Flexibility options and energy storage

– a systems perspective on micro-level

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2. Herbstworkshop ”Energiespeichersysteme”
TUD Dresden, 29. November 2017

Aalto University
School of Science

Outline of the talk

Main contents:

①Combined effects from several flexibility measures

②Optimization & Modelling & Control Strategies

Case results from the following journal papers:

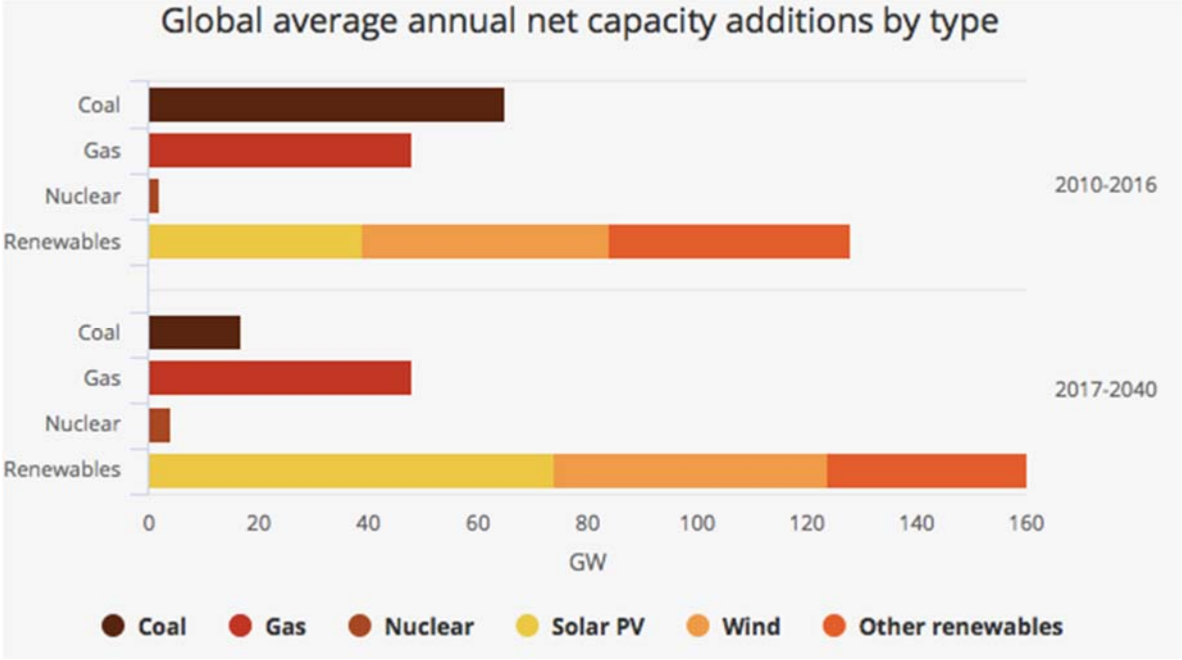
[if you want a copy of the papers, send an email to peter.lund@aalto.fi]

1. Lund, P., Mikkola, J., Salpakari, J., Lindgren, J., Review of energy system flexibility measures to enable high levels of variable renewable electricity, *Renewable & Sustainable Energy Reviews* 45 (2015) 785-807.
2. Salpakari, J., Lund, P.. Optimal and rule-based control strategies for energy flexibility in buildings with PV. *Applied Energy* 161 (2016) 425-43.
3. Salpakari, J., Mikkola, J., Lund, P.D.. Improved integration of large-scale variable renewable power in cities through optimal control of DSM and power-to-heat measures. *Energy Conversion and Management* 126 (2016)649-661.
4. Lindgren, J., Asghar, I., Lund, P.D., A hybrid Lithium-ion battery model for system-scale analyses. *International Journal of Energy Research* , 2016; 40(11):1576-1592
5. Lindgren, Lund, P.D., Effect of low temperatures on battery charging and performance of electric vehicles. *J. of Power Sources*, 2016, 328, 37-44

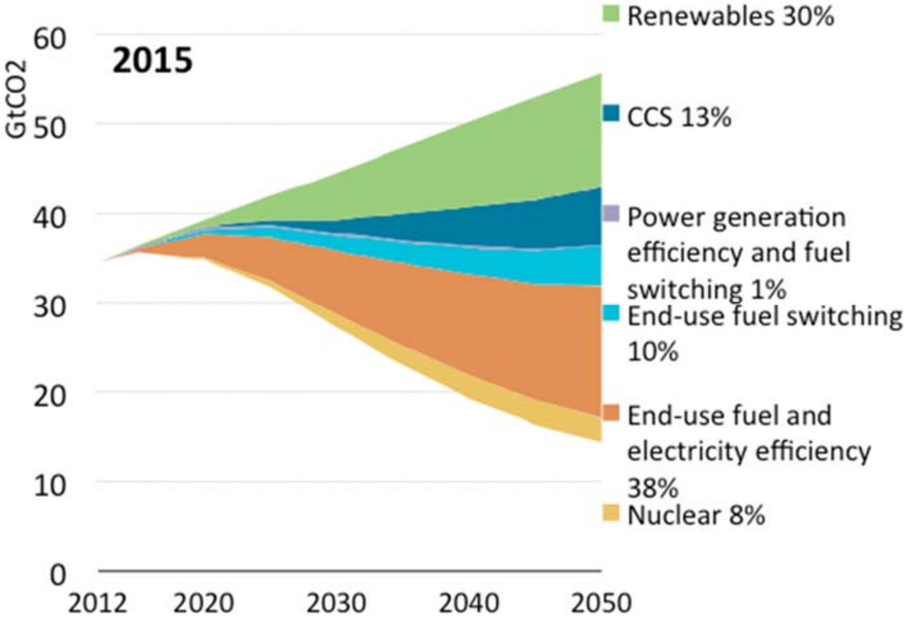
Forthcoming energy transition

- RES & PV constitute major part of future power investment
- RES &EE constitute most of the measures for the Paris Accord

IEA WEO 2017



IEA 2015



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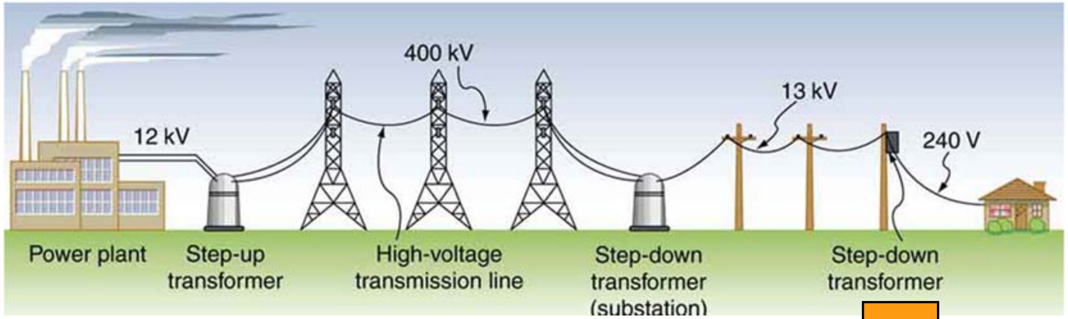
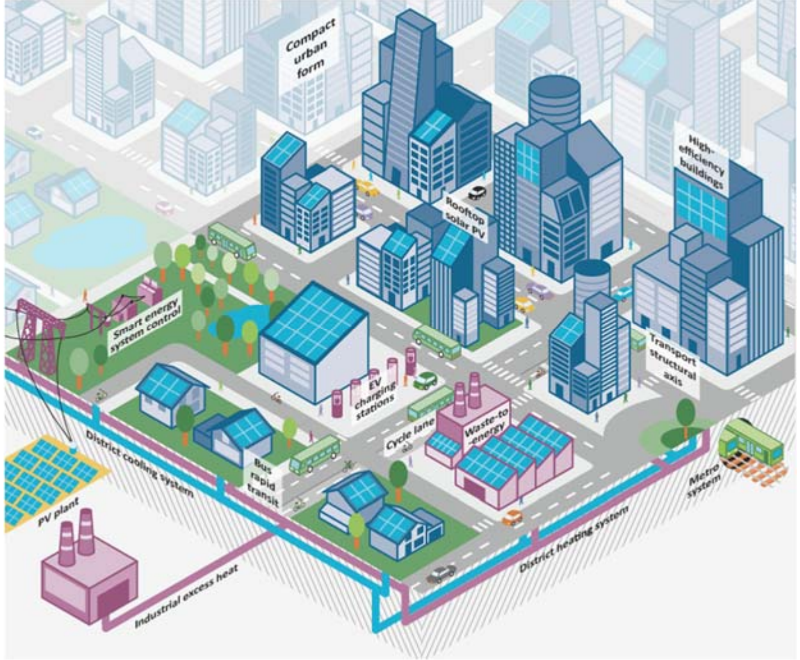
Transitions in the energy systems

Traditional power system



Future energy system



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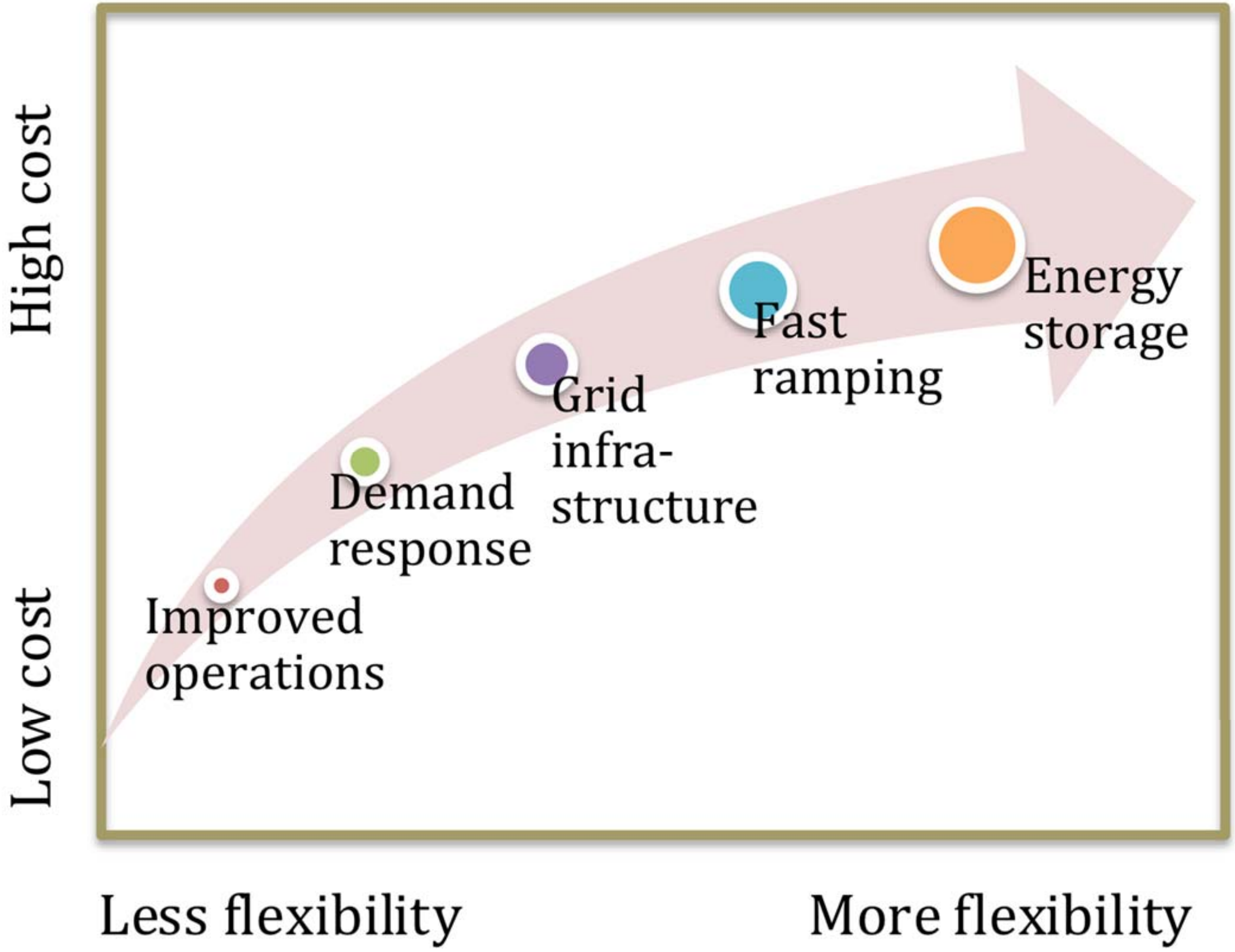
- Hiearchies replaced by communities
- Energy production units similar in size to load
- Production and consumption communicating and keeping system stable
- Small integrated systems, loose interconnections
- From commodity to service thinking
  - Prosumers, enabling grids, adaptive generation, market logistics

Flexibility options



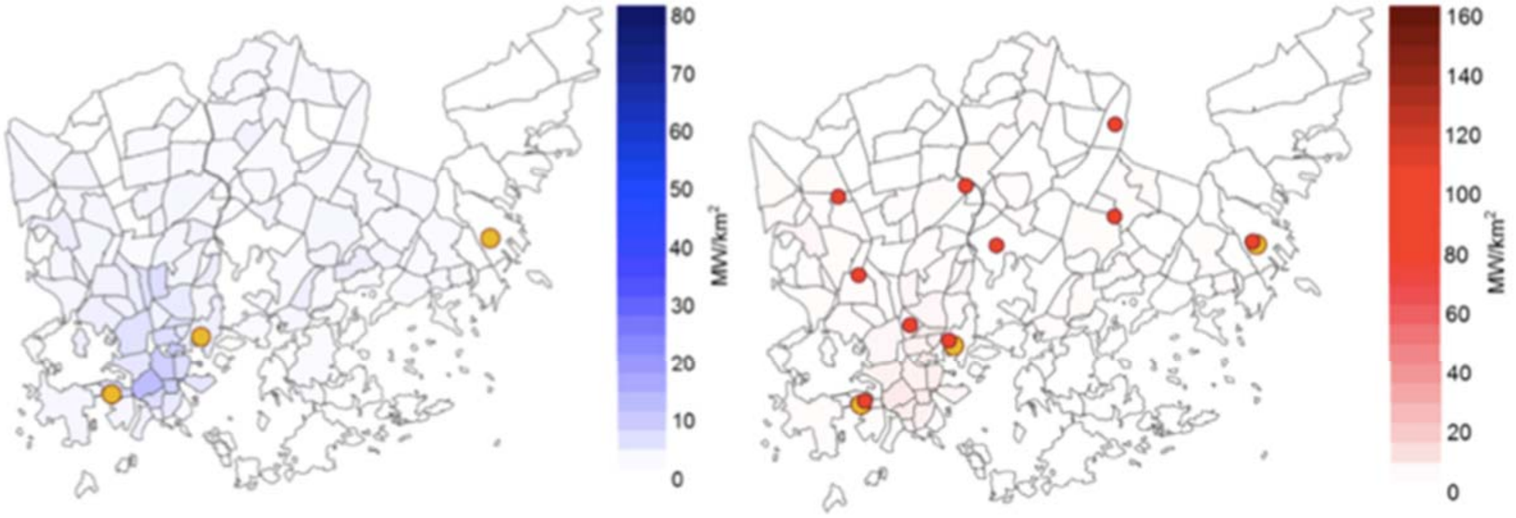
Ref: Energy Innovation, 2015

Storage functions:

- Voltage regulation
- Frequency regulation
- Load following
- Black start
- T&D deferral
- Arbitrage
- Grid support
- Self-consumption
- Off-grid
- Interseasonal storage

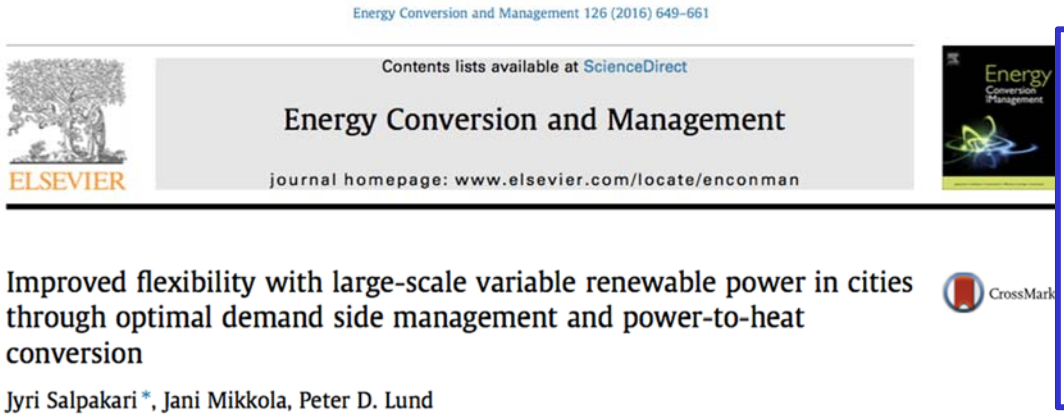
Energy system in Helsinki (Finland)

Power and heat demand & plants in Helsinki



$1GW_{el}$;$1.3GW_{th,CHP}$; $2.0GW_{th,peak}$
(coal, gas); district heating

#1: Improved flexibility through DSM + P2H + Storage



Energy Conversion and Management 126 (2016) 649–661

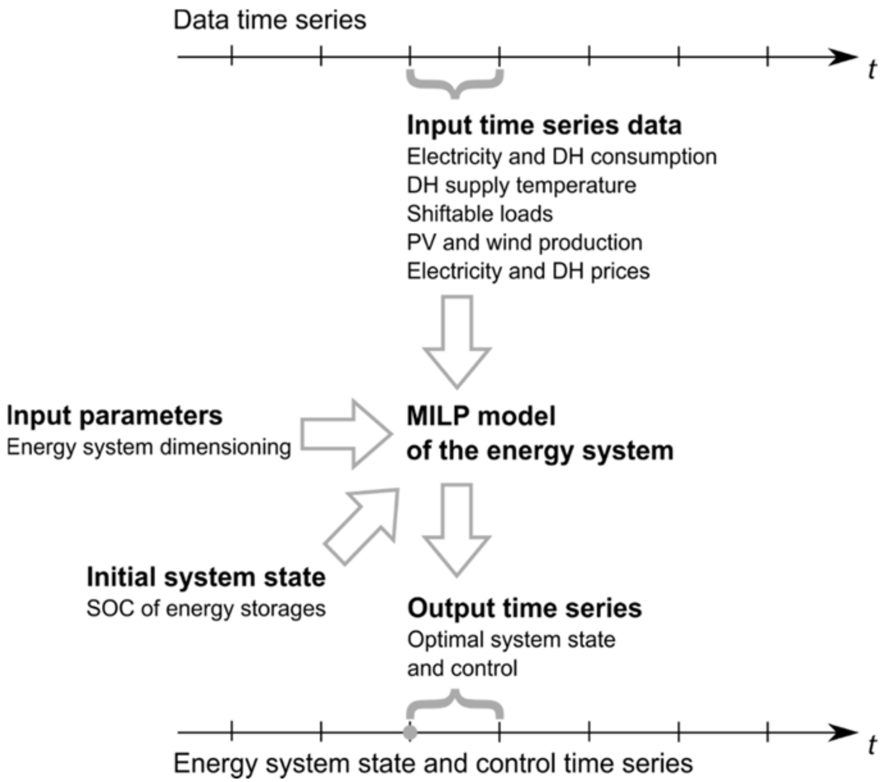
Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion

Jyri Salpakari *, Jani Mikkola, Peter D. Lund



Data time series

t

Input time series data
Electricity and DH consumption
DH supply temperature
Shiftable loads
PV and wind production
Electricity and DH prices

Input parameters
Energy system dimensioning

MILP model
of the energy system

Initial system state
SOC of energy storages

Output time series
Optimal system state
and control

t

Energy system state and control time series

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Aim

- Optimal matching of wind & PV with demand in cities
- Understand technical & economic potential of optimal control

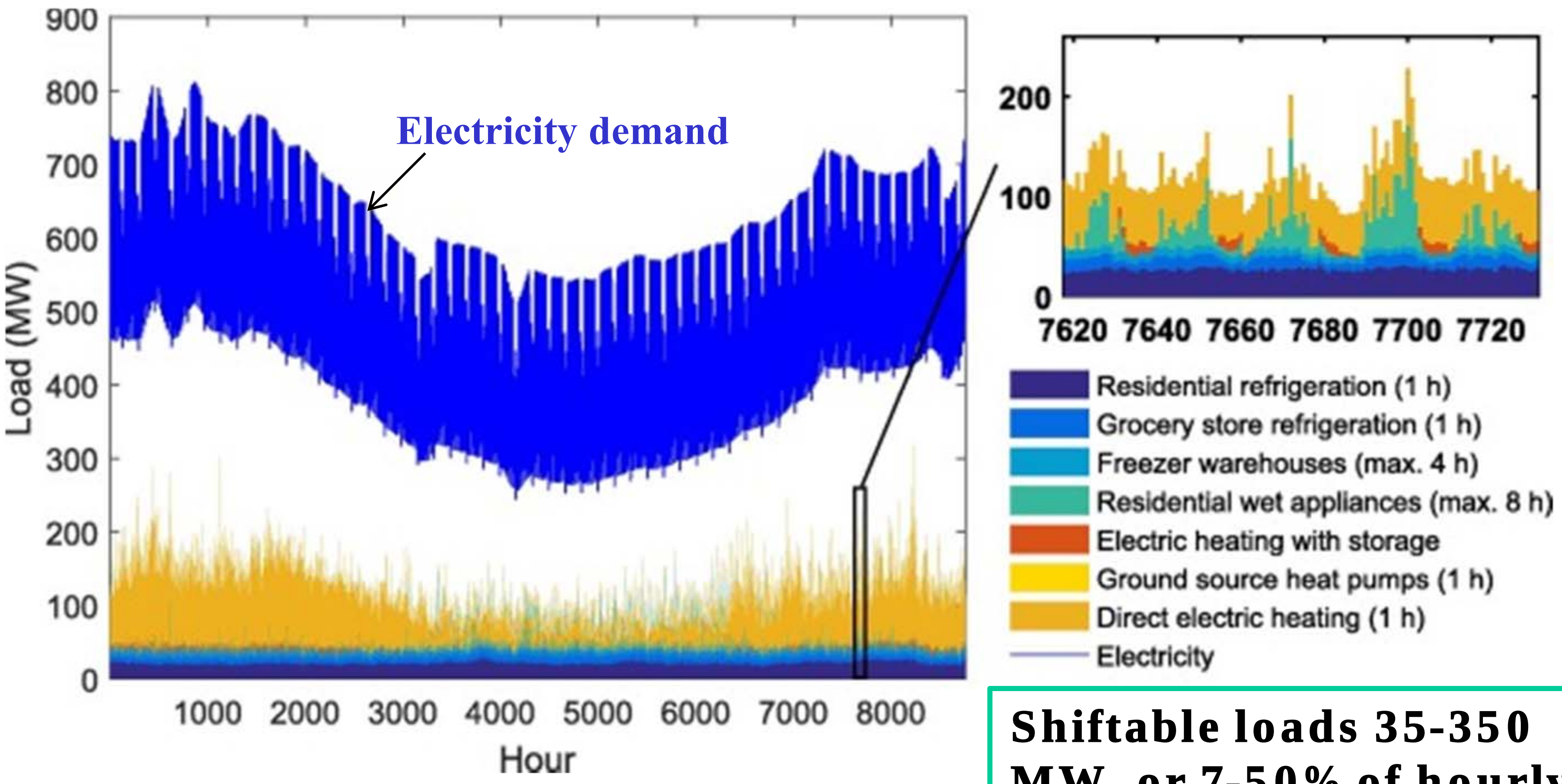
Solution

- Optimal control & simulation model
- DSM, P2H, storage, DH
- Detailed time series of shiftable loads (DSM)

Control strategies (flexibility)

a) load and supply matching ; b) link to electricity market + investments

Power profile + shiftable loads



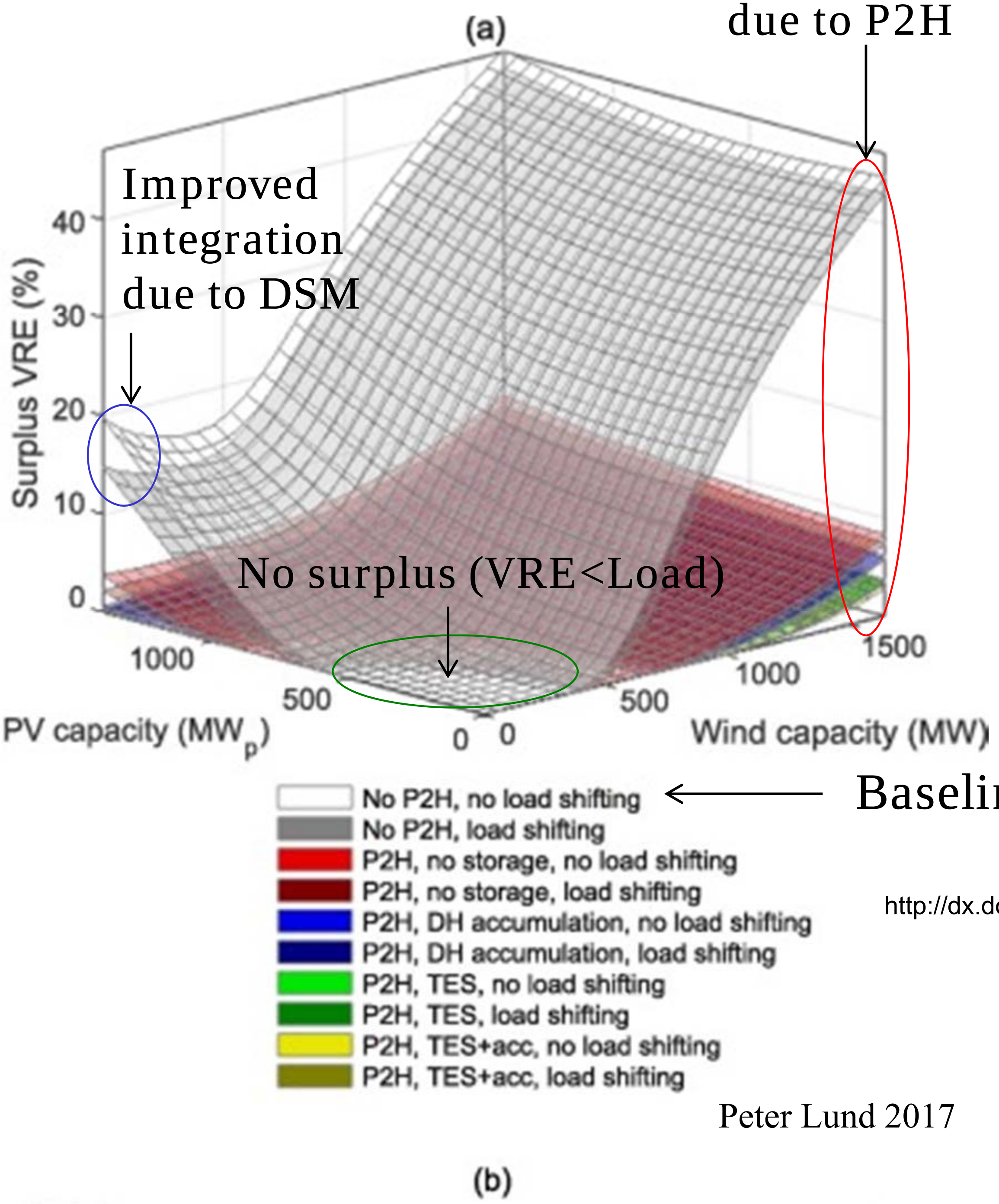
Shiftable loads 35-350 MW, or 7-50% of hourly power demand

Electricity load in Helsinki with shiftable components (DSM). The duration that a load can shift its consumption is indicated in the legend

Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion
Energy Conversion and Management, Volume 126, 2016, 649–661

http://dx.doi.org/10.1016/j.enconman.2016.08.041

Surplus VRE production



Improved integration due to P2H

Improved integration due to DSM

No surplus (VRE<Load)

- DSM enables more VRE (wind and PV)
- P2H very effective (cross-sectorial integration to increase flexibility)

Baseline (topmost surface)

http://dx.doiorg/10.1016/j.enconman.2016.08.041

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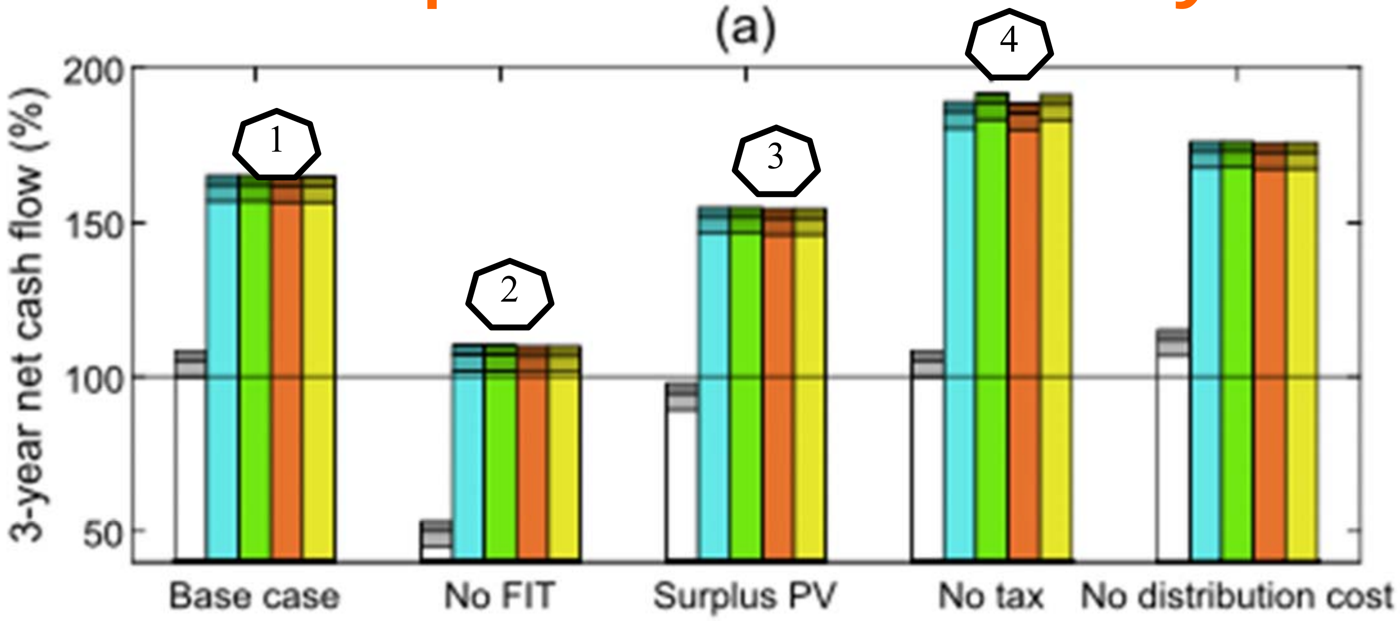
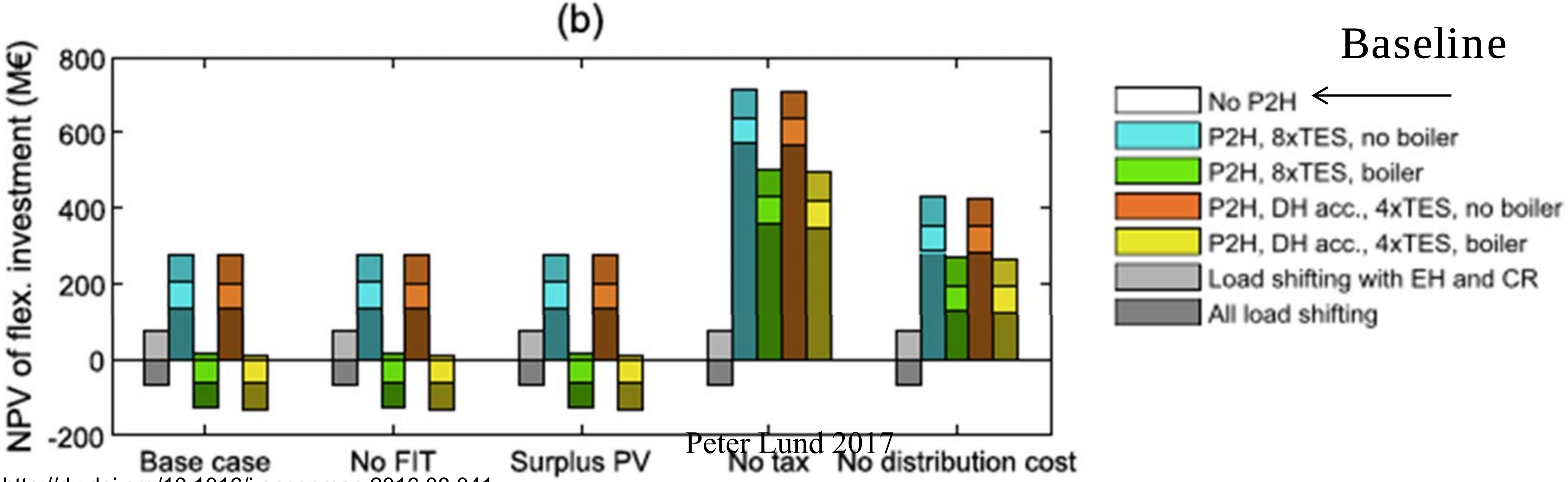
Cash-flow & NPV when linked to spot electricity market



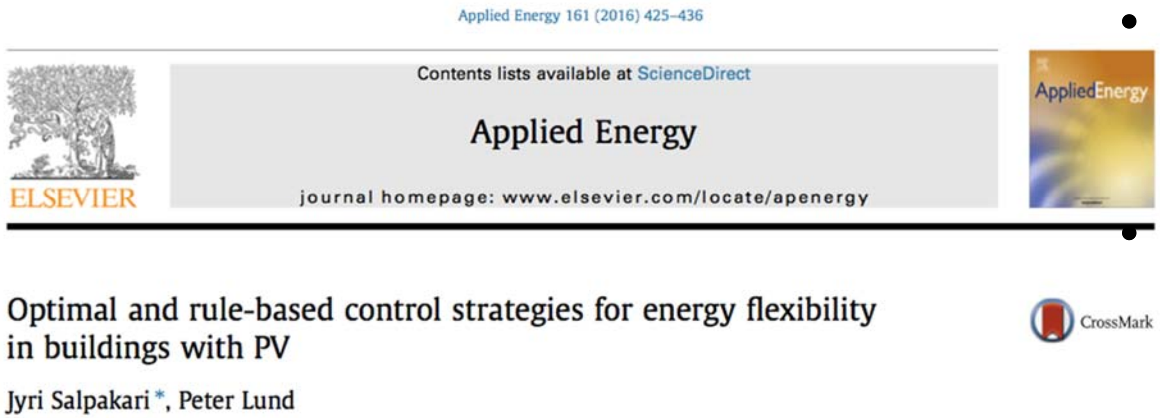
650MWp of PV and 726MW of wind = ca ½ of all electricity



Baseline ←

http://dx.doi.org/10.1016/j.enconman.2016.08.041

#2:Optimal and rule-based control strategies for energy flexibility in buildings with PV


Applied Energy 161 (2016) 425–436

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimal and rule-based control strategies for energy flexibility in buildings with PV

Jyri Salpakari *, Peter Lund

- Simulation: on-site building flexibility resources to balance supply and demand mismatch
- Optimization: minimize variable costs & maximize self-use of PV

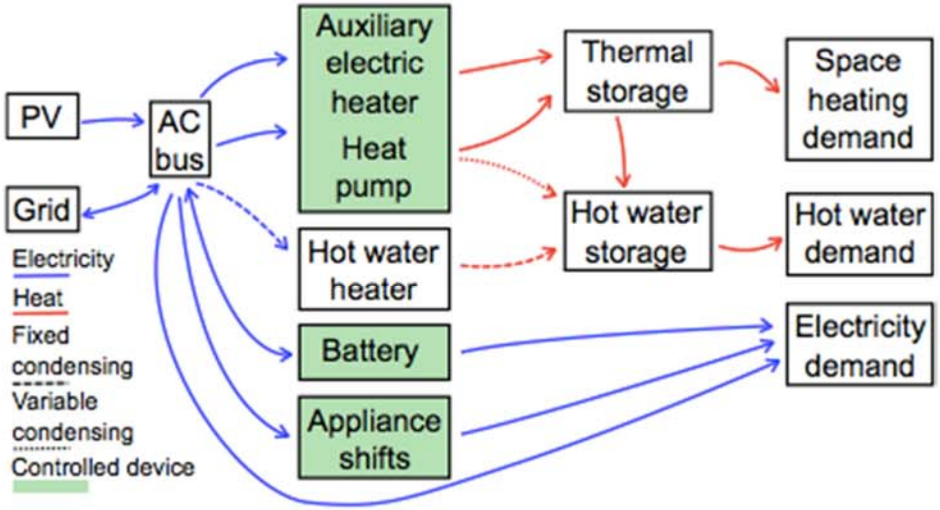
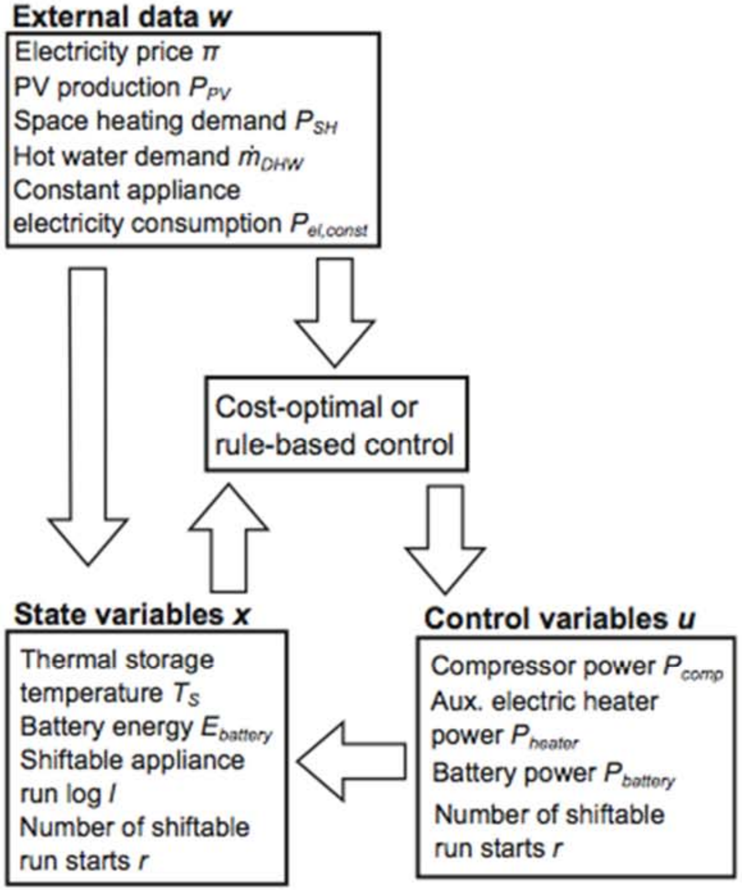
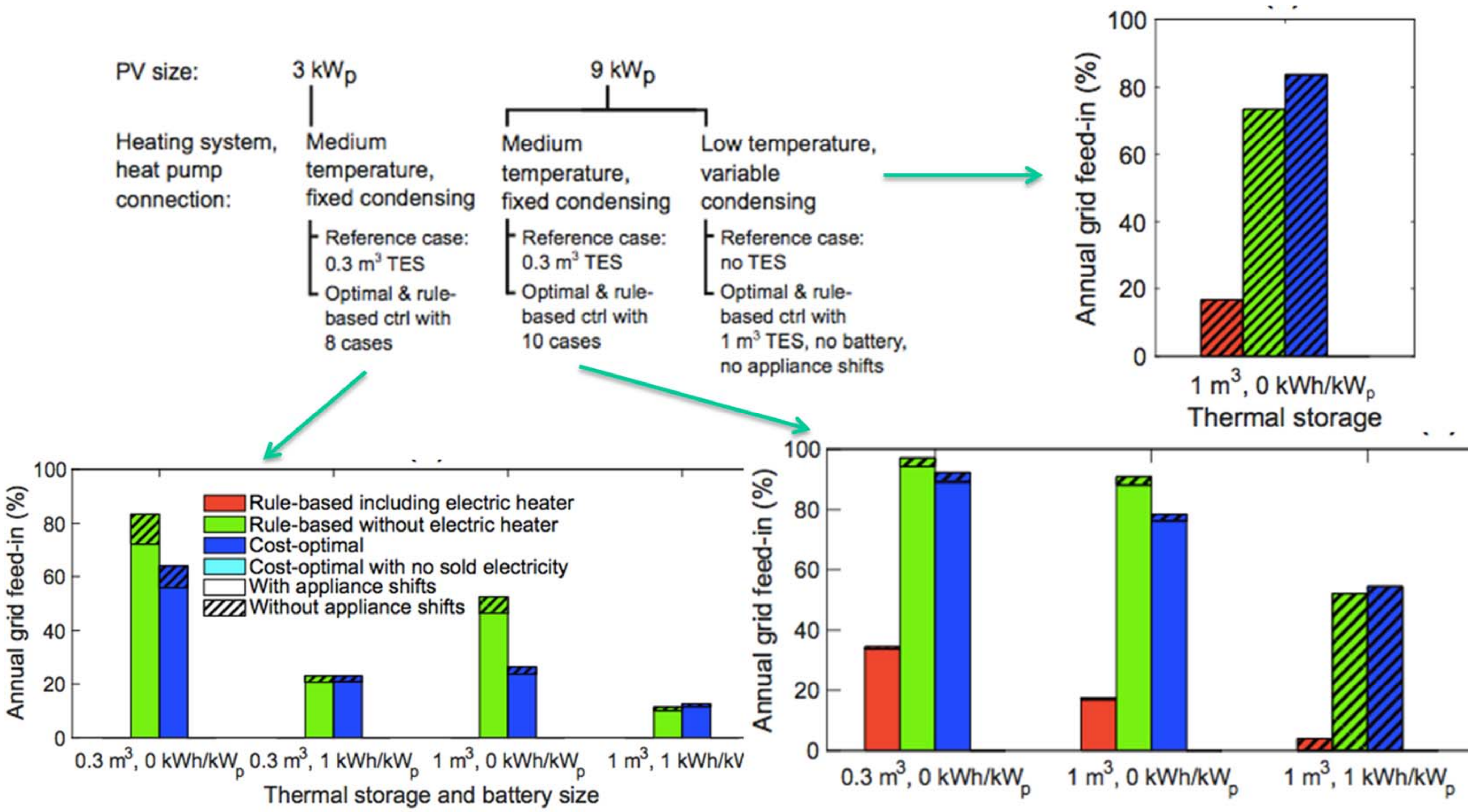


Fig. 1. Energy flows and controls in the modeled system.



Grid Feed-in

- 8–88% decrease in electricity fed into the grid (relative to reference case)
- 13–25% savings in electricity bill with cost-optimal control (1h-based price)

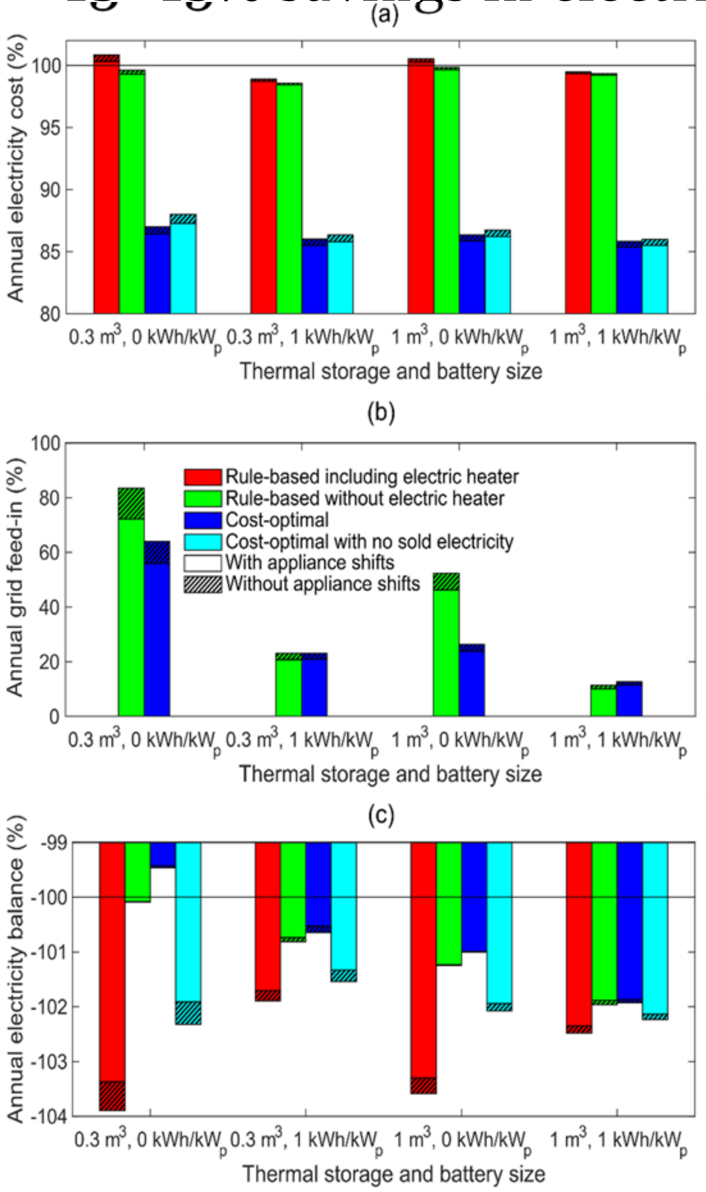


relative to reference case with self-use of ca 80%)

relative to reference case with self-use of ca 40%)

3 kWp PV system with TES+HP

- 36–88% decrease in electricity fed into the grid
- 13–15% savings in electricity bill with cost-optimal control (1h-based price)



Simulation results with a 3-kWp PV system:
(a) annual electricity cost relative to the reference case (1344 €)
(b) grid feed-in relative to the reference case (537 kWh)
(c) electricity balance relative to the reference case (11,039 kWh).

The heating system is medium-temperature and the heat pump is connected in fixed condensing.

System-scale battery modelling

International Journal of Energy Research

INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. 2016; **40**:1576–1592
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/er.3617

A hybrid lithium-ion battery model for system-level analyses

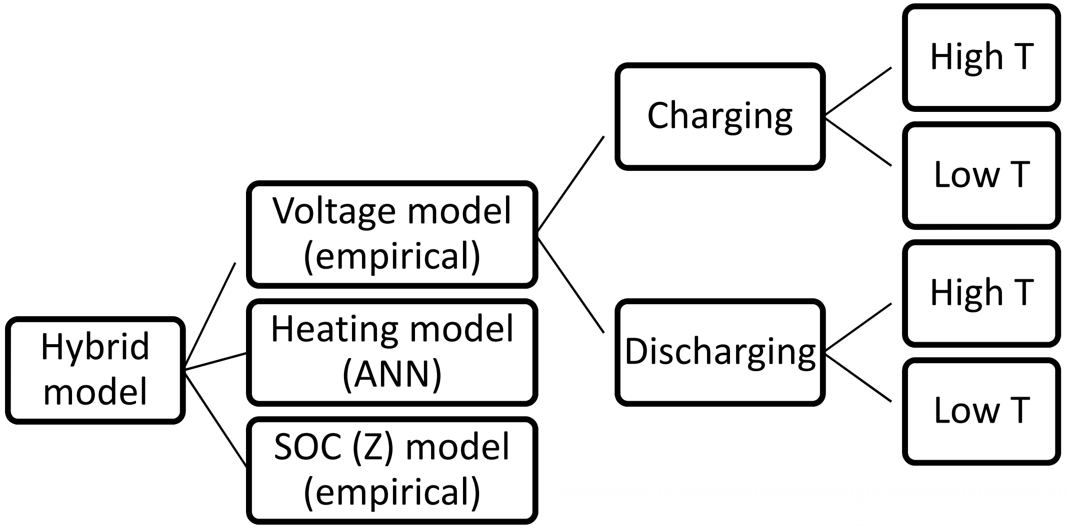
Juuso Lindgren*,†, Imran Asghar and Peter D. Lund

Aim

- System level fast model
- Adequate accuracy
- Thermal effects
- Internal heating

Solution

- Empirical multiparameter model; Artificial neural network (ANN)
- ’Big Data’ from real conditions (battery in weather chamber)



Hybrid model

Voltage model (empirical)

Heating model (ANN)

SOC (Z) model (empirical)

Charging

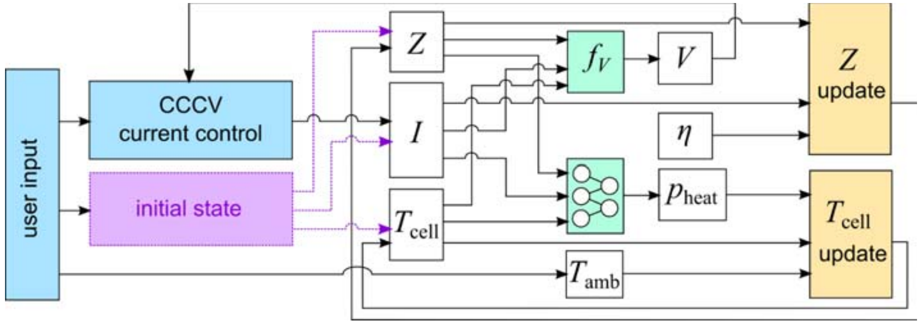
Discharging

High T

Low T

High T

Low T



$$V(Z,I,T_{cell}) = V_{OC} + R_{eff}I$$

$$V_{OC} = x_{15} - \overbrace{\exp[x_{16}(Z - x_{17})] + x_{18}Z + x_{19}(Z - x_{20})^2}^{\text{SOC dependency}} + \overbrace{x_{11}T_{cell} + x_{13}T_{cell}^2}^{\text{Cell temperature dep.}}$$

$$R_{eff} = \left\{\overbrace{\exp[(T_{cell} - x_1)x_2]}^{\text{Cell temperature dep.}} + x_3 + x_4 I\right\}\left\{\overbrace{\exp[x_6(Z - x_7)] + x_8 Z}^{\text{SOC dependency}} + x_9 + x_{10} I\right\} x_5 + x_{12} + x_{14} I$$

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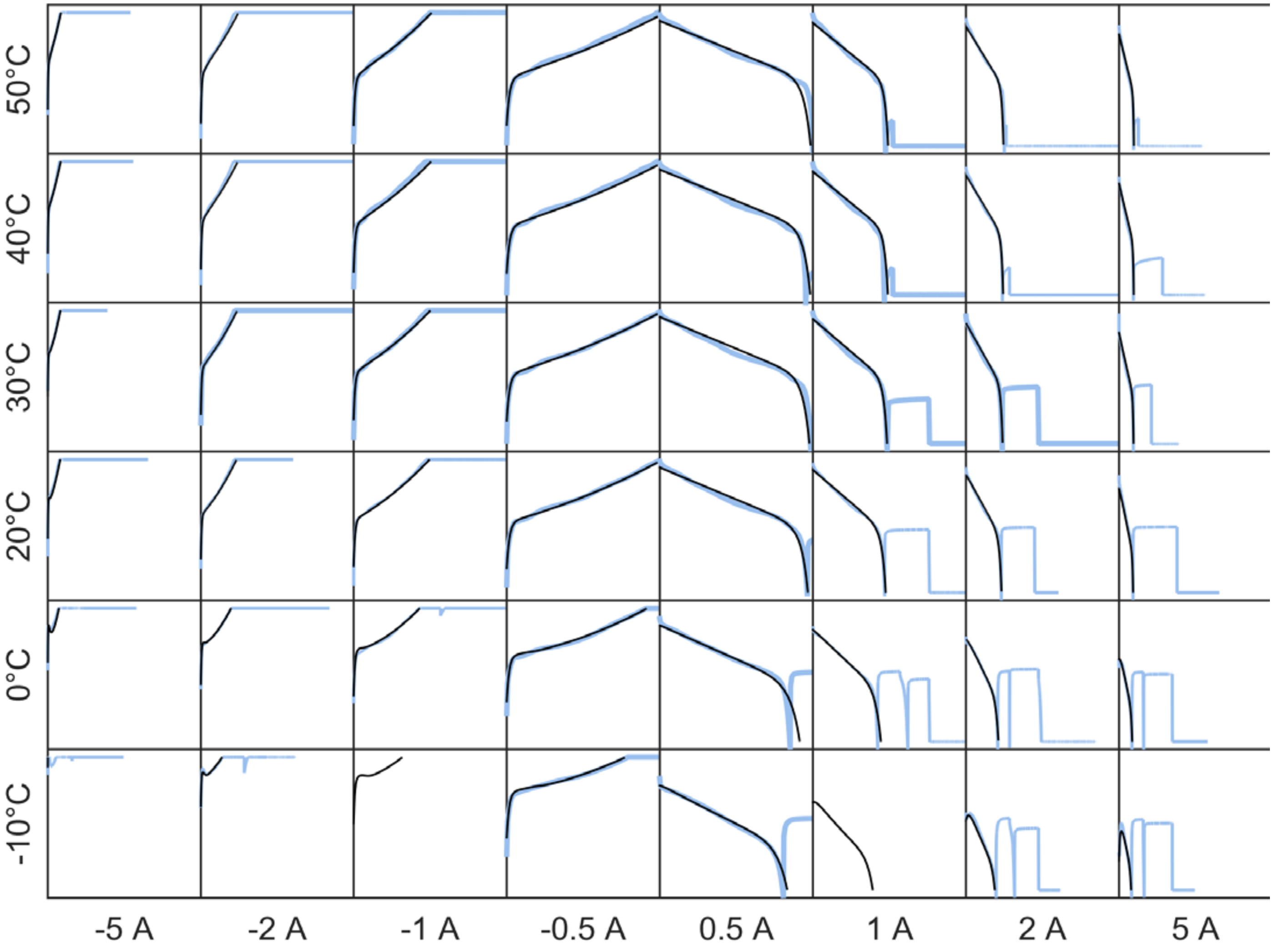
Battery model verification (V)

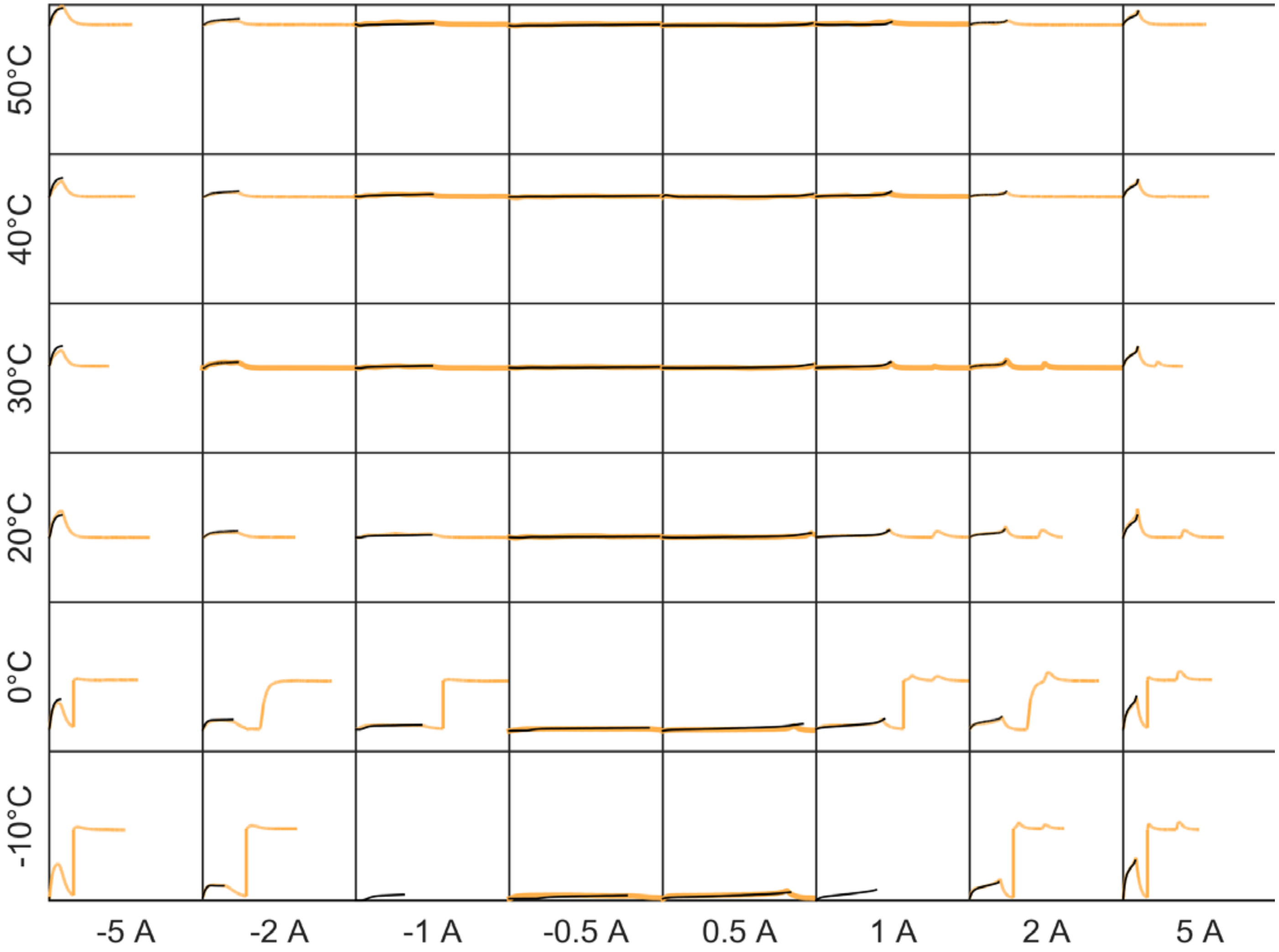


48 different scenarios
(voltage vs time)
Y=2.4-4.3 V
X=0-19000 s

Blue=measured
Black=model

RMSE<10% of operating voltage range

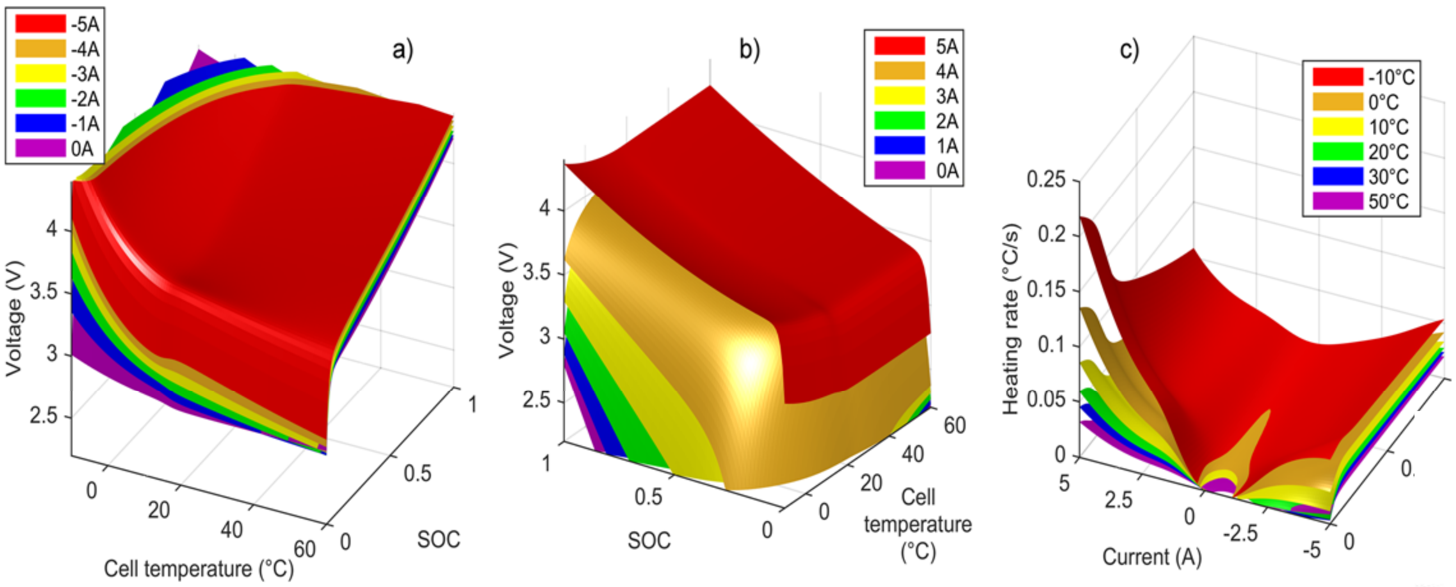
Battery model verification (T)



48 different scenarios
(temperature vs time)
Y=-10 -60 C
X=0-19000 s

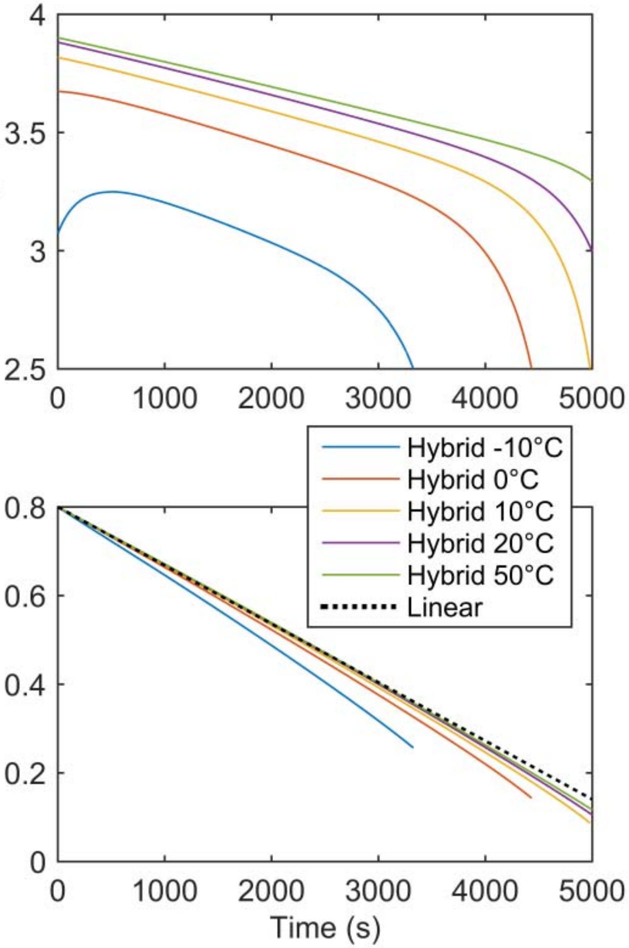
Blue=measured
Black=model

RMSE<3 % of operating temperature range



Voltage response (a,b) from the empirical voltage model with different SOC, cell temperature and current inputs

Heating rate response (c) from the artificial neural network with different SOC, cell temperature and current inputs



Comparison of the hybrid model and a simple linear battery model. Constant power discharge at different ambient temperatures.

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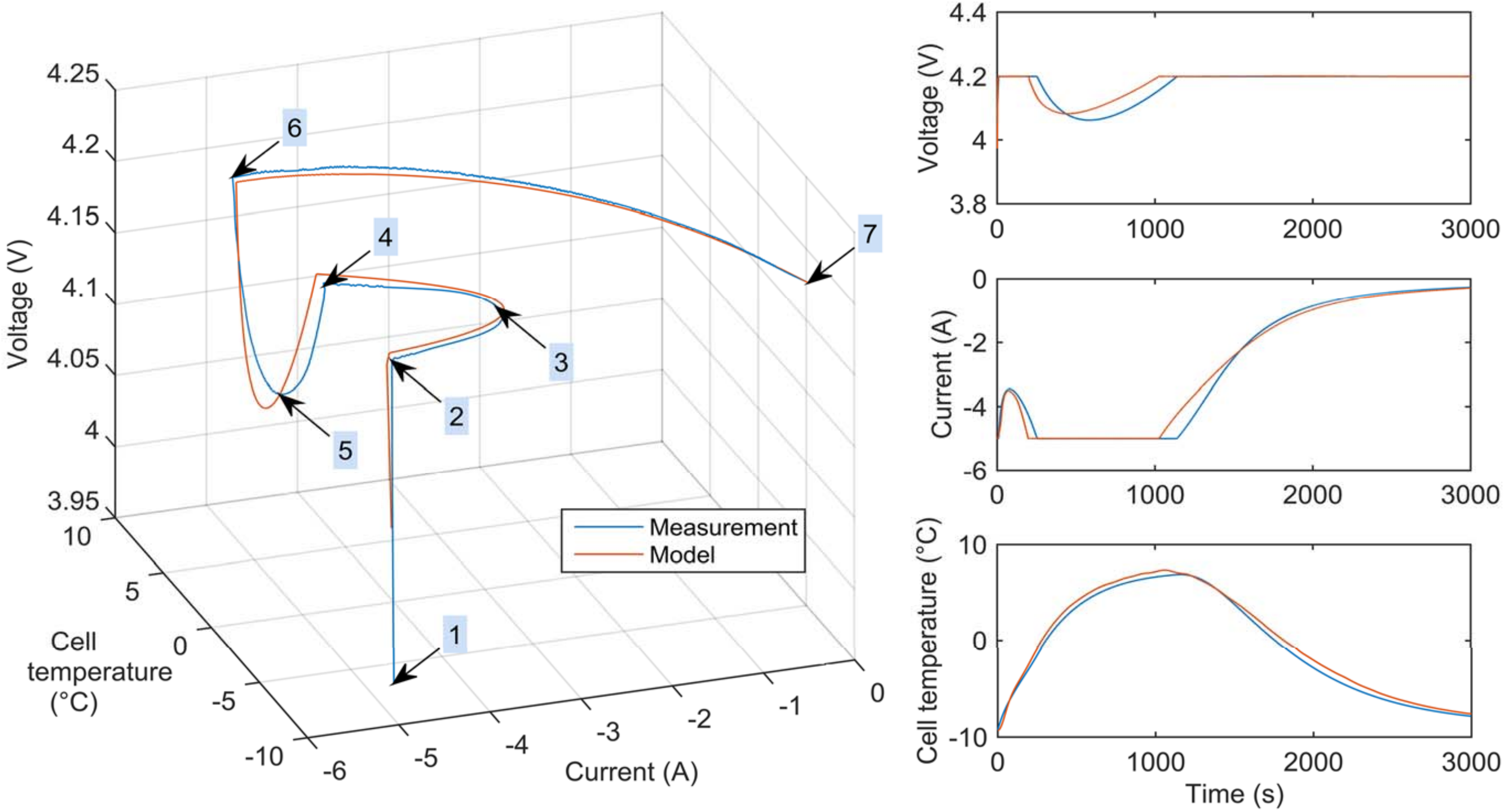
Application to complex charging



Measured and simulated voltage, cell temperature and current when charging the cell at −10°C ambient temperature with the constant current constant voltage method starting at 5 A. 7 key points of the process are highlighted.

Extras

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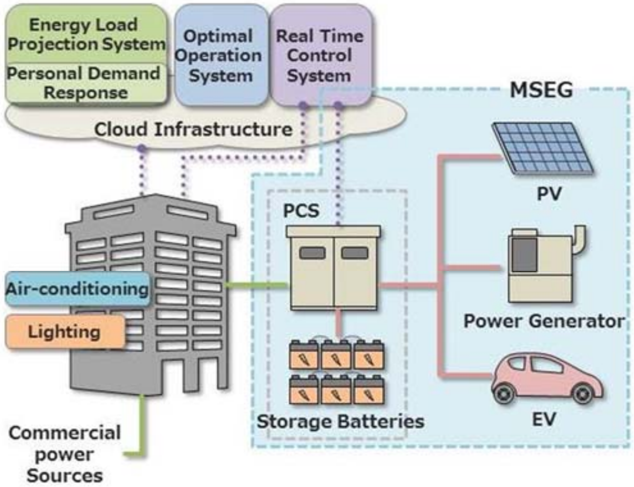
Flexibility approaches for the energy system transformation

Figure 2 Key elements of the flexibility vision



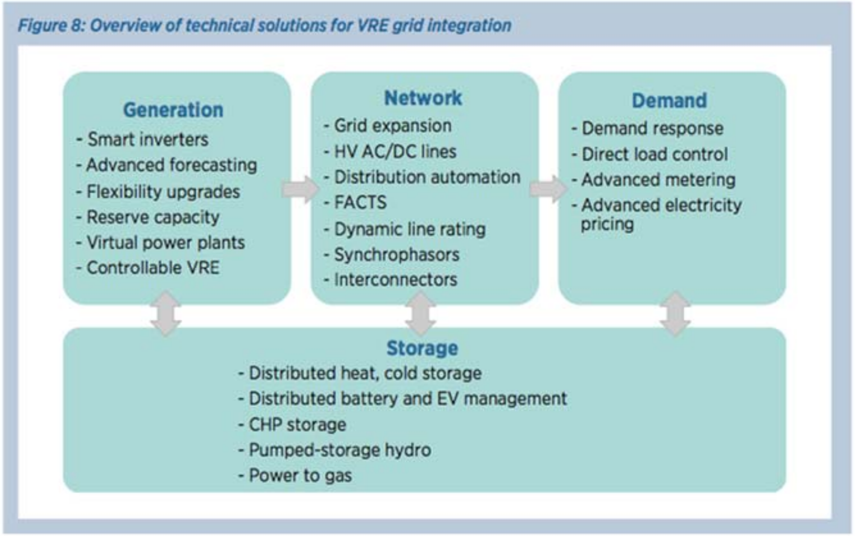


Figure 8: Overview of technical solutions for VRE grid integration

Generation
- Smart inverters
- Advanced forecasting
- Flexibility upgrades
- Reserve capacity
- Virtual power plants
- Controllable VRE

Network
- Grid expansion
- HV AC/DC lines
- Distribution automation
- FACTS
- Dynamic line rating
- Synchrophasors
- Interconnectors

Demand
- Demand response
- Direct load control
- Advanced metering
- Advanced electricity pricing

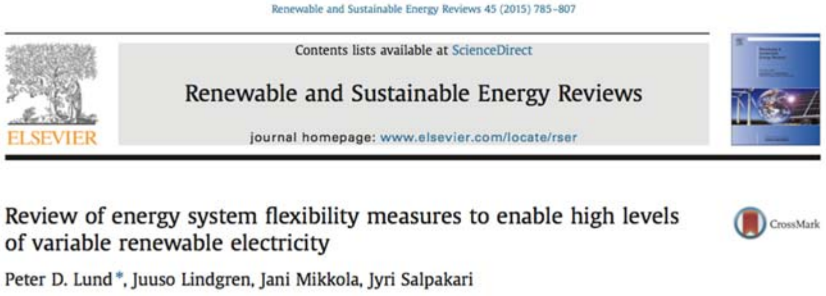
Storage
- Distributed heat, cold storage
- Distributed battery and EV management
- CHP storage
- Pumped-storage hydro
- Power to gas

ECOFYS
sustainable energy for everyone

Power System Flexibility Strategic Roadmap
Preparing power systems to supply reliable power from variable renewable energy sources

IRENA
International Renewable Energy Agency

THE AGE OF RENEWABLE POWER
DESIGNING NATIONAL ROADMAPS FOR A SUCCESSFUL TRANSFORMATION


Renewable and Sustainable Energy Reviews 45 (2015) 785–807

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of energy system flexibility measures to enable high levels of variable renewable electricity

Peter D. Lund *, Juuso Lindgren, Jani Mikkola, Jyri Salpakari

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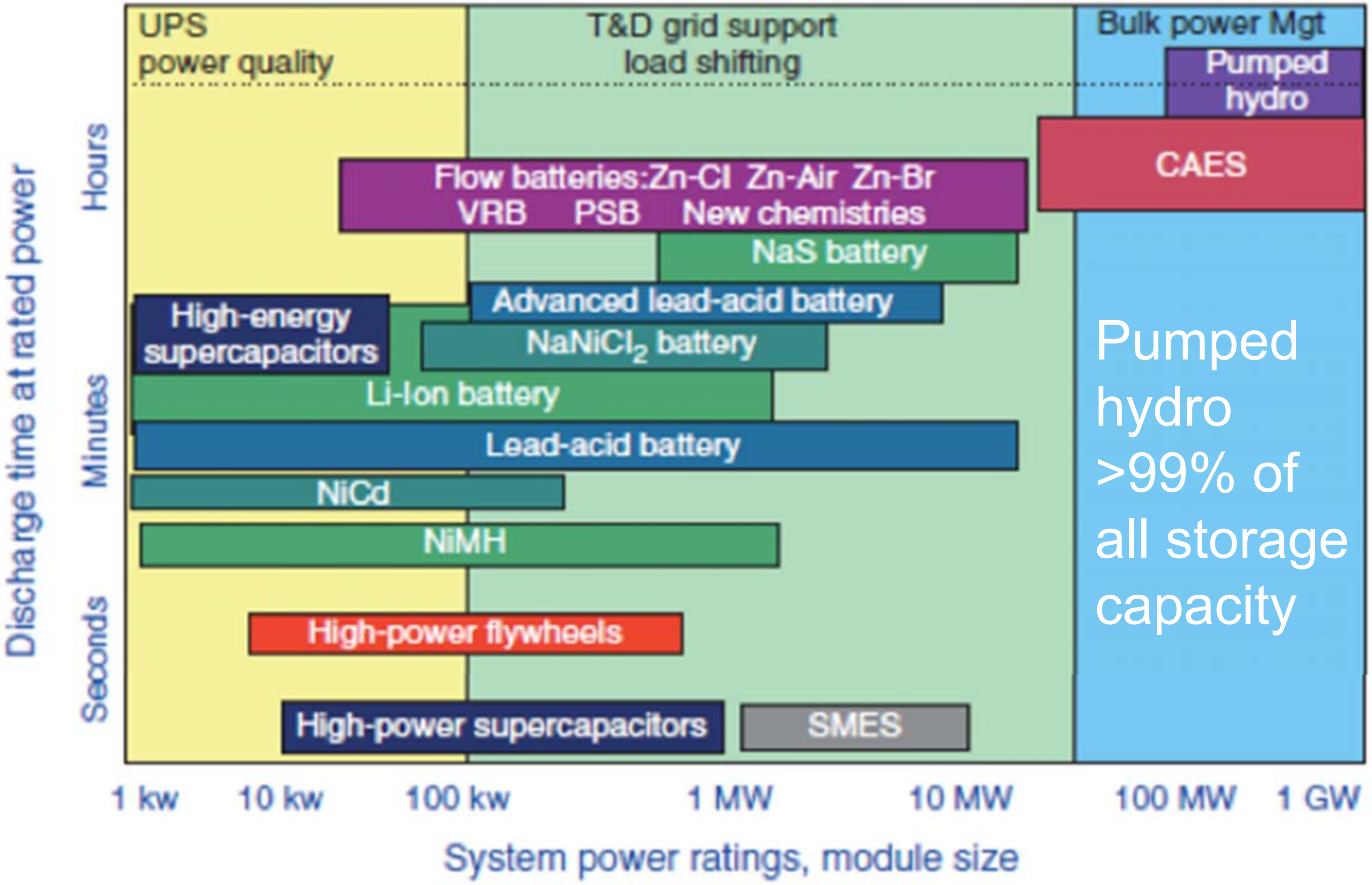
Storage vs energy system requirements



WIREs Energy Environ 2015, 4:115–132. doi: 10.1002/wene.114

Applications:

- Voltage regulation
- Frequency regulation
- Load following
- Black start
- T&D deferral
- Arbitrage
- Grid support
- Self-consumption
- Off-grid
- Interseasonal storage

nature climate change
LETTERS
PUBLISHED ONLINE: 23 MARCH 2015 | DOI: 10.1038/NCLIMATE2564

2015

Rapidly falling costs of battery packs for electric vehicles

Björn Nykvist[1]* and Måns Nilsson[1,2]

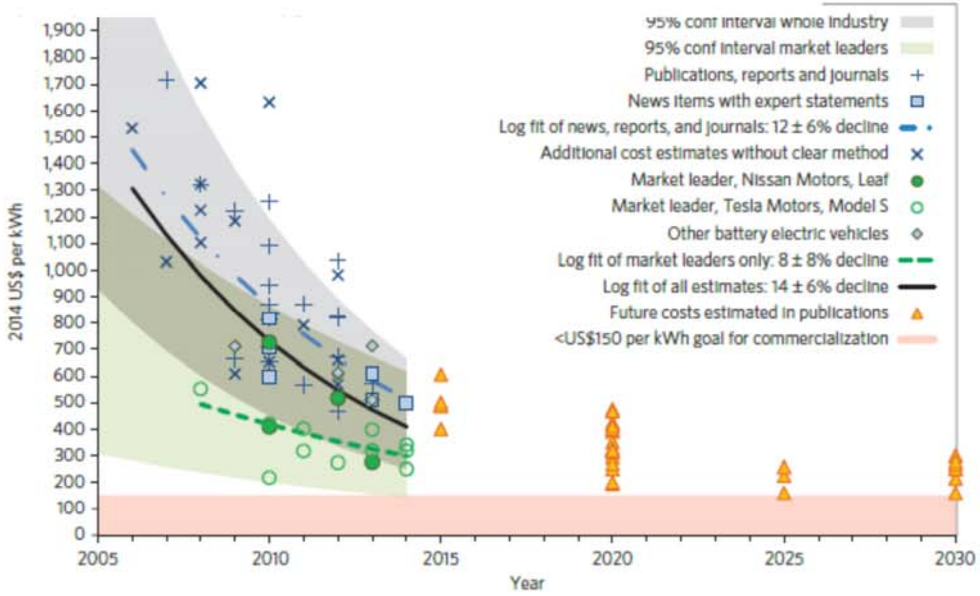
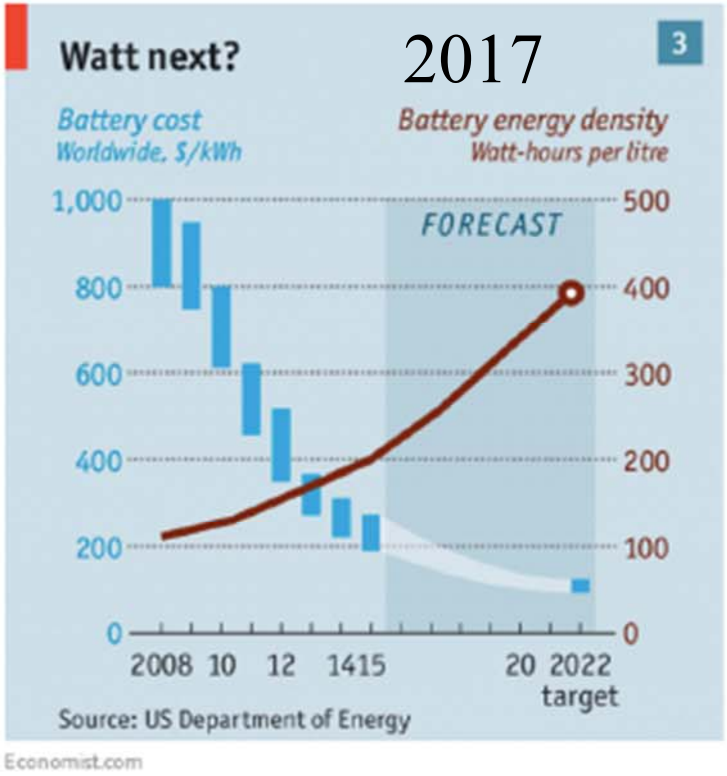
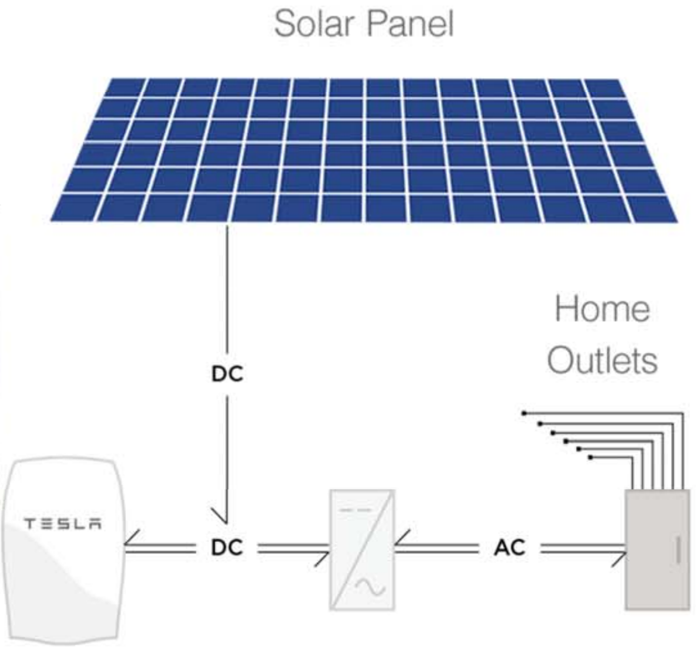


Figure 1 | Cost of Li-ion battery packs in BEV. Data are from multiple types of sources and trace both reported cost for the industry and costs for market-leading manufactures. If costs reach US$150 per kWh this is commonly considered as the point of commercialization of BEV.

2017



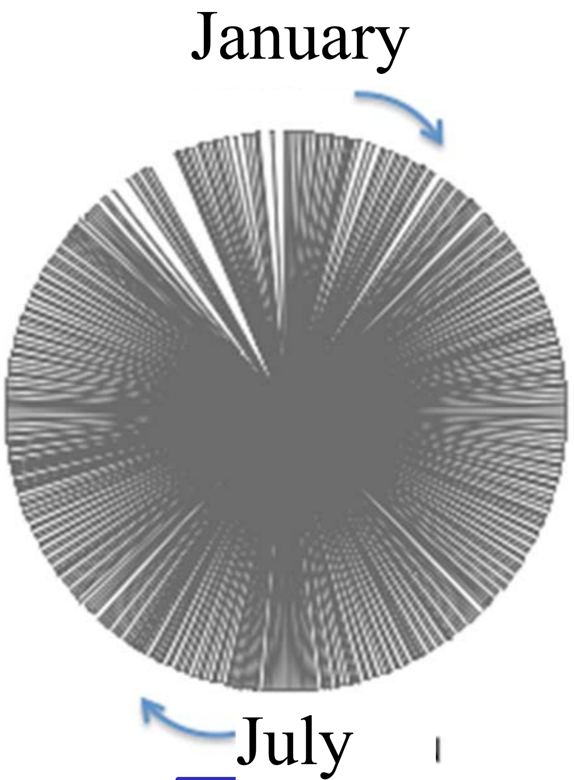


PV & Tesla battery

Hours when PV NOT meeting supply (black)

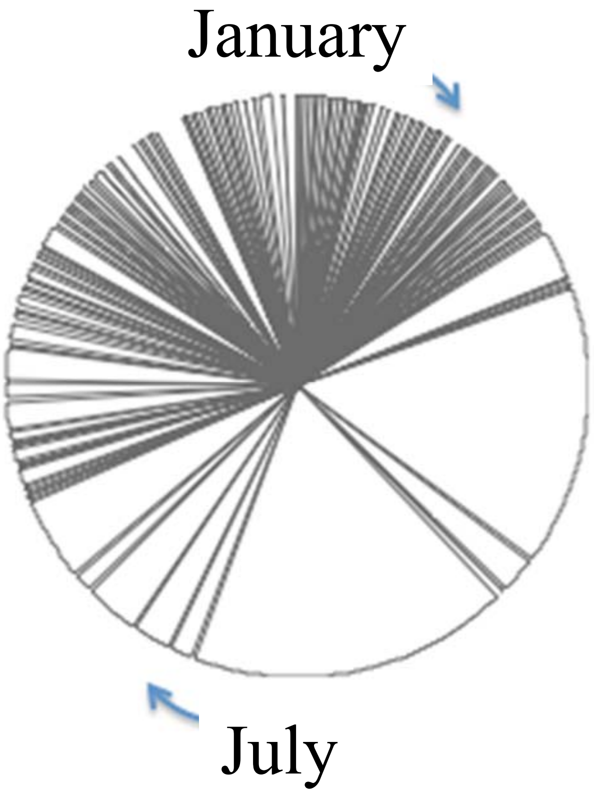
Case Finland: 3 kWp PV for a household (100%)

PV no battery



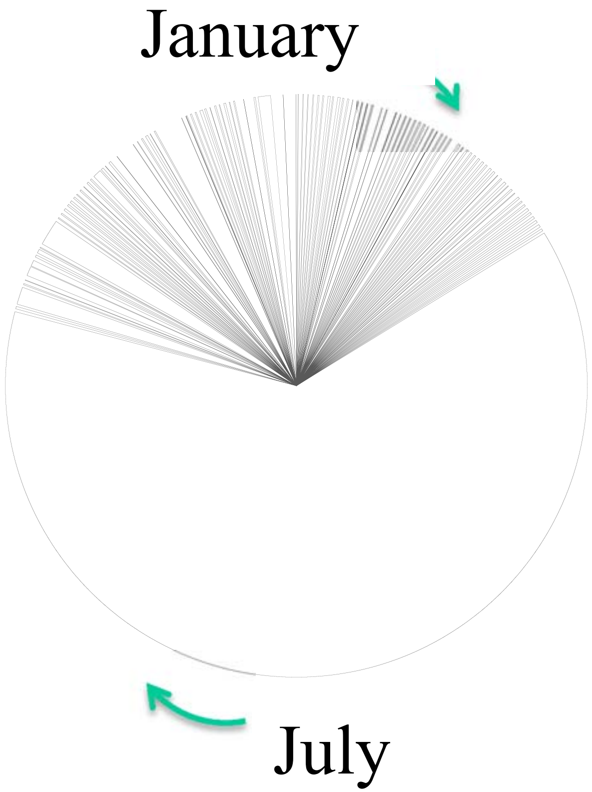
32%

PV + 1 Tesla batt.



74%

PV + 2 Tesla batt



76%

Direct use of PV

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