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PV performance monitoring in a 100% renewable society

Wilfried van Sark

PEARL-PV Training School Enschede, 9 March 2022

Contents

- Intro
  - 100%RE
- Security of supply challenge
  - reliability, statistics
- Monitoring: modeled and measured yield
- Conclusion

Introducing myself

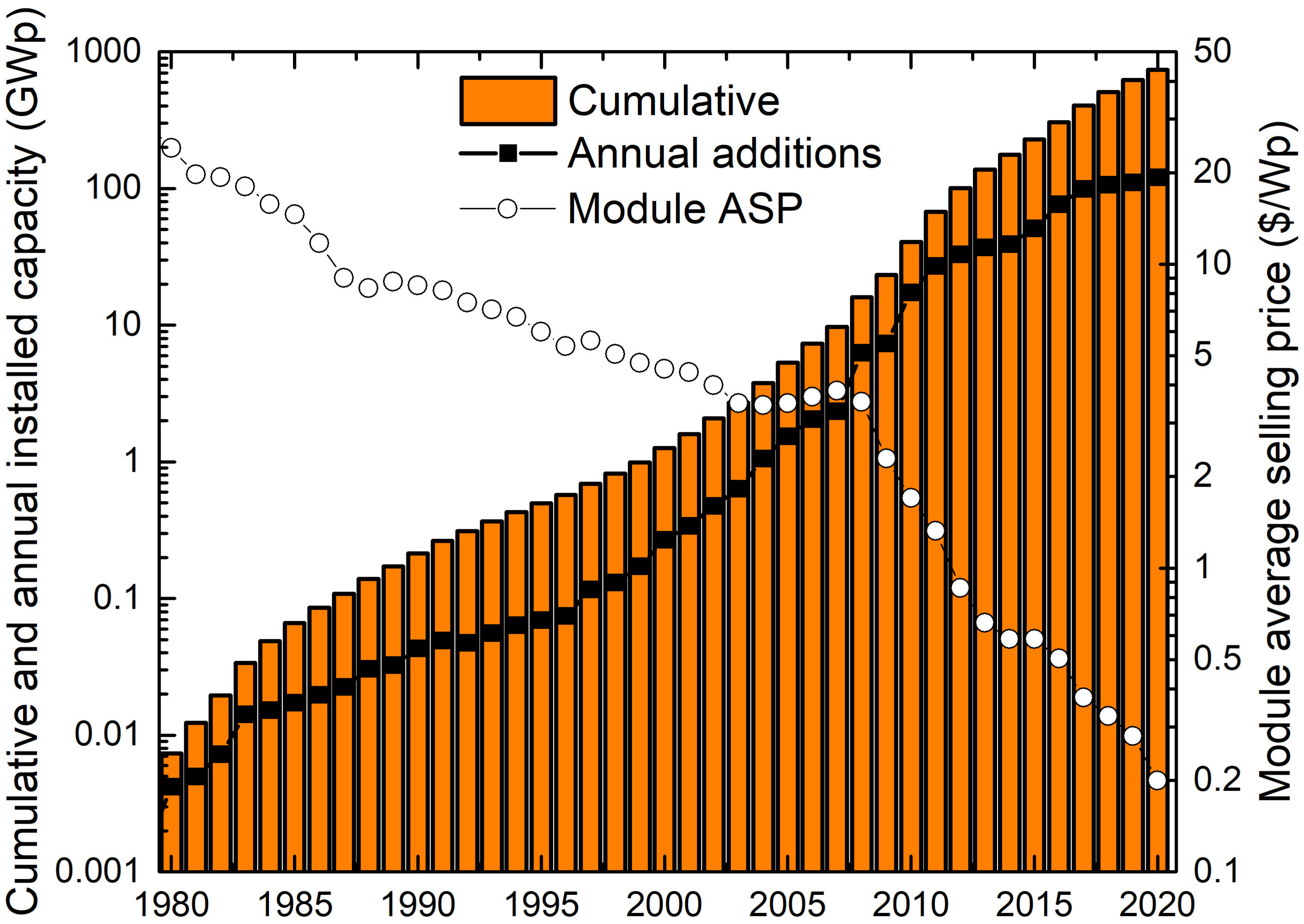
Main research topics

- Integration of PV in grids and integration in buildings
- PV system performance analysis and forecasting
- Energy management using EVs and V2G
- Solar energy harvesting windows (LSC)

Short resume

- Professor of Integration of Photovoltaic Solar Energy, Copernicus Institute, Utrecht University (2018 – present)
- Associate/Assistant Professor Copernicus Institute, Utrecht University (2001 – 2018)
- Postdoc/PhD/MSc/BSc in Experimental Physics on PV cell development (1977– 2001)

PV development 1980-2021



My "PV life"

1982:

20 MWp, 20 $/Wp

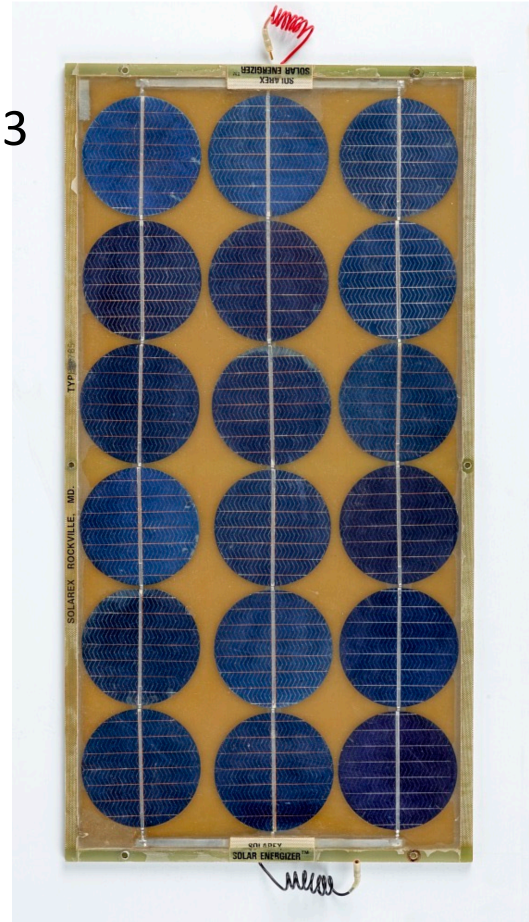
2020:

740 GWp, 0.20 $/Wp

2021:

>900 GWp (est)

1983



Solarex, 50x25cm^2,
3-inch wafers, 10Wp,
3x6=24 cells

1999

Shell Solar ACN 2000E, 95 Wp
12x6=72 10x10 cm^2 cells

2020

Sunpower, 400 Wp
15x15 cm^2 monoSi cells

https://americanhistory.si.edu/collections/search/object/nmah_1804625

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Solar park at Kolham near Hoogezand, one of the big parks that have been realized in the North

Harry Cock, Volkskrant, 10 October 2019

QUIZ

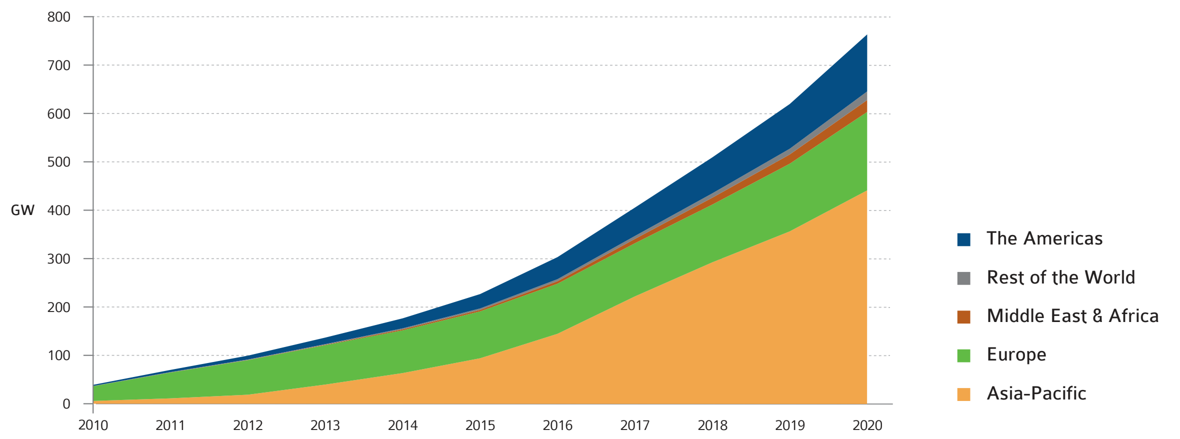
When will the total installed PV capacity globally have reached 1 terawattpeak?

Assumptions:
900 GWp end 2021
annual market 150 GWp
→ 1 September 2022

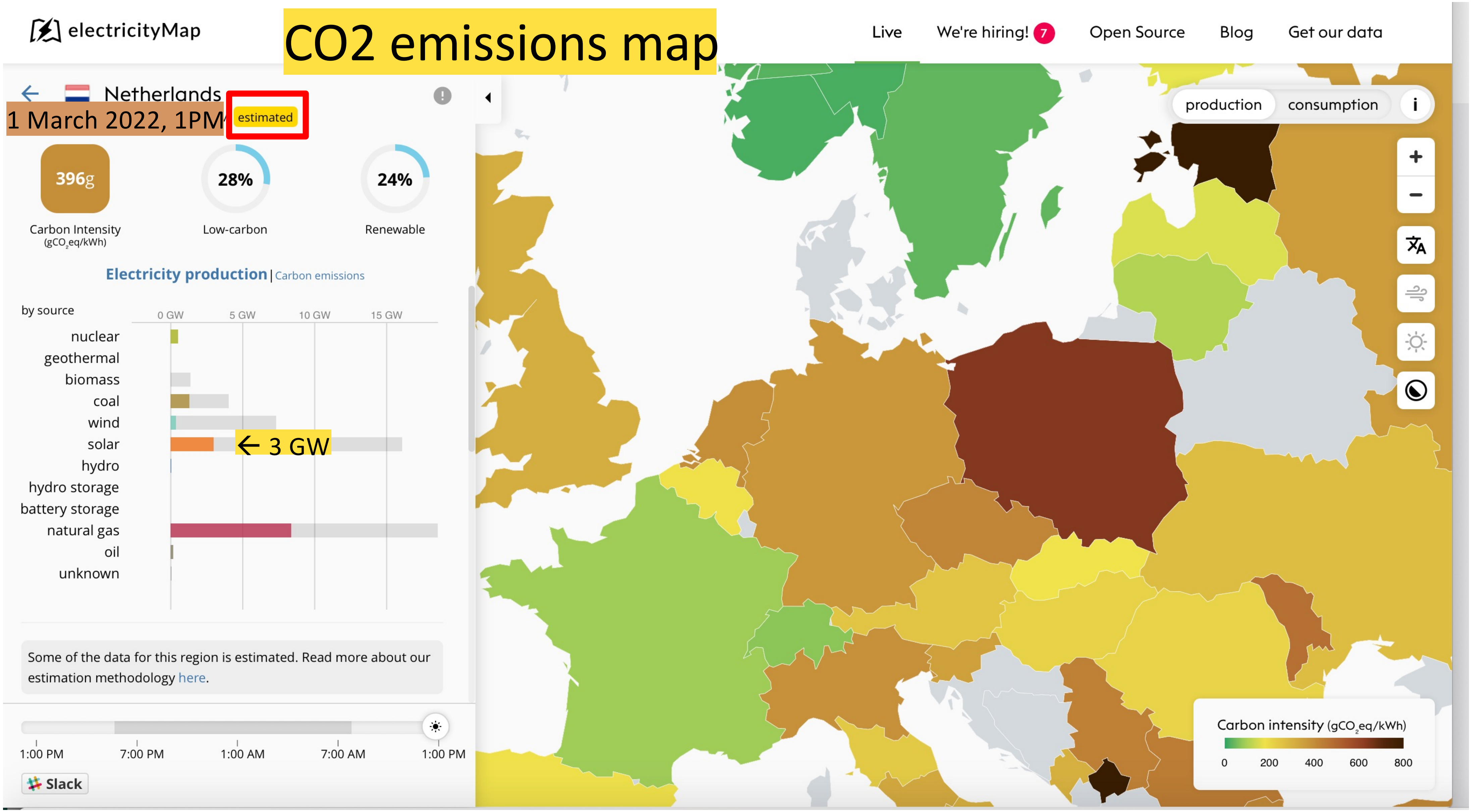
Europe

- Globally installed PV (2020): 740 GWp → 1000 TWh
- In Europe: 150 GWp → 200 TWh
- Growth has been slow in the past years

FIGURE 2.7: EVOLUTION OF REGIONAL PV INSTALLATIONS

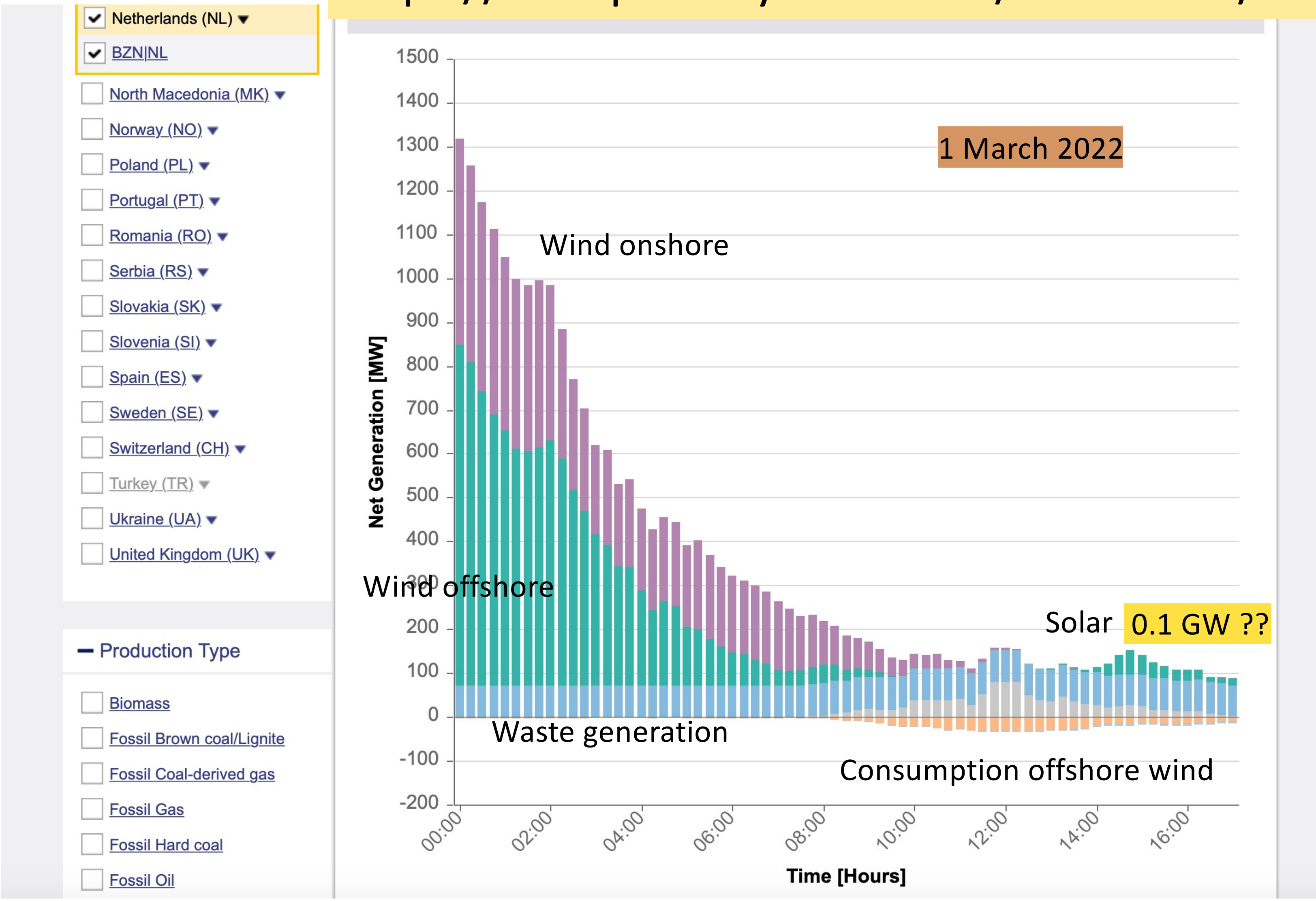


IEA-PVPS, Trends in Photovoltaic Applications 2021


electricityMap
CO2 emissions map
Live
We're hiring! 7
Open Source
Blog
Get our data
Netherlands
1 March 2022, 1PM
estimated
396g
Carbon Intensity (gCO2eq/kWh)
28%
Low-carbon
24%
Renewable
Electricity production | Carbon emissions
by source
0 GW
5 GW
10 GW
15 GW
nuclear
geothermal
biomass
coal
wind
solar
← 3 GW
hydro
hydro storage
battery storage
natural gas
oil
unknown
Some of the data for this region is estimated. Read more about our estimation methodology here.
1:00 PM
7:00 PM
1:00 AM
7:00 AM
1:00 PM
Slack
production
consumption
Carbon intensity (gCO2eq/kWh)
0
200
400
600
800

ENTSOE

https://transparency.entsoe.eu/dashboard/show



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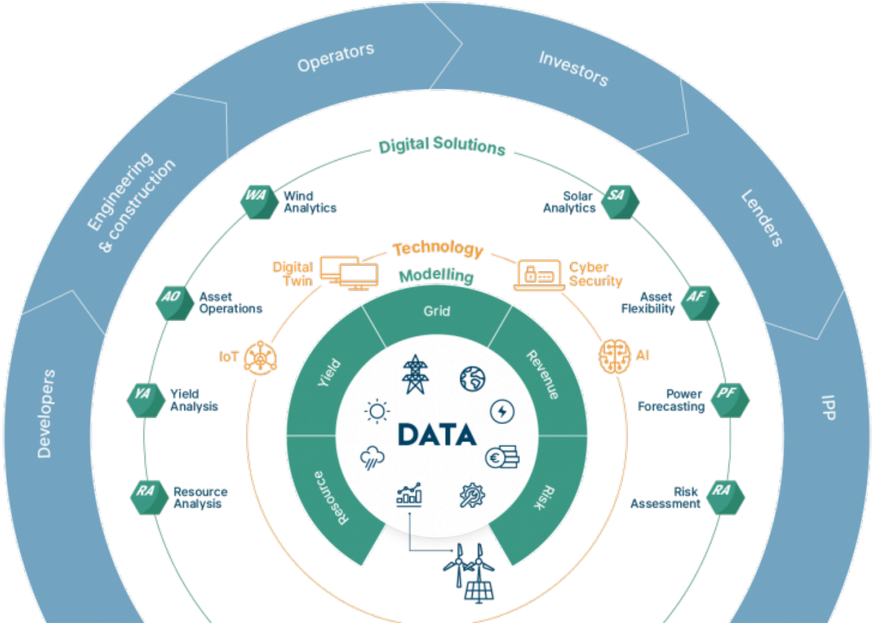
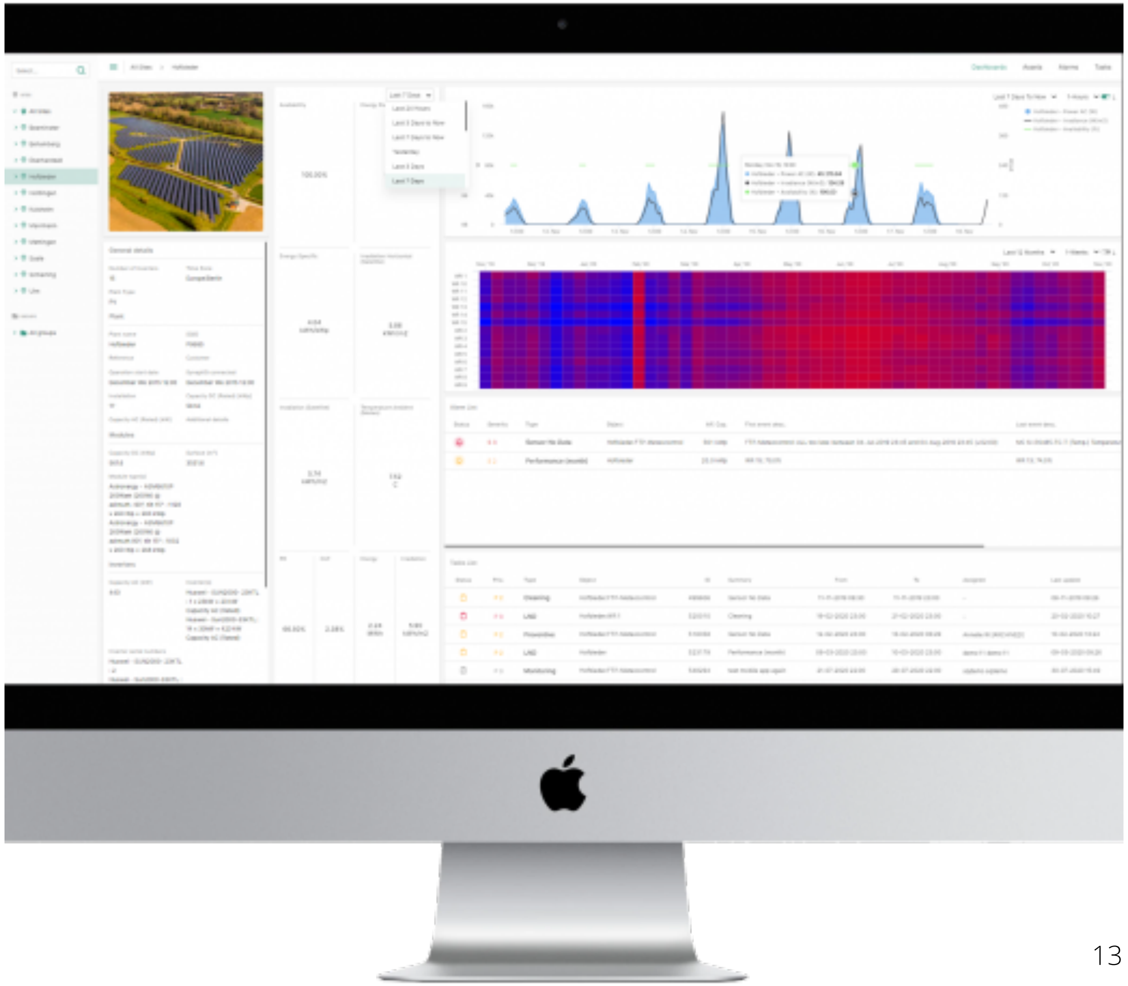
PV in Europe

- Generated amount of electricity? CALCULATED!
- Conventional power plants: properly monitored (~7000)
  - JRC Open Power Plants Database (JRC-PPDB-OPEN)
- Wind/solar parks monitored (utility scale)
  - Supervisory Control And Data Acquisition (SCADA)
  - Measured yield determines subsidy!
- Residential PV monitored???

SCADA (example: 3E, Synaptic)





Residential monitoring (example: SMA)

Inverter with display

Inverter with app

Residential monitoring (example: SolarLog)

connected to inverter

Residential monitoring (example: SolarCare)

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SolarCare

Residential monitoring (example: PVOutput.org)

1900 systems
10.135 MWp
→ 5.3 kWp
system average

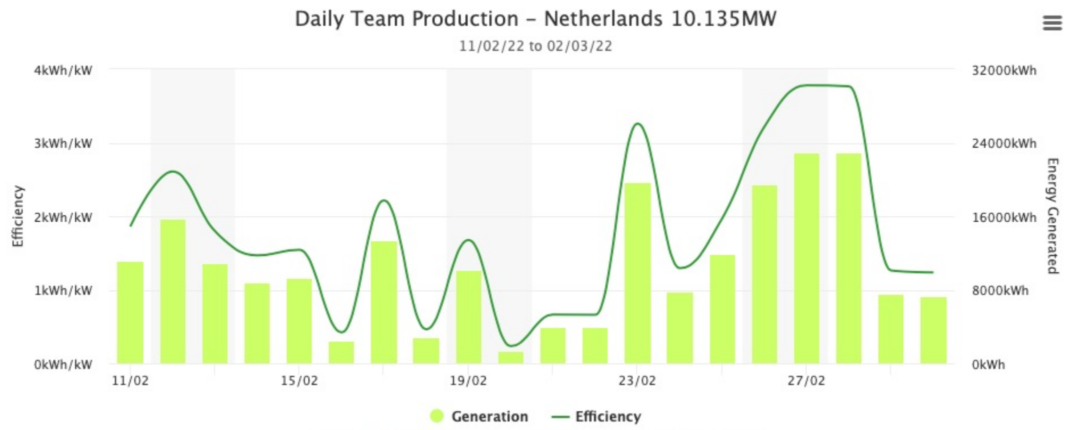
Web and app

PVOutput 4+
Corrado Bellini
Ontworpen voor iPhone
3,0 • 2 beoordelingen
Gratis
Bekijk in de Mac App Store ↗

PVOutput

You are logged in as **wvansark**

Add Output | Your Outputs | PV Ladder | Statistics | Live Outputs | Teams | Favourites | Settings | Community | Donations | Help | Logout



Prev 1 2 3 4 5 6 7 8 9 10 11 Next

Live | Weekly | Monthly | Yearly | Map | Join or Leave Team | Comments

Health 60% **$2,570** · **1896** Members · **22,621** Outputs · **38.3** GWh

Netherlands 10.135MW

Compare: Tips

Date	Generated	Efficiency	Consumption	Exported	Imported	Credit	Debit	Balance	Low	High	Average	Outputs
02/03/22	7.322MWh	1.236kWh/kW	2.755MWh	2.174MWh	1.860MWh	$528.07	$341.47	$186.60	0.000kWh	400.910kWh	6.602kWh	1109
01/03/22	7.622MWh	1.262kWh/kW	5.810MWh	1.950MWh	4.484MWh	$461.85	$787.75	($325.90)	0.000kWh	423.517kWh	6.738kWh	1131
28/02/22	22.968MWh	3.766kWh/kW	5.977MWh	7.128MWh	3.909MWh	$1,701.14	$687.11	$1,014.03	0.000kWh	1,179.060kWh	20.112kWh	1142
27/02/22	22.997MWh	3.780kWh/kW	12.018MWh	7.463MWh	10.291MWh	$1,693.13	$2,088.03	($394.90)	0.000kWh	1,137.540kWh	20.190kWh	1139
26/02/22	19.507MWh	3.218kWh/kW	4.812MWh	6.097MWh	3.150MWh	$1,390.35	$509.82	$880.53	0.000kWh	1,099.260kWh	17.186kWh	1135
25/02/22	11.923MWh	1.969kWh/kW	5.988MWh	3.339MWh	4.556MWh	$803.60	$802.14	$1.46	0.000kWh	680.480kWh	10.514kWh	1134
24/02/22	7.808MWh	1.294kWh/kW	6.778MWh	2.204MWh	5.707MWh	$521.19	$883.68	($362.49)	0.000kWh	405.810kWh	6.909kWh	1130
23/02/22	19.756MWh	3.260kWh/kW	6.196MWh	6.137MWh	4.459MWh	$1,473.22	$701.77	$771.45	0.000kWh	983.750kWh	17.406kWh	1135
22/02/22	3.970MWh	0.660kWh/kW	6.790MWh	890.387kWh	6.010MWh	$213.75	$922.49	($708.74)	0.000kWh	304.640kWh	3.522kWh	1127

PV installations: Residential vs utility scale

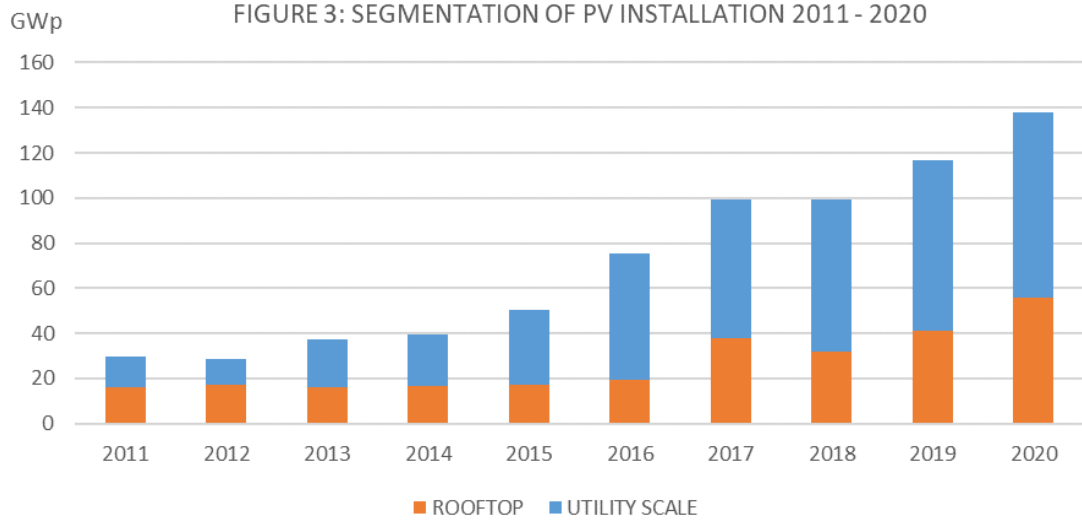
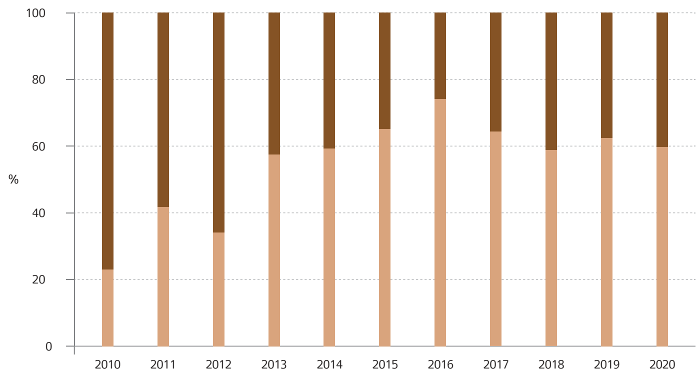
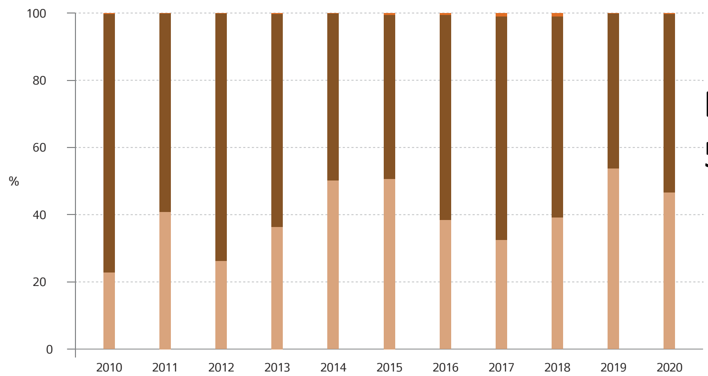


FIGURE 2.13: ANNUAL SHARE OF CENTRALIZED AND DISTRIBUTED GRID-CONNECTED INSTALLATIONS 2010 - 2020



Global:
40% residential

FIGURE 2.19: EVOLUTION OF PV INSTALLATIONS IN EUROPE PER SEGMENT



Europe:
50% residential

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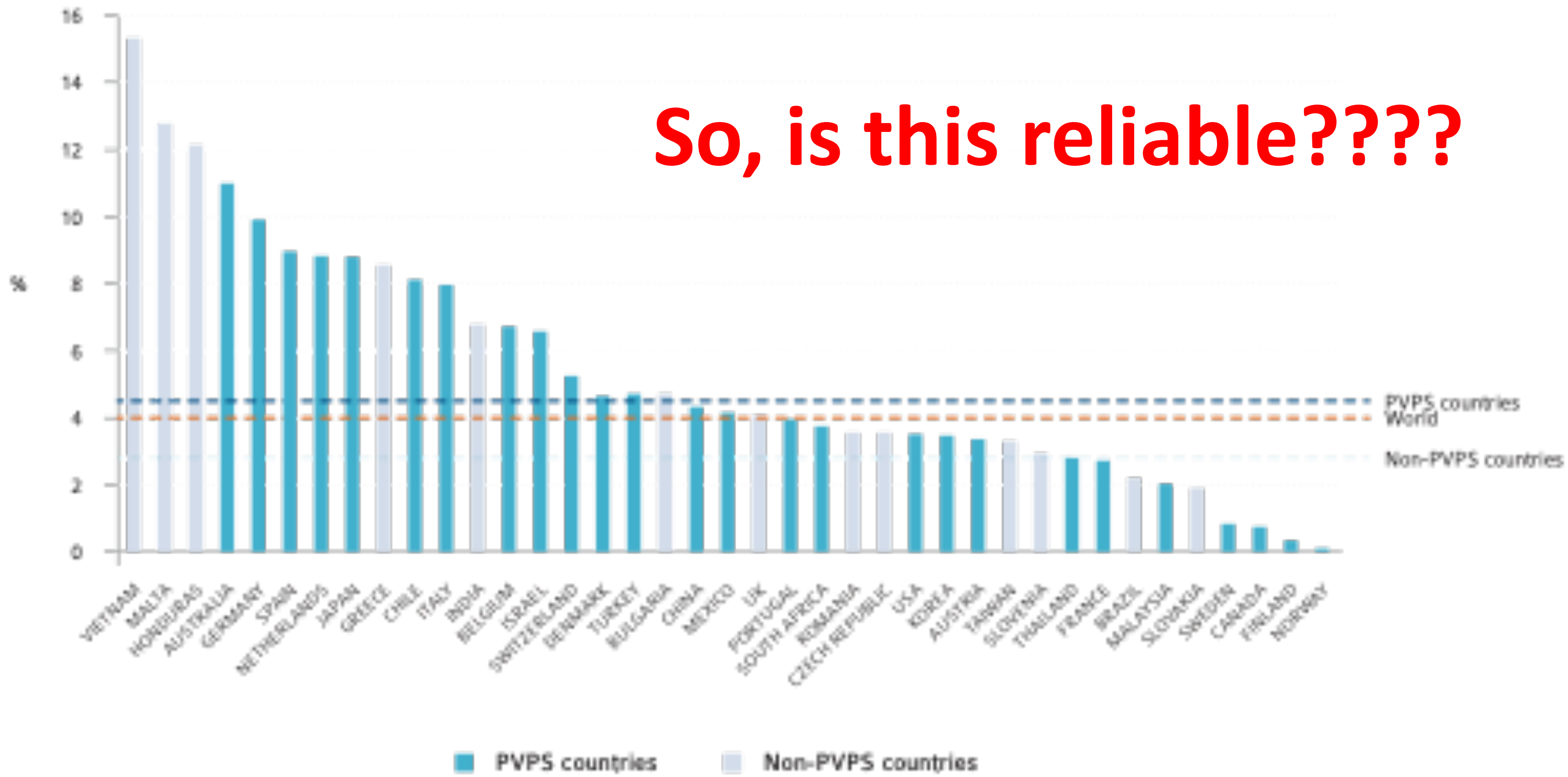
IEA-PVPS, Trends in Photovoltaic Applications 2021

For half of PV capacity monitoring data is not available or difficult to access

PV contribution to electricity demand in 2020

So, is this reliable????



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PV in Europe

- **CALCULATED** contribution of PV to electricity is a few percent, so **TODAY** data unavailability is a **minor** issue

- With PV as major contributor (backbone!) to 100% renewable society, data unavailability is a **major** issue, and unacceptable

- Security of supply is at stake, loss of load probability (LOLP) less than x (3?) hours per year

2050: A 100% global renewable energy system with ZERO CO2 emission

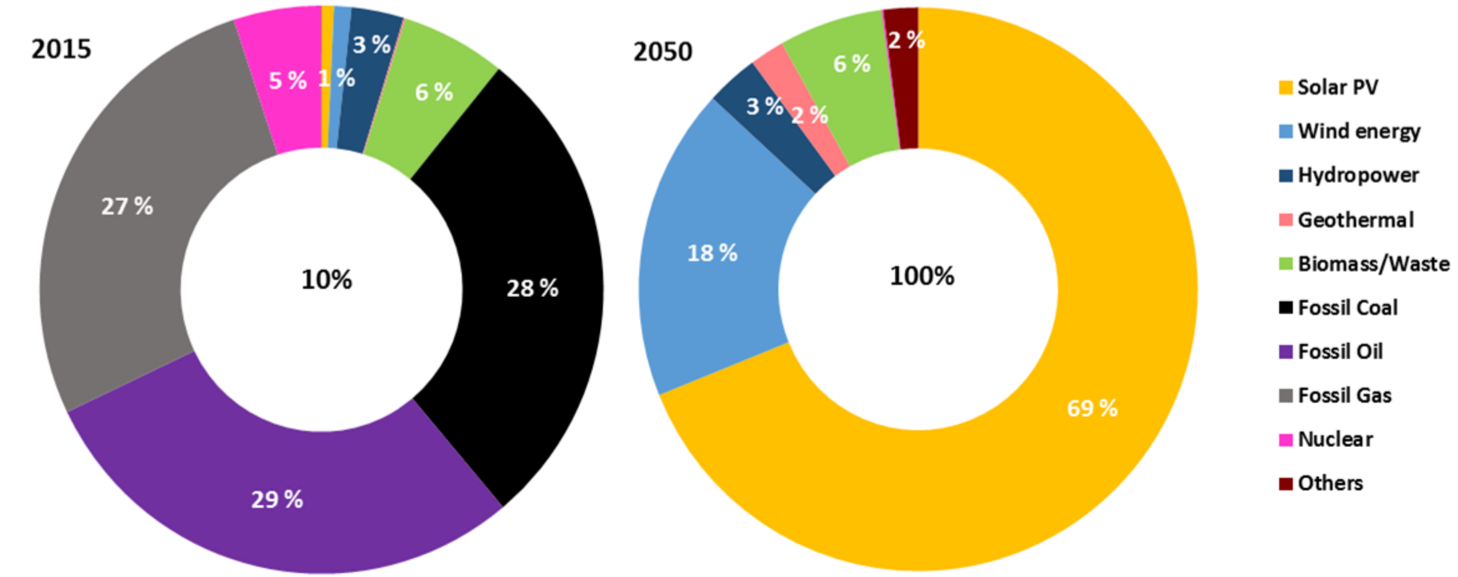
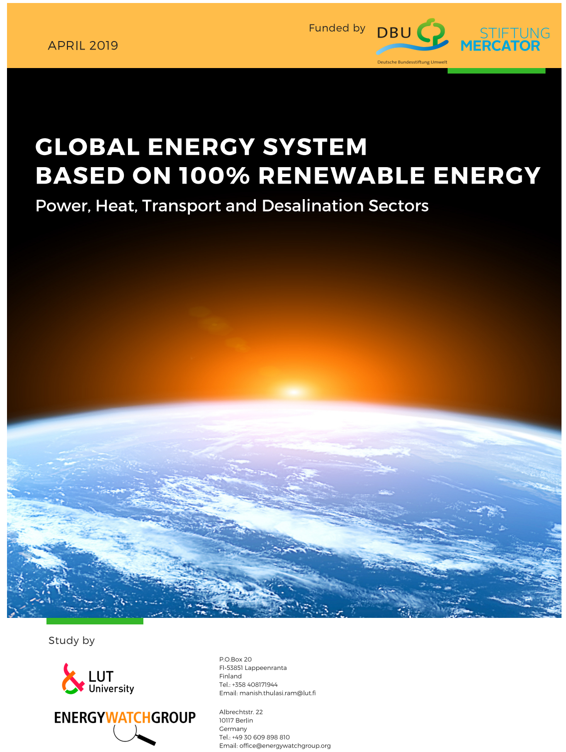
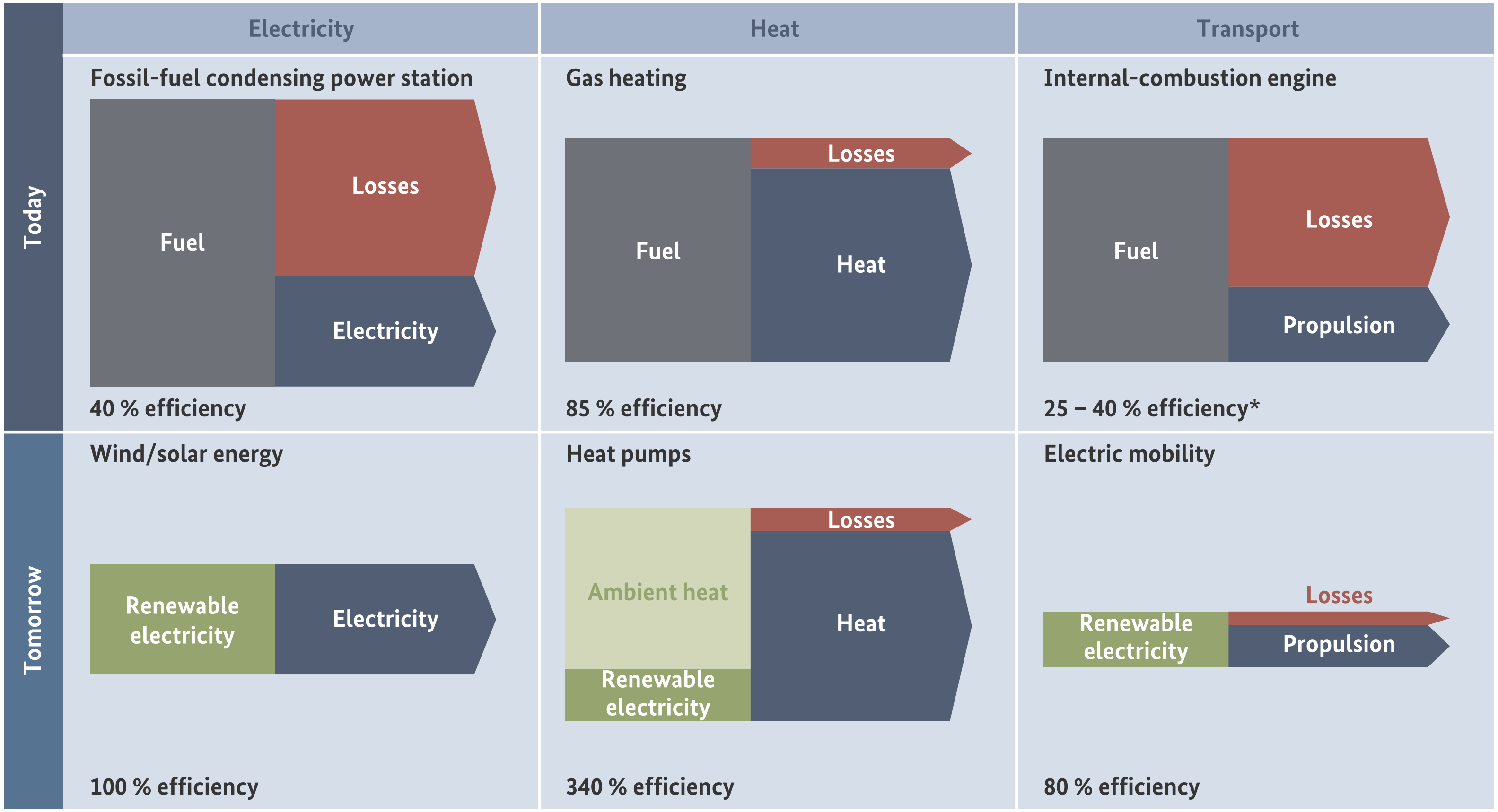


Figure KF-2: Shares of primary energy supply in 2015 and 2050.



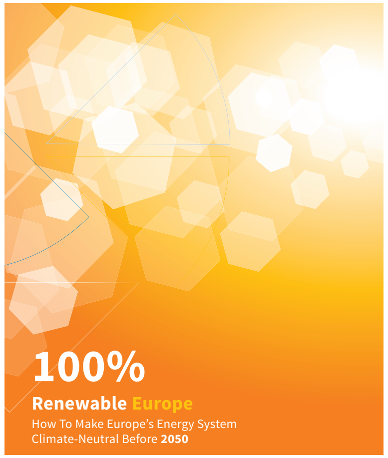
63.4 TW PV
8 TW wind

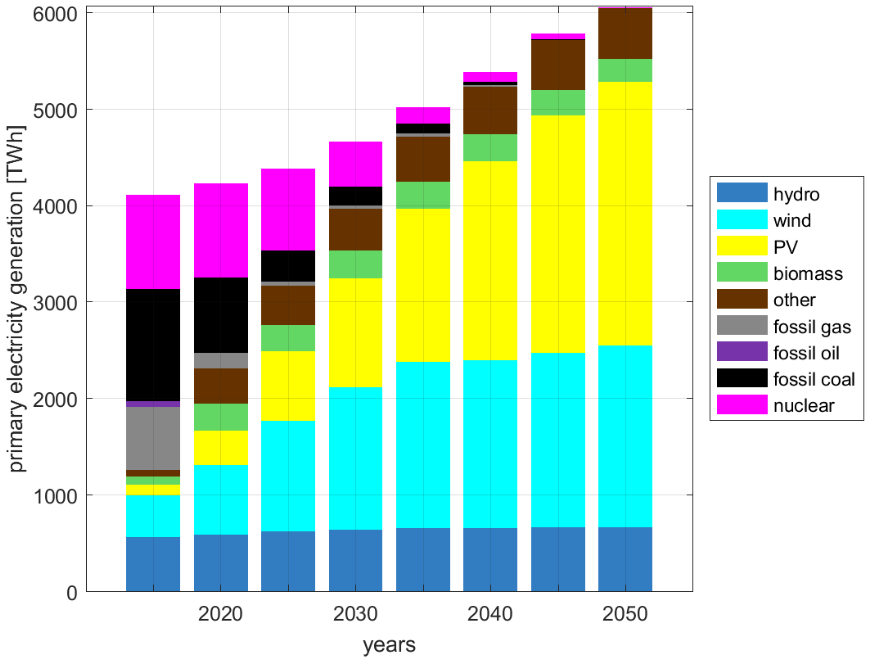
Renewable electricity is backbone

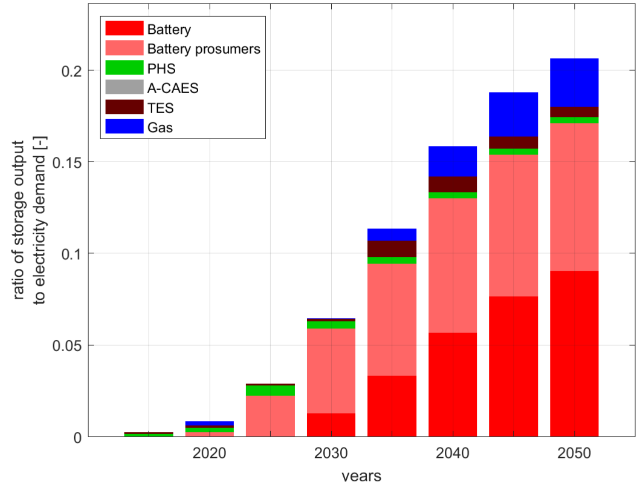


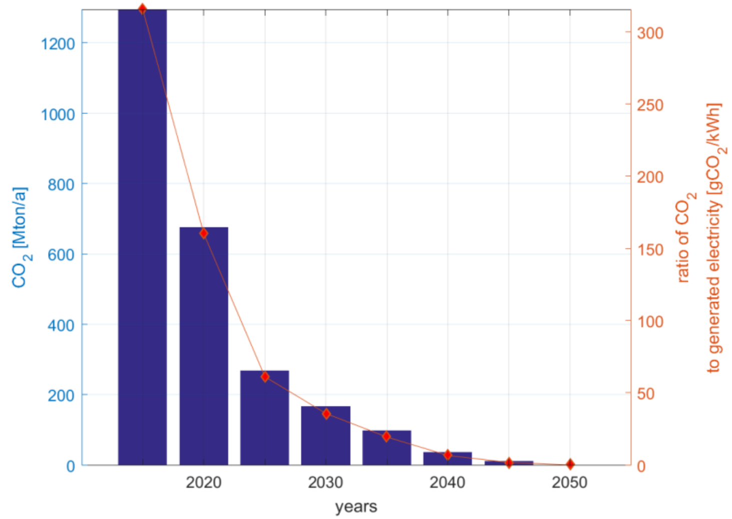
Brown et al, RSER 2018

Energy Transition Modeling: Europe (Breyer, Solar Power Europe)









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Challenges

- Inventory of all PV installations in all the regions of the world → installed capacity

- Database of annual (monthly/daily/hourly/quarterly) energy yield → contribution to electricity demand

- Realtime power production required for grid management (HV/MV/LV, TSO/DSO)

Data availability – Utility Scale PV

- Example Netherlands
  - Utility scale
    - CertiQ issues Guarantees/Certificates of Origin for renewable electricity, and registers PV systems >15 kWp for receiving subsidy (SDE++) per kWh generated
    - A calibrated energy sensor is required to be installed per system
    - Annual yield is reported

Data availability – Residential PV

- Residential scale Netherlands
  - By law, every PV system owner must register PV system (or his/her installer), however this is not enforced
  - National register CERES, also includes wind, biomass, small hydro)
  - NO information on tilt/azimuth is provided
  - Statistics Netherlands (CBS) collects all data: only about 80% of residential systems is actually registered

Data availability – Residential PV

- Residential scale Netherlands
  - Smart meter collects data, demand and net energy fed back into the grid: self consumption is subtracted from PV generation
  - Smart meter data is private (GPDR)
  - Contribution to electricity demand can only be ESTIMATED

Contribution to electricity demand -NL

- Estimation procedure Statistics Netherlands (CBS)
- Installed capacity on 1 January and 31 December of year YY
- Calculate average addition in year YY
- Multiply with average agreed annual yield of 875 kWh/kWp

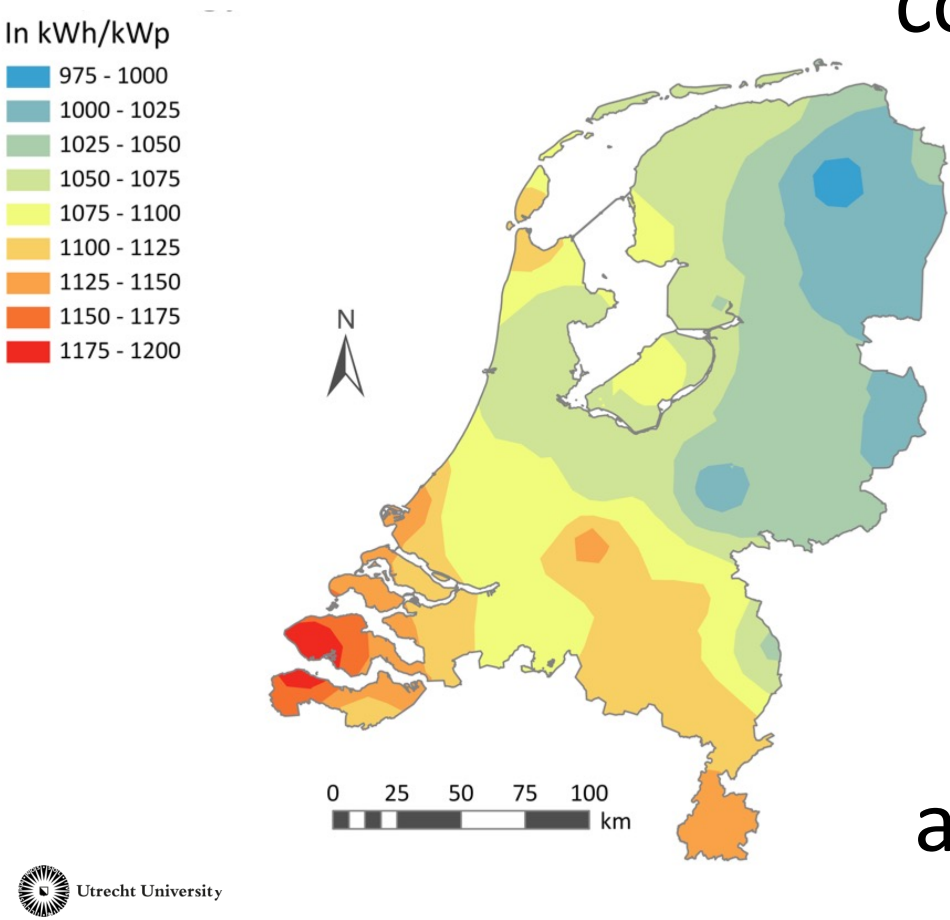
- For 2021: (14+10)/2 x 875 = 10 TWh
- About 9% of present Dutch electricity demand

Contribution to electricity demand -NL

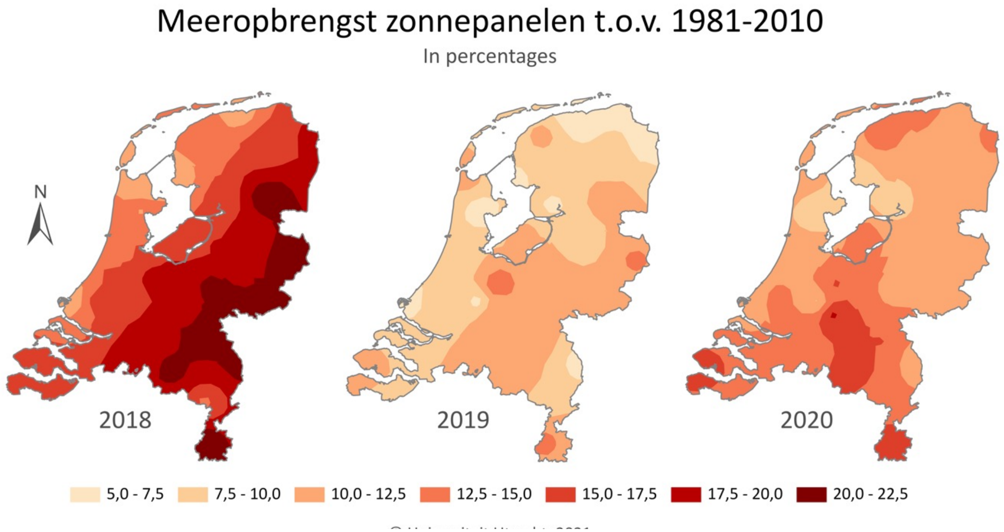
- Revised procedure suggested
- Use monthly average capacity, per municipality/province
- Use meteorological data to calculate monthly yield, spatially resolved
- Sum to get national estimate

- Calculations to be validated, using a representative set of monitored PV systems
- CRUCIAL: are the PV systems running as expected?

Annual yield (2020)



Yield increase compared to 1981-2020 average



CALCULATED

assumptions: south, 37° tilt

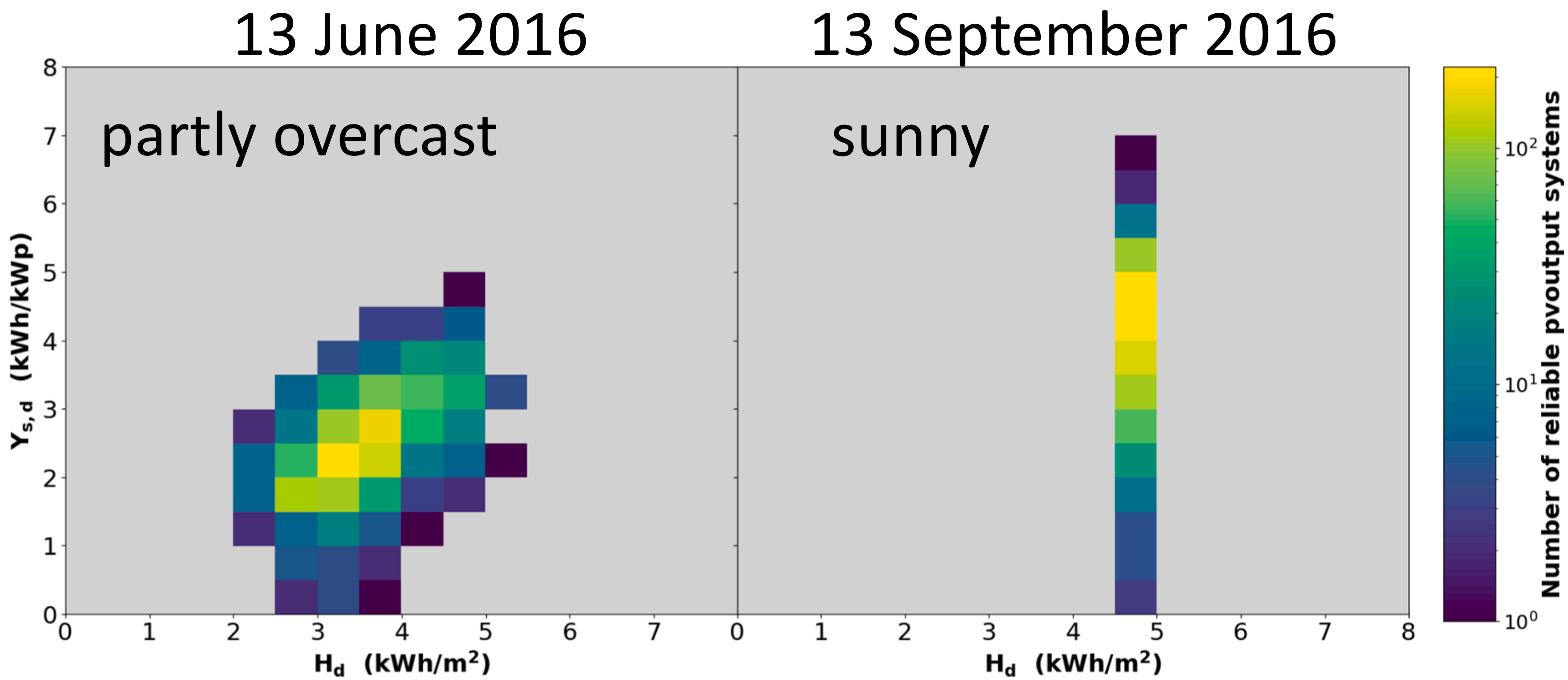
no malfunctions/shade

Statistical analysis of monitoring

- Use PVoutput.org systems in the Netherlands, 50 MWp
- Meta data (static, time independent): 2016 and 2017
  - power: number of panels (*Np*), panel power (*Pp*), total system size (*P*), inverter size (*Pi*) and number of inverters (*Ni*).
  - geometry: azimuth (φ) and tilt (ϑ)
  - brand: panel and inverter brands
  - location: Postal code 4 (pc4) area , longitude (*l*) and latitude (*b*)
  - time: installation date of the system (*d*)
- Energy data:
  - instantaneous (*Yinst*) and cumulative (*Ycum*), with time stamp

Laevens et al., Solar Energy 228 (2021) 12–26

Distribution of daily yield vs daily irradiance sum



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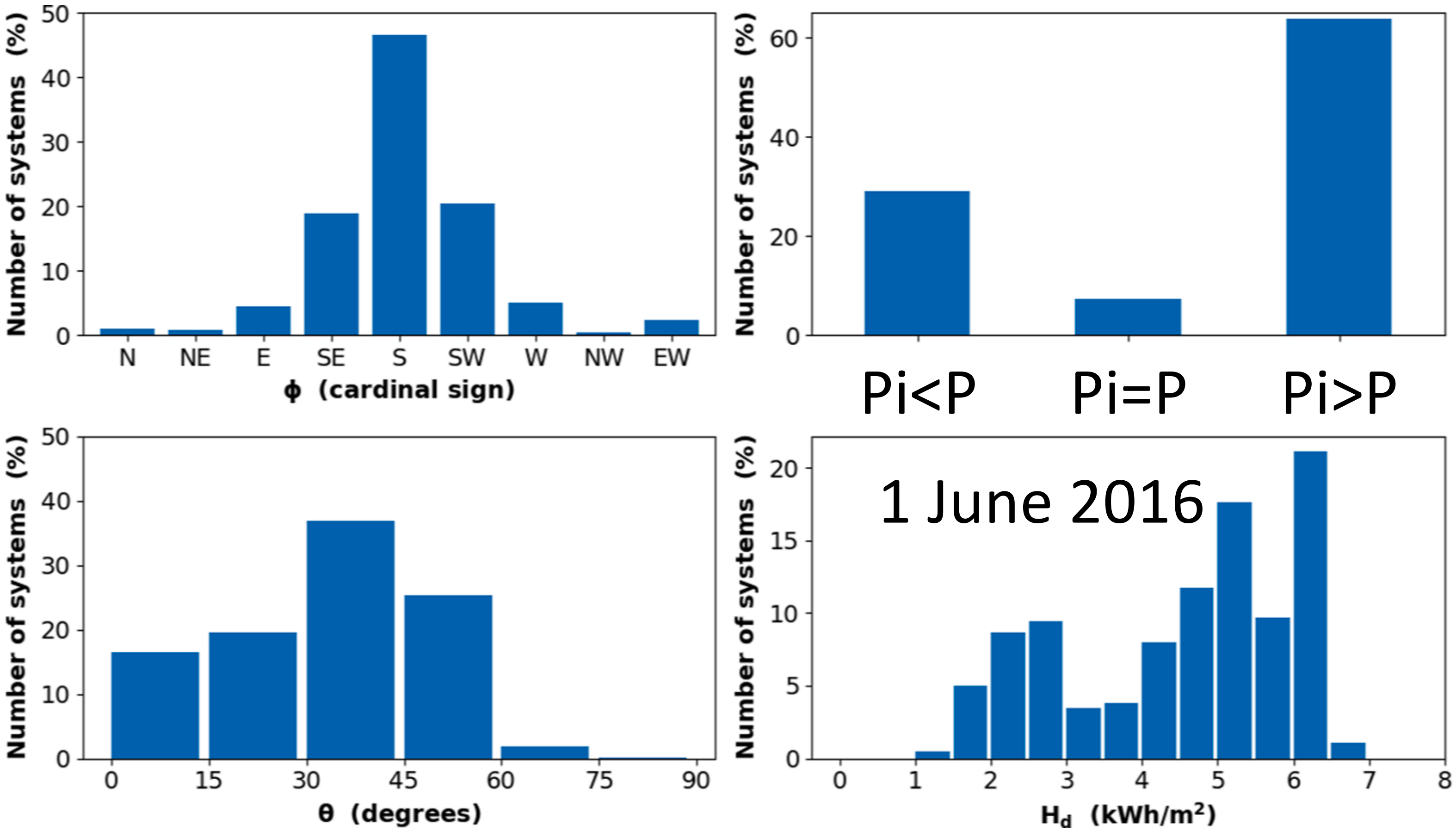
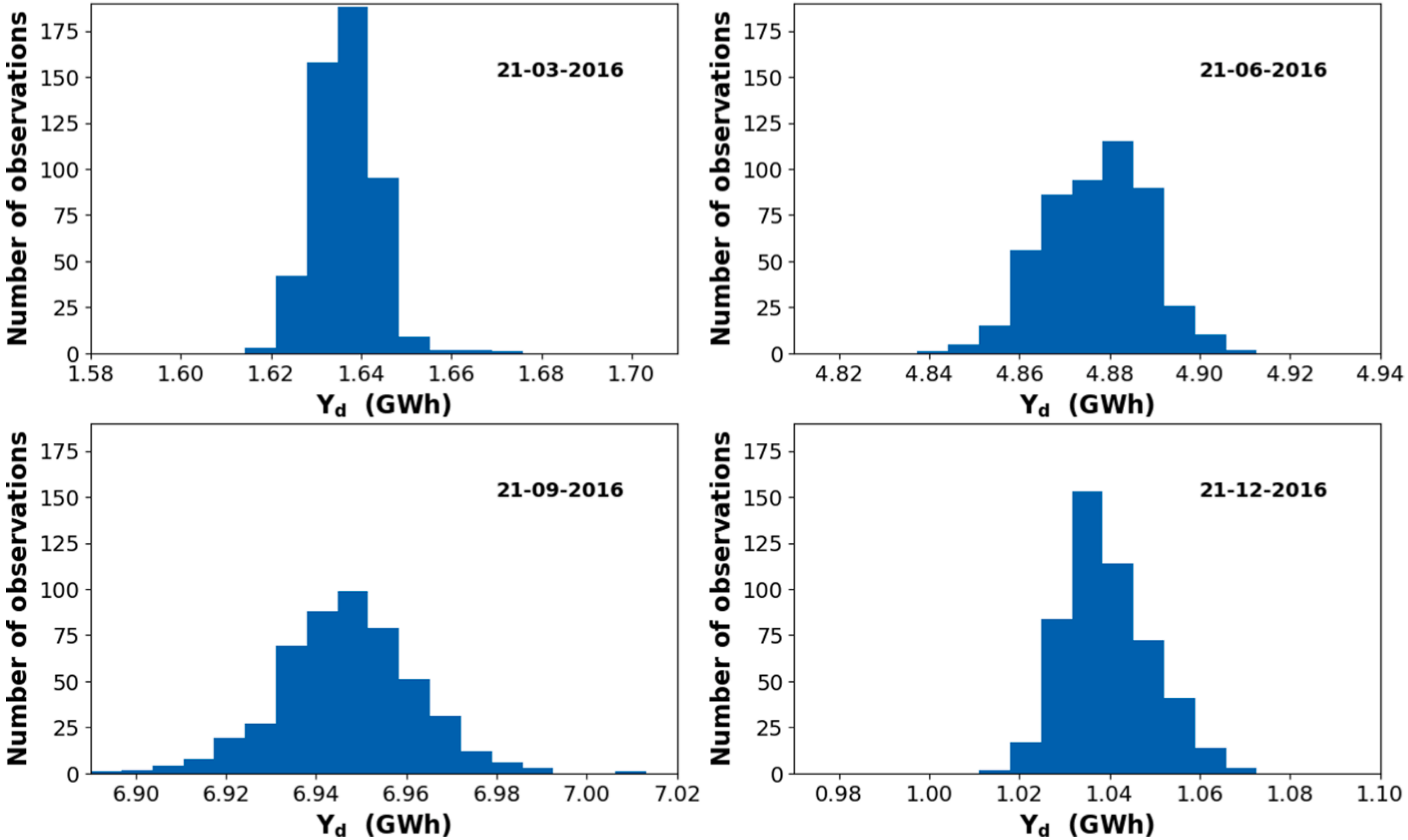
Laevens et al., Solar Energy 228 (2021) 12–26

Distribution of orientation, tilt, inverter loading ratio



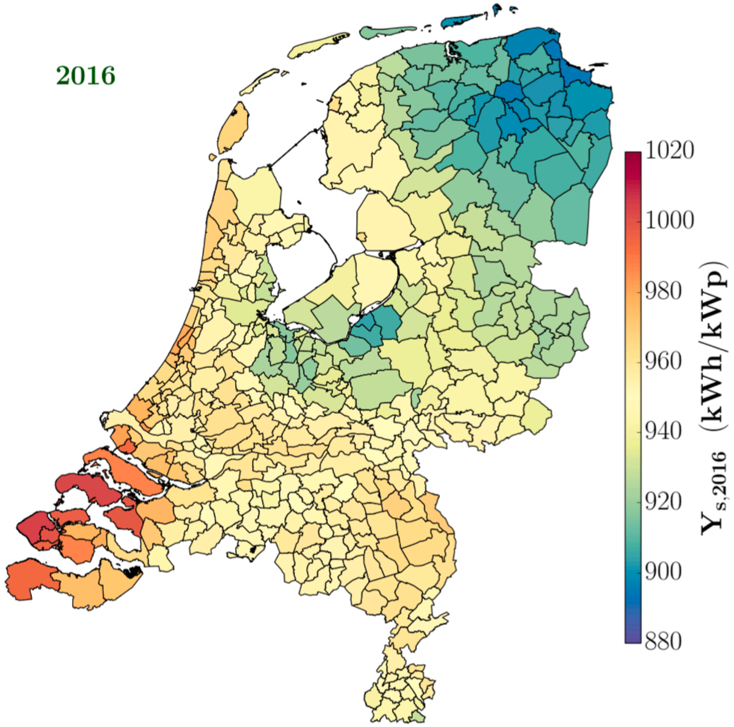
Laevens et al., Solar Energy 228 (2021) 12–26

Distribution of daily yield at solstices

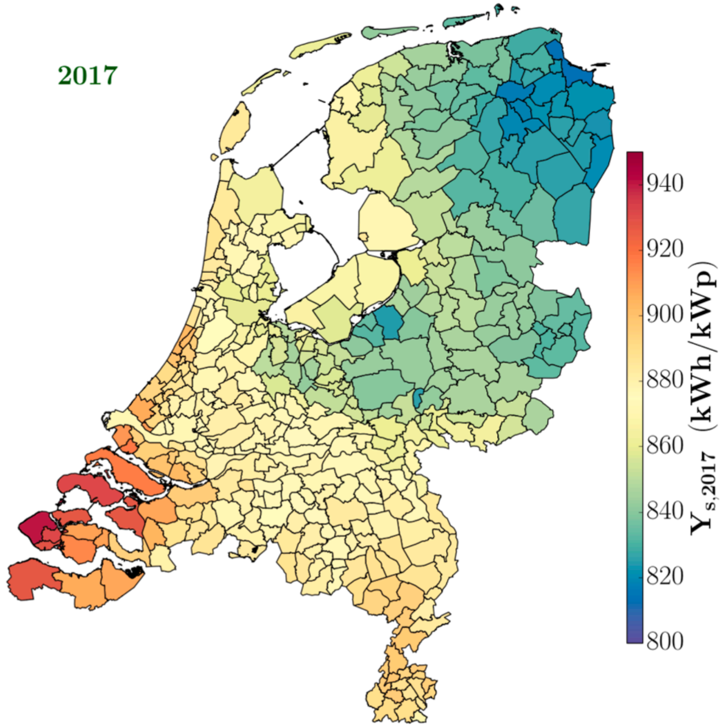


Laevens et al., Solar Energy 228 (2021) 12–26

Geographical distribution of annual yield



Yield: 877 – 946 kWh/kWp



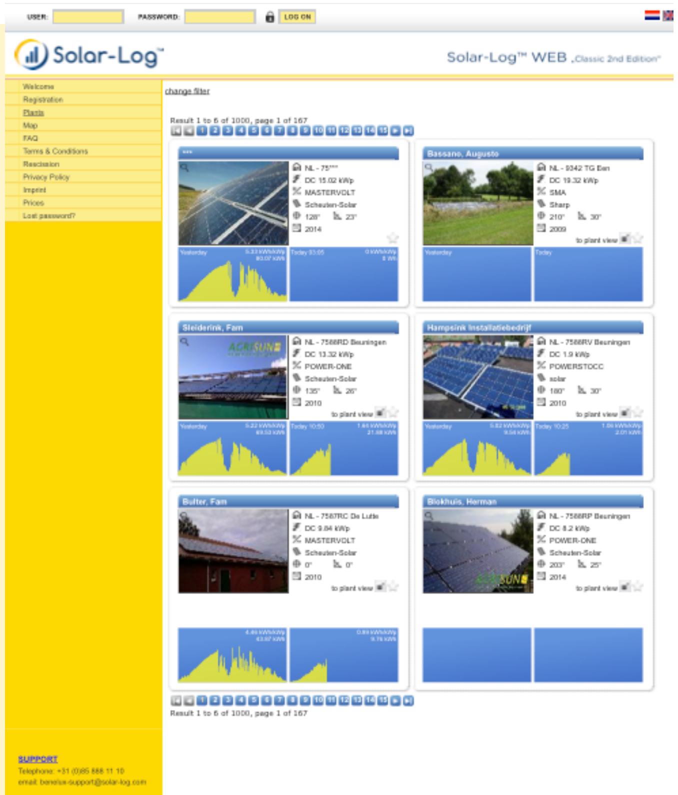
Yield: 838 – 899 kWh/kWp

Used yield by CBS: 875 kWh/kWp

Laevens et al., Solar Energy 228 (2021) 12–26

Monitoring - webscraping data

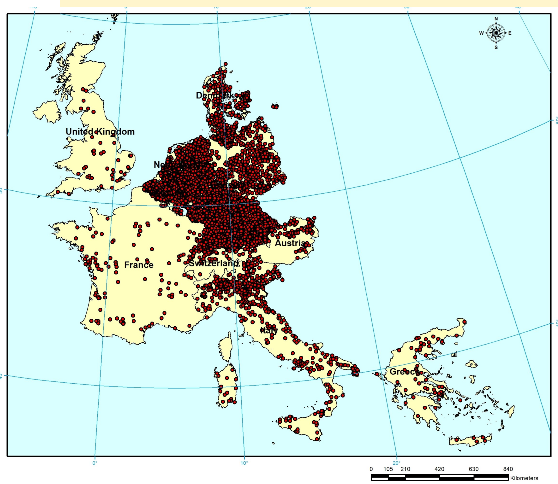
- Market is introducing web tools for system owners to share monitor data, e.g., SolarLog
- This data can (could…) be obtained by web scraping techniques
- “What you see, is what you can extract”
- Python scripts developed to mimic human navigation

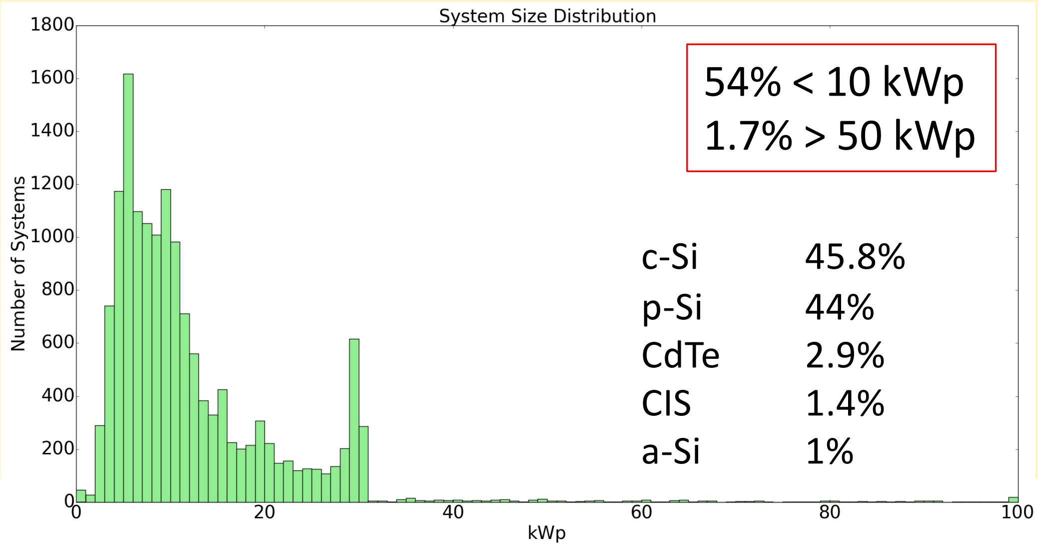


Kausika et al., Energies 2018, 11, 1330.

Monitoring - webscraping data

- Data from systems in the Netherlands, Germany, United Kingdom, France, Italy, Greece
- Daily AC and DC yields and PV system details (orientation, tilt, size)





Kausika et al., Energies 2018, 11, 1330.

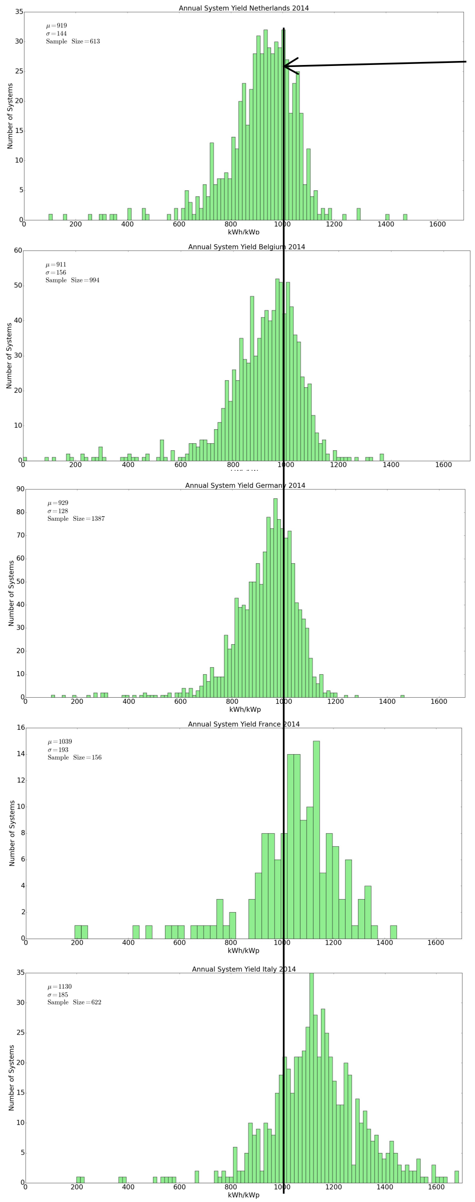
Netherlands

Belgium

Germany

France

Italy



1000 kWh/kWp

Annual yield <u>2014</u>

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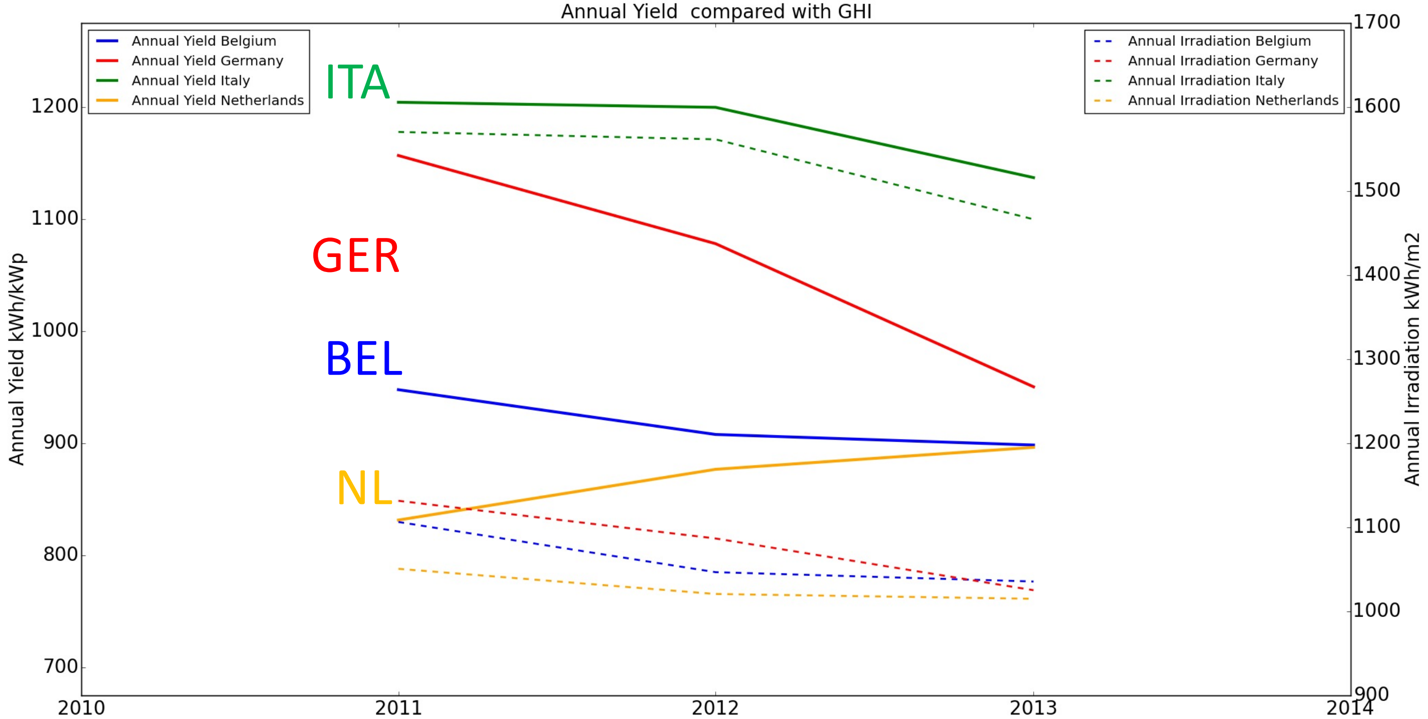
Kausika et al., Energies 2018, 11, 1330.

Well correlated annual yields and GHI

Yield/GHI
NL: increases
GER: slightly decreases

Scale yield axis is 0.75 times scale irradiation axis



Kausika et al., Energies 2018, 11, 1330.

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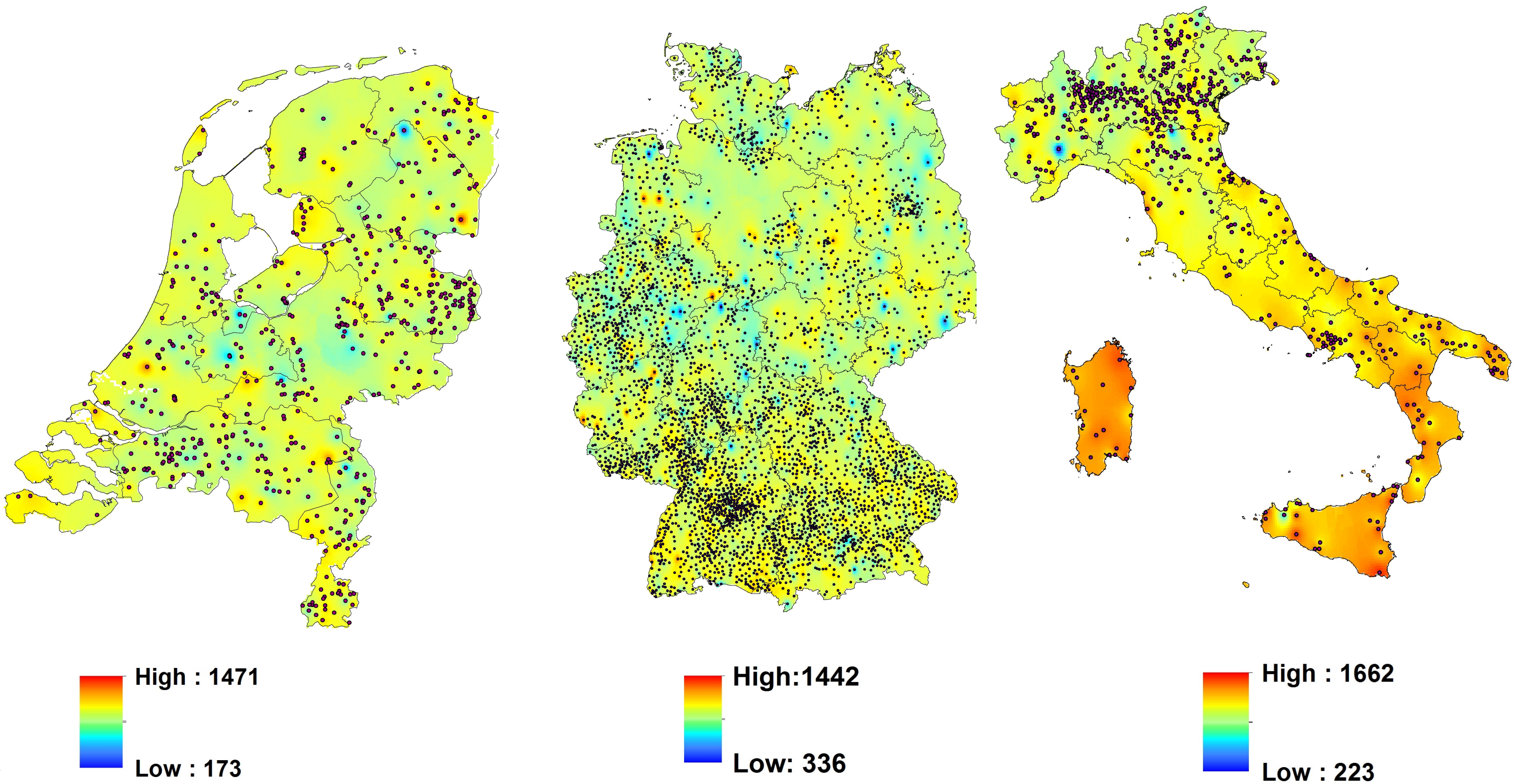
GIS mapping of yield 2014



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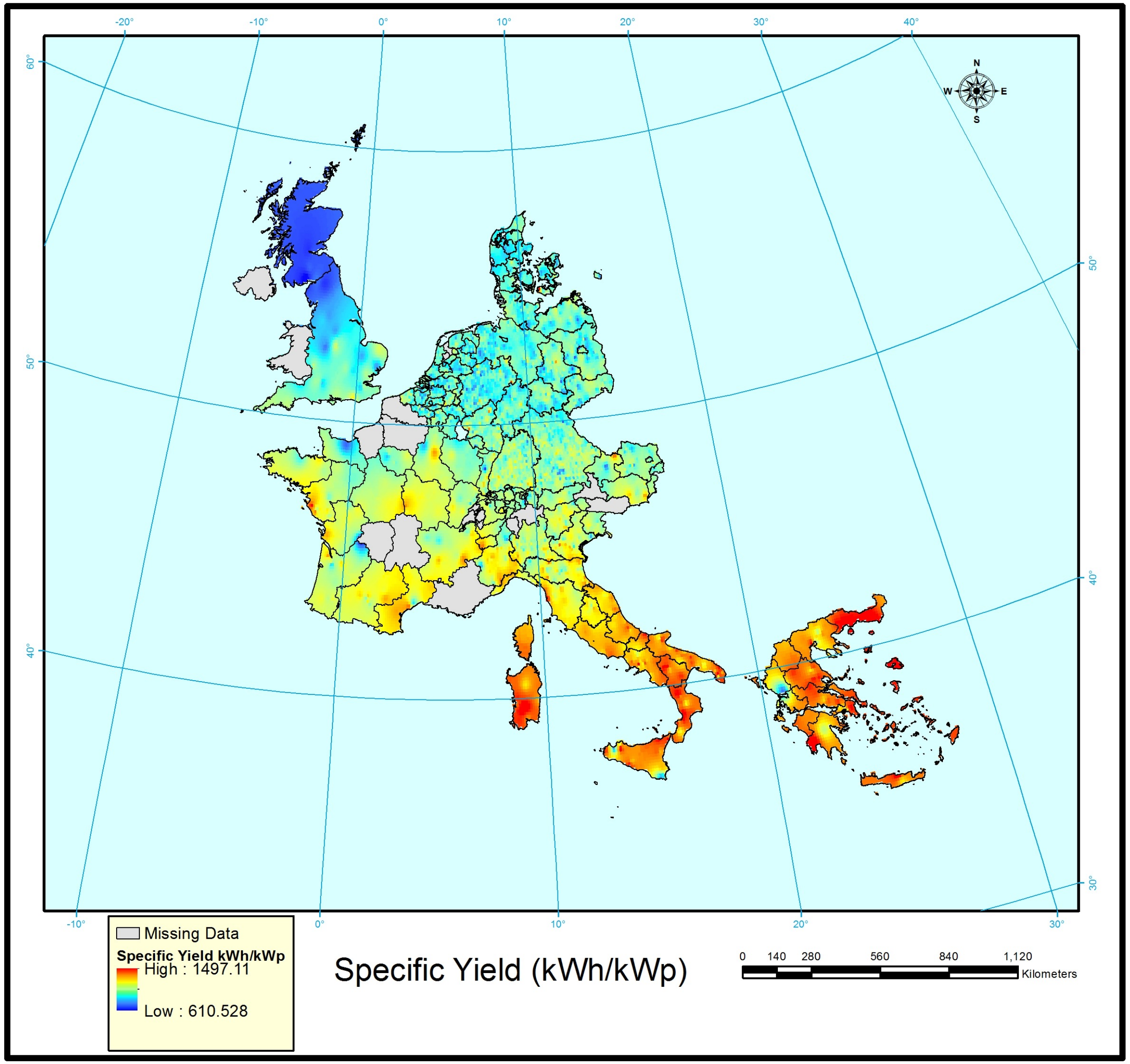
Kausika et al., Energies 2018, 11, 1330.



Kausika et al., Energies 2018, 11, 1330.

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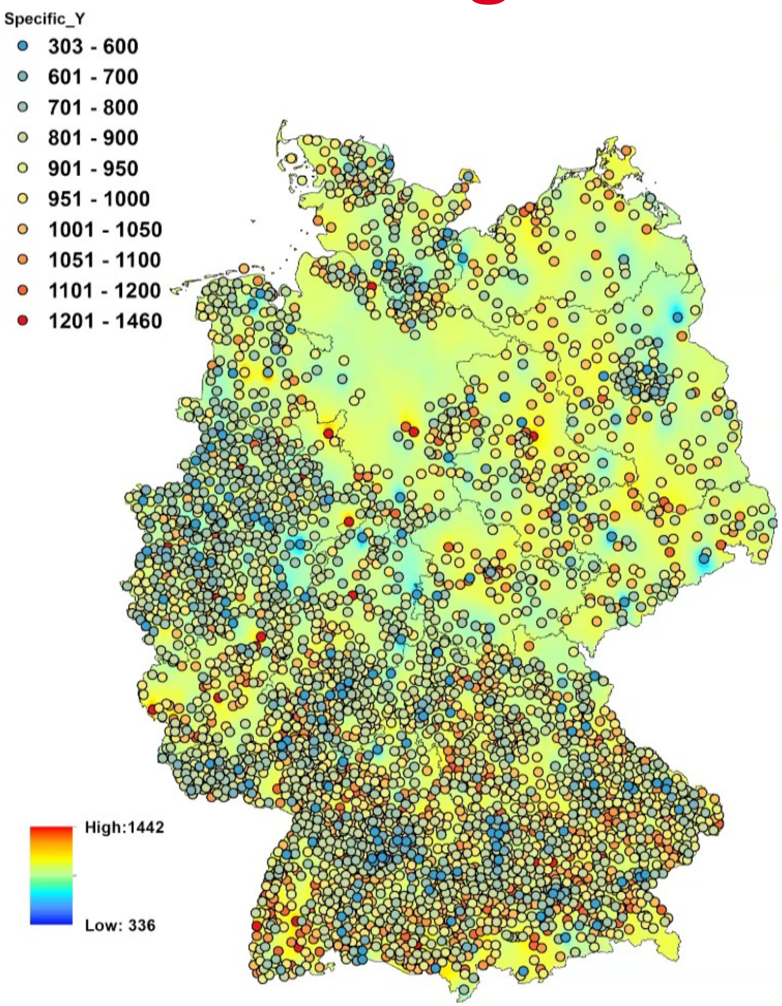
Moving the colors



Color coding allows to find underperforming systems

Move through colors to visualize them

Movie
Start: all systems
Then, from low to high yield

Higher yield in south due to higher irradiation

Monitoring – global study

- Worldwide study using 2,802,797 PV systems located in Europe, USA, Japan and Australia, representing a total capacity of 59 GWp
- Various data sources combined: PVoutput.org, solar-log, sonnenertrag, openpv.nrel.gov, jyuri.jp, bundesnetzagentur.de, bdpv.fr
- Data records: installed capacity (100%), valid tilt/azimuth (11%), location (97%), specific annual yield (70%)

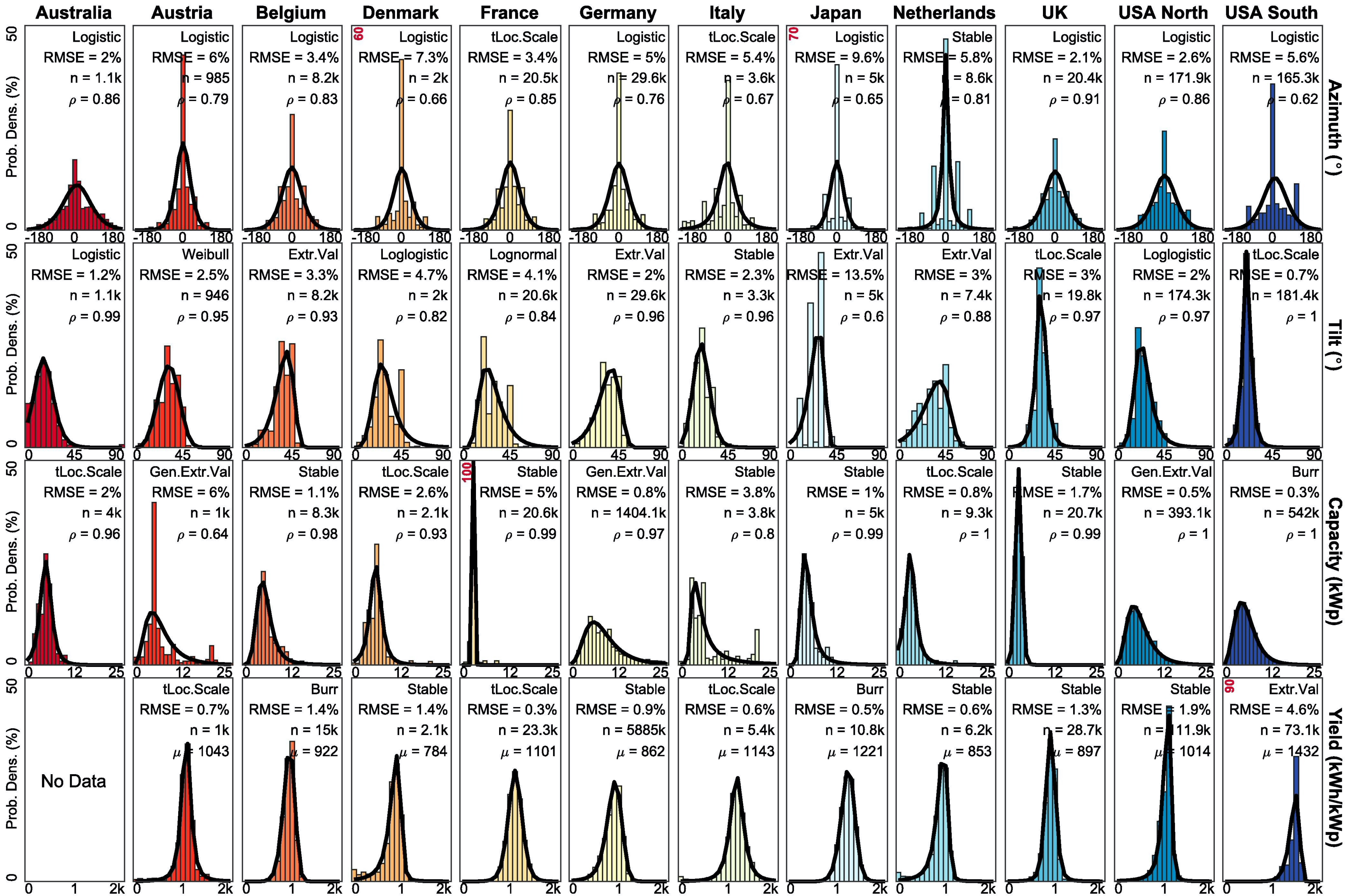
Killinger et al., Solar Energy 143 (2017) 120–131

Towards Equator

Correlated with lattitude

Average 3 – 9 kWp

Correlated with lattitude



Killinger et al., Solar Energy 143 (2017) 120–131

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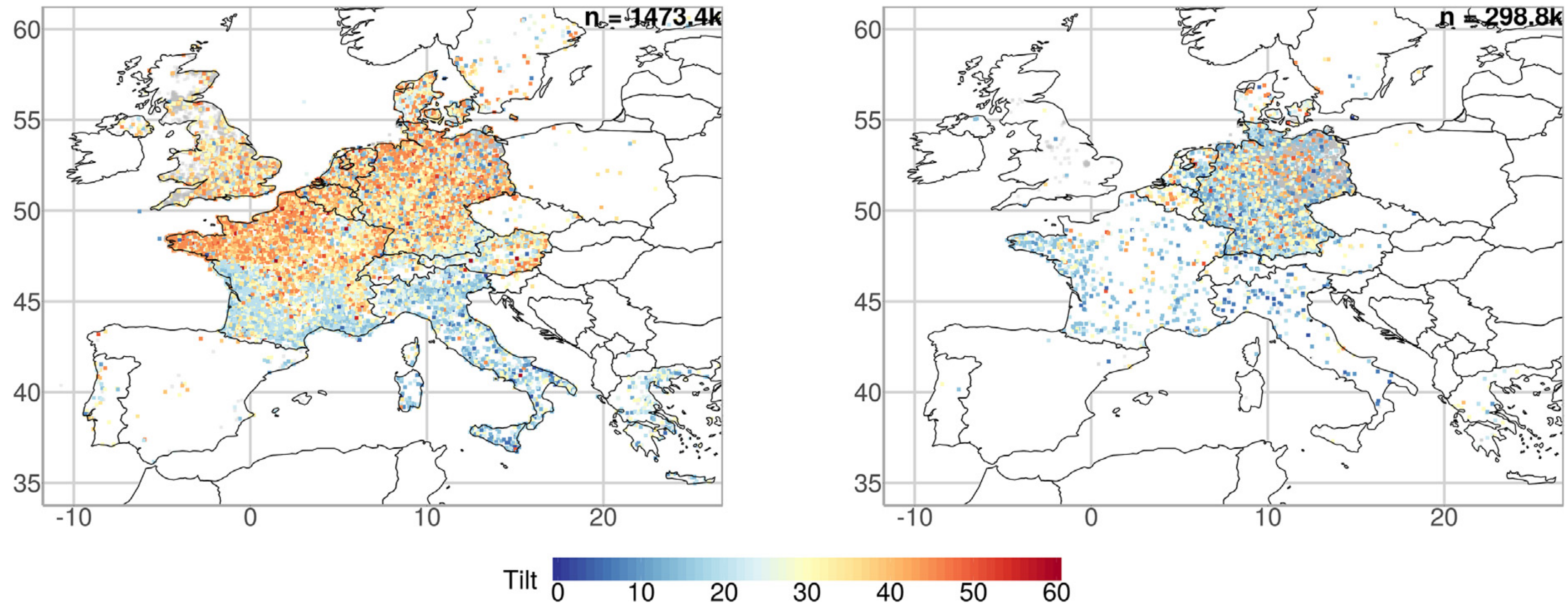
Actual tilt of systems



systems ⩽25 kWp
mostly roofs

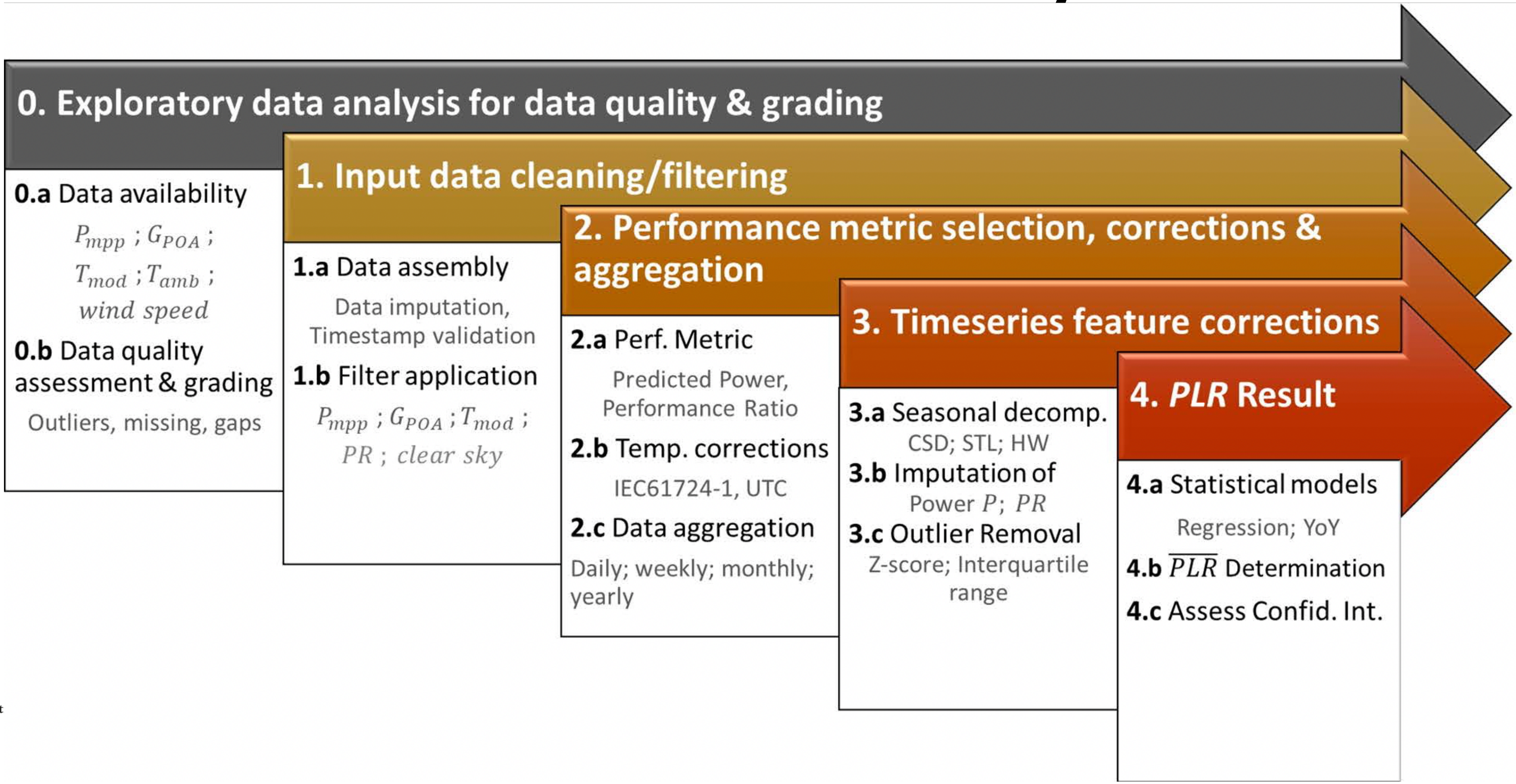
systems >25 kWp
open fields

Killinger et al., Solar Energy 143 (2017) 120–131

Monitoring issues

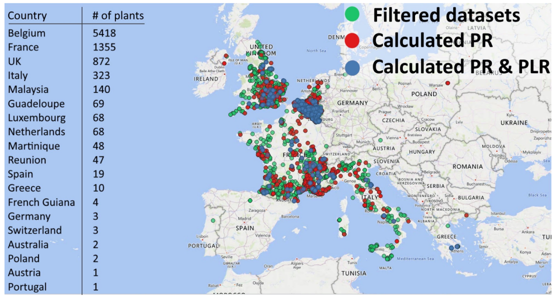
- Large data sets show yields to be expected, however with distribution (due to tilt/azimuth only?)
- What is quality of data quality, data gaps, accuracy?
- Does a PV system degrade?
  - Performance ratio degradation method of choice for analysis → performance loss rate (PLR)
- Malfunction? Shading?

Performance Loss Rates of PV system



Lindig et al., Prog Photovolt Res Appl. 2021;29:573–602.

Data quality assessments



Letter Grade	Outliers [%]	Missing percentage [%]	Longest gap [days]
A	Below 10	Below 10	Below 15
B	10 to 20	10 to 25	15 to 30
C	20 to 30	25 to 40	30 to 90
D	Above 30	Above 40	Above 90

Pass/fail criteria	Time series > 24 months => PASS

Lindig et al., Prog Photovolt Res Appl. 2021;29:573–602.

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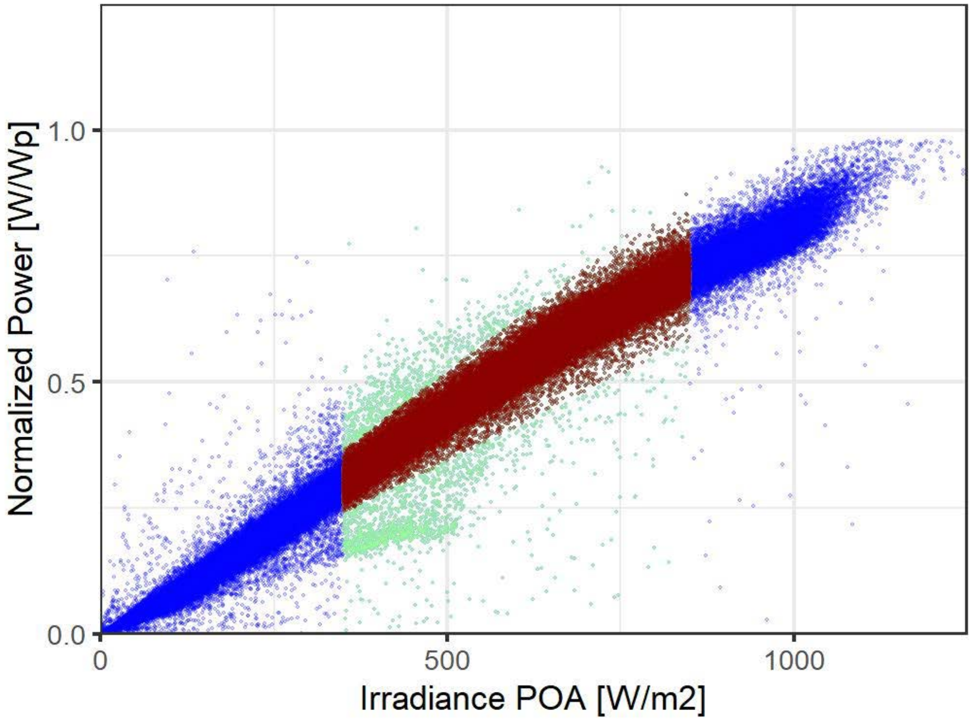
Filtering methods (Metric & statistical model constant)



Raw data: G_{POA} vs Normalized power

Filter 1 –irradiance threshold filter:
350 W/m² < G_{POA} < 850 W/m²

Filter 2 – statistical PR filter:
±2sd around instantaneous PR

Lindig et al., Prog Photovolt Res Appl. 2021;29:573–602.

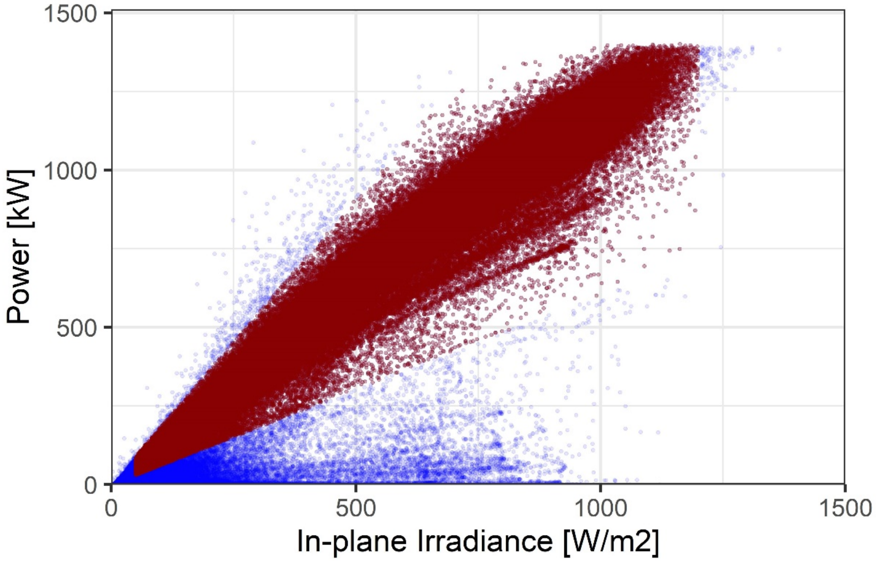
Performance Loss Rates of PV system

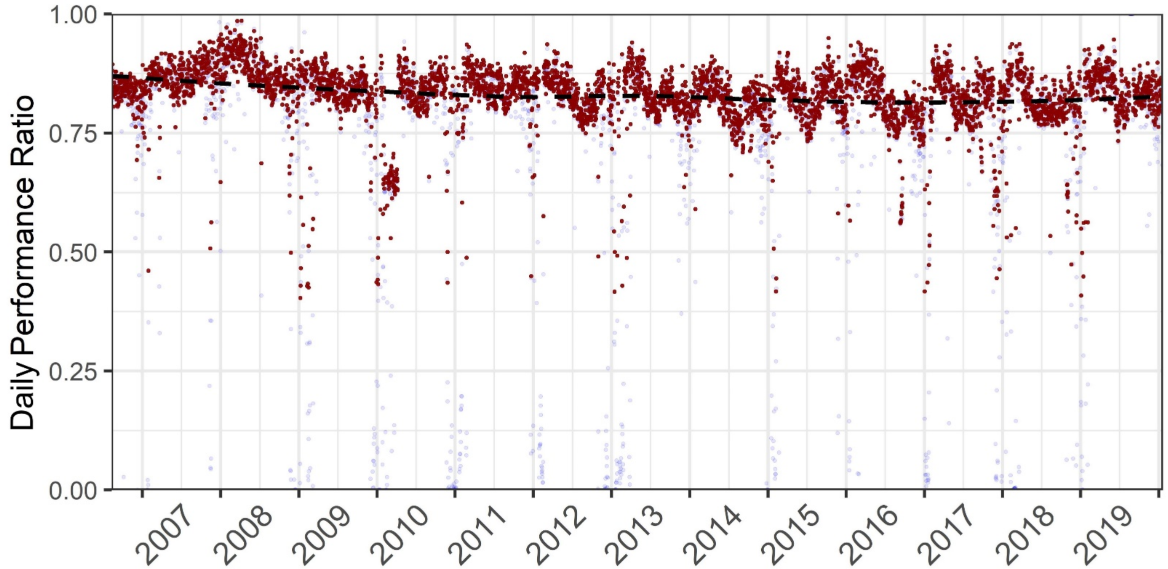
Filter 1 - Threshold filter:

$$0.01 * P_{nom} < P_{AC} < 1.02 * P_{nom}$$

$$50\ \text{W/m}^2 < G_{POA} < 1200\ \text{W/m}^2$$

$$0.3 < PR_{5min} < 1.2$$





Performance loss rate: -0.4%/year

Lindig et al., Prog Photovolt Res Appl. 2021;29:573–602.

Effects of shading

- On rooftops shading may be present, dormers, chimneys…
- No irradiance sensor, meteo data needed (satellite, local weather stations) → geospatial errors and plane of array irradiance errors (GHI → POA models)

Effects of shading

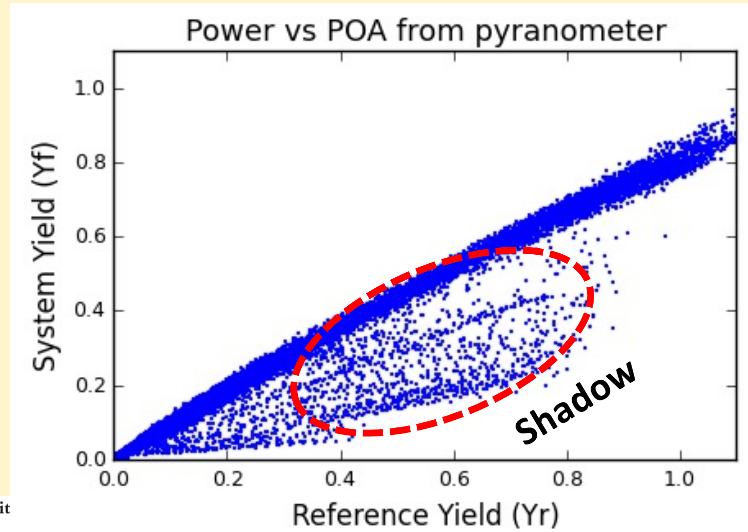
$$\boldsymbol{Performance\ Ratio (PR)} = \boldsymbol{Y_f / Y_r}$$

- Power vs POA irradiance

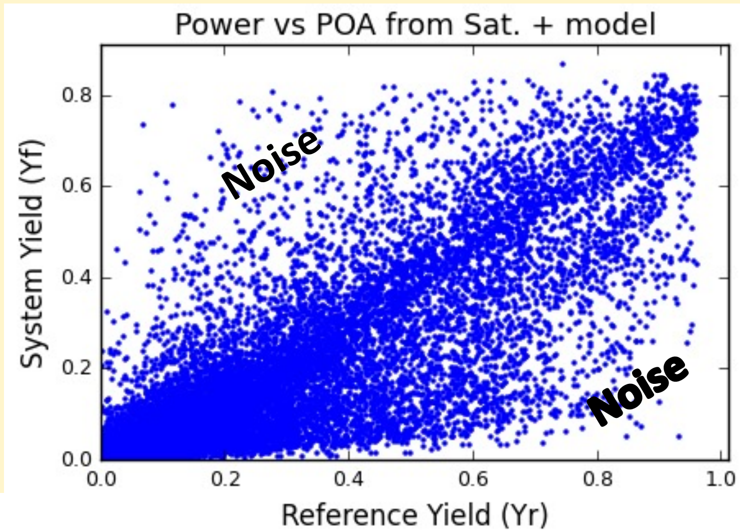
$$System\ Yield\ (Y_f) = \frac{E_{AC}}{W_{peak}} \left[{}^{Wh}/_{W}\right]$$

$$Reference\ Yield\ (Y_r) = \frac{H_{poa}}{G_{STC}} \left[\frac{{}^{Wh}/_{m^2}}{1000\ {}^{Wh}/_{m^2}}\right]$$

irradiance sensor



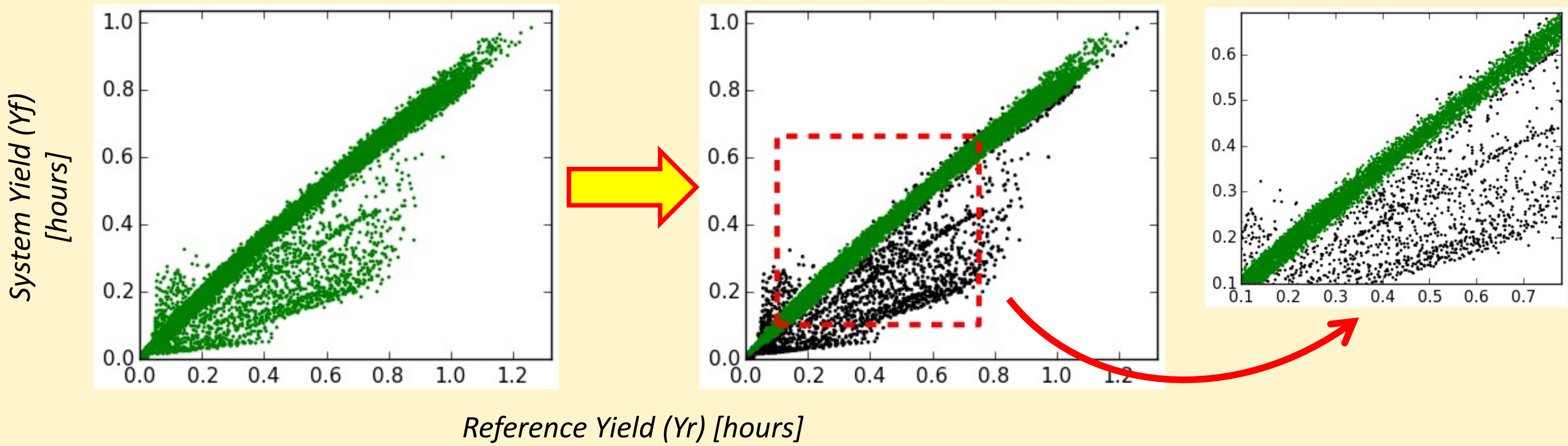
satellite and model



Tsafarakis et al., Energies 2018, 11, 977

Effects of shading

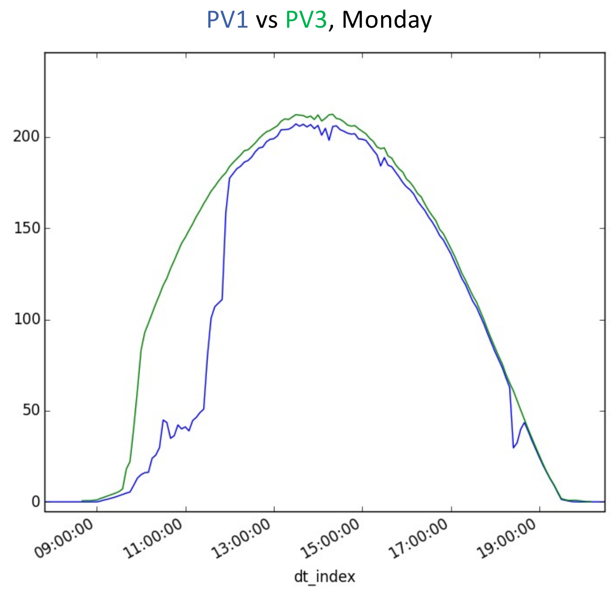
- Use DBSCAN algorithm to cluster inliers and outliers

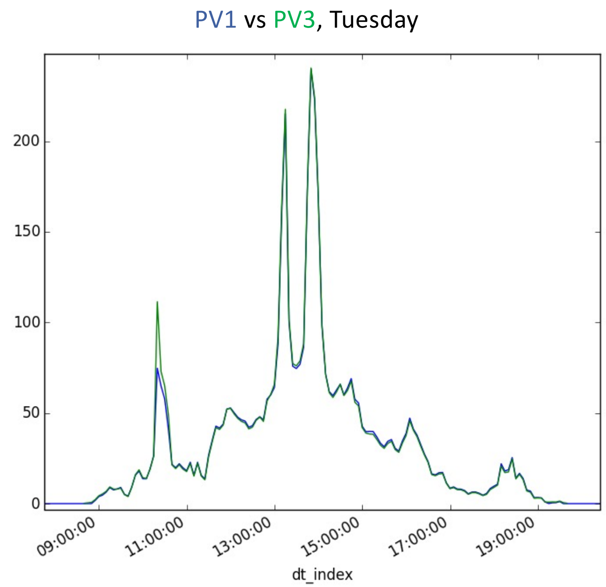


Tsafarakis et al., Energies 2018, 11, 977

The shadow story

- Shadow detection, sunny day and cloudy day
- Identical panels, with power optimizers: peer-to-peer monitoring

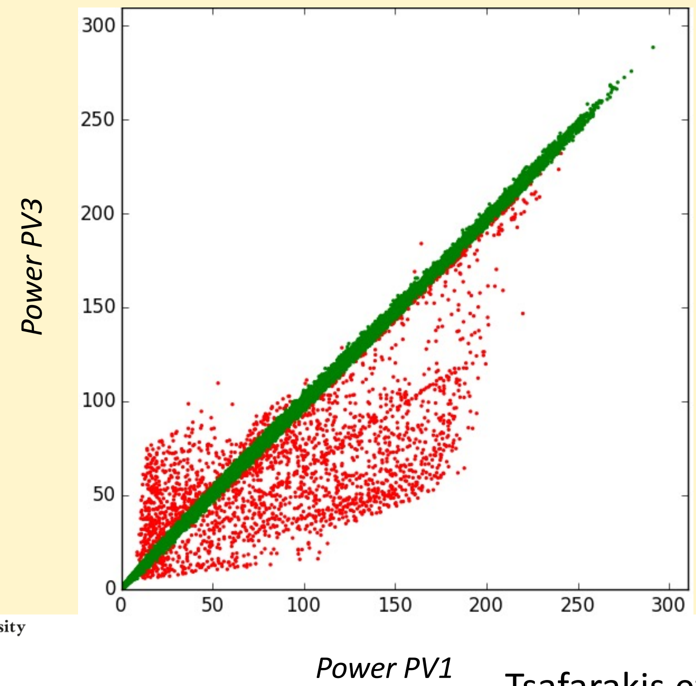




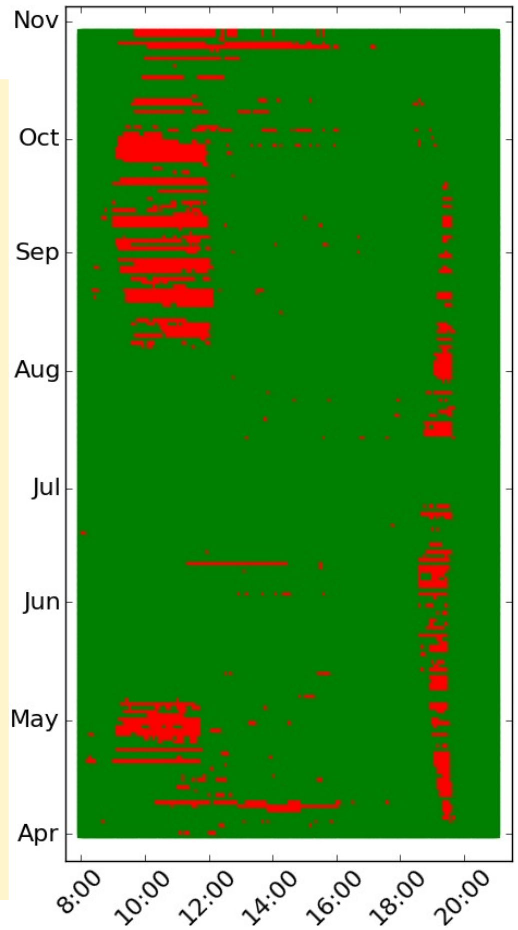
Tsafarakis et al., Energies 2019, 12, 1722

The shadow story

- Use DBSCAN algorithm to cluster inliers and outliers, data April to November



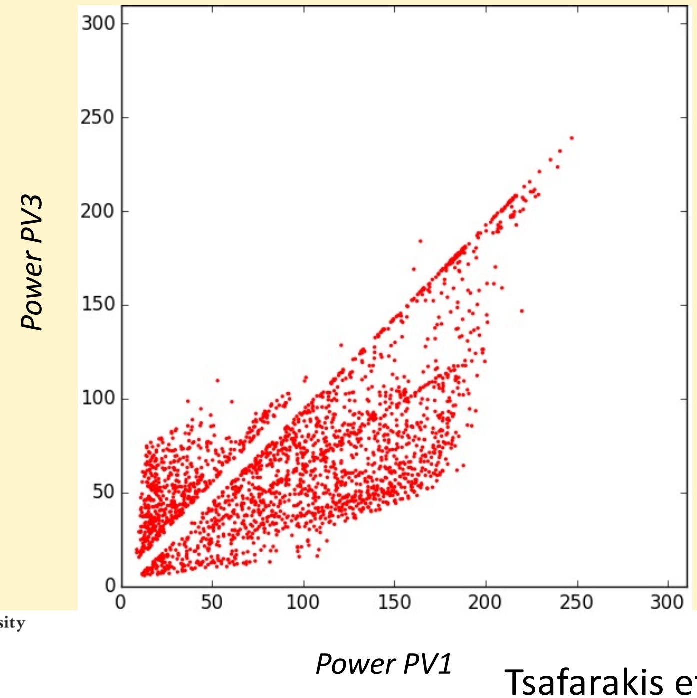
data-time plot →

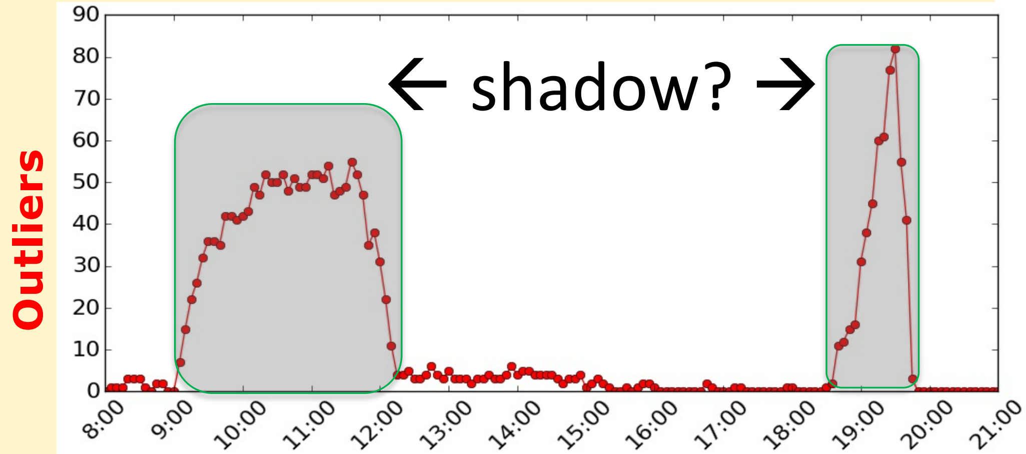


Tsafarakis et al., Energies 2019, 12, 1722

The shadow story

- Remove inliers, plot outliers as a function of time





Tsafarakis et al., Energies 2019, 12, 1722

The shadow story

- Potential hours in which shade may occur
- Further cluster analysis

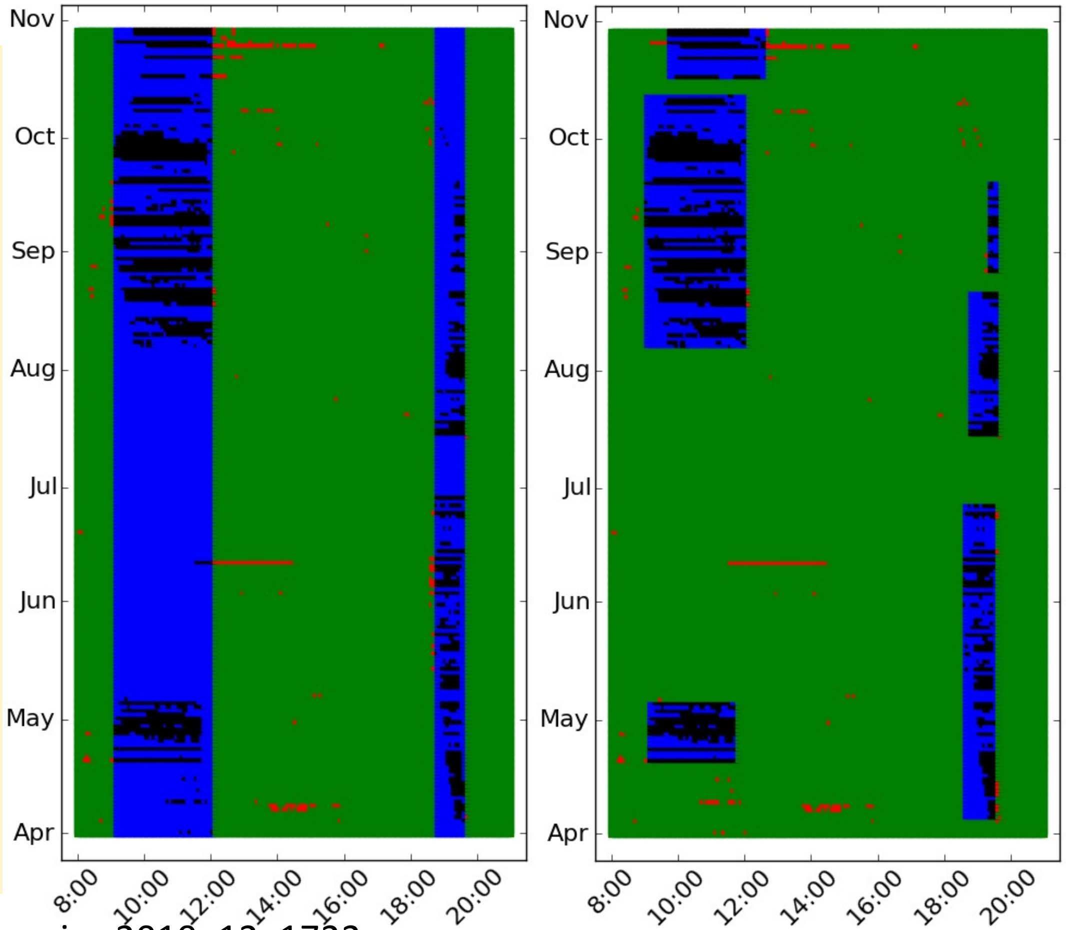
→ Final shadow story

- Calculation of yield loss:

PR (inliers): 87%

PR (all): 82%

→ 6% annual loss



Tsafarakis et al., Energies 2019, 12, 1722

Summary

- PV will reach TWp level late Summer
- **Reliable yield data from half of systems is not available**

- Resort to statistical means/modeling in combination with measured meteo data
- Monitor representative systems covering a full country
- What is a representative system? Not necessarily a well-performing system!?

Best solution?

open data

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