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Copernicus Institute of Sustainable Development

Solar Energy for Experiment Design

Wilfried van Sark

1 October 2020, Utrecht

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Contents

- Intro
- Climate and energy
- City/citizen solutions/challenges
  - Examples, EV charging, solar forecasting
- Near zero energy building

Copernicus Institute

- The scientific institute for sustainability research and teaching at Utrecht University
- Mission: to contribute to the transition to a sustainable society through scientific excellence in a multi-disciplinary environment
- Four multi-disciplinary research groups:
  - Energy and Resources
  - Environmental Governance
  - Environmental Sciences
  - Innovation Studies

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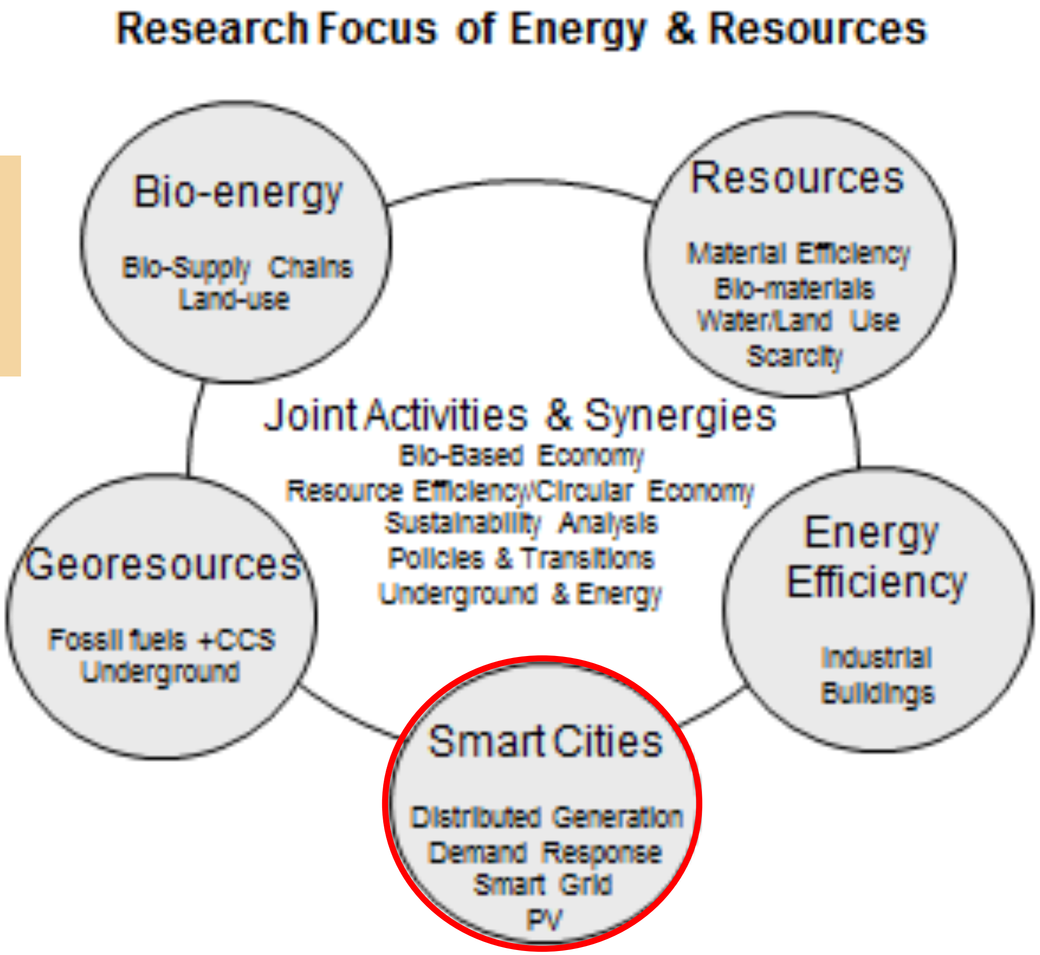
Energy & Resources:

Education:
MSc Energy Science
MSc Sustainable Development

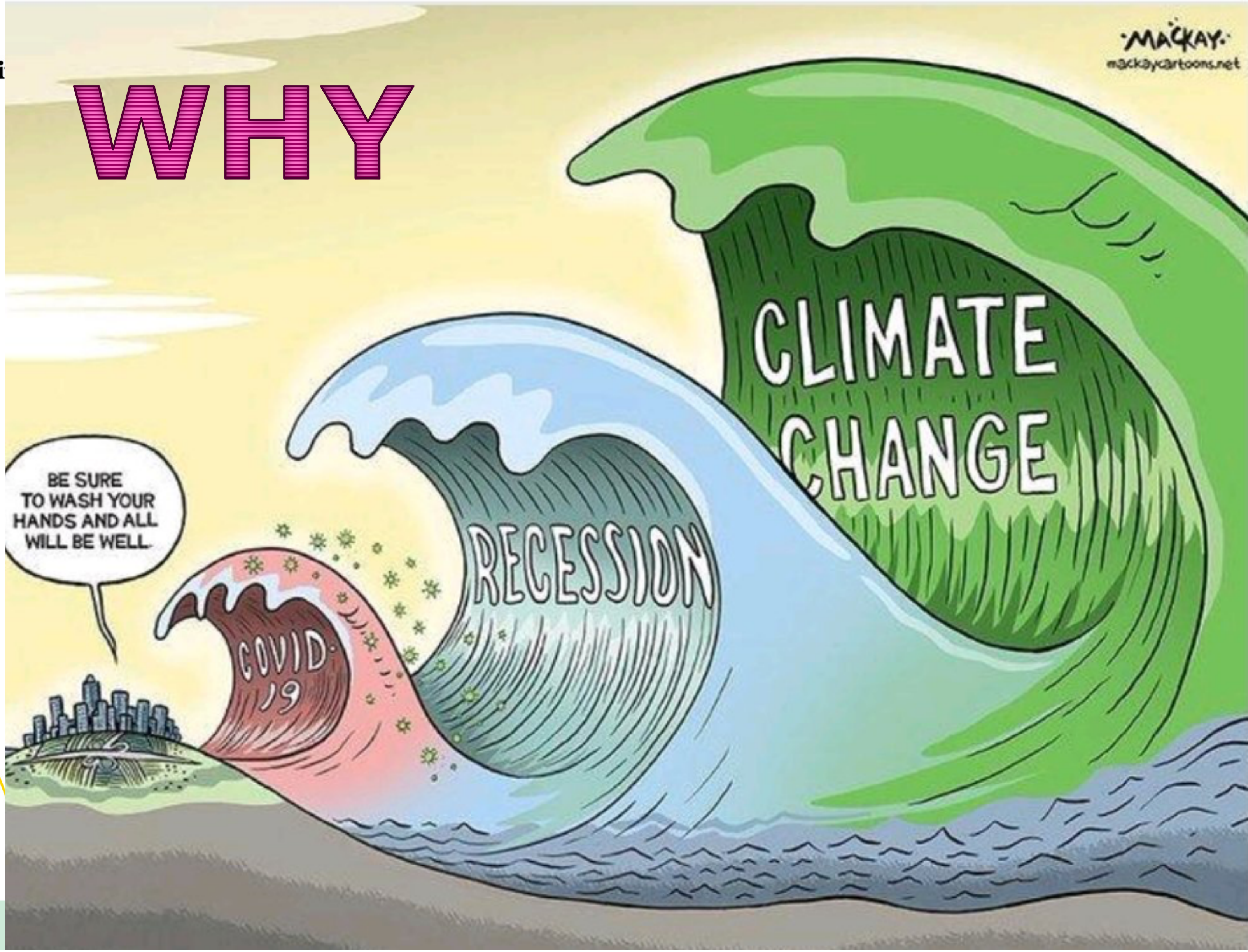
PV/RE integration group addresses topics in relation to Smart Cities focus

2 professors
2 assistant professors
4 postdocs
12 junior/PhD

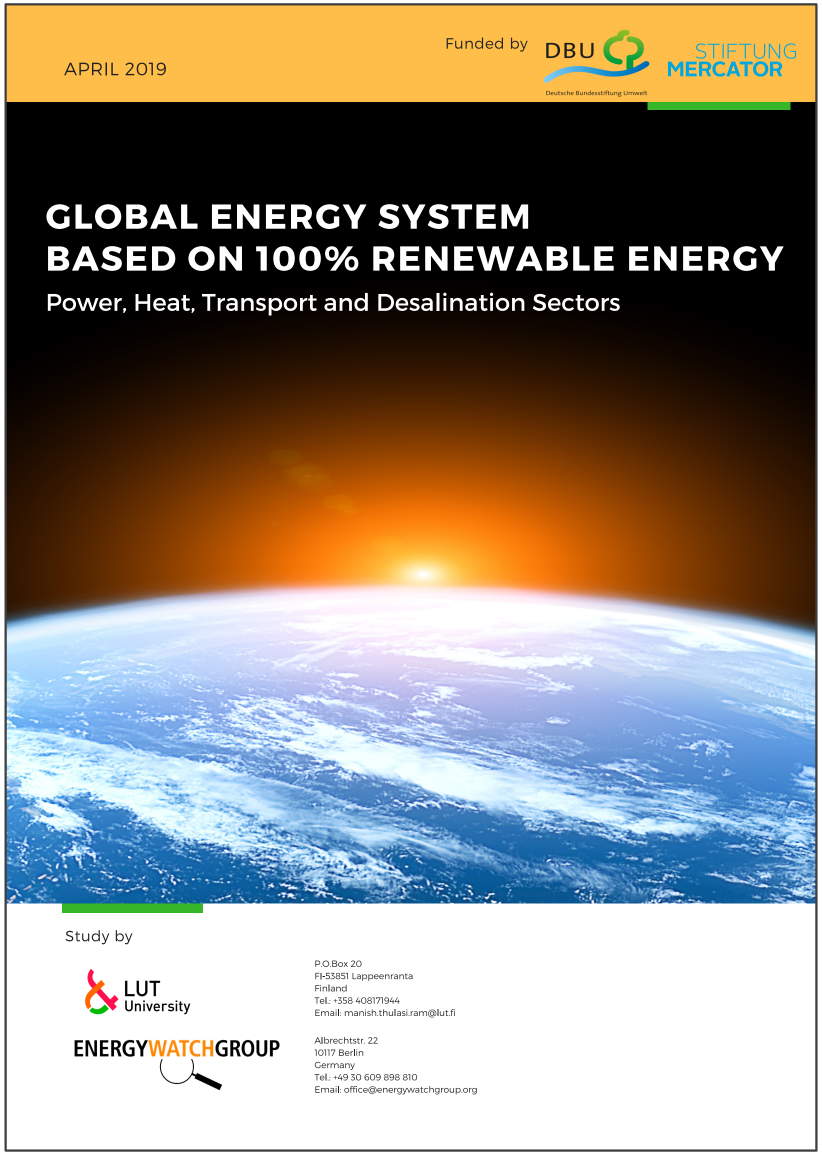


Uni

WHY


MACKAY
mackaycartoons.net
CLIMATE CHANGE
RECESSION
COVID-19
BE SURE TO WASH YOUR HANDS AND ALL WILL BE WELL.

Economist, 19 Sept 2020



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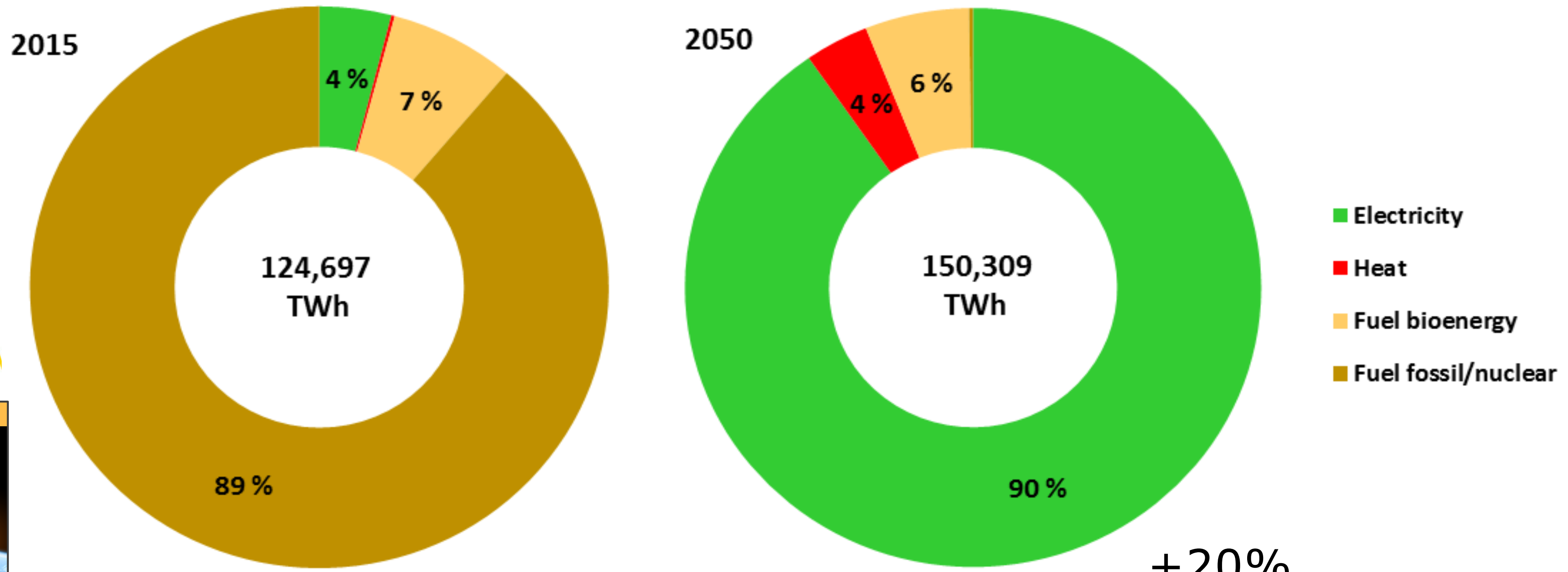
Energy demand development



+20%

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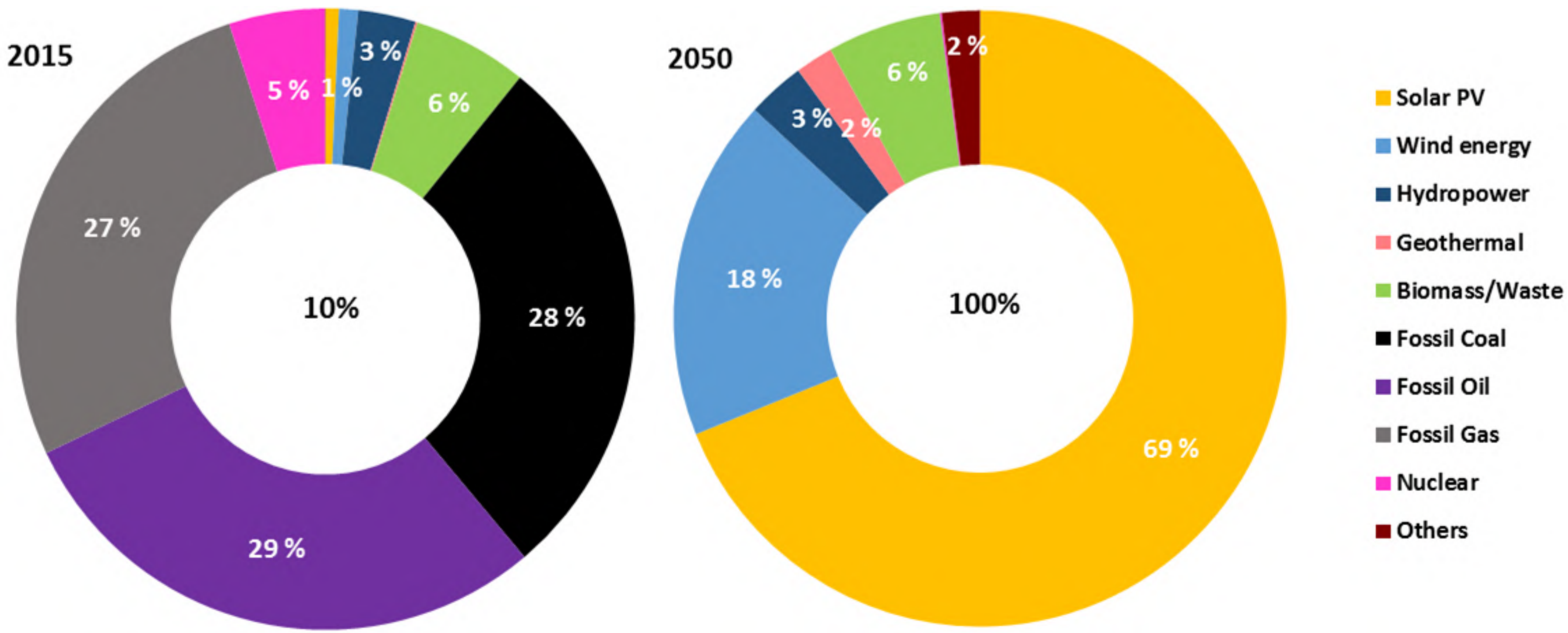
Energy supply



Renewables: 10% → 100%

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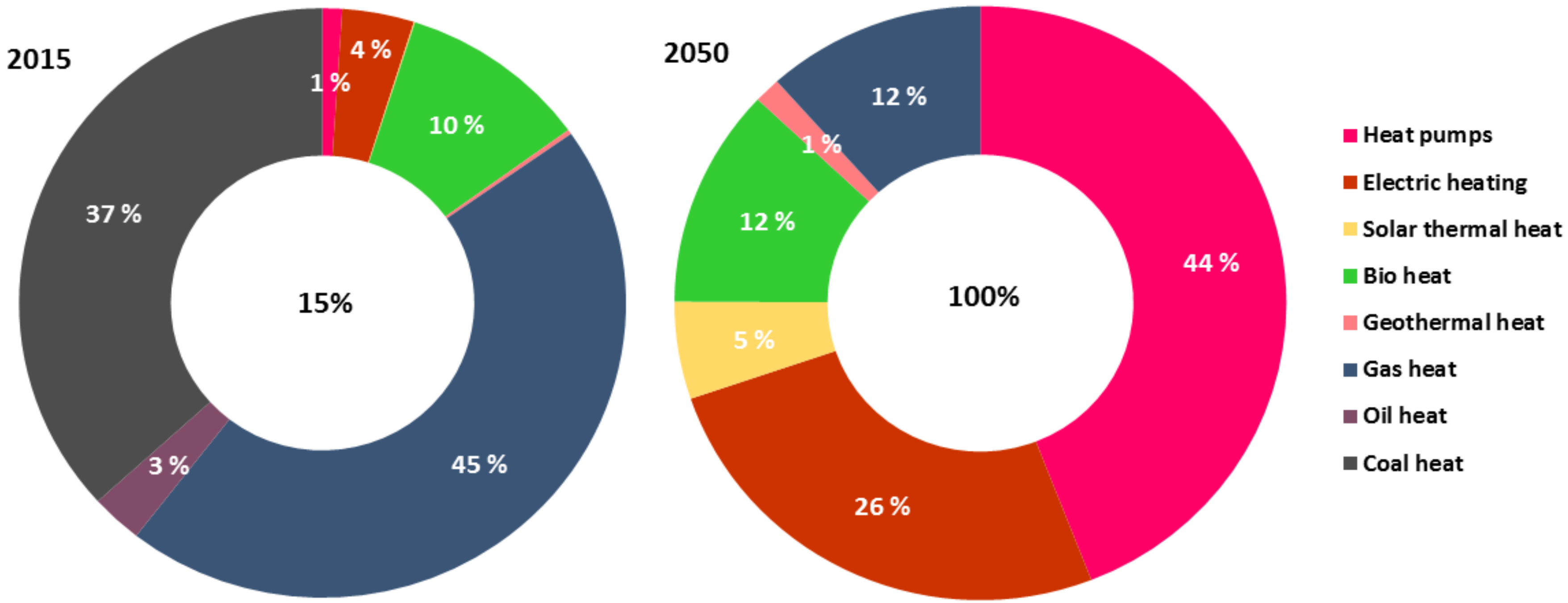
Heat supply



Electrification

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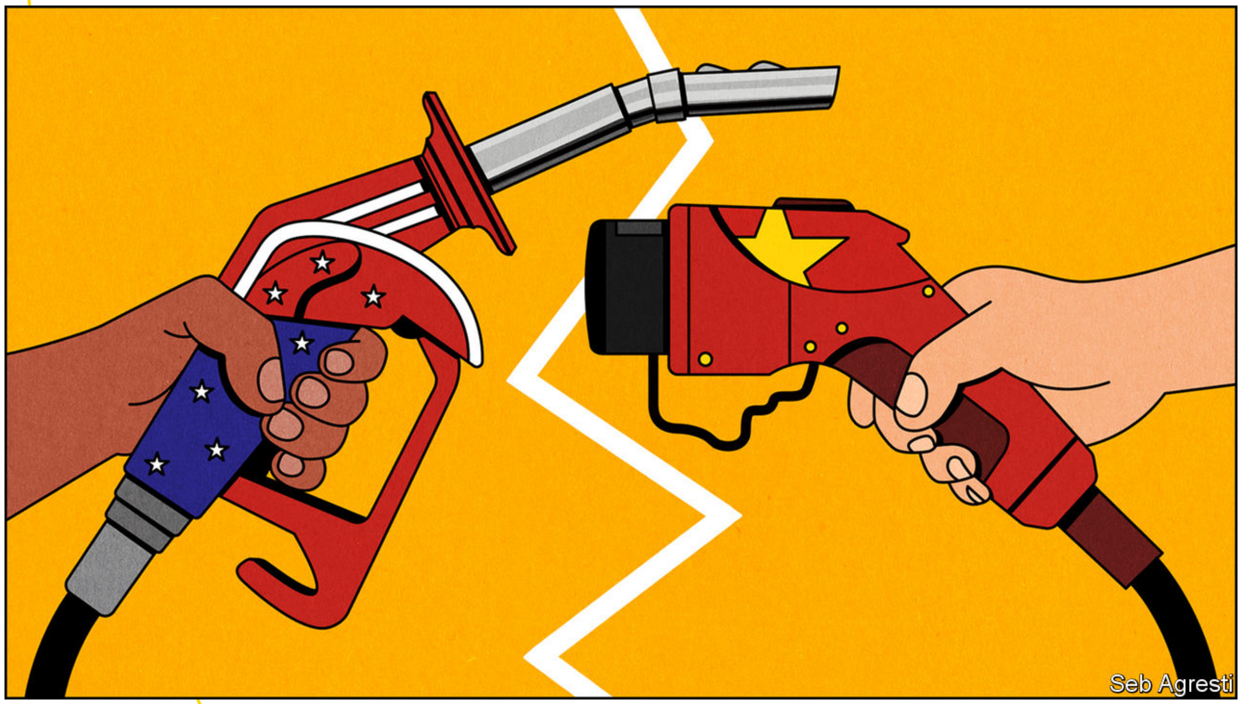
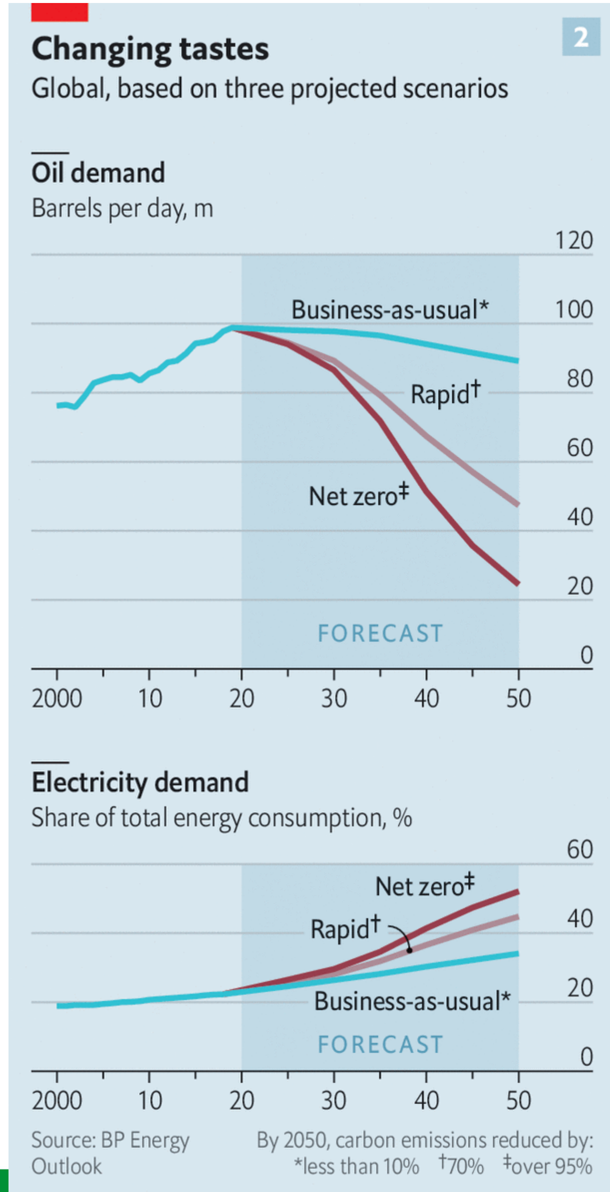
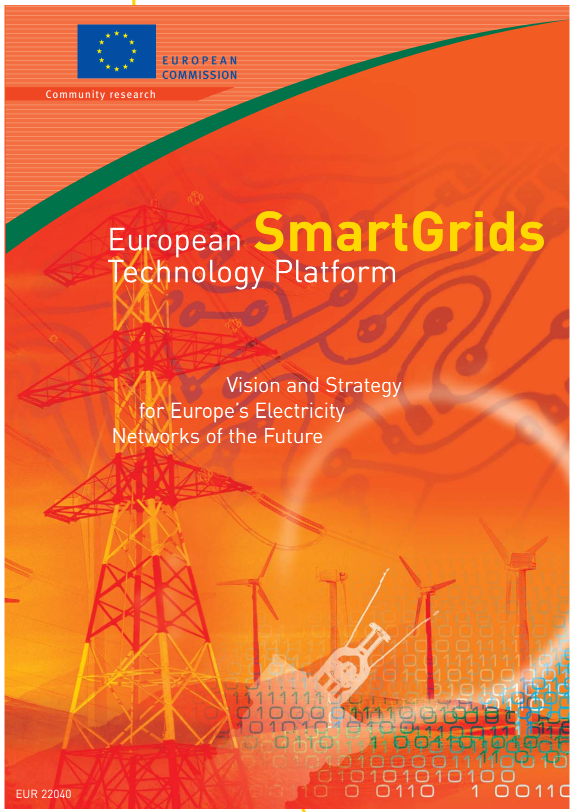
Petrostate vs Electrostate

Economist, 19 Sept 2020

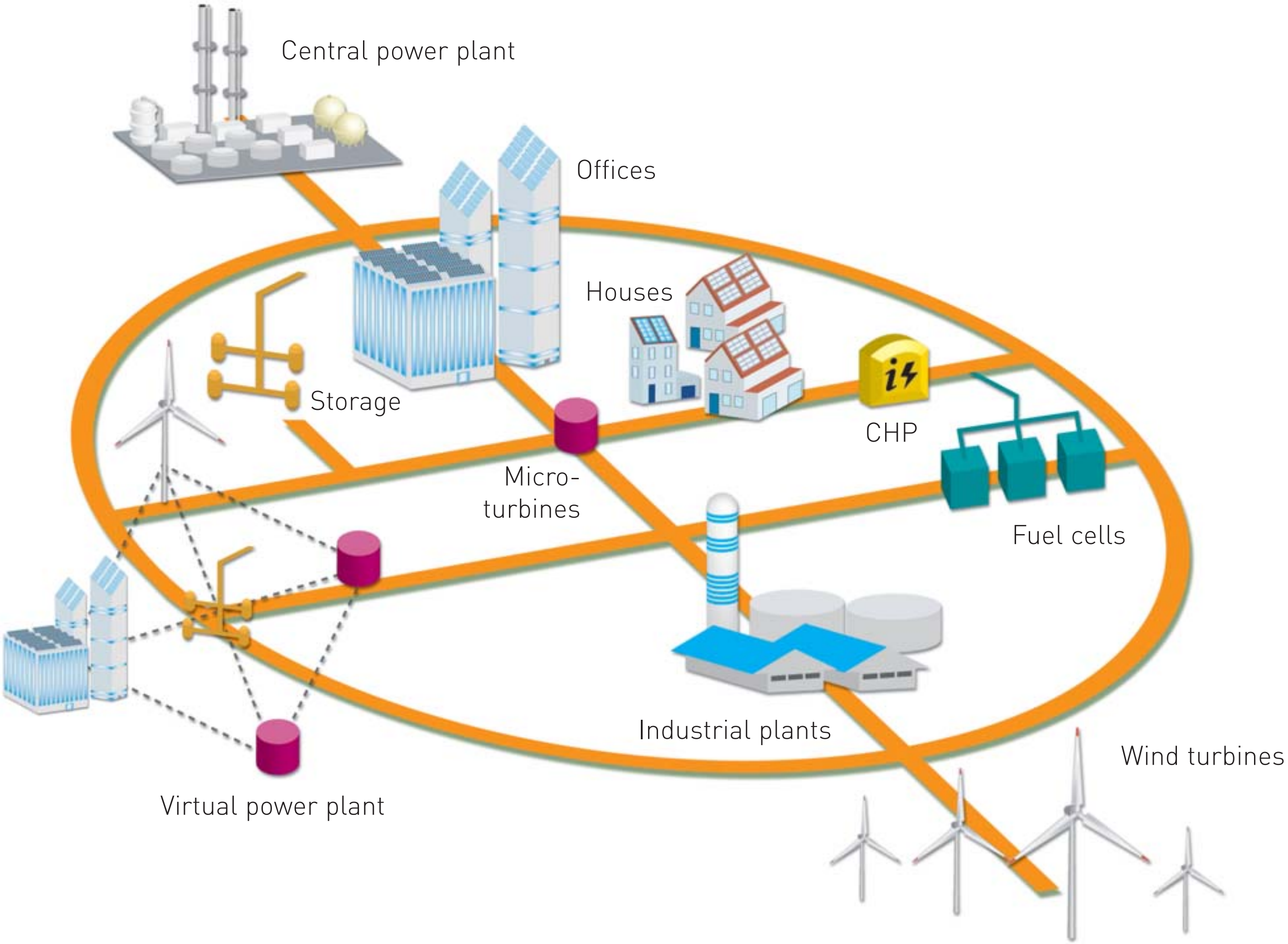




The Economist

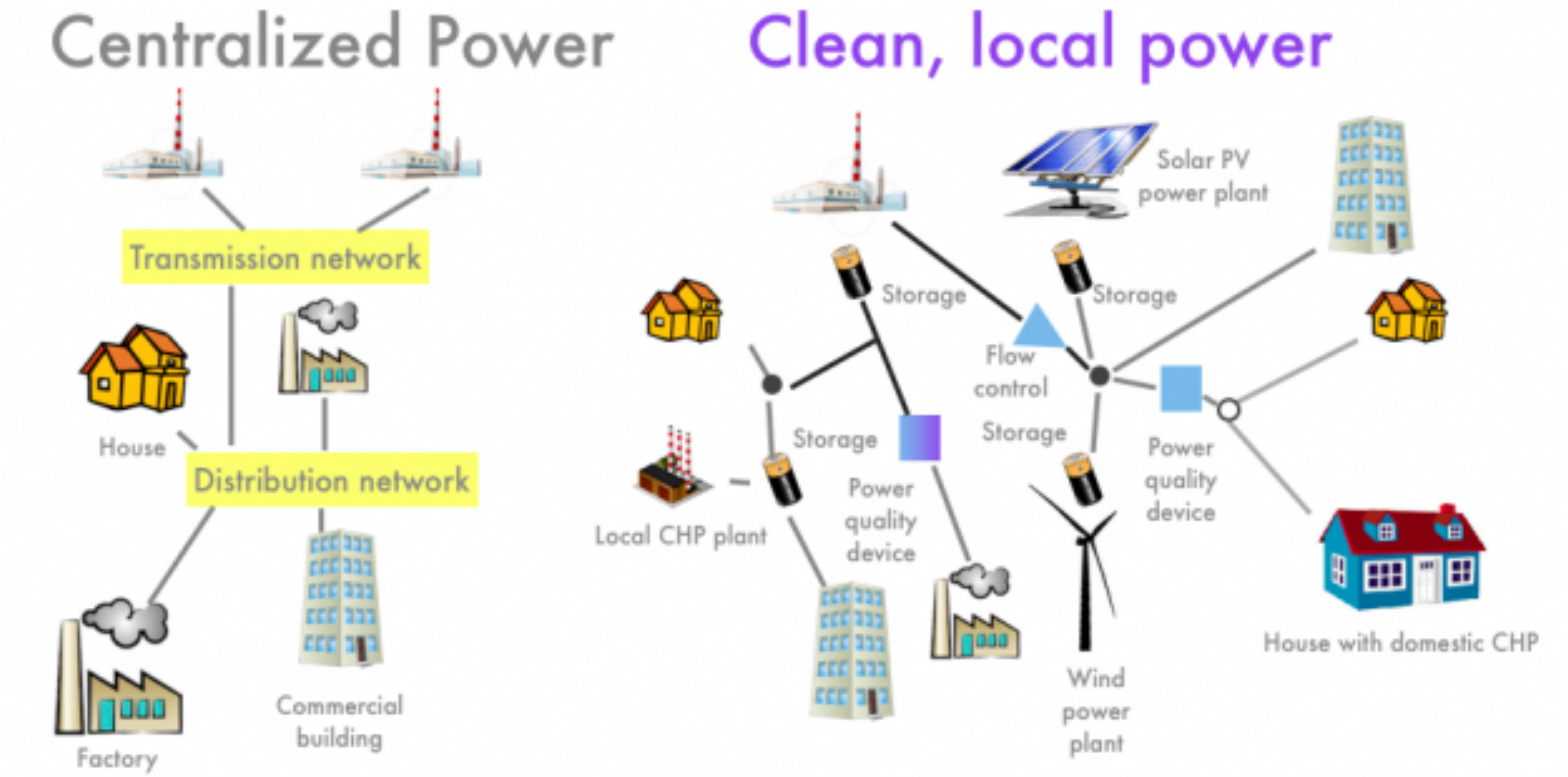

EUROPEAN COMMISSION
Community research
European SmartGrids
Technology Platform
Vision and Strategy
for Europe's Electricity
Networks of the Future
EUR 22040

EC, 2006


Central power plant
Offices
Houses
Storage
CHP
Micro-
turbines
Fuel cells
Industrial plants
Wind turbines
Virtual power plant

Yesterday

Tomorrow



https://ilsr.org/challenge-reconciling-centralized-v-decentralized-electricity-system/

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The new legislation of the EU Energy Union
European Green Deal – Main outlines

- "World's first climate neutral continent"
  European Climate Law
- More ambitious GHG emissions reductions:
  "at least 50% and toward 55% by 2030"
- New industrial strategy & Circular economy
- Von der Leyen: "to encourage renewable self-consumption"

"The European Green Deal is our new growth strategy. It will help us cut emissions while creating jobs."

Ursula von der Leyen, President of the European Commission

"We propose a green and inclusive transition to help improve people's well-being and secure a healthy planet for generations to come."

Frans Timmermans, Executive Vice-President of the European Commission

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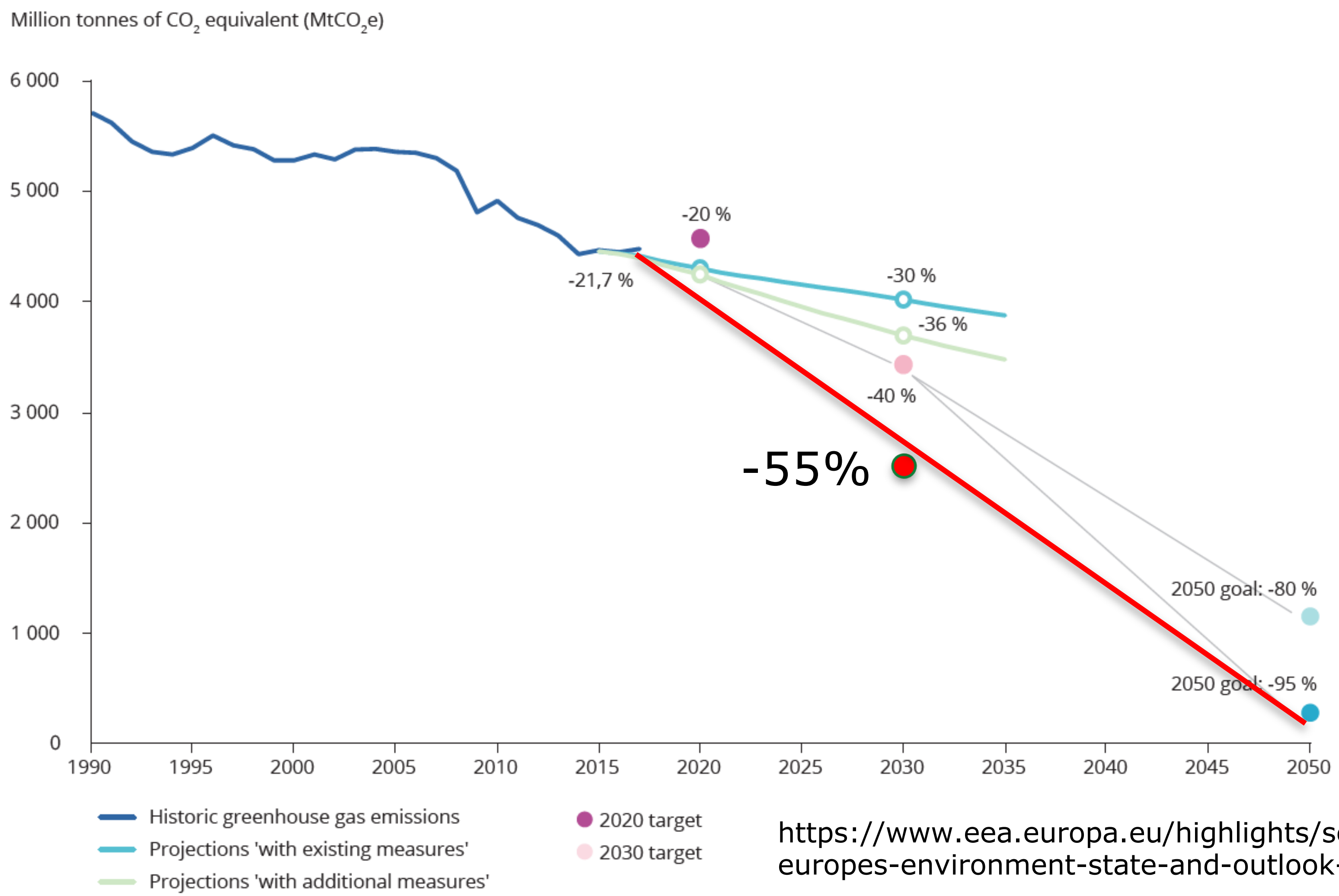
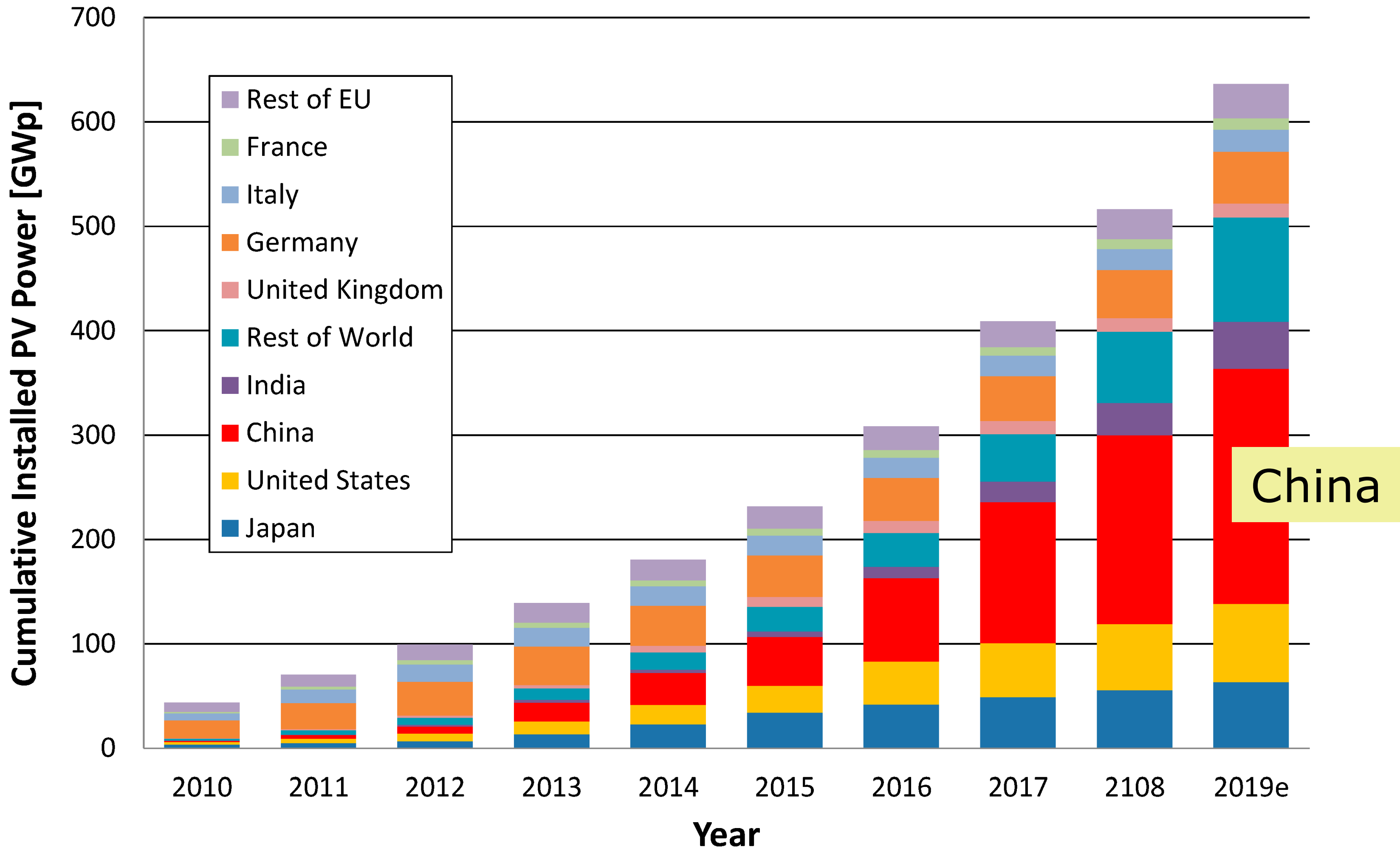


https://www.eea.europa.eu/highlights/soer2020-europes-environment-state-and-outlook-report

Total Global PV installed capacity



Jäger-Waldau, Energies 12 (2019) 769

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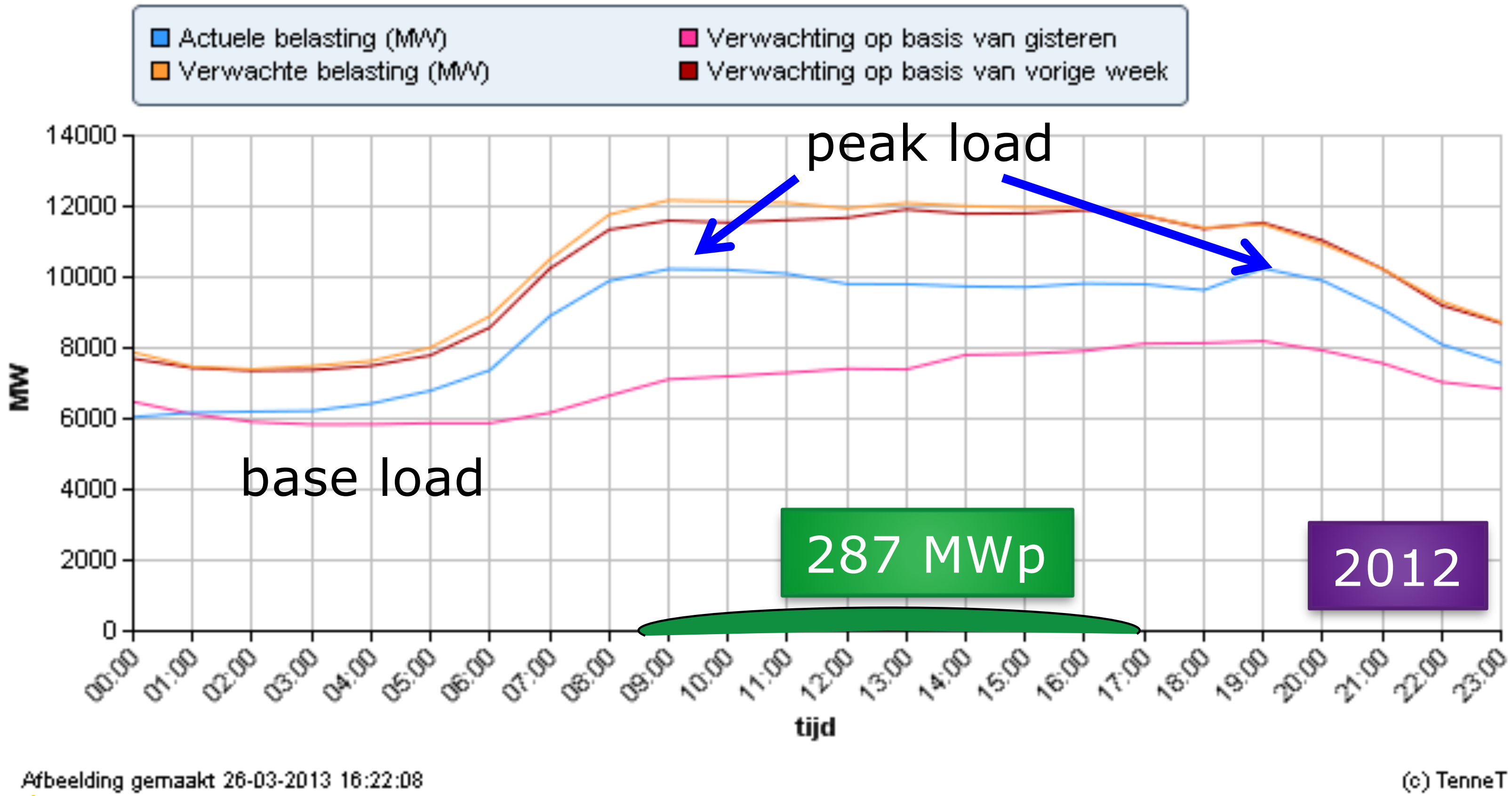
Electricity demand (NL)



(25/3/2013)

21 GW fossil capacity

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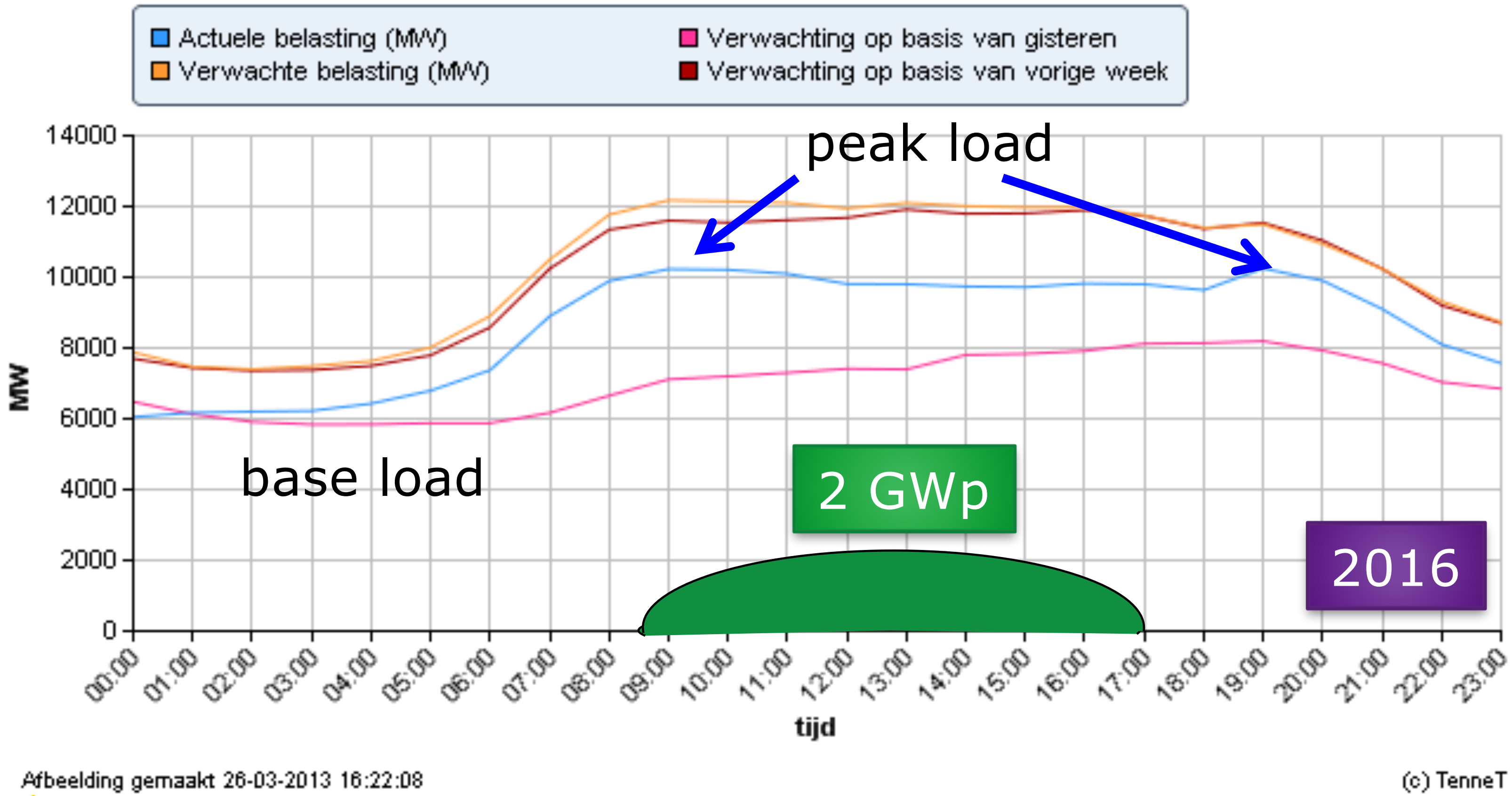
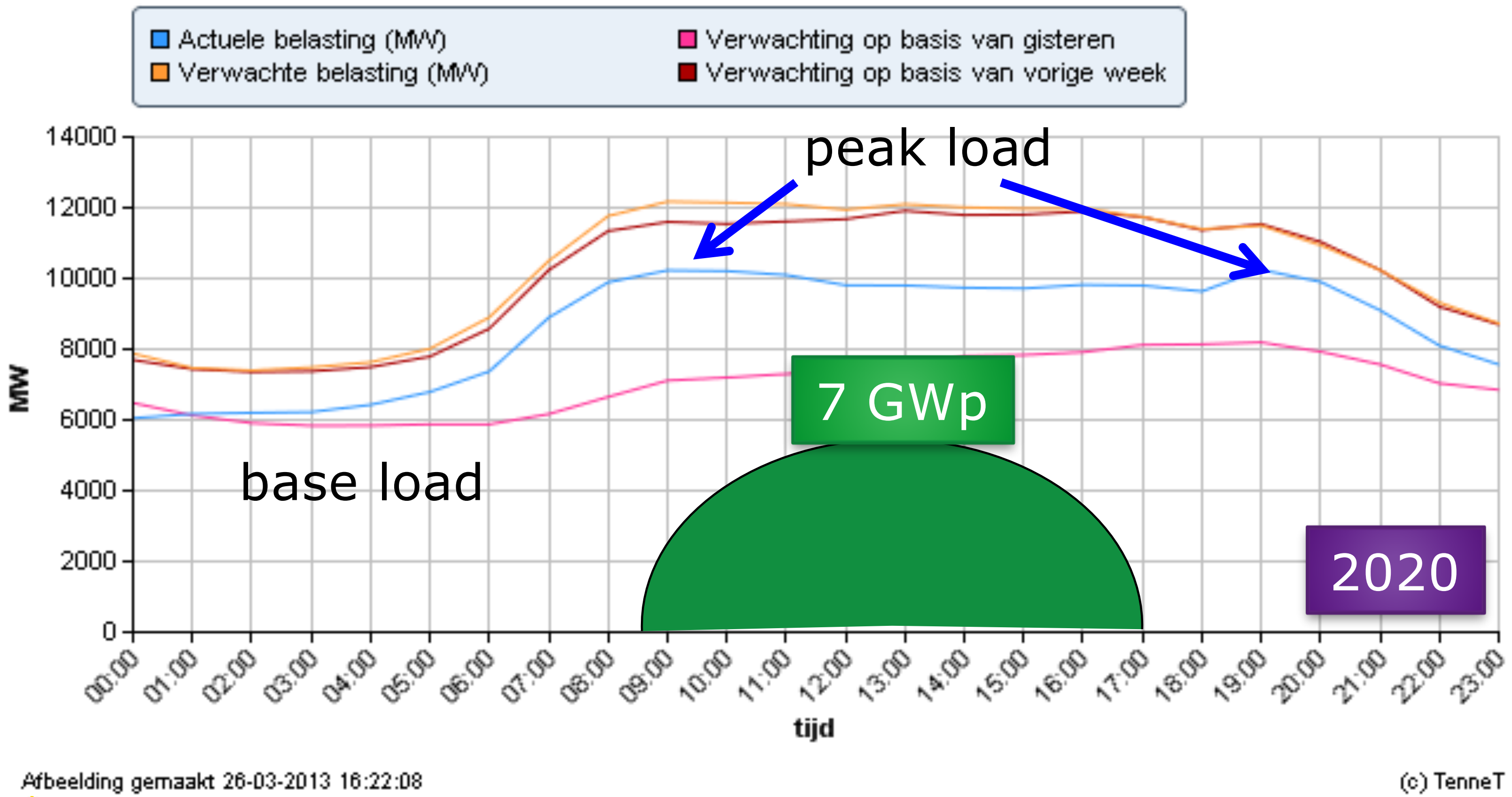
Electricity demand (NL)



(25/3/2013)

21 GW fossil capacity

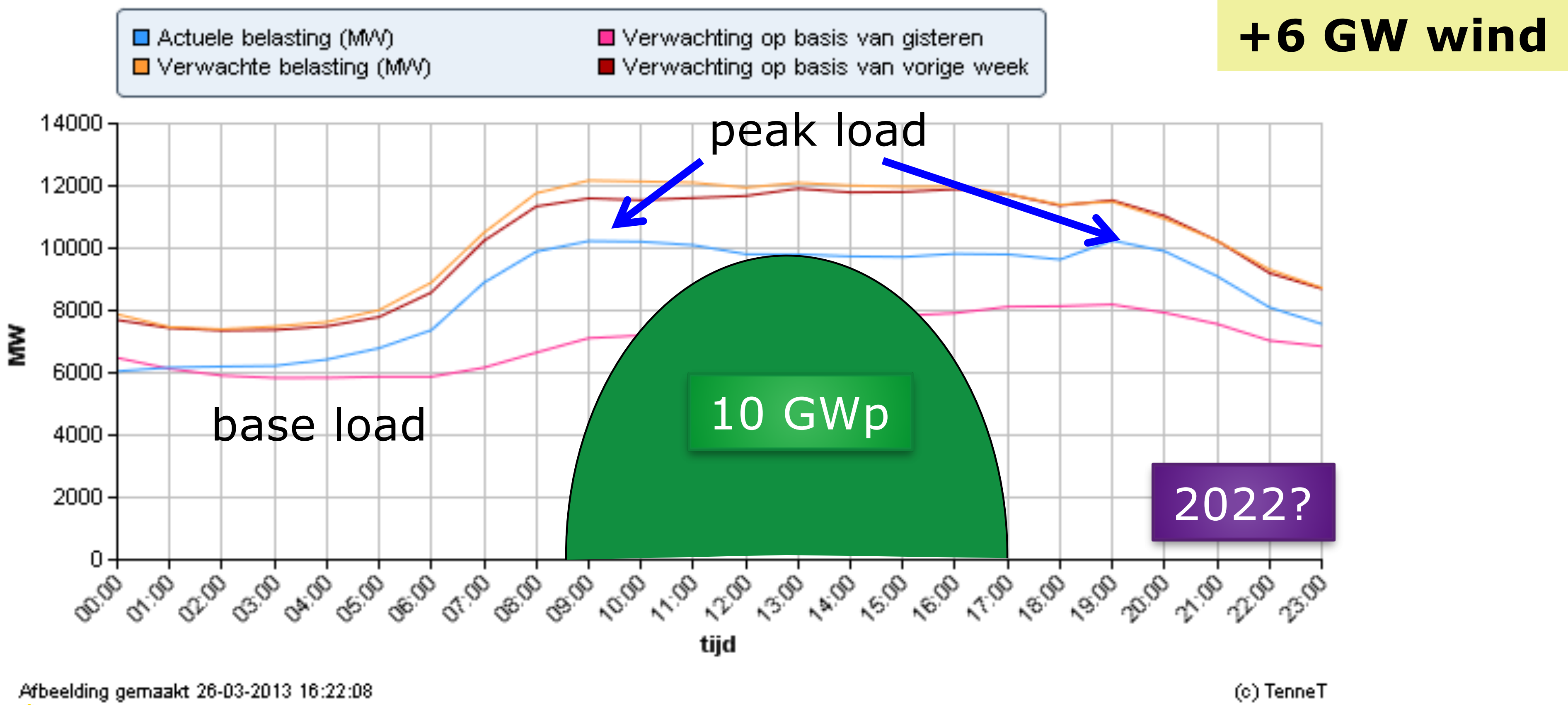
Electricity demand (NL)



(25/3/2013)

21 GW fossil capacity

Electricity demand (NL)



(25/3/2013)

21 GW fossil capacity

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Future developments (NL)

- More photovoltaic solar energy installations due to decreasing prices: >10 GWp (50 GWp in 2030?)
- More electric mobility
  - no more gasoline cars by 2030
- More heat pumps
  - no more gas-based heating (natural gas phase-out)

→ electricity grid stress

- bidirectional power in grids (LV, MV, HV)
- highly variable, intermittent (solar, wind)

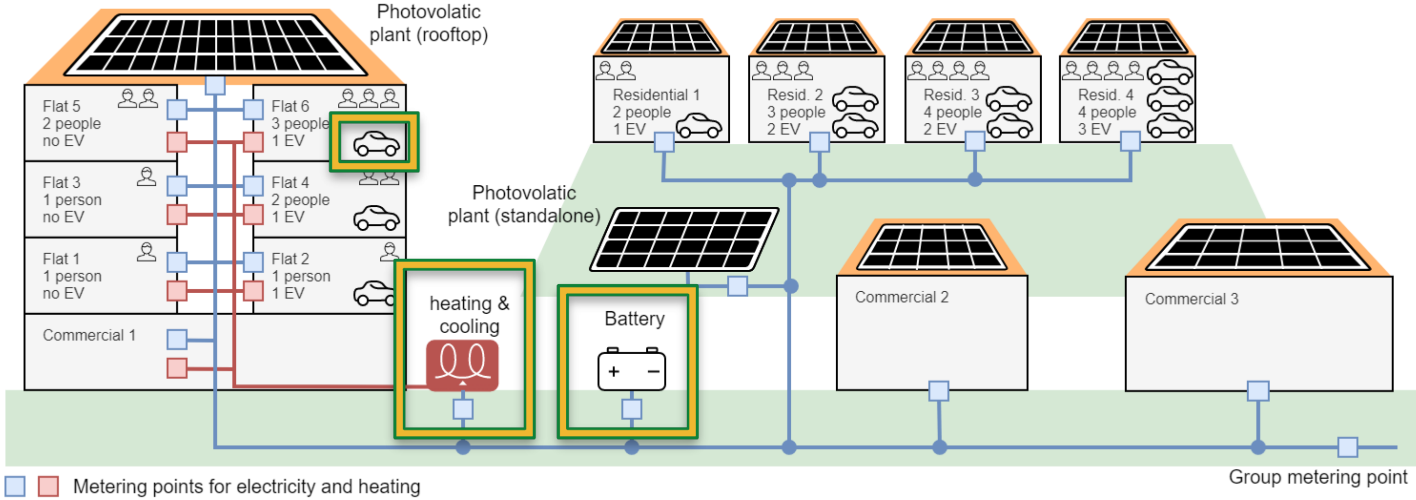
Solution: energy management

"Smart Grid"

- Forecasting is key!
  - Electricity demand (heat pumps, EVs)
    - Heat demand → **weather, temperature**
    - Car demand → weather, rain
    - Household appliances: demand side management, however poor on household level, ~10%
  - Electricity supply (solar PV) → **WEATHER**
  - Pro/Consumer is important stakeholder

European renewable energy community

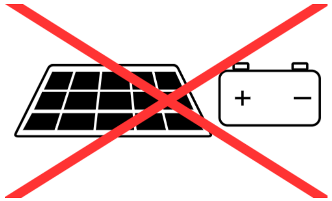
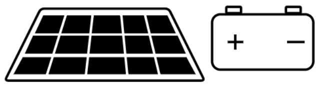
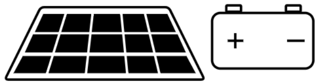
- "European Village" represents average housing situation in Europe



- Electricity cost minimization model (TU Wien)

Community Scenarios

- ***Grid consumption*:**
  - No investments in PV and storages
  - Demand is satisfied via the grid
- ***No community*:**
  - Investments in PV and storages are possible
  - Energy sharing not allowed
- ***Community*:**
  - Investments in PV and storages are possible
  - Energy sharing allowed

Technologies	***Metering point***
	separately
	separately
	aggregated

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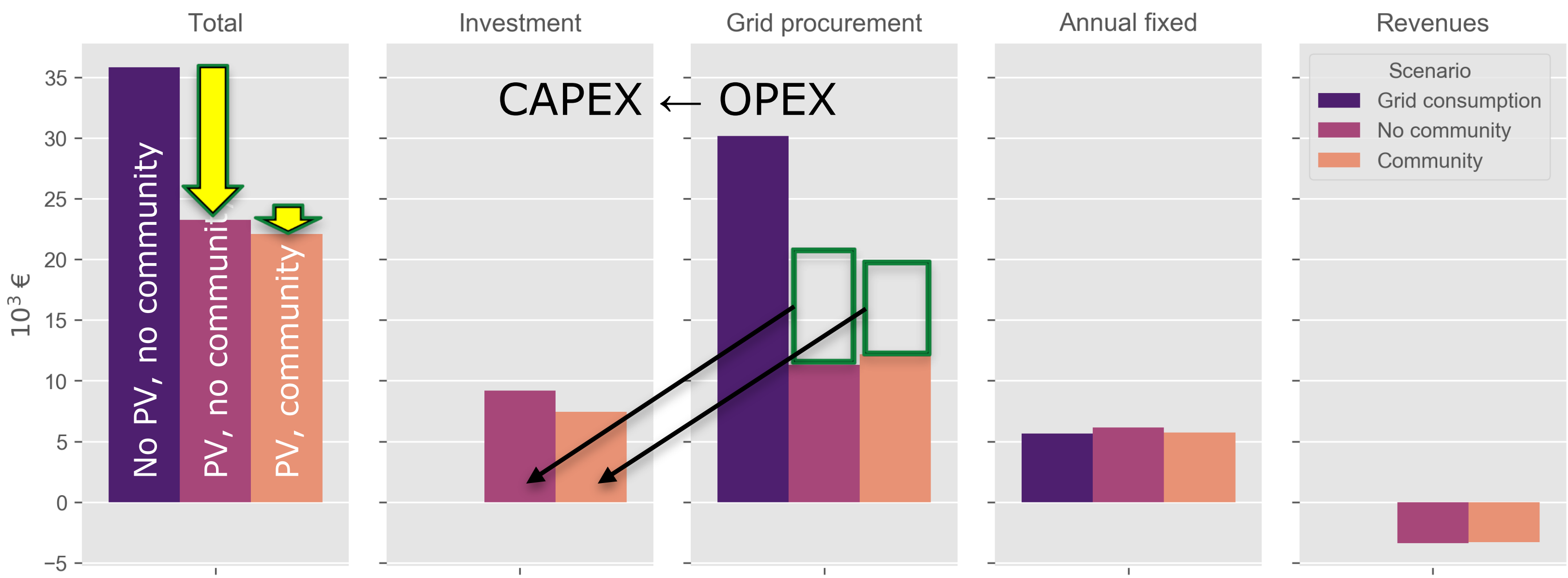
Results for “European Village“ Electricity costs with investments

$$Total\ Costs(Year) = \alpha * Investment + Grid + Fixed - Revenues$$



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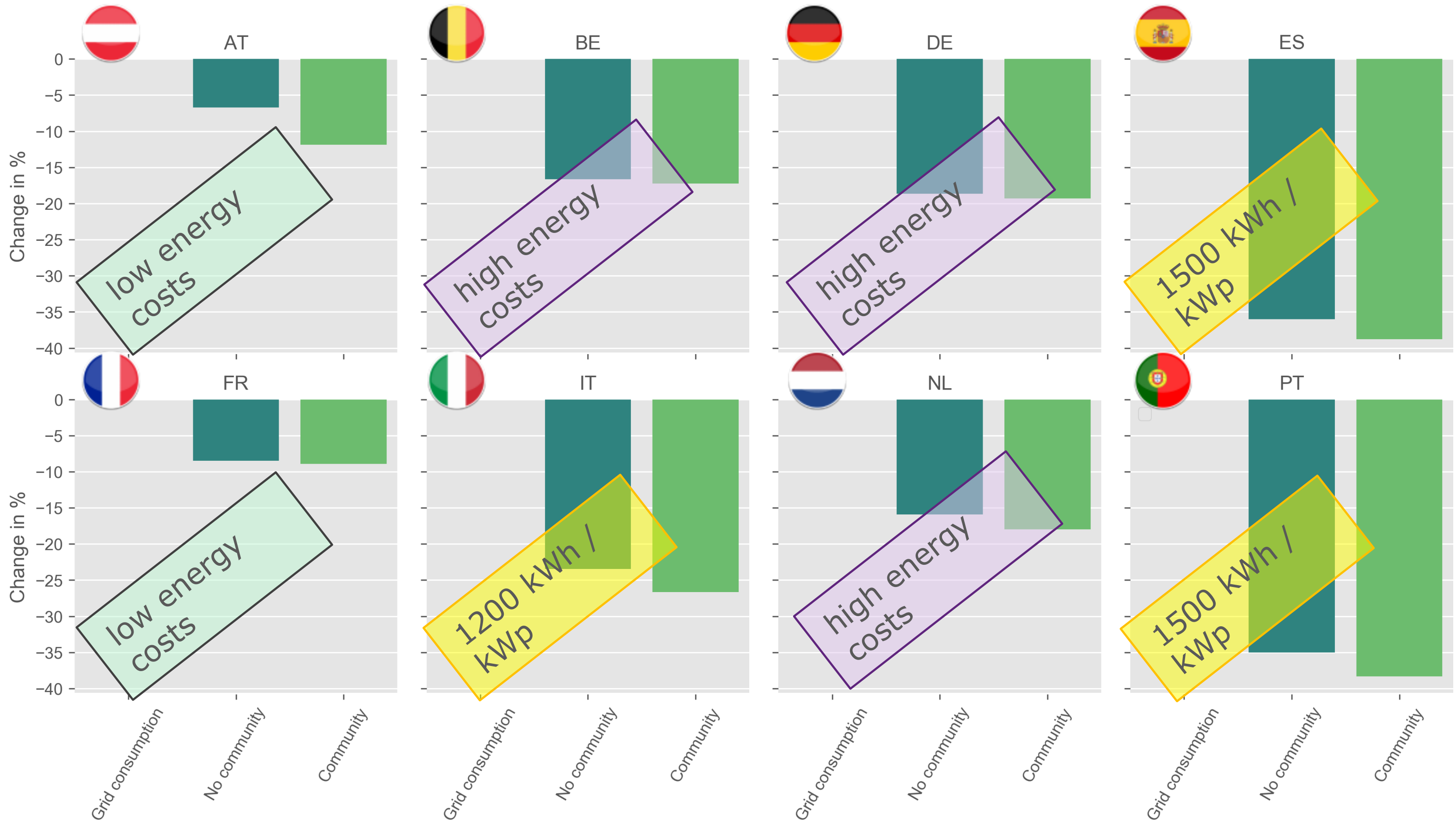
Change in Total Costs (compared to Grid Consumption)



Greenhouse Gas Emissions of Renewable Energy Communities

Greenhouse Gas Emissions are released (indirectly) due to:

1. Manufacturing of PV systems, Batteries, Electric vehicles, Heat pumps → LCA study (EcoInvent database)
2. Electricity use from the grid and electricity feed-in PV electricity to grid ("negative" emissions!)
   - Electricity-related emissions calculated with timeseries of Hourly Emissions Factors and Electricity Consumption

Since the emission factor of grid electricity fluctuates every hour, timing of electricity use (or grid feed-in) is important

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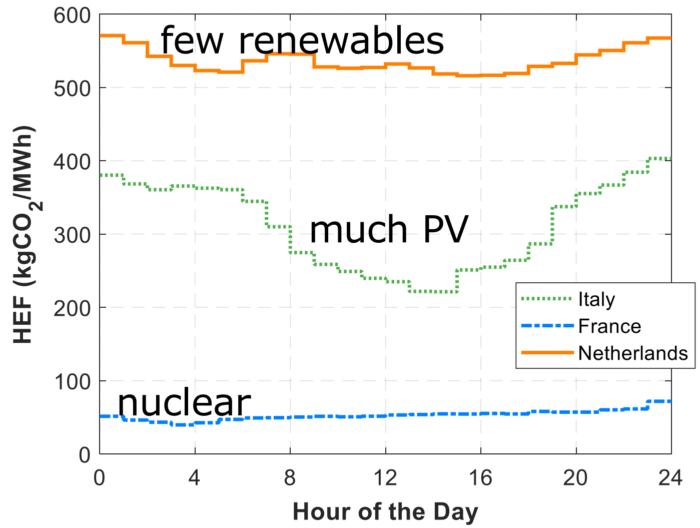
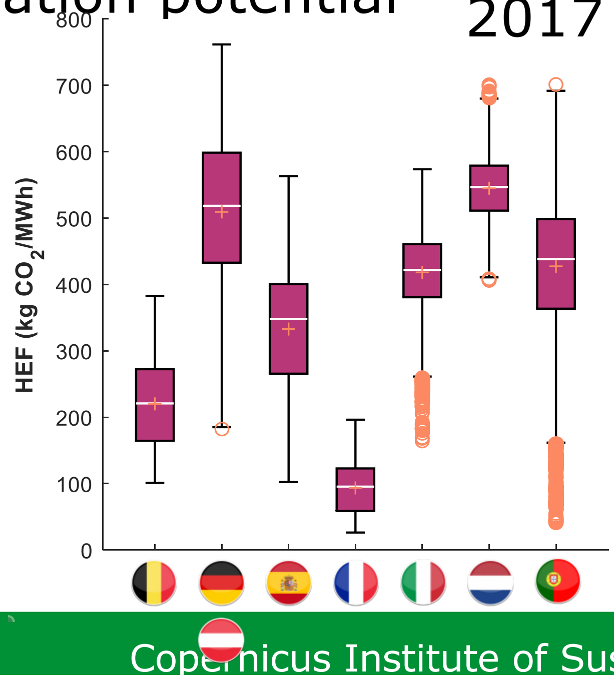
Hourly Emission Factor (HEF, in [kg CO_2 / MWh])

- If you feed-in PV electricity in hour *x*, you mitigate emissions in that hour *x*
- Shows where in Europe energy transition technologies can have highest CO_2 mitigation potential



2017 data



[Schram, 2019]

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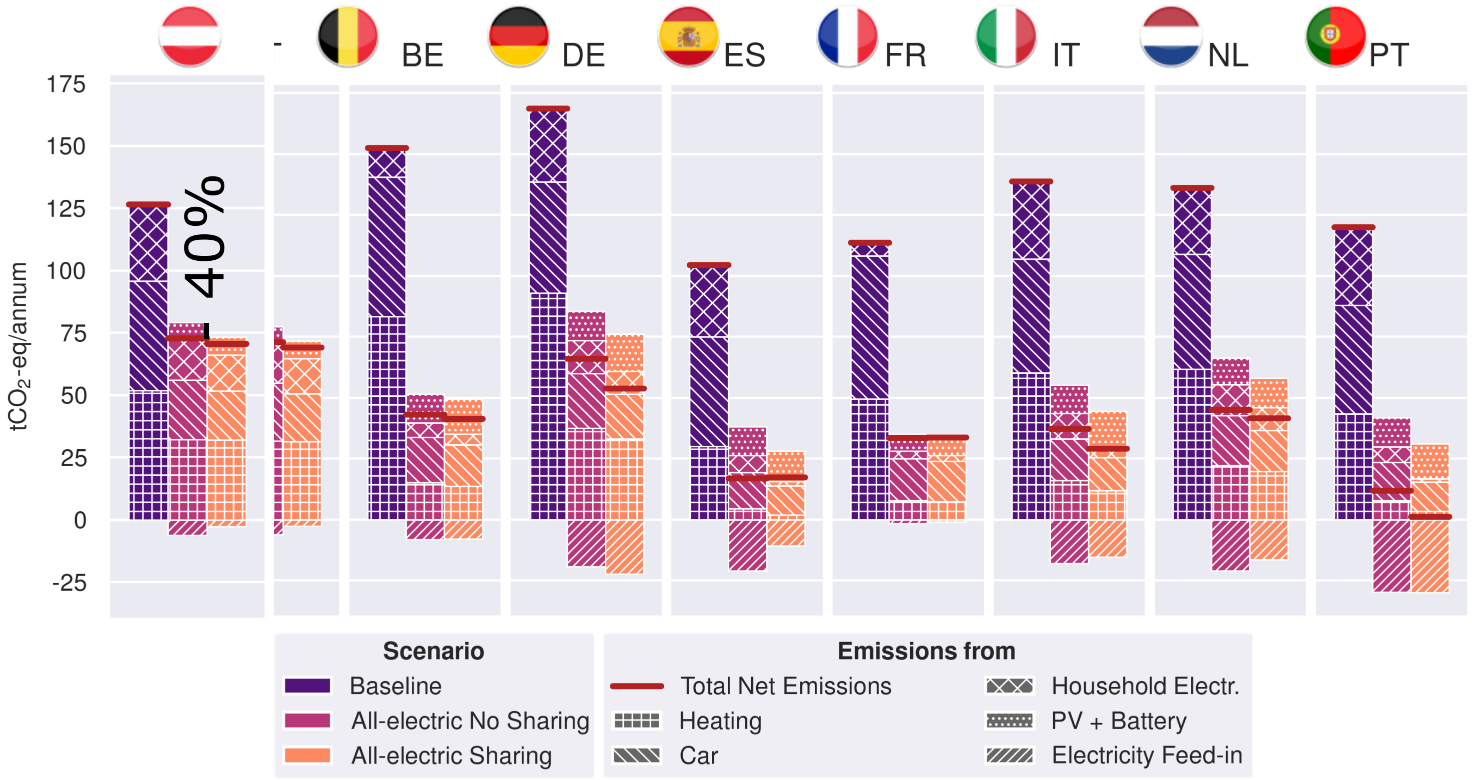
GHG reduction potential of all-electric energy communities



[Schram, 2019]

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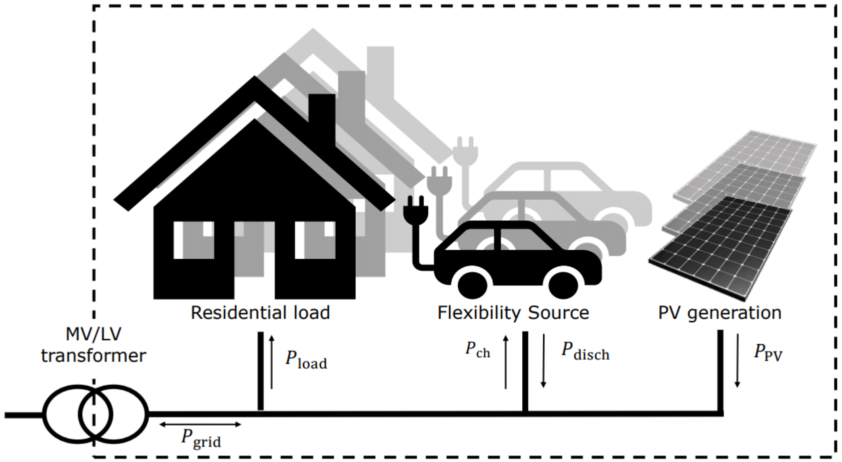
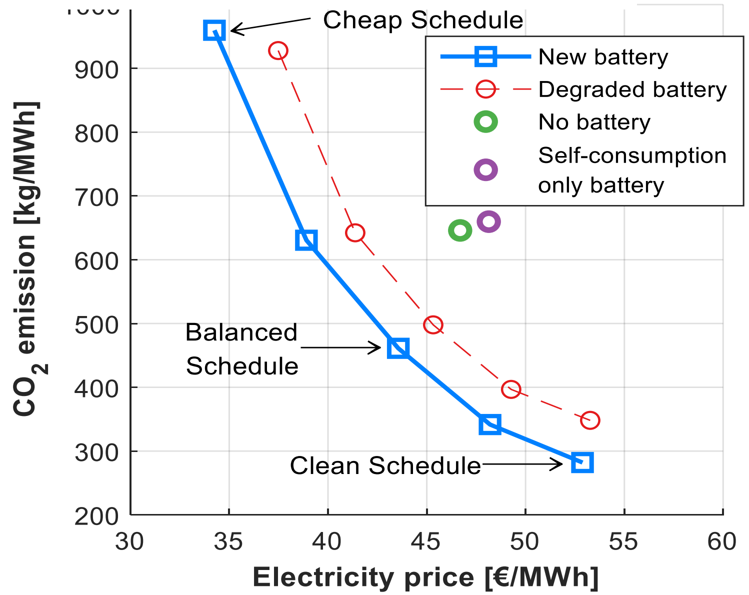
Cost vs emissions?

IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, VOL. 11, NO. 4, OCTOBER 2020 2653

On the Trade-Off Between Environmental and Economic Objectives in Community Energy Storage Operational Optimization

Wouter L. Schram, Tarek AlSkaif, Ioannis Lampropoulos, Sawsan Henein, and Wilfried G.J.H.M. van Sark





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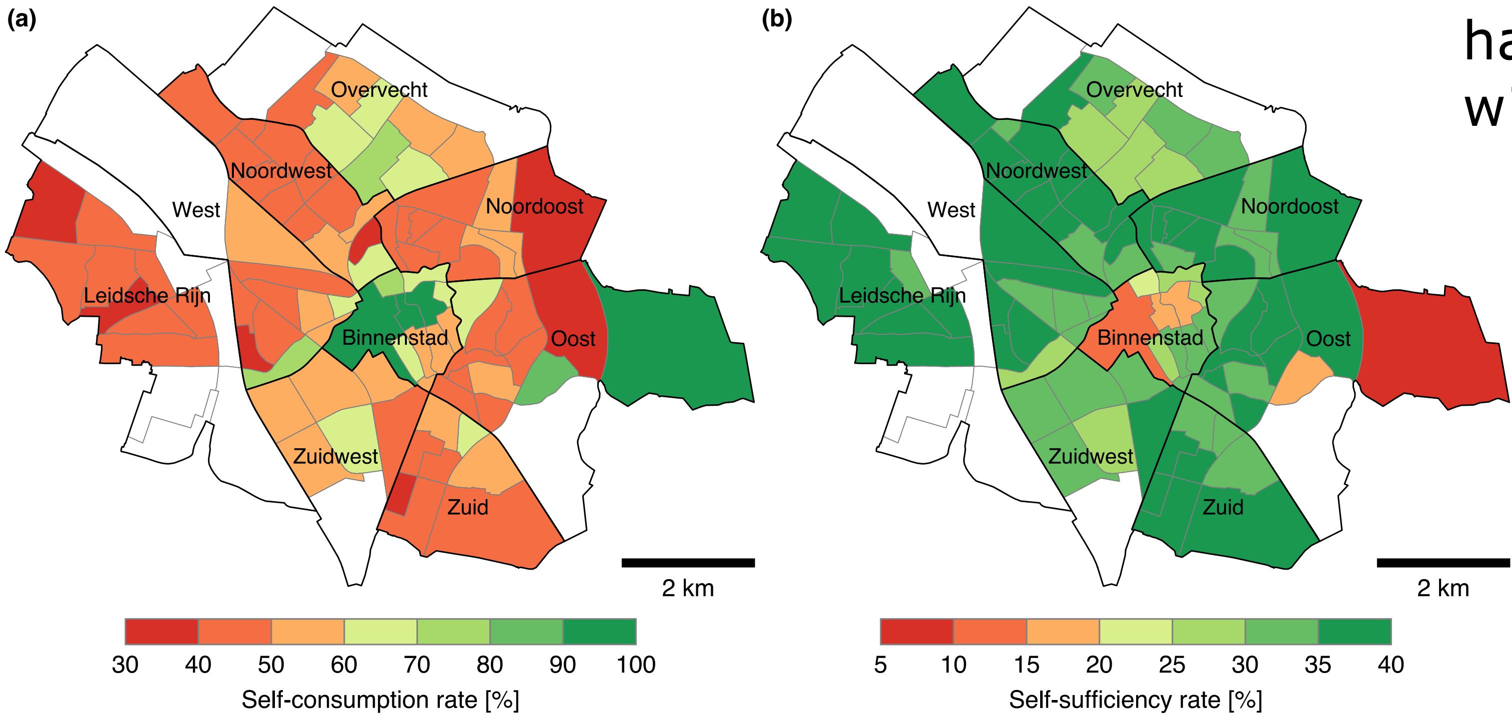
Self consumption and self sufficiency (Utrecht, GIS-based)

G.B.M.A. Litjens et al. Solar Energy 174 (2018) 1185–1197



half of roofs with PV

Fig. 6. Potential PV self-consumption ratio (a) and self-sufficiency ratio (b) for 88 neighbourhoods with only PV systems, for the city of Utrecht.

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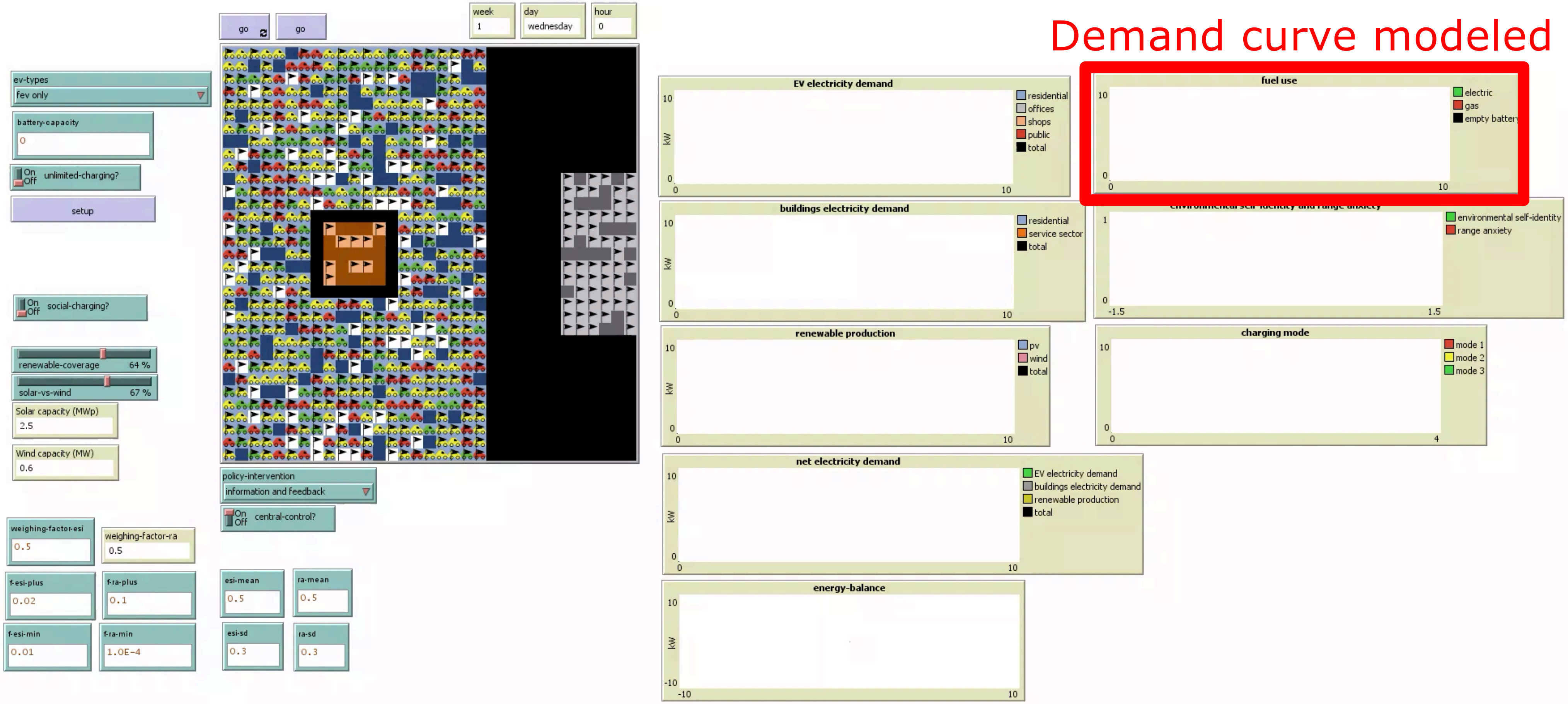
Agent based modeling EVs

Demand curve modeled



(van der Kam, 2019)

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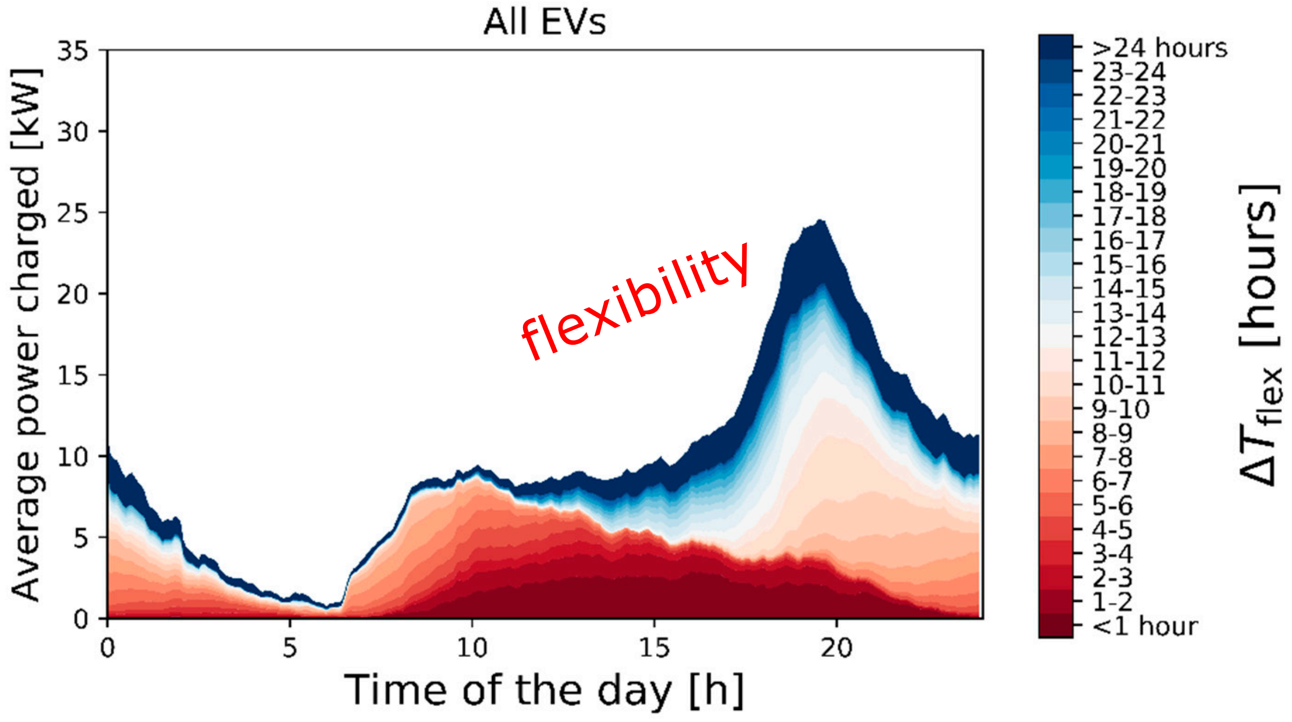
Measured charging profiles

- Utrecht district ”Lombok”
- Mix of BEV and PHEV, local and visiting



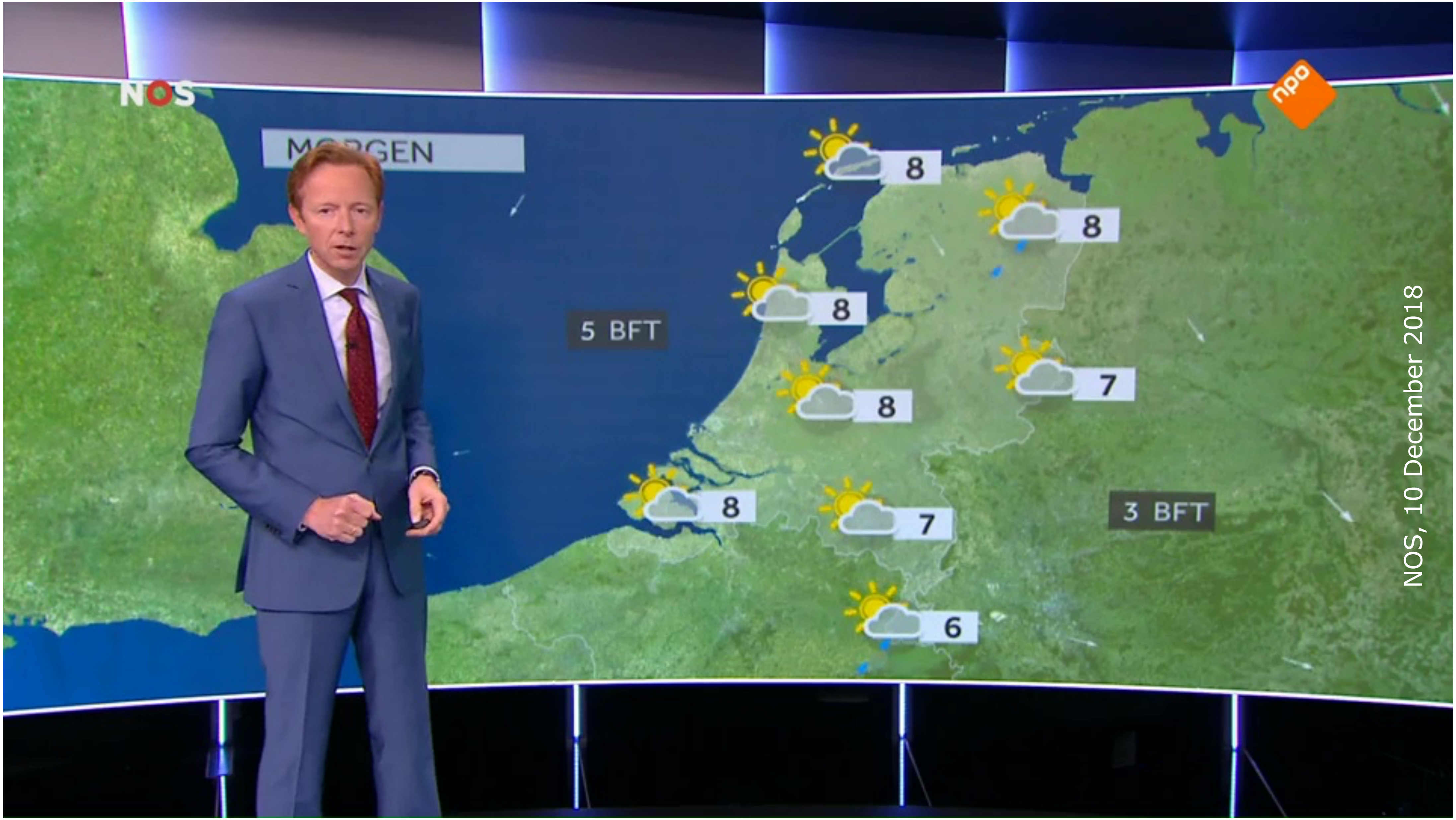
(Gerritsma, 2019)

EV car sharing

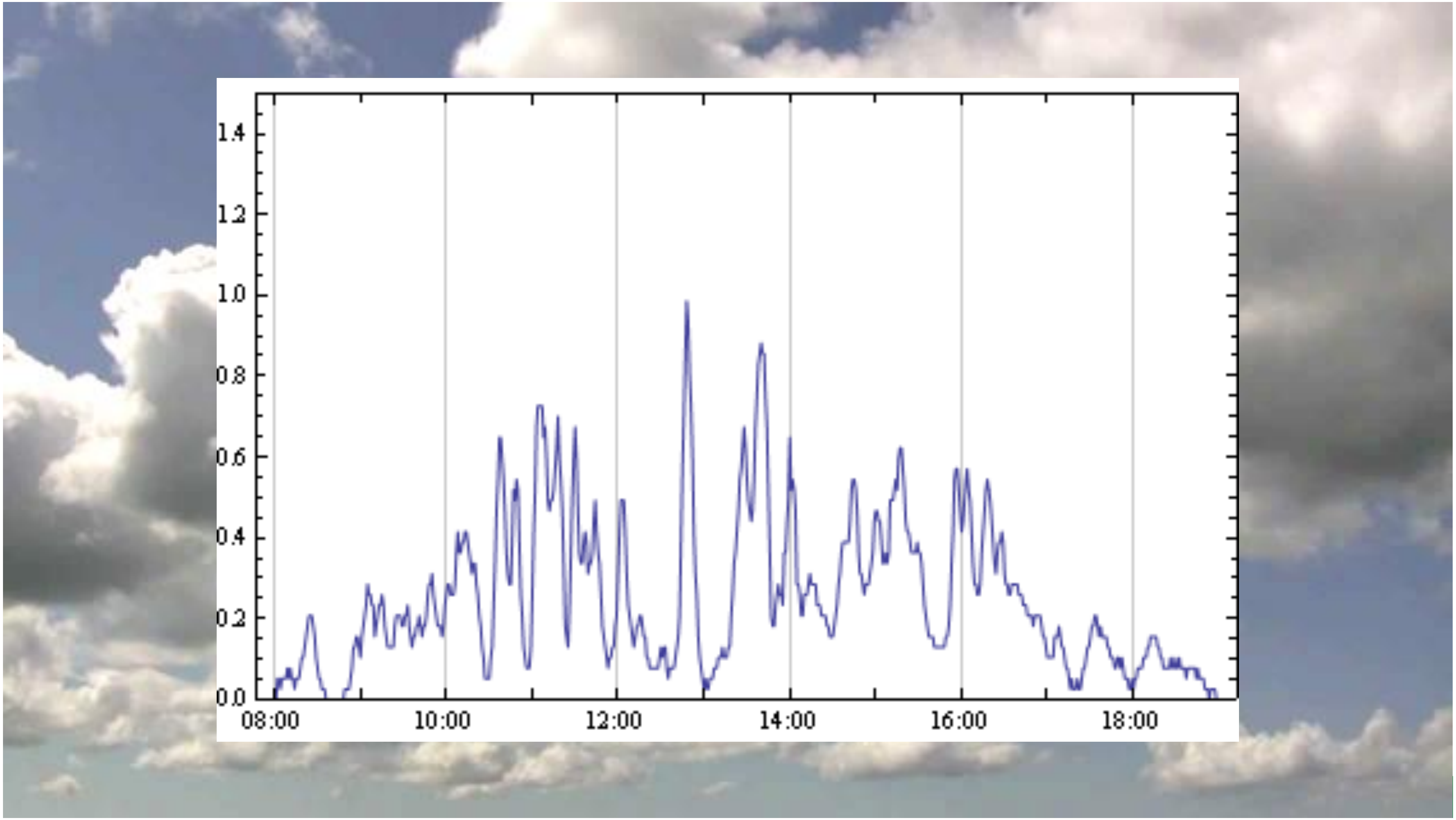
Lombok district

- Do we need private ownership, or just mobility?
- In dense urban areas, reduce cars/household: increase liveability!
- Mobility need depends on distance: walking, (e-)cycling, public transport, car
- “We Drive Solar”: EVs charged with local PV,

WE DRIVE SOLAR



NOS, 10 December 2018


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
08:00
10:00
12:00
14:00
16:00
18:00

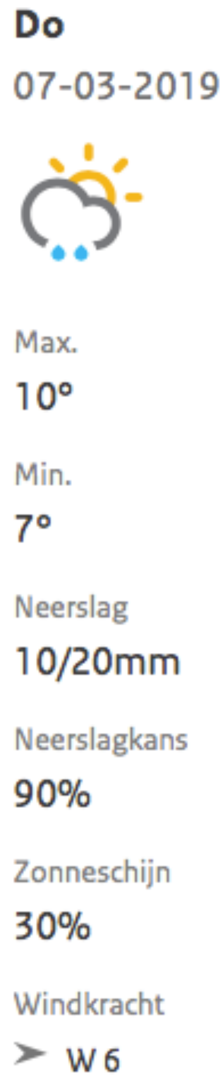
Solar forecast

Long/short term

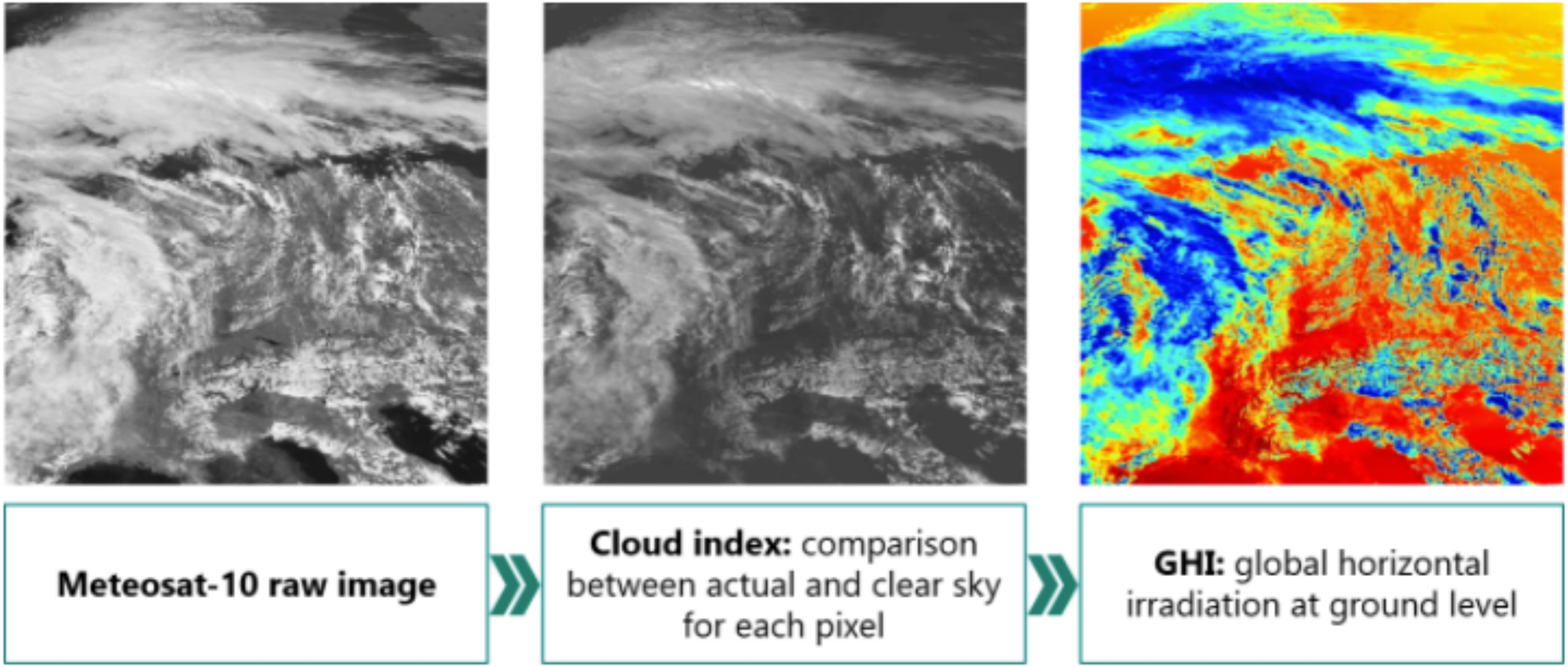
- Week, Per day, in % of max
- Per hour
- Per 15 min (electricity trading)
- Per 5 min (local management)

Spatial scale: 10 m – 100+ km

Various methods: machine learning

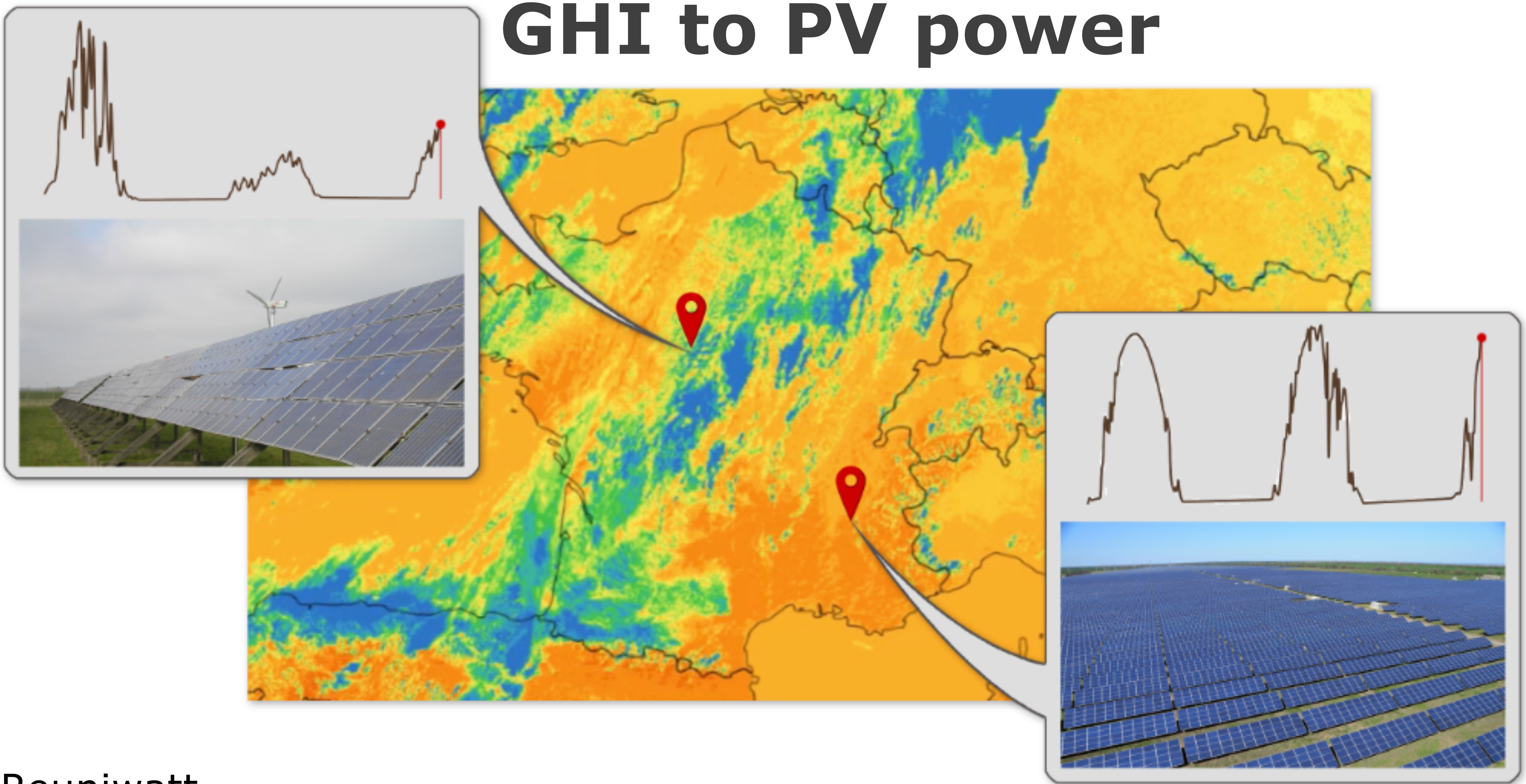


Satellite to GHI



Reuniwatt

GHI to PV power

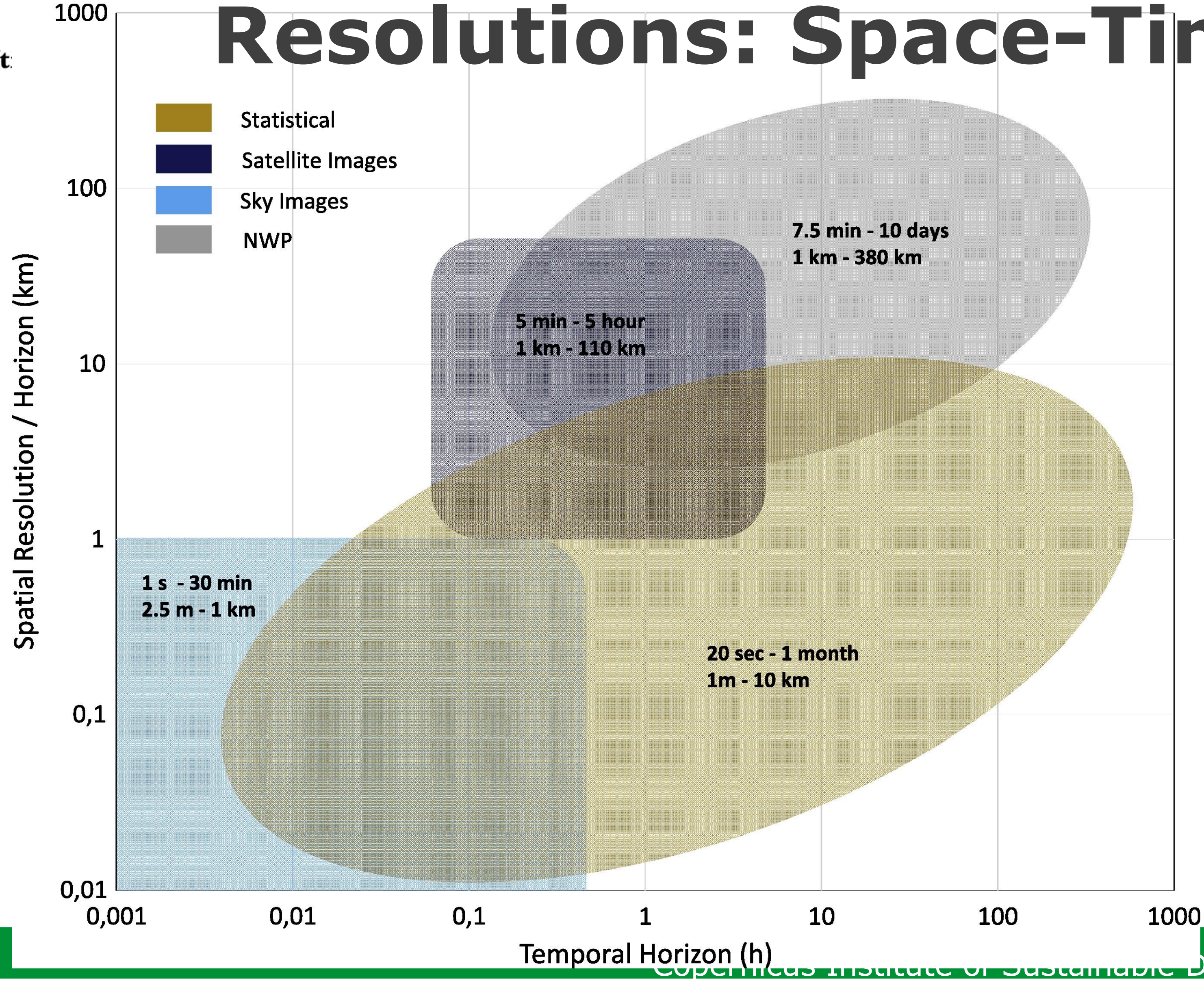


Reuniwatt

Irradiance to electrical power

- Global horizontal irradiance (GHI)
  - Or clear-sky index
- Transpose to tilt irradiance (GTI)
  - Use models for direct and diffuse irradiance, reflection (Orgill/Hollands, Perez)
- With PV model: P = f(GTI,Temp, …)

Resolutions: Space-Time

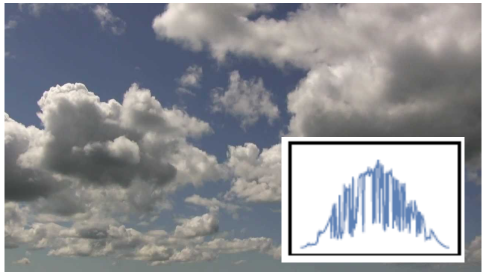


Antonanzas, Solar Energy, 2016

Forecasting for different weather types

Clear, constant

Clear, scattered clouds



Cloudy, constant

Cloudy, varying

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Alternative: Peer-to-peer forecasting

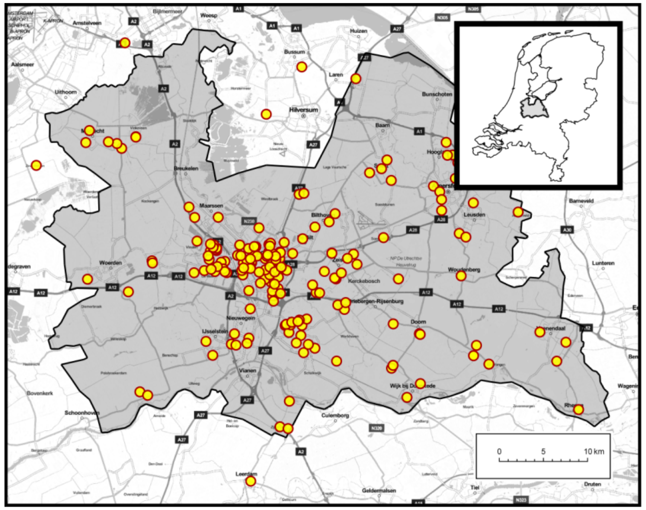
- Forget the weather (-forecast)
- Use only power data from PV systems
- Correlation of power at high temporal resolution
- Inverse GHI-to-PV model needed

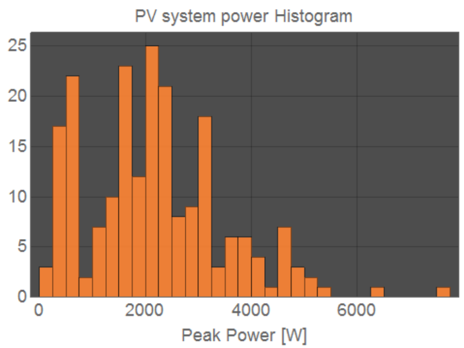
- Elsinga, PhD thesis, 2017

Solar Forecasting: Sensor Netwerk

- **202** PV-systems in province of Utrecht
- Power: 0.5 - 5 kW_p
- Measurement accuracy:

  0,7 W; **2** sec.
- Operational since Aug 2013





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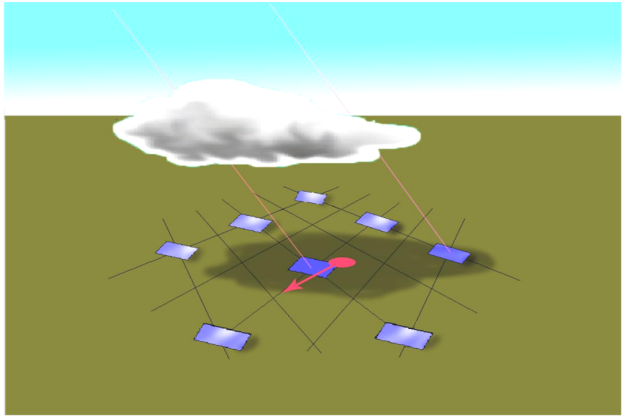
Peer-to-Peer (P2P) Forecasting

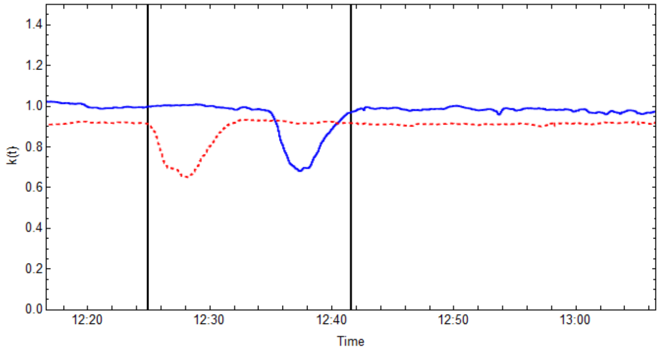


Principles:

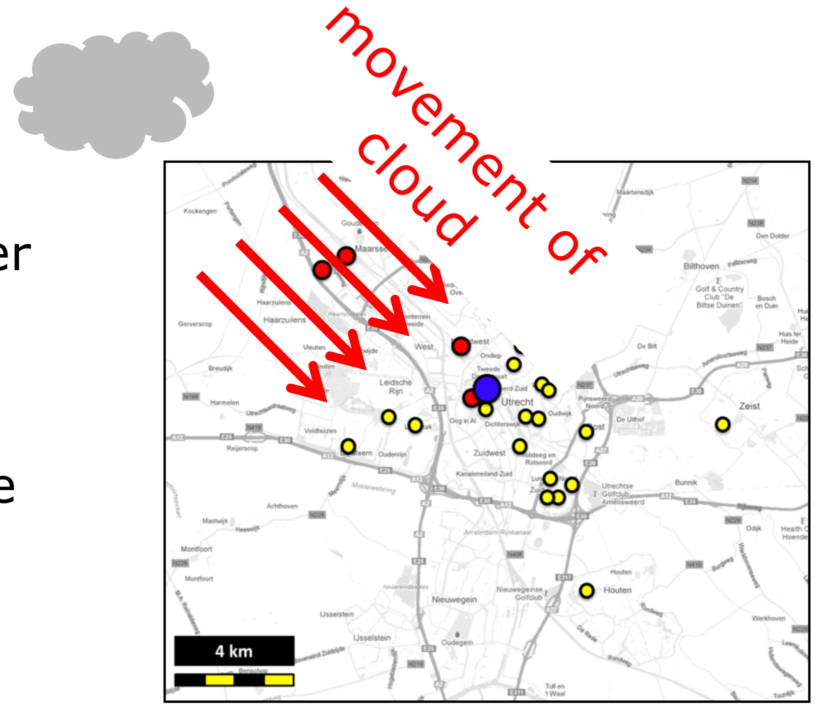
- **Clouds** influence PV systems subsequently
- Use measurements of closeby PV systems (*peers*)

Assumptions:

- System data are correct
- Change of clearness k(t) only depends on **clouds**
- Movement of clouds ~**uniform**
- Clouds keep their **form**



Peer-to-Peer (P2P) Forecasting



At any moment:

- Compare clearness with earlier and elsewhere measured clearness
- Shift time-series and calculate ***time lag*** (without knowing wind direction)
- Mean of shifted series gives ***forecast***

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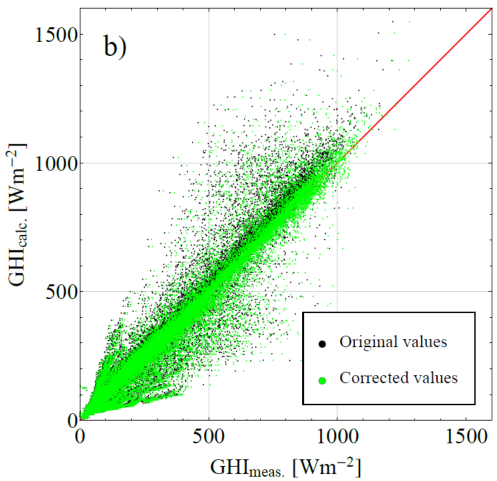
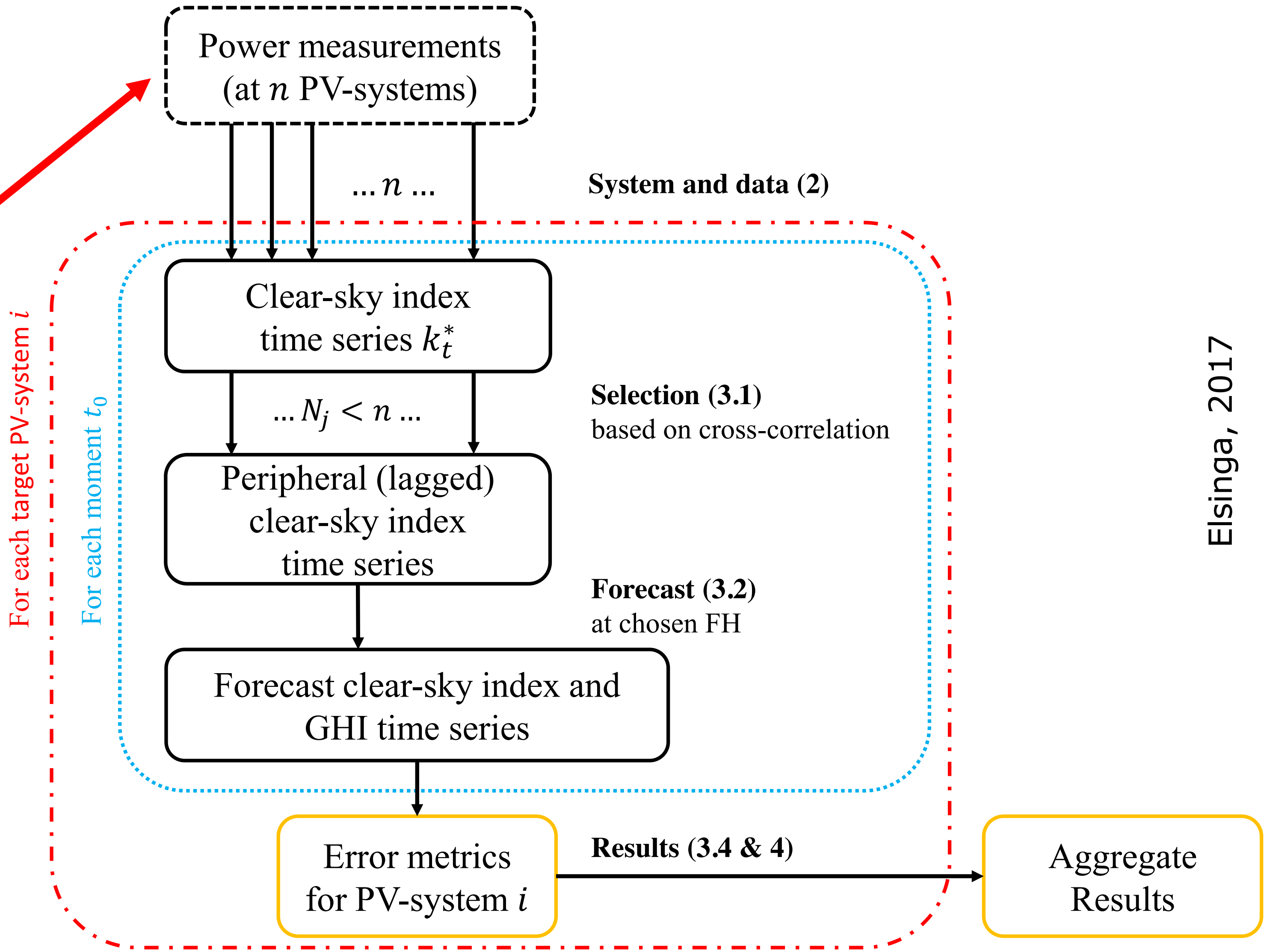
Method

Inverse GHI-PV model





Elsinga, 2017

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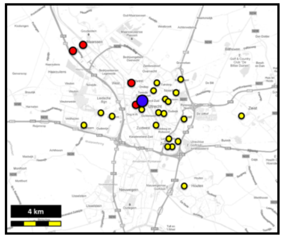
Finding the Time Lag



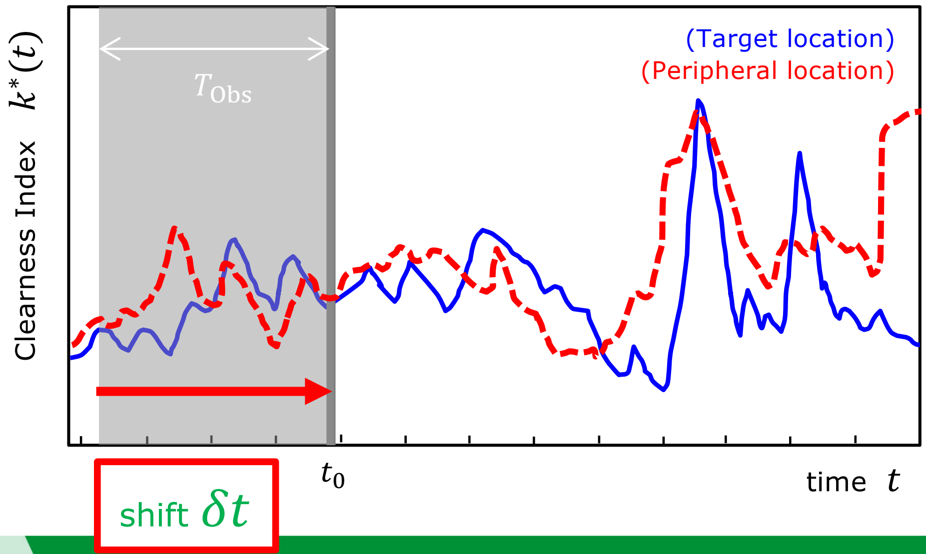
Compare $k^*(t)$ to $k^*(t-\delta t)$

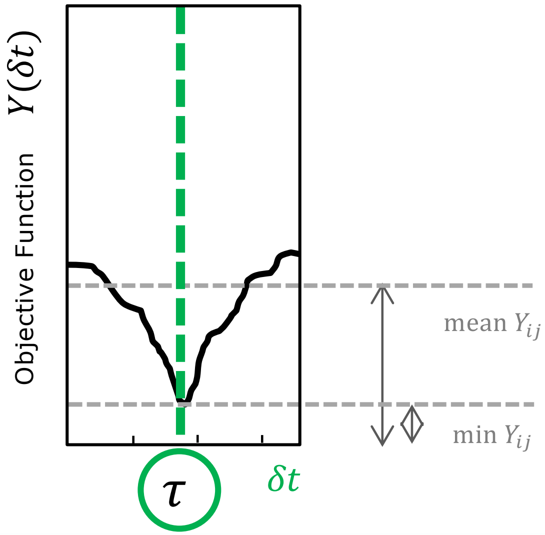
- Objective function $Y_{ij}(\delta t)$:
  - ✓ ***Pearson Correlation***

Calculate *time lag* $\boldsymbol{\tau}$ and quality $\boldsymbol{Q}$

$$\tau_{ij,w} = \arg\min\left(Y_{ij,w}(\delta t)\right)$$

$$Q_{ij,w} = \left|\frac{\min Y_{ij,w}}{\text{mean } Y_{ij,w}} - 1\right|$$





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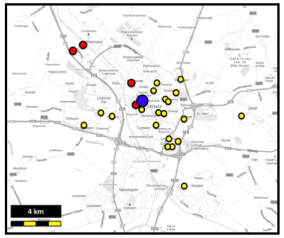
Finding the Time Lag



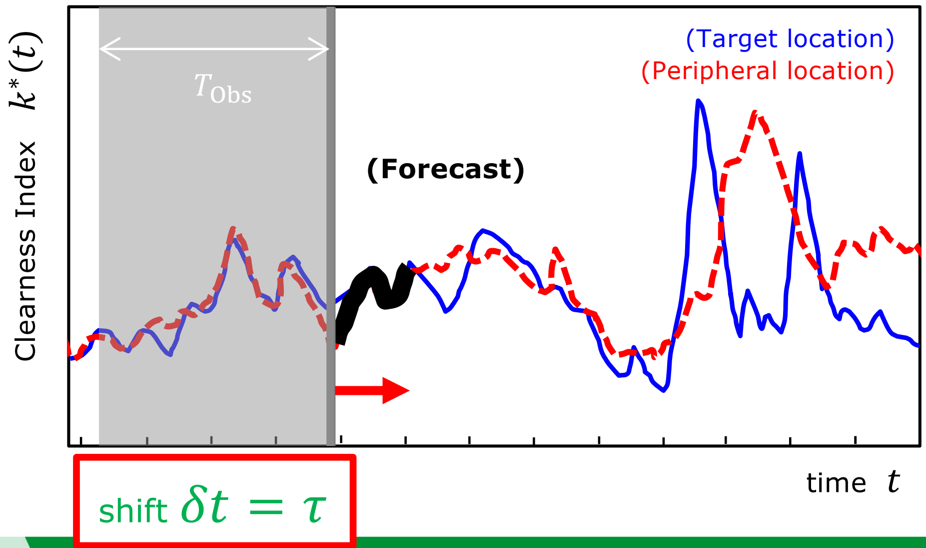
Compare $k^*(t)$ to $k^*(t-\delta t)$

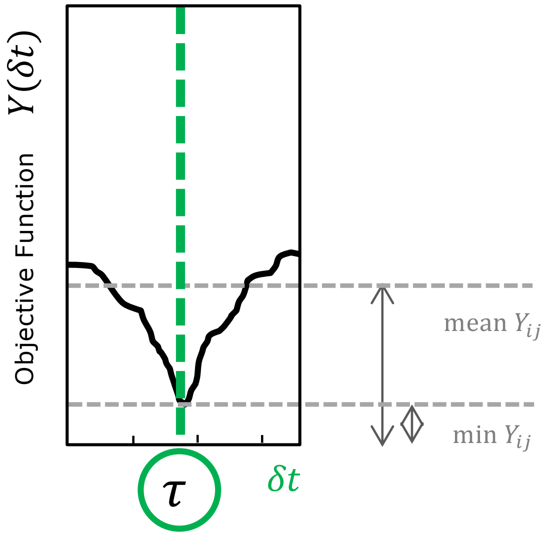
- Objective function $Y_{ij}(\delta t)$
  - ✓ *Relative RMS*
  - ✓ *St. Dev. of Fluctuation*
  - ✓ ***1-Correlation***

Calculate *time lag* $\boldsymbol{\tau}$ and quality $\boldsymbol{Q}$

$$\tau_{ij,w} = \arg\min\left(Y_{ij,w}(\delta t)\right)$$

$$Q_{ij,w} = \left|\frac{\min Y_{ij,w}}{\text{mean } Y_{ij,w}} - 1\right|$$





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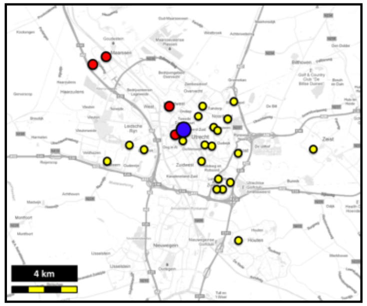
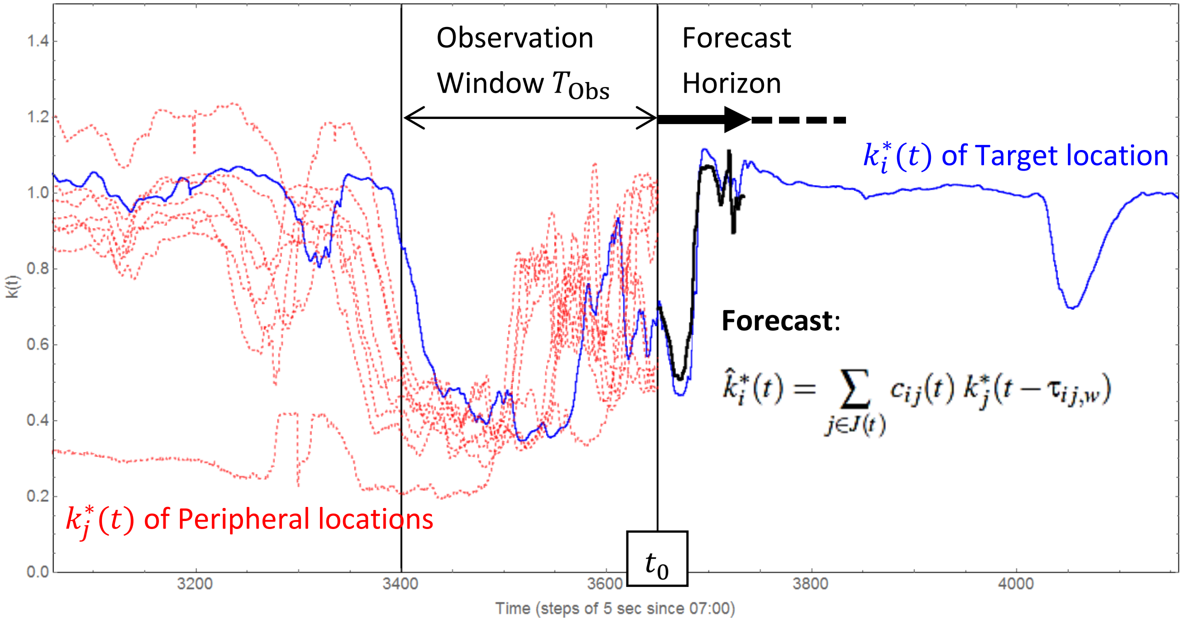
Generating P2P Forecasts



- More peers
- Mean of shifted $k^*(t)$ ⇒ **Forecast**
  - Variable Forecast Horizon (FH)
  - *Sensitive* to choice of parameters



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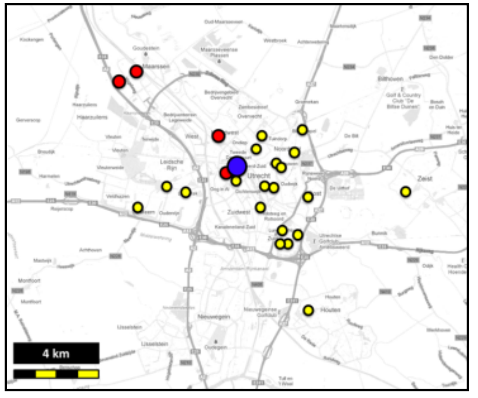
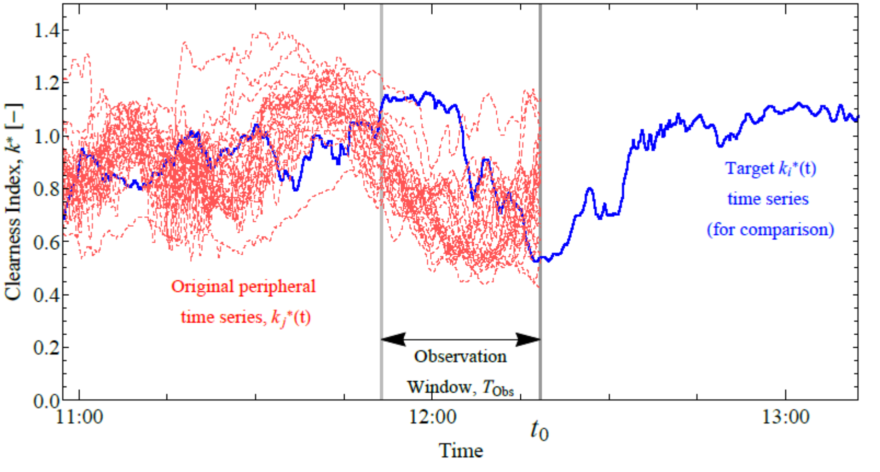
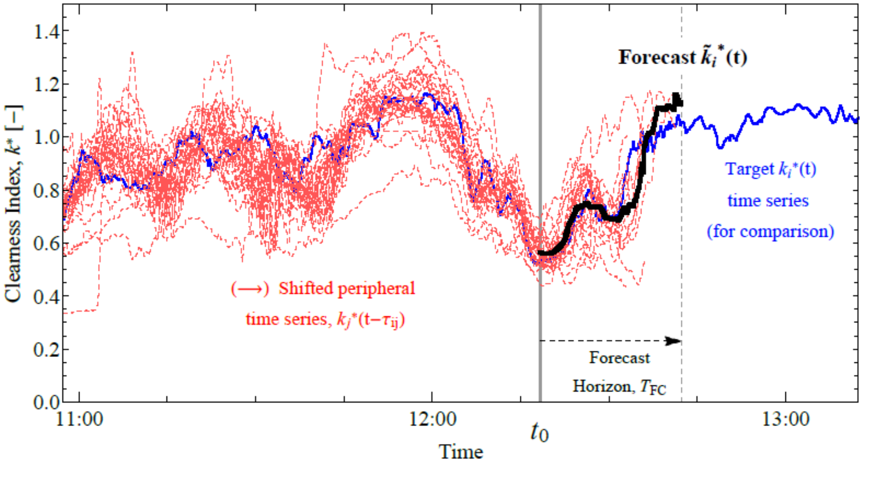




- Mean of shifted $k^*(t-\tau)$
  $\Rightarrow$ **Forecast (FC)**

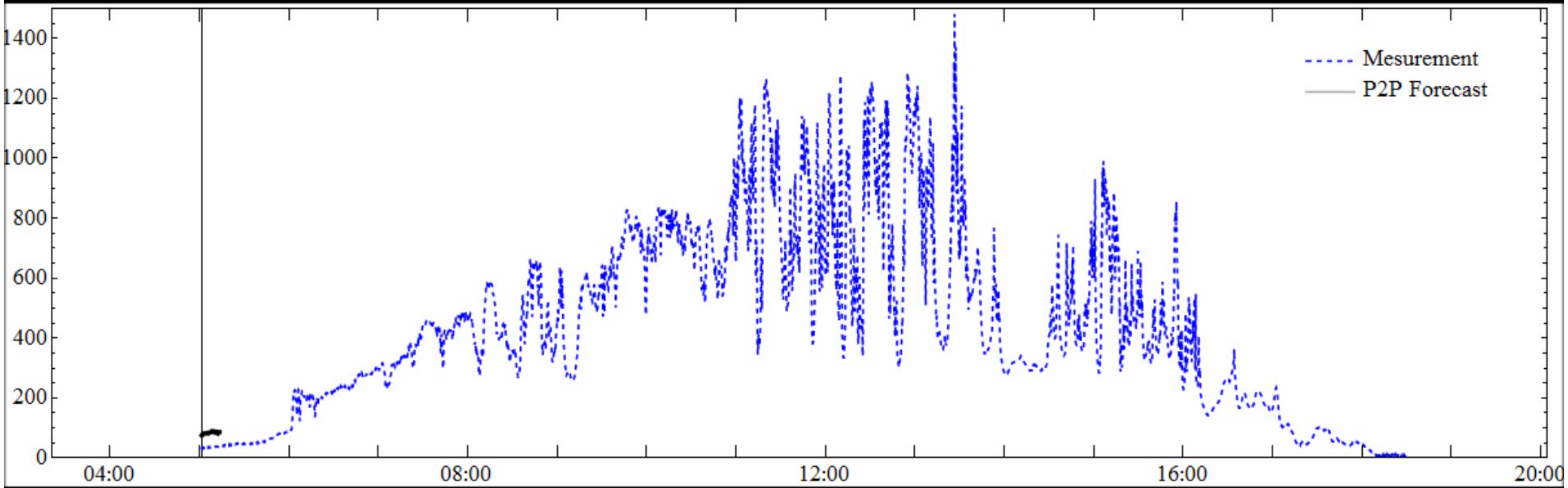
- FC consists of **time series**, not only one step ahed!

- Length[T_{FC}] $\leq$ Length[T_{Obs}]
  e.g. 30 min. at 30 sec. resolution!



B. Elsinga, W. van Sark, Applpied Energy 2017

“real-time implementation”



Metrics: Forecast Skill*

Root **M**ean **S**quare **E**rror of forecast compared to **RMSE** of persistence

"how well are you beating persistence?"

$$\mathrm{FS} \approx 1 - \frac{\mathrm{RMSE}_{(\mathrm{FC})}}{\mathrm{RMSE}_{(\mathrm{p})}}$$

Worse than pers:	$-\infty < \mathrm{FS} < 0$
Equal to pers:	$\mathrm{FS} = 0$
Better than pers:	$0 < \mathrm{FS} \leq 1$

*[R. Marquez, C.F.M. Coimbra *Proposed Metric for Evaluation of Solar Forecasting*, Journal of Solar Energy Engineering (135), 2013]

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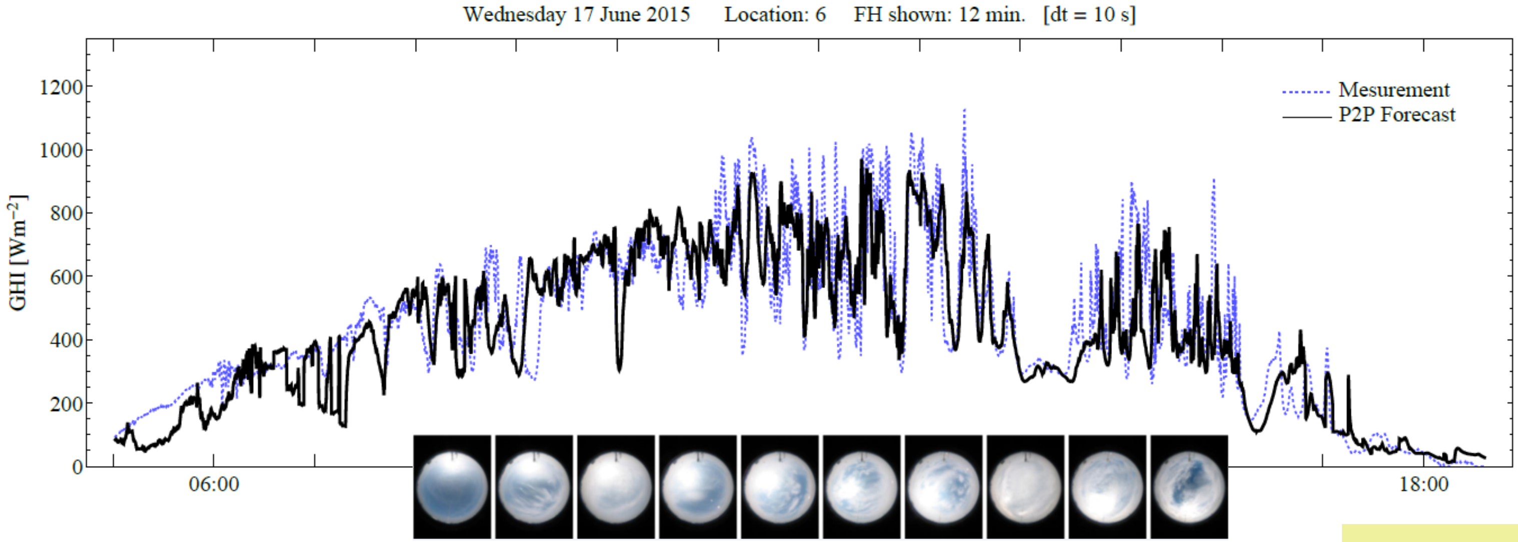
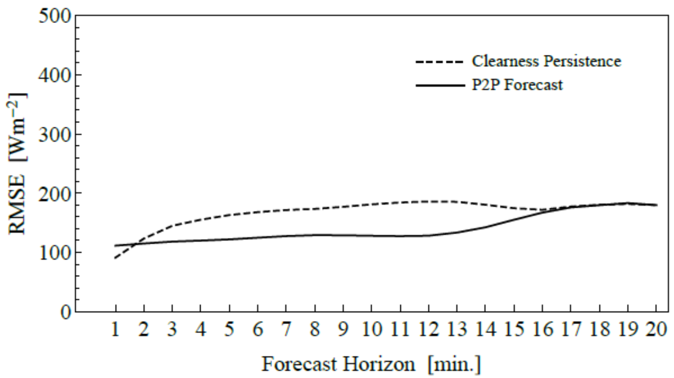
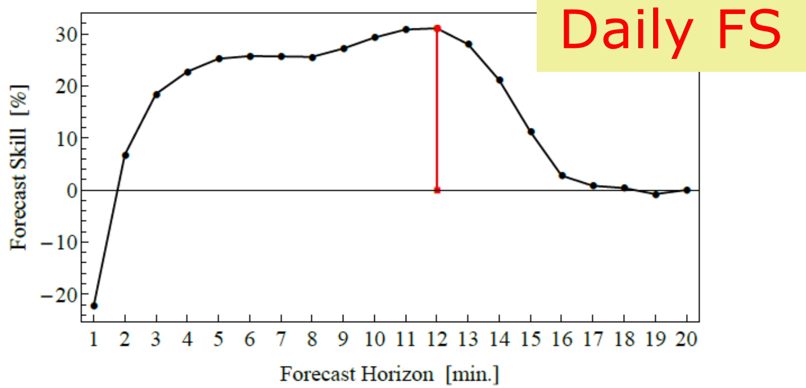
Results: Example



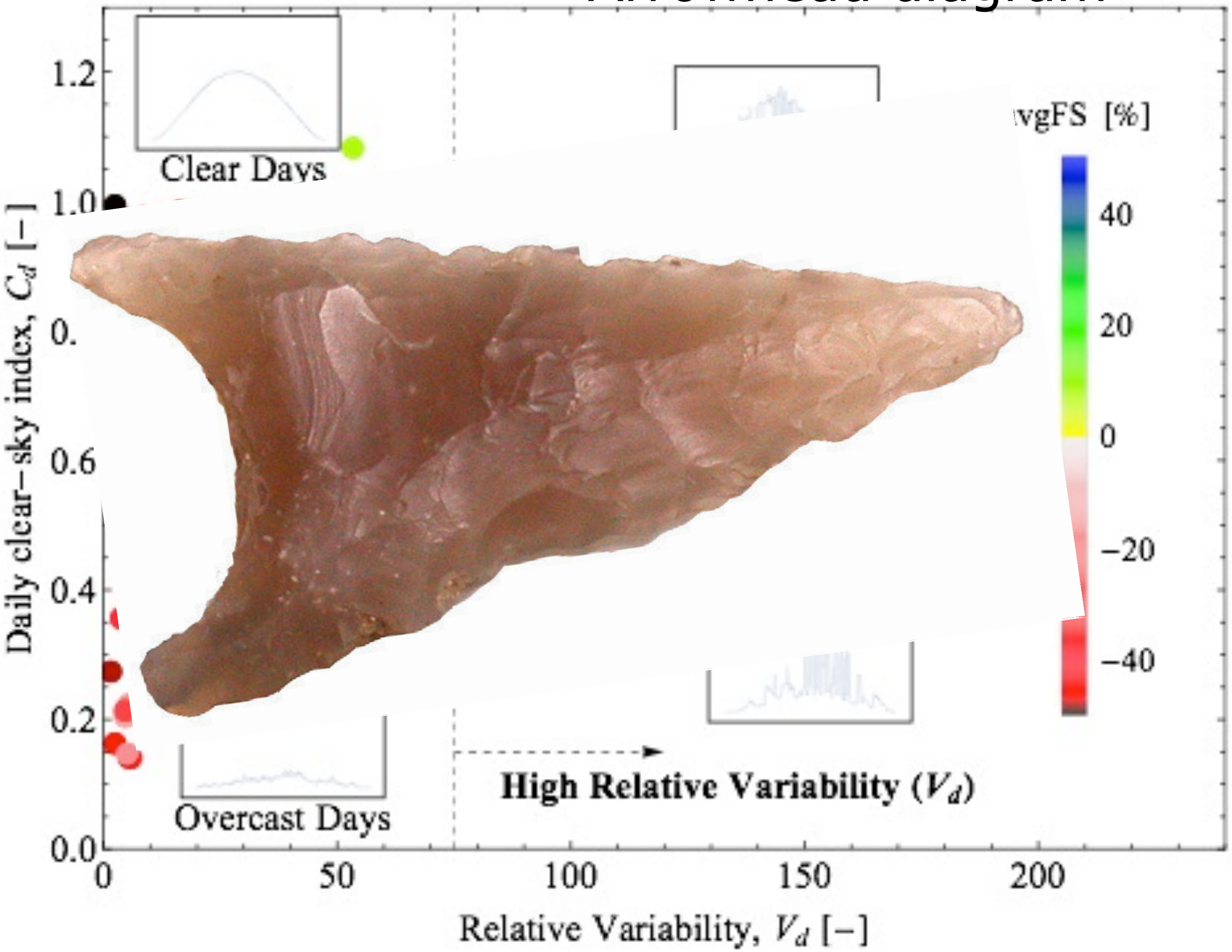




B. Elsinga, W. van Sark, Applied Energy 2017

Daily Irr. Characterization 1st of April - 30th September 2015: 12 central PV-systems

"Arrowhead diagram"



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Outlook

- Peer-to-peer Short-term Solar Forecasting method applicable for generic PV/Sensor Network
  - Forecasts best for central locations in PV-Network
  - Choose persistence FC at low V_d and/or low FH
- Combine with weather forecast
  - Satellite pixel few km^2, time step 1-3 hr
- Forecast based on sky-imagers (project started)
  - Spatial resolution m^2-km^2, time step minutes

- Assess economic benefits for smart grids

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Utrecht Science Park

Van Unnik building

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Case study NZEB

- 22-storey high-rise building from the 1960s
- Renovation to near-zero energy building (NZEB)
- Use all suitable parts of facades and roof using building integrated photovoltaic (BIPV) components
- N-S facades large, E-W facades small
- Self-sufficiency, self-consumption

Energy demand

- Electricity: 1.28 GWh/year (2017)
  → 38 kWh per m^2 floor area
  (half of the building was not used)
- Excludes heating, includes cooling/ventilation

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Demand (6 days)

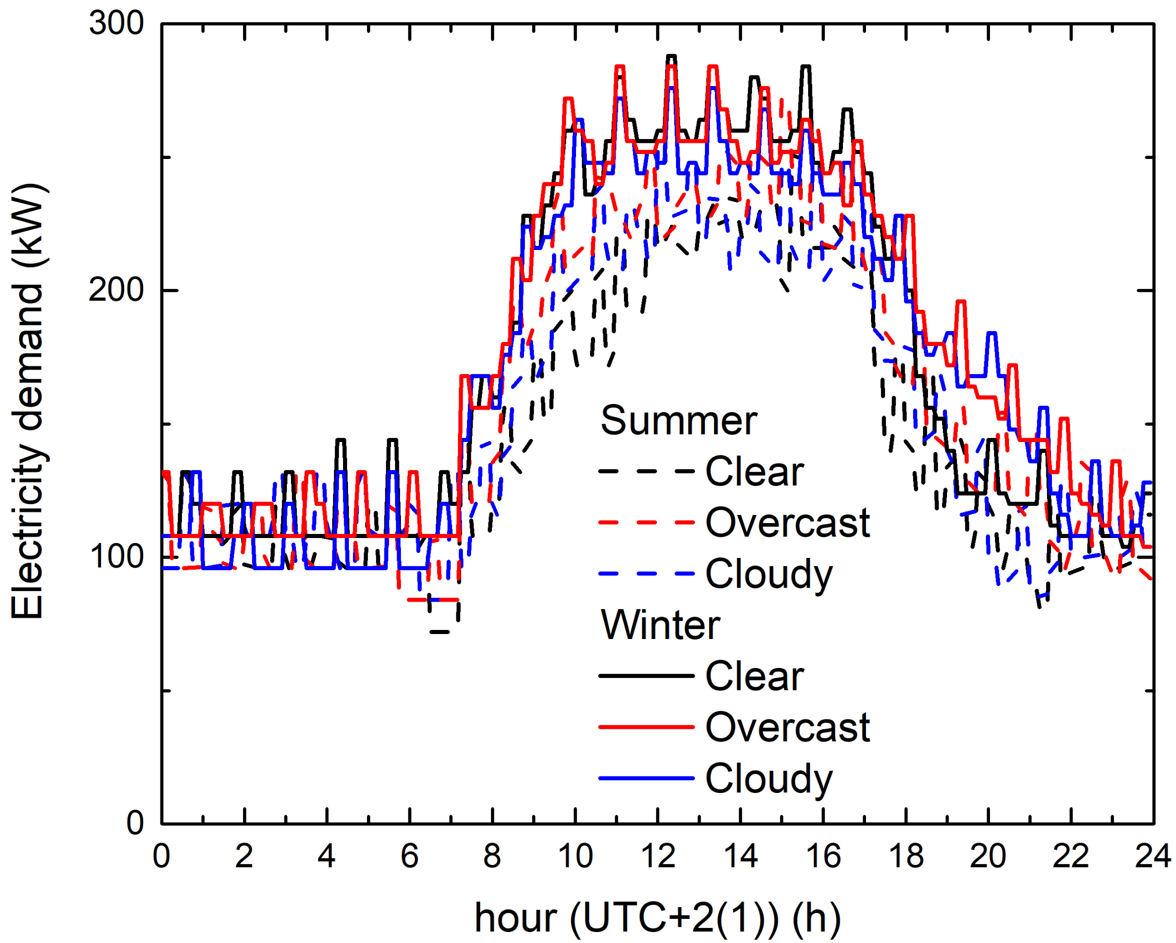
Winter, Summer

Clear, cloudy, overcast

Baseload: 100 kW

Peakload: 280 kW

Small winter/summer difference



PV potential area

- Building dimensions
  - Height: 76 m; width: 57 m; depth: 27 m
- N/S facade: 4332 m^2
- E/W facade: 2052 m^2
- Facade suitability 60% (windows)
- Roof: 1539 m^2
  - a) South, 37^o tilt, b) E/W 10^o tilt

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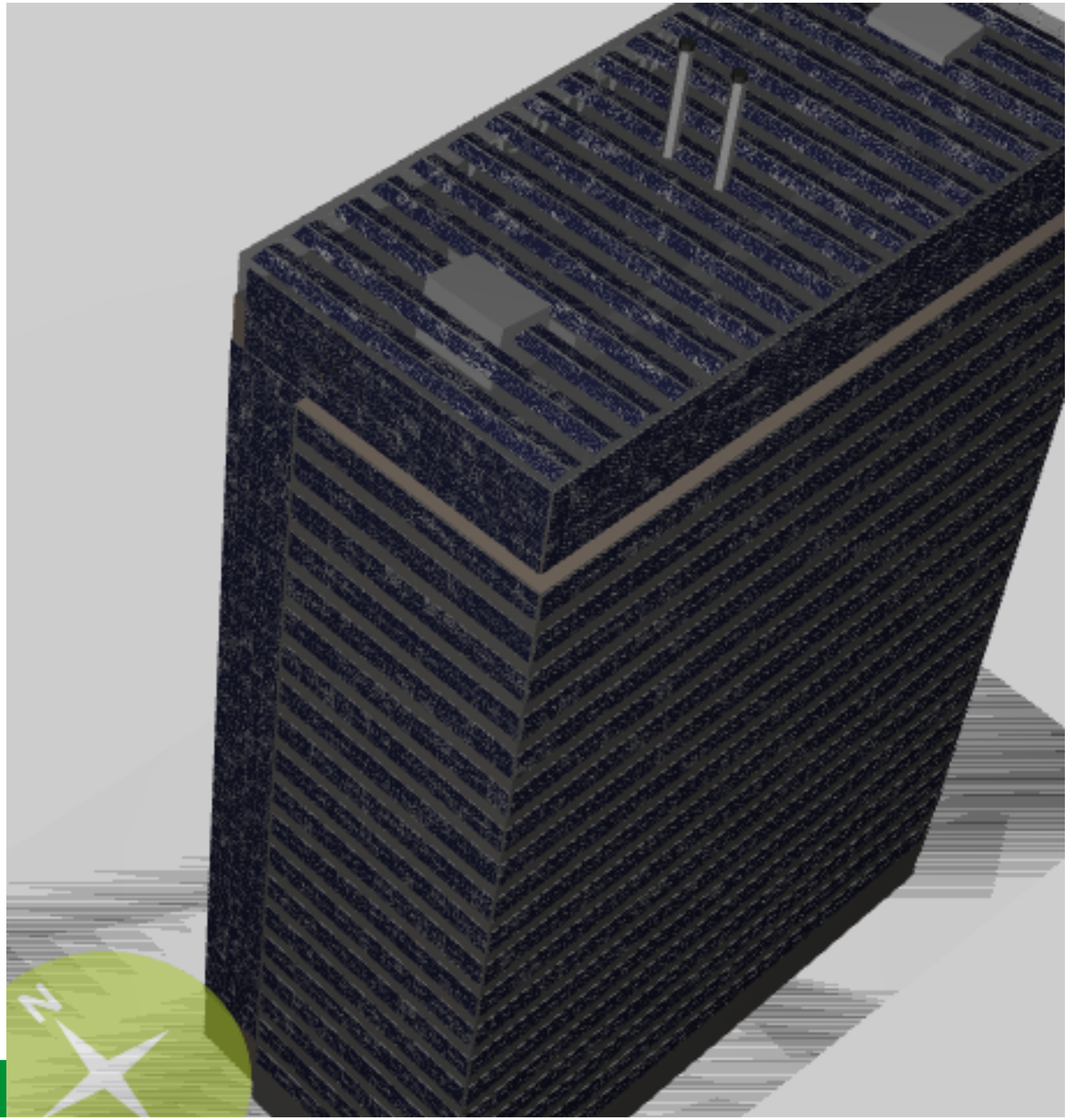
PVSITES design

Sunpower 320 Wp

ABB inverters

Total capacity:
1.69 MWp

www.pvsites.eu



PVsites

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PVSITES design

Irradiation analysis

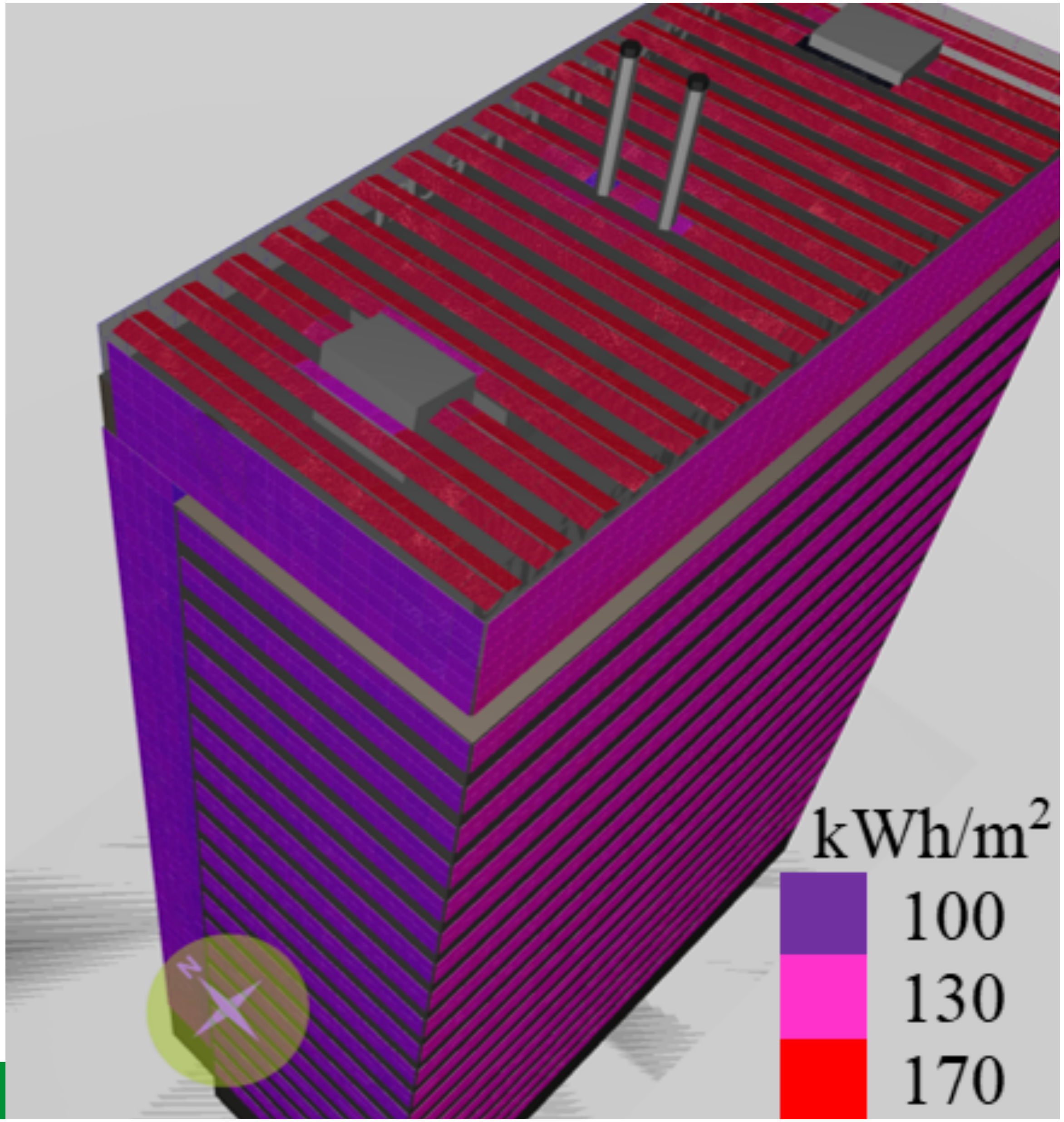
Energy yield:

853 MWh/year

Specific yield:

506 kWp/kWp

Self-sufficiency: 67%



PVsites

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Detailed annual yields

Calculated PV capacity, annual yield and specific yield

Surface	PV capacity (kWp)	Annual energy yield (MWh)	Specific yield (kWh/kWp)	Yield per unit area (kWh/m^2)
South facade	519.8	311.1	**598.5**	71.18
North facade	519.8	151.9	292.2	35.06
East facade	246.2	112.9	458.4	55.02
West facade	246.2	125.1	507.9	60.96
Roof (South tilt)	153.9	152.1	**988.6**	98.83
Roof (East tilt)	153.9	132.9	863.5	86.35
Roof (West tilt)	153.9	134.2	872.1	87.20

60%

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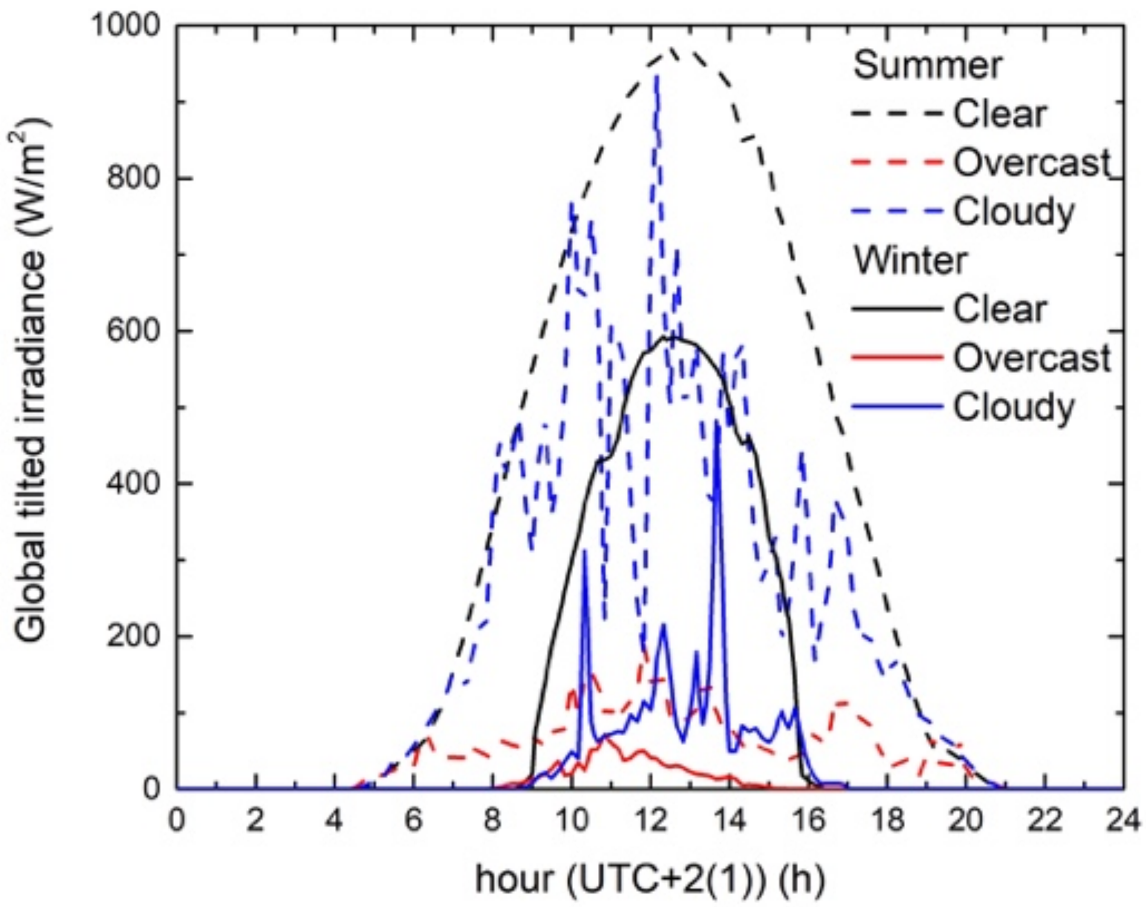
Demand (6 days)

Winter, Summer

Clear, cloudy, overcast



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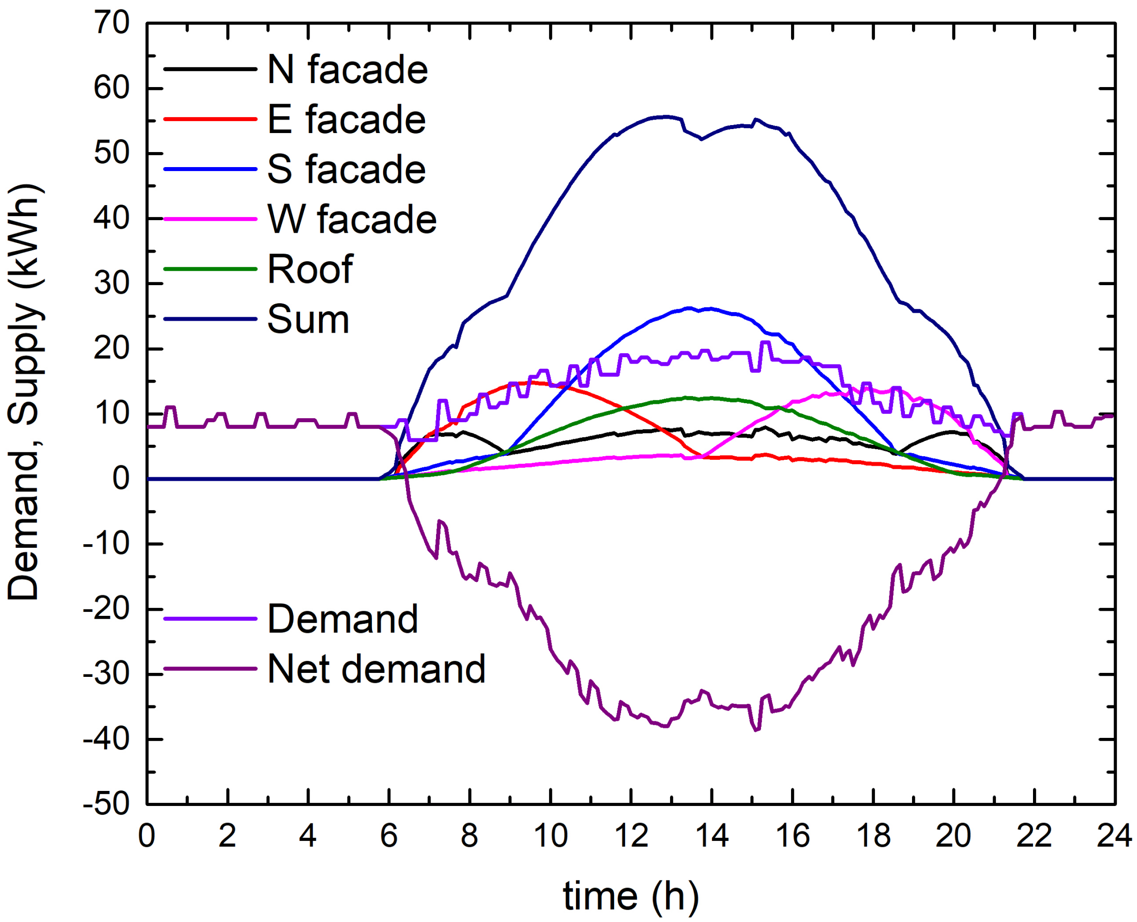
Clear summer day

Sum of N, E, S, W and roof is larger than demand, but time-dependent



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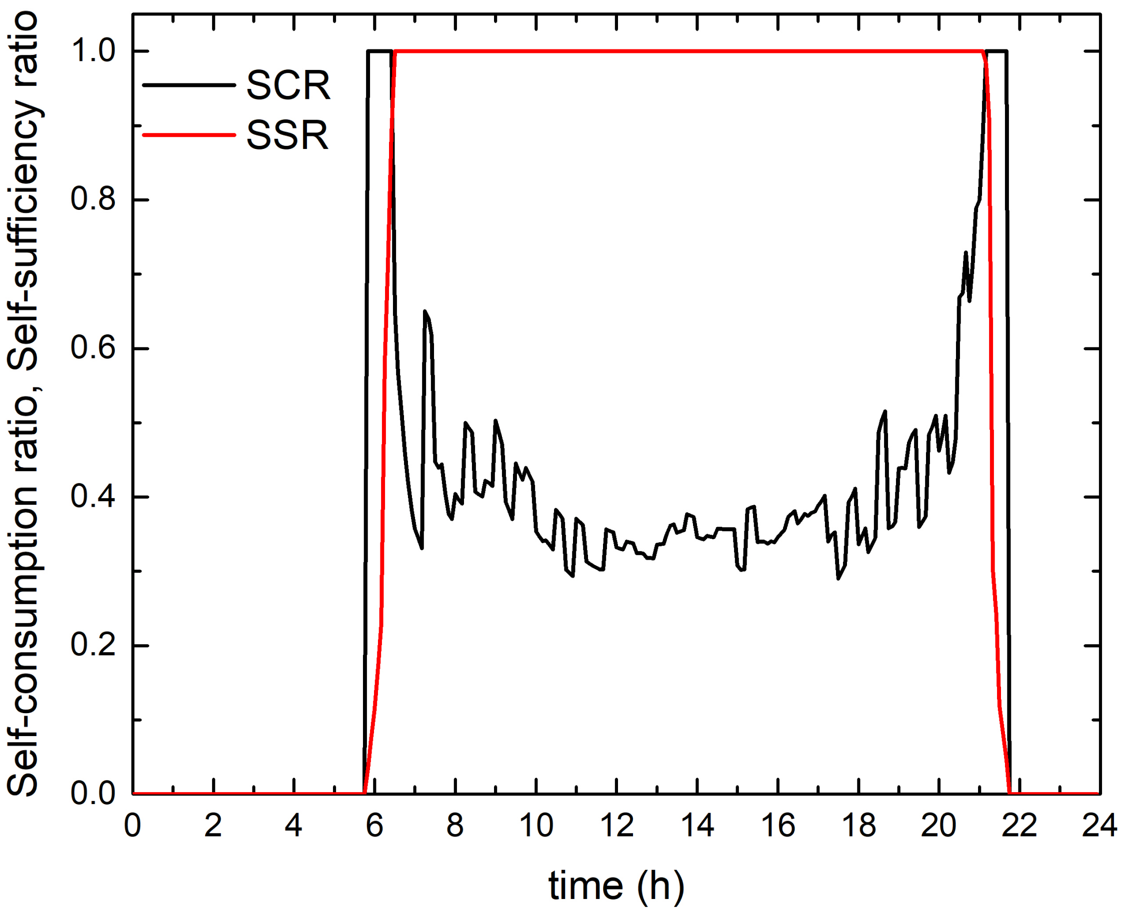
Clear summer day

Self-consumption low (~40%)

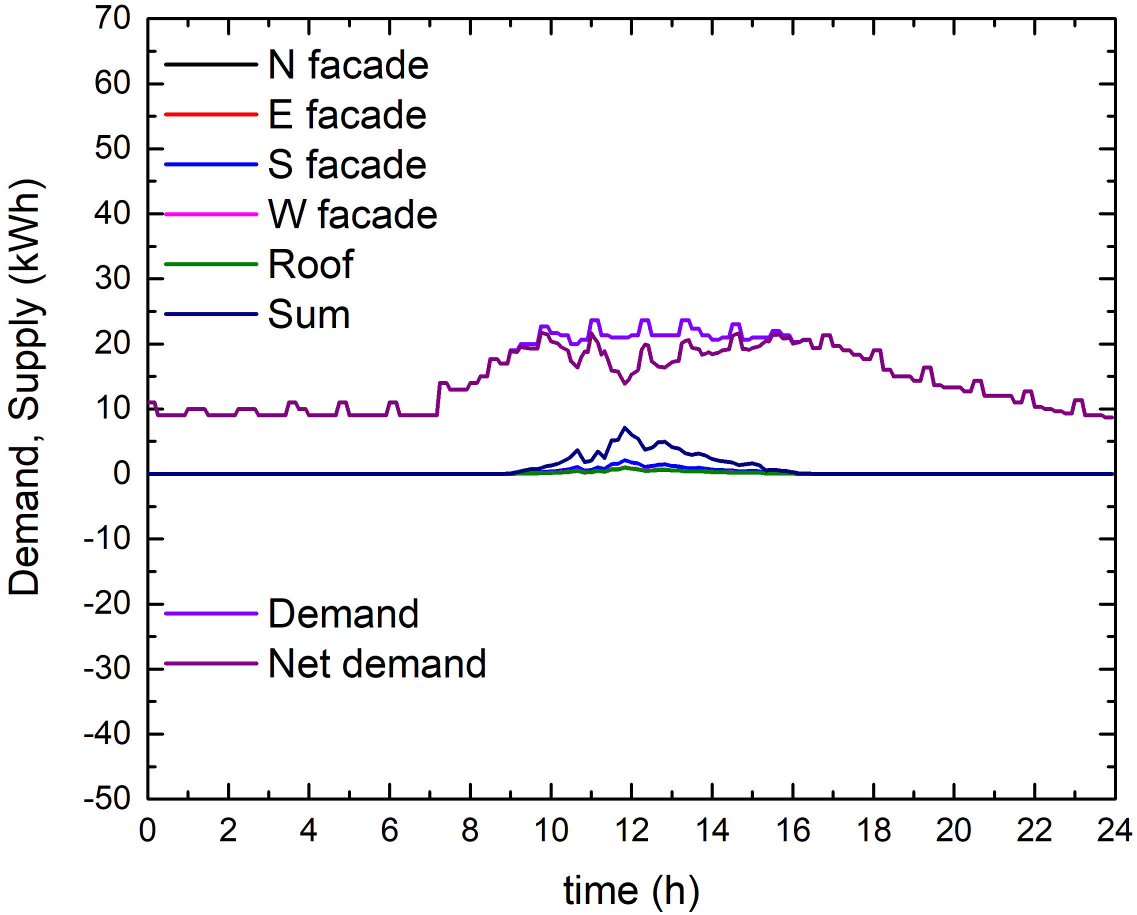
Self-sufficiency high (100%)

Electricity is fed back to the grid



Overcast winter day

Small contribution from PV



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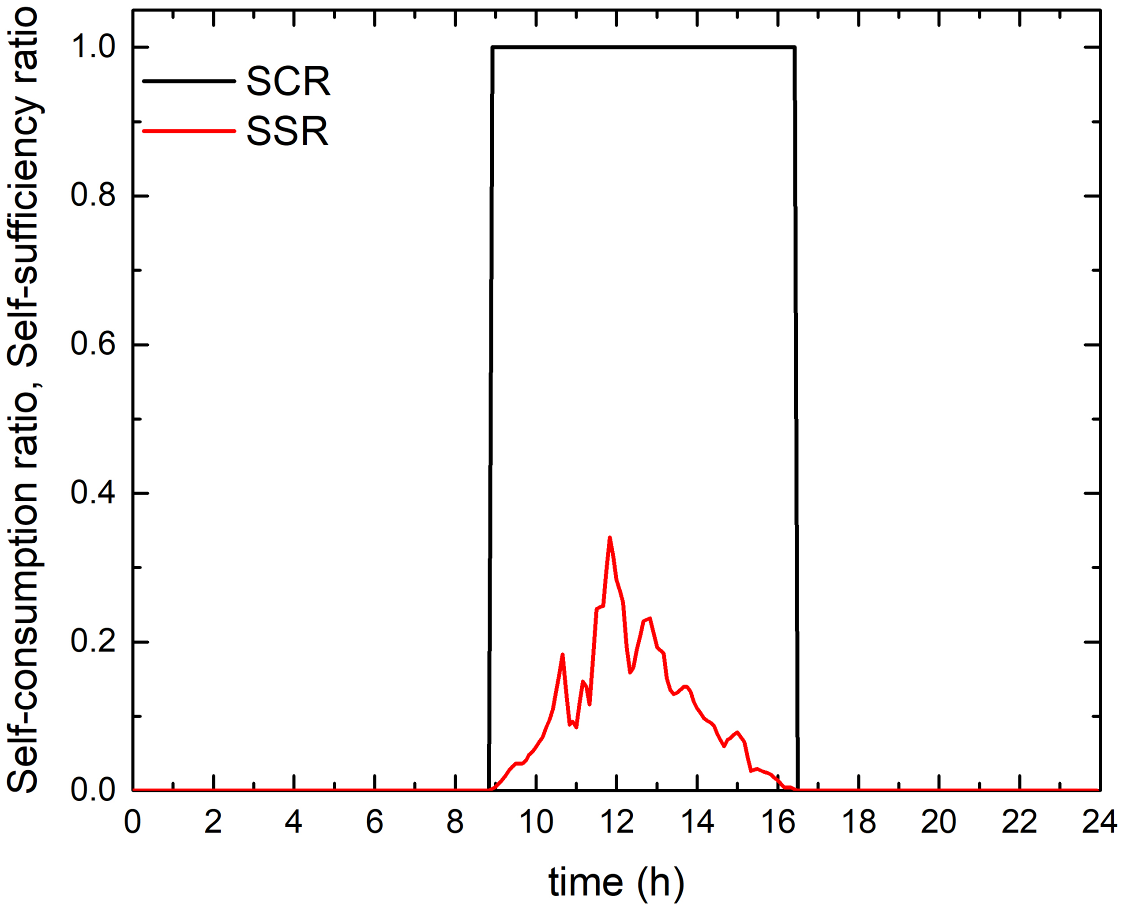
Clear summer day

Self-consumption high (100%)

Self-sufficiency low (10-20%)

No electricity is fed back to the grid



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Conclusion

- BIPV design for landmark university building
- Annual and daily supply/demand matching, self-consumption/self-sufficiency
- NZEB?
  - Not presently, with self-sufficiency of 67%
  - Need to lower electricity demand to about 25 kWh/m^2
- Next step: convince University board!

Thank you

Climate problem

→ to 100% renewables

→ decentralized electricity

→ local management (PV, EV, forecast)

→ NZEB

→ citizens are key