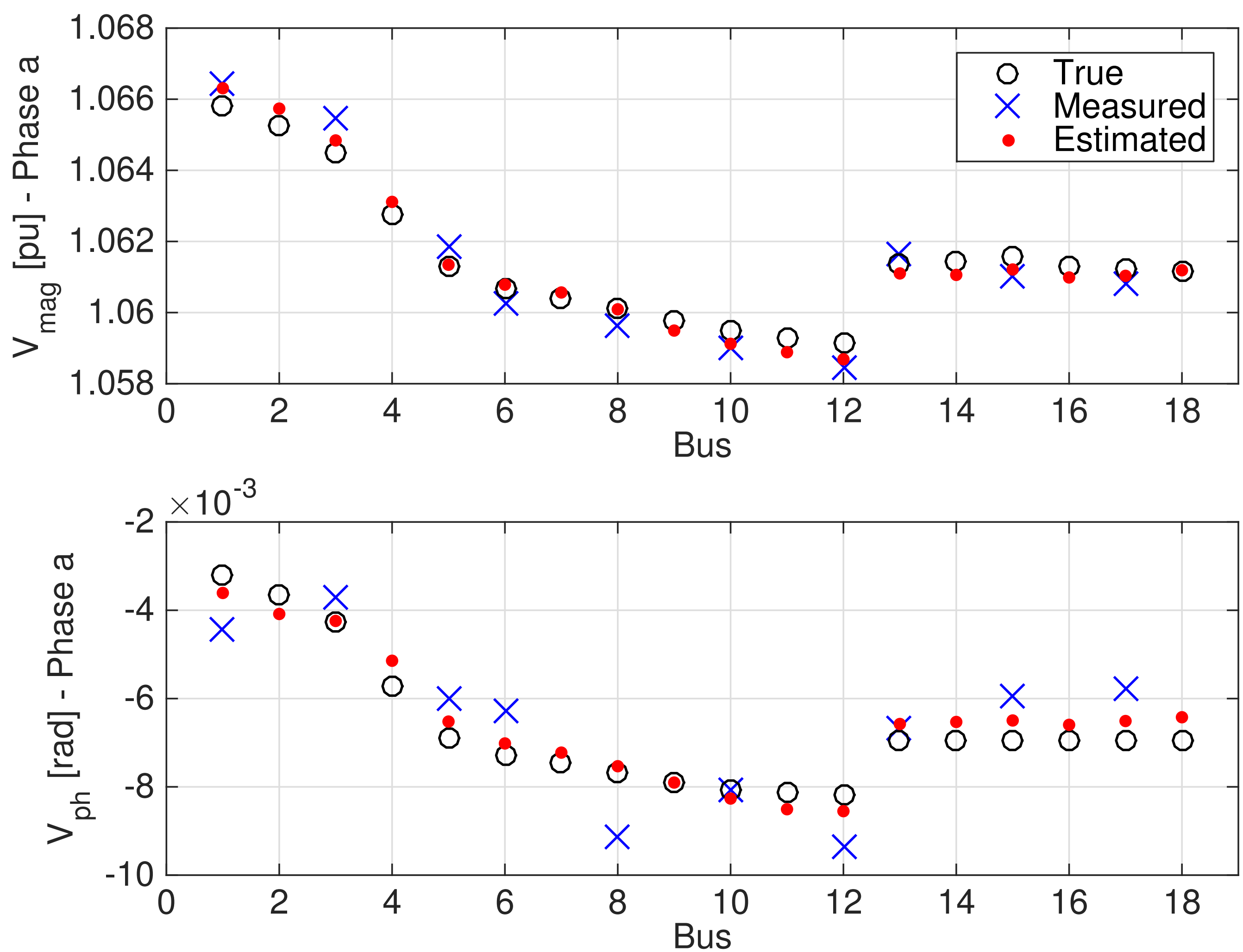

| Mean | Stdev | Max | Min | Data Loss (%) |
|---|---|---|---|---|
| 70.9 ms | 8.1 ms | 770.5 ms | 49.2 ms | 0.0053 |

# Synchrophasor data latencies (4G network)




| Mean | Stdev | Max | Min | Data Loss (%) |
|---|---|---|---|---|
| 70.9 ms | 8.1 ms | 770.5 ms | 49.2 ms | 0.0053 |

# Estimated vs measured voltage profiles



# Wrap-up

# Summary

- Challenge: deal with renewable sources
- Demand response algorithms: initial feasibility studies

  (How close to “best” possible? Scalable? What are achievable benefits?)
- Get insight in consumption/production: e.g., clustering as first step
- Quantify flexibility, e.g., the EV case study
- Flexible data communications platform w/ C-DAX middleware
- What’s next?

  E.g., refine “disutility” from user; “imbalance” from business perspective; evaluate using real(istic) data…

  - Can we **learn/predict** flexibility, e.g., from smart metering data?
  - Can we infer **user behavior**, and from there (context-aware) preferences?
  - Evaluation of the **business case** of flexibility?
  - Convincingly demonstrate flexibility exploitation in the real world?

# Thank you … any questions?

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Ghent University – iMinds