Intelligent solutions for energy management and environmental monitoring

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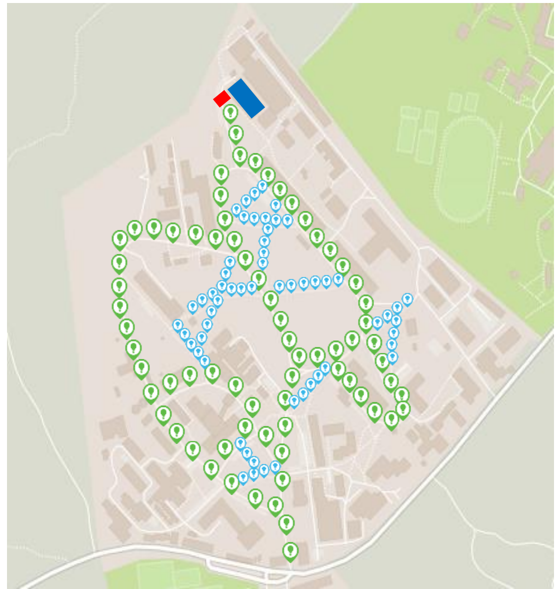
Motivation

- Changing grid environment
  - Generation less controllable (renewables)
  - Consumers more controllable (EVs, ICT)
  - Need for demand response management
  - Power systems & street lighting as infrastructure for smart city services
  - Plethora of challenges for AI

- E+grid: intelligent energy-positive street lighting system
  - Intelligent: lighting according to traffic and environmental conditions
  - Energy-positive: produces more energy than it consumes in a year
  - Consortium: GE Hungary, BME, MFA, SZTAKI

Prototype system configuration

- 191 intelligent LED luminaries with motion sensors (6,4 kW)
- Roof-mounted PV panels (21 kWp total)
  - KORAX monocrystalline (3.50 kWp)
  - SHARP thin-film (3.46 kWp)
  - TrinaSolar polycrystalline (13.51 kWp)



- Battery storage (18 kWh total)
  - Hopecke lead-acid (8 kWh)
  - Akasol Li-ion (5.5 kWh)
  - Shaft Li-ion (5 kWh)
- At a research campus of the Academy
  - Since 2014

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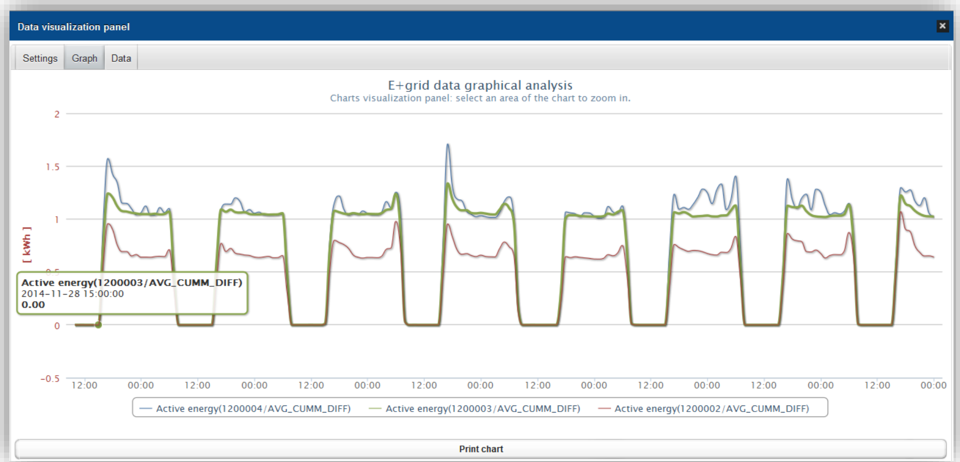
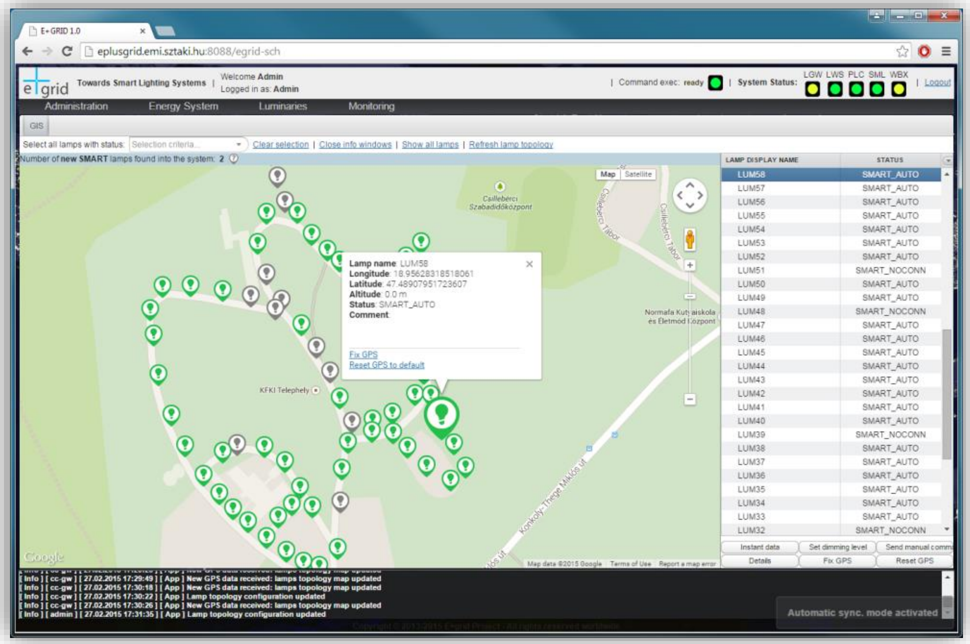
Central controller

- Software application running in computational cloud
  - Monitoring and controlling the lighting system
  - Visualization and basic data analysis, smart city services
  - Optimizing the energy flow





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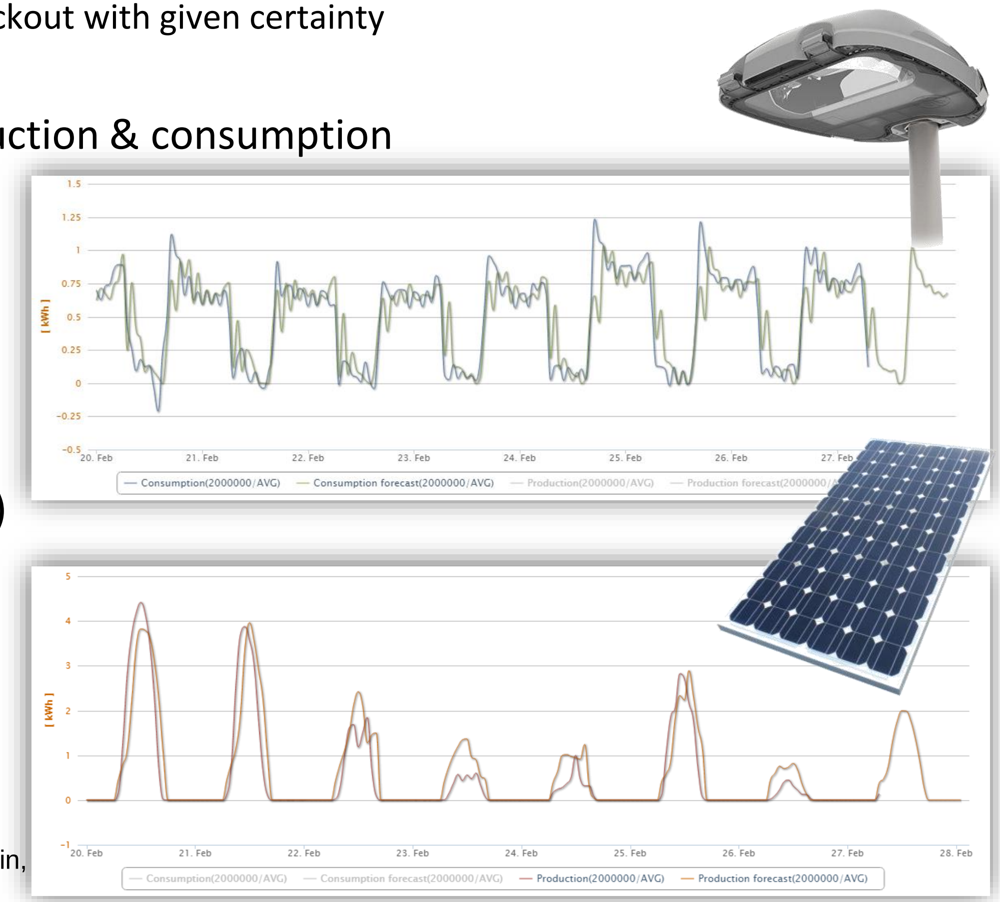
Energy management in E+grid

- Minimizing cost of energy (maximizing profit)
  - Subject to a time-of-use variable energy tariff
  - Directly controlling battery charge and discharge
  - Ensure sufficient battery charge to bridge a 3-hours blackout with given certainty

- Dynamic time series for predicting energy production & consumption
  - Linear ARX (live system)
  - Adaptive aggregation of time series (research)

- Robust optimization approach
  - Linear program (live system)
  - Stochastic model-predictive control (research)



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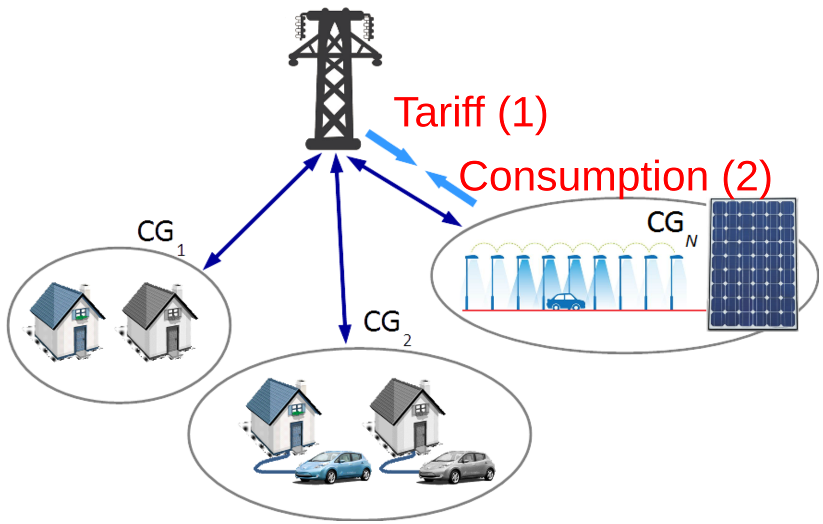
Bilevel tariff optimization for demand response management



- Stackelberg game model
- Electricity retailer (leader in game)
  - Computes day-ahead time-varying electricity tariff, with hourly resolution
  - Objective: maximizing profit
- Consumers (multiple followers in game)
  - Classified into consumer groups with similar profiles
  - Respond to tariff by scheduling controllable loads and battery (dis)charge
  - Objective: min. cost of electricity & max. utility
- Assumption: retailer knows perfectly the decision model of consumers

Bilevel tariff optimization: mathematical formulation

Maximize

$$f = \sum_{t=1}^{T} \left(\sum_{i=1}^{N} (Q_t^+ x_{i,t}^+ - Q_t^- x_{i,t}^-) \; - \; P_t^+ y_t^+ \; + \; P_t^- y_t^- \right)$$

subject to

$$y_t^+ - y_t^- = \sum_{i=1}^{N} (x_{i,t}^+ - x_{i,t}^-) \qquad \forall t$$

$$\underline{Q} \le Q_t^- \le Q_t^+ \le \overline{Q} \qquad \forall t$$

$$\frac{1}{T} \sum_{t=1}^{T} Q_t^+ \le \tilde{Q}$$

Leader's objective & constraints

$$\begin{pmatrix} x_{i,t}^+ \\ x_{i,t}^- \end{pmatrix} \in \arg\min \left\{ \sum_{t=1}^{T} (Q_t^+ x_{i,t}^+ - Q_t^- x_{i,t}^- - U_{i,t} L_{i,t}) \;\middle|\; \right.$$

s.t.

$$C_{i,t}^+ - C_{i,t}^- + x_{i,t}^+ - x_{i,t}^- - L_{i,t} = r_{i,t}^+ - r_{i,t}^- \qquad \forall t$$

$$\eta_i r_{i,t}^+ - r_{i,t}^- = b_{i,t} - b_{i,t-1} \qquad \forall t$$

$$\sum_{t=1}^{T} L_{i,t} = M_i$$

$$L_{i,t} \le \bar{L}_{i,t} \qquad \forall t$$

$$\underline{B}_{i,t} \le b_{i,t} \qquad \forall t$$

$$b_{i,t} \le \overline{B}_i \qquad \forall t$$

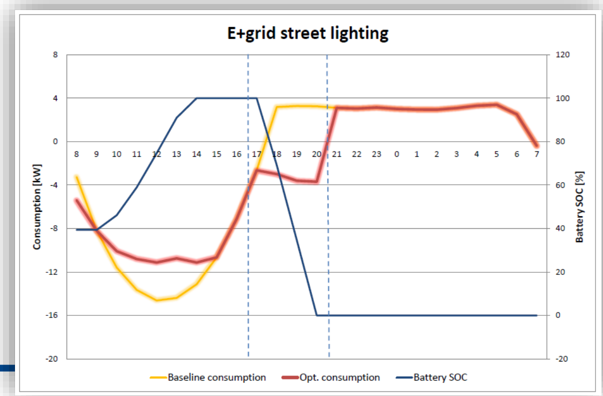
$$r_{i,t}^+ \le R_i^+ \qquad \forall t$$

$$r_{i,t}^- \le R_i^- \qquad \forall t$$

$$\left. 0 \le x_{i,t}^+, x_{i,t}^-, r_{i,t}^+, r_{i,t}^-, L_{i,t} \qquad \forall t \right\} \quad \forall i$$

Followers' model

- Solution approach
  - Reformulation to single-level problem
    - Followers' problem is an LP
    - Classical approach: KKT reformulation to MIP
    - Proposed new approach: primal-dual reformulation to QCQP
    - Solving the QCQP by successive linear programming
- Solvable in practically relevant sizes
  - E.g., up to 20 consumer groups & 48 periods
  - In ca. 5 minutes
  - <0.1% optimality gap



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Bringing the bilevel approach closer to reality

- Crucial assumptions in the game theoretical model
  - Leader has perfect information about the followers' problems
  - Follower selects the optimal solution most favorable for the leader
  - Current research focuses on relaxing these assumptions

- Estimating followers' model parameters from past behavior
  - Challenge: dependency of consumption on electricity tariff
  - Inverse optimization approach to parameter estimation
  - Consumer behavior can be reliably predicted based on noisy historic samples

- Robust optimization approaches
  - Safeguard the leader from followers selecting a different optimal response: "Pessimistic" bilevel formulation
  - Robust bilevel optimization with followers' parameter in an uncertainty set

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