

# Fotovoltaïsche technologie

A hand holding a crystal ball that reflects a sunset over a landscape, symbolizing technology and sustainability.

## Ontwikkeling en inpassing in elektriciteitsnetten

**Prof. Miro Zeman**

Technische Universiteit Delft

Afdelingshoofd Electrical Sustainable Energy

April 3, 2023



My dream



Photovoltaics



TU Delft research



Energy transition

Den Haag  
28 juni 2019

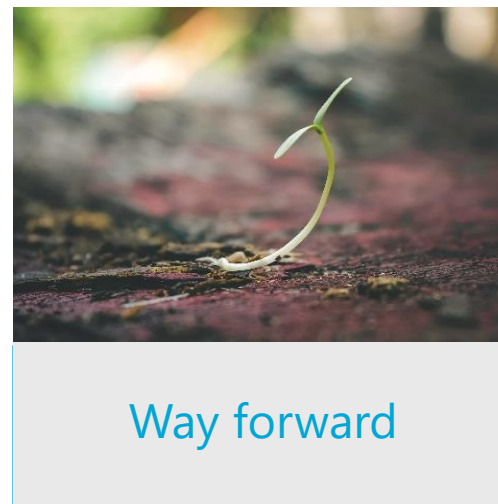


**Klimaatakkoord**

Climate agreement



The ESP Lab



Way forward



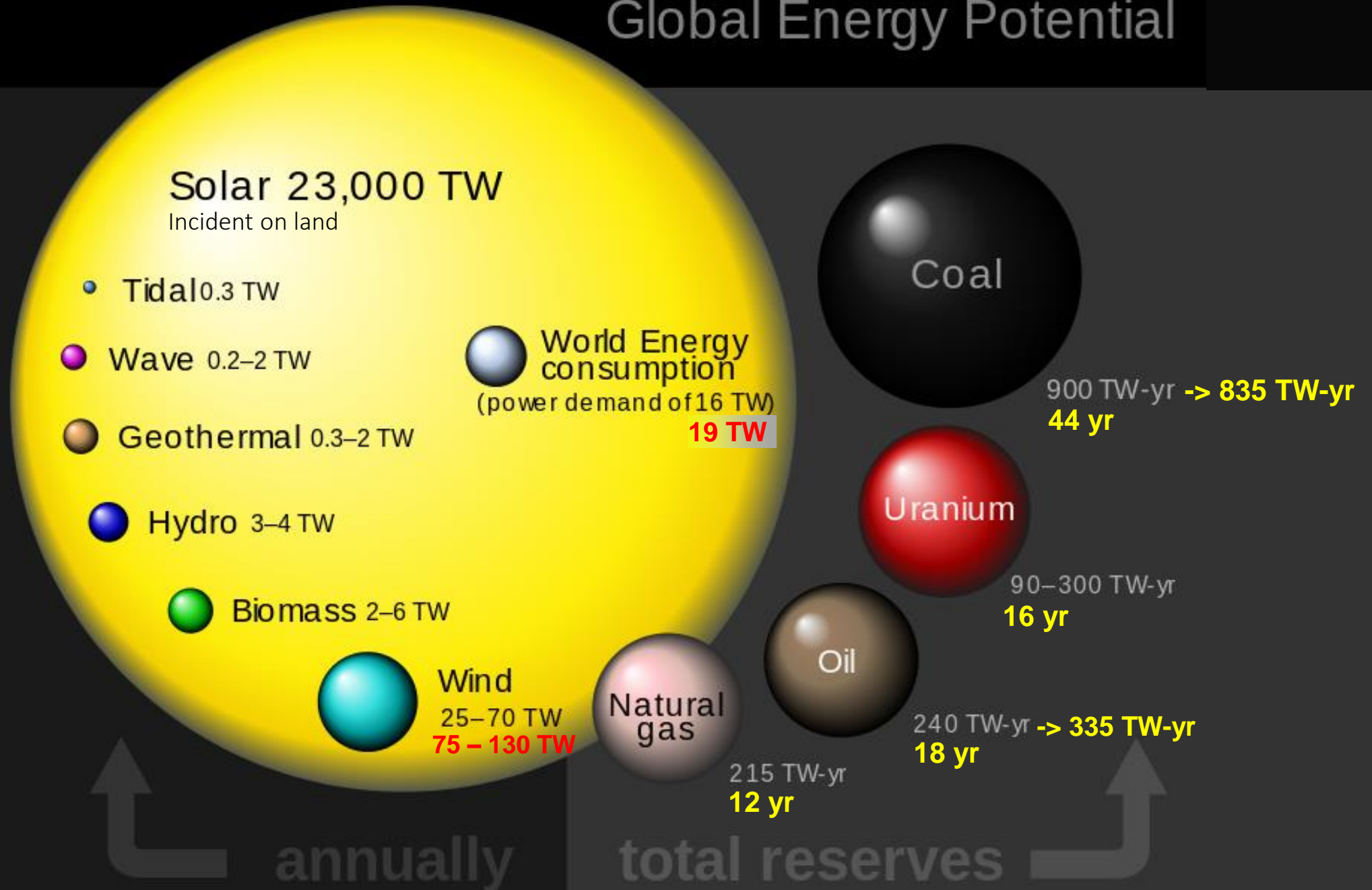


# PHOTOVOLTAIC SOLAR ENERGY: Key to a sustainable energy future

Miro Zeman  
Delft University of Technology  
February 1, 2010

# De droom

# Global Energy Potential



# Mijn DROOM

Alle mensen in de wereld hebben toegang tot betaalbare en duurzame energie in de meest elegante vorm die we vandaag de dag gebruiken;  
**ELEKTRICITEIT.**

# Mijn DROOM

De primaire bron van deze elektriciteit  
is de donor van al het leven op deze planeet;  
**de ZON.**

# Mijn MISSIE

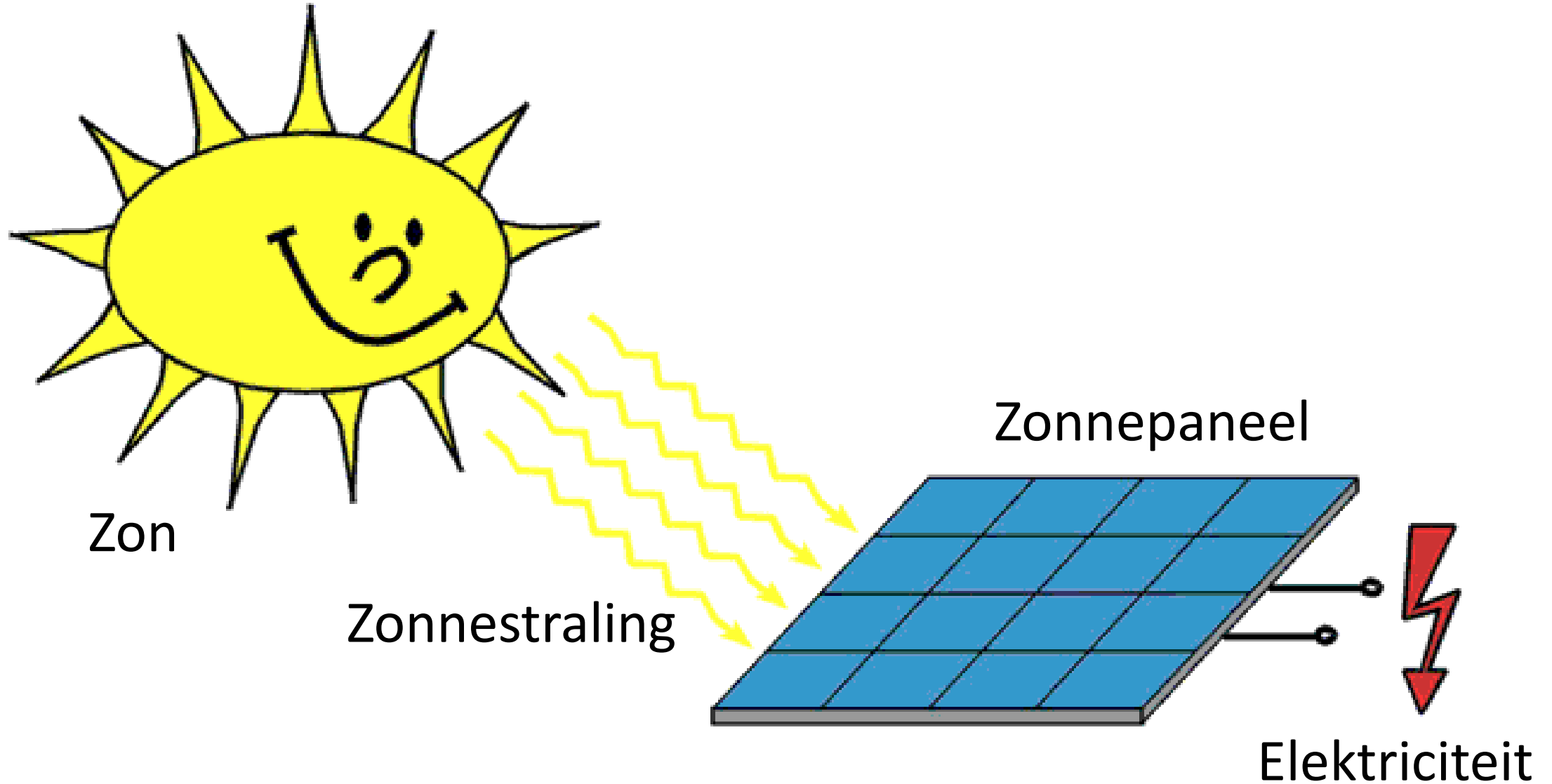
Mijn missie is om  
het **energiesysteem**  
**van de toekomst**  
te bouwen,  
die groene zonnestroom  
**aan iedereen**  
in de wereld zal leveren.





# Fotovoltaïsche technologie

# Fotovoltaïsche technologie



# Fotovoltaische technologie

Urban-Integrated  
Photovoltaics (UIPV)



Built-Added  
Photovoltaics (BAPV)



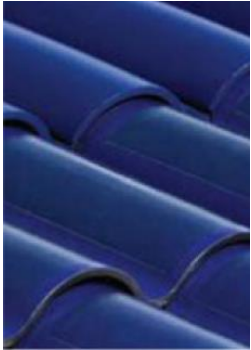
E-bike charging  
station by TU Delft



Solaroad  
by TNO



Infotainment spot  
by TU Delft



Building/Invisibly Integrated  
Photovoltaics (BIPV/IIPV)



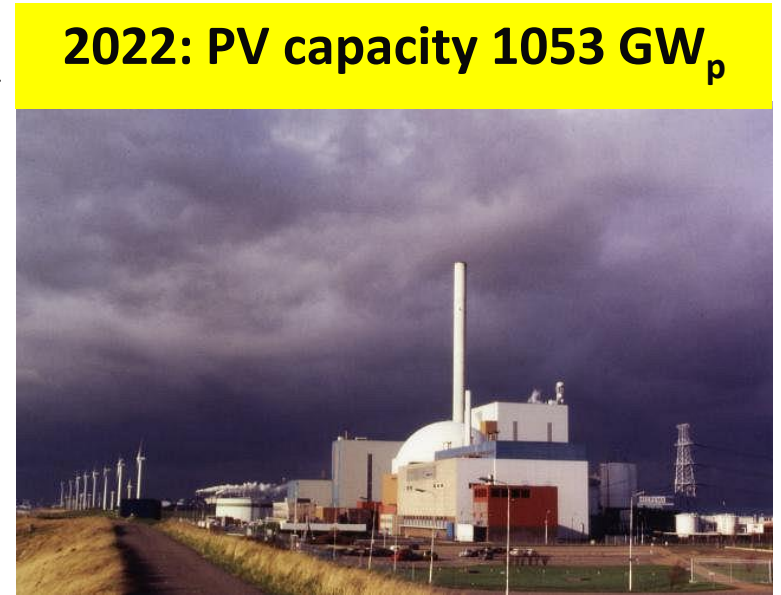
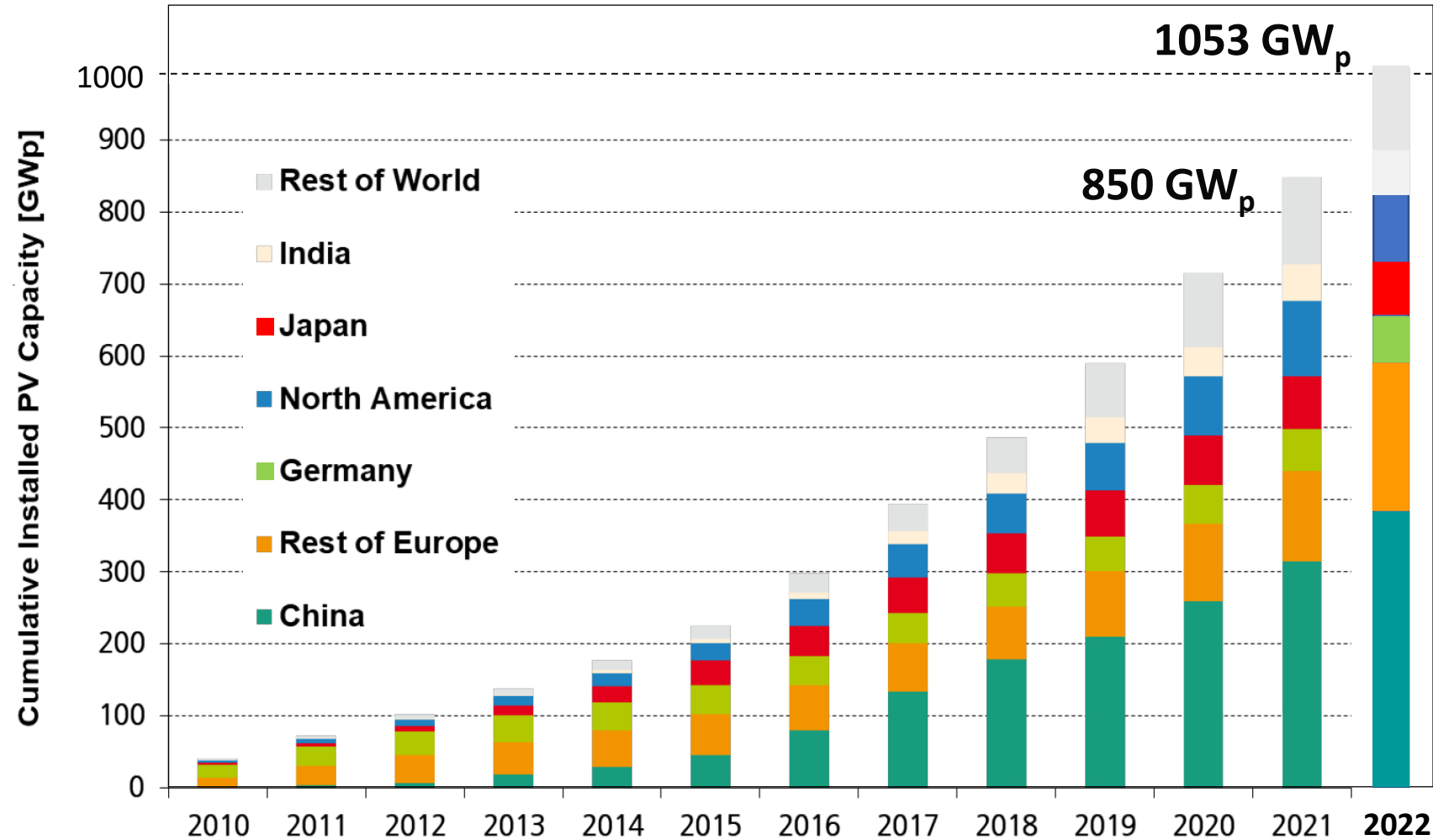
Environment-Integrated  
Photovoltaics (EIPV)

E-mobility



Vehicle-Integrated  
Photovoltaics (VIPV)

# Geïnstalleerd PV vermogen



2022: PV capacity 1053 GW<sub>p</sub>

## Borssele Nuclear Power Plant

Installed capacity: 0.485 GW

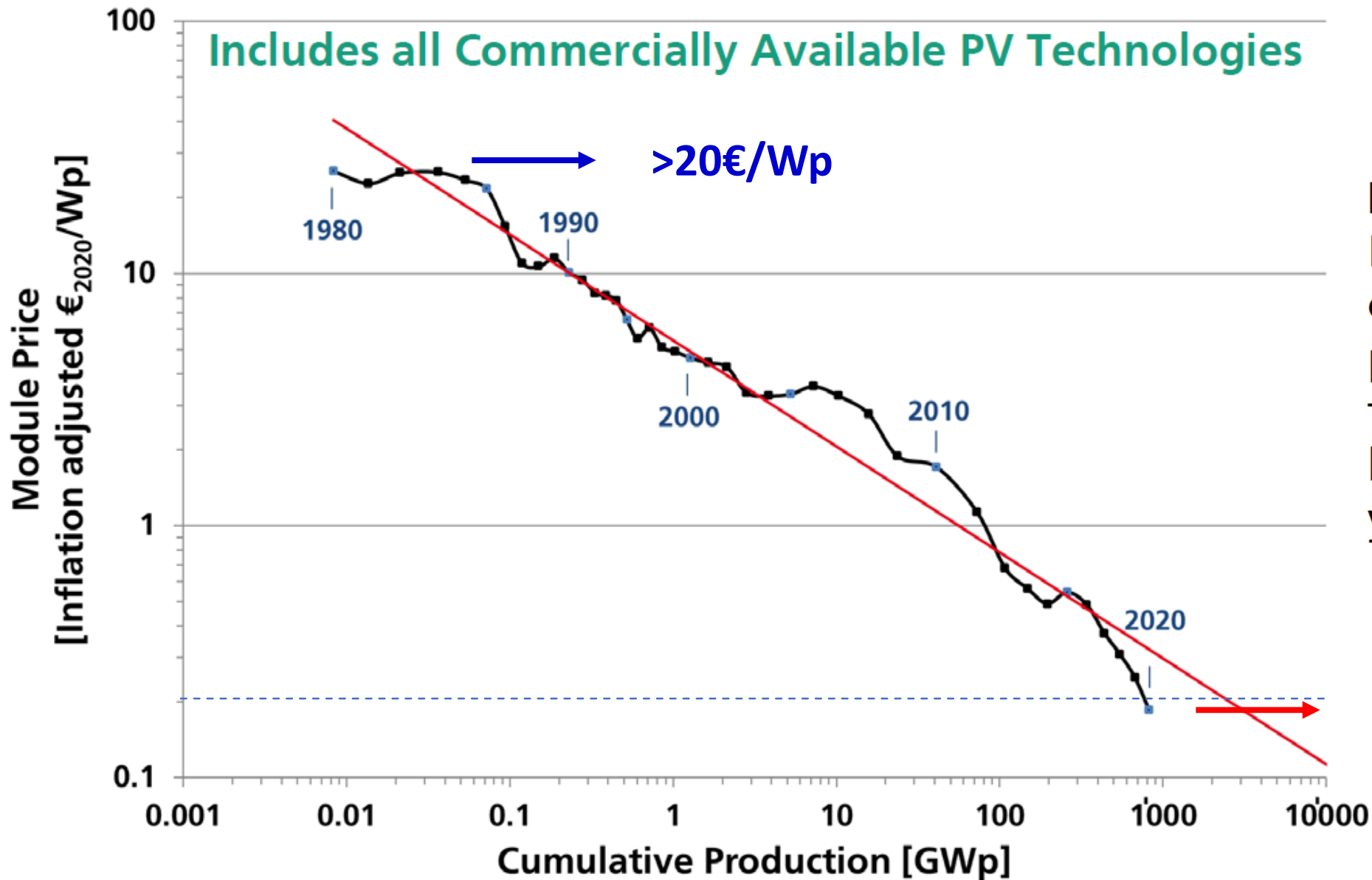
PV capacity (2022): 1053 GW

PV capacity: **≈ 360 Borssele plants**

PV capacity (2021): 850 GW

PV capacity: **≈ 290 Borssele plants**

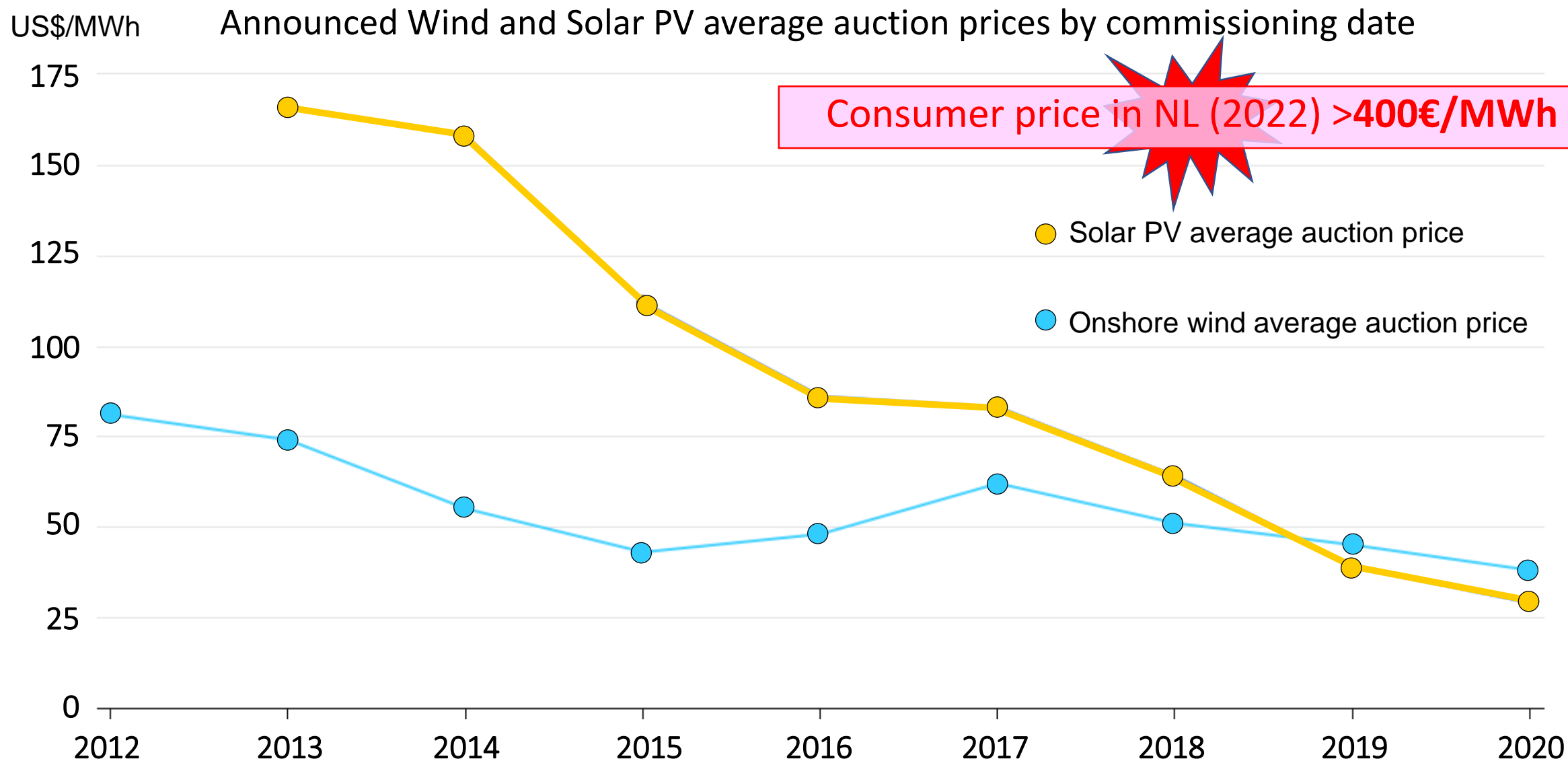
# Prijs van zonnepanelen



**Learning Rate:**  
Each time the cumulative PV module production doubled, the price went down by 25% for the last 40 years.

~0.20€/Wp

# Prijs van PV elektriciteit



# Toekomst van PV: PV overal



- Onzichtbaar
- Intelligent
- Circulaire

# TU Delft

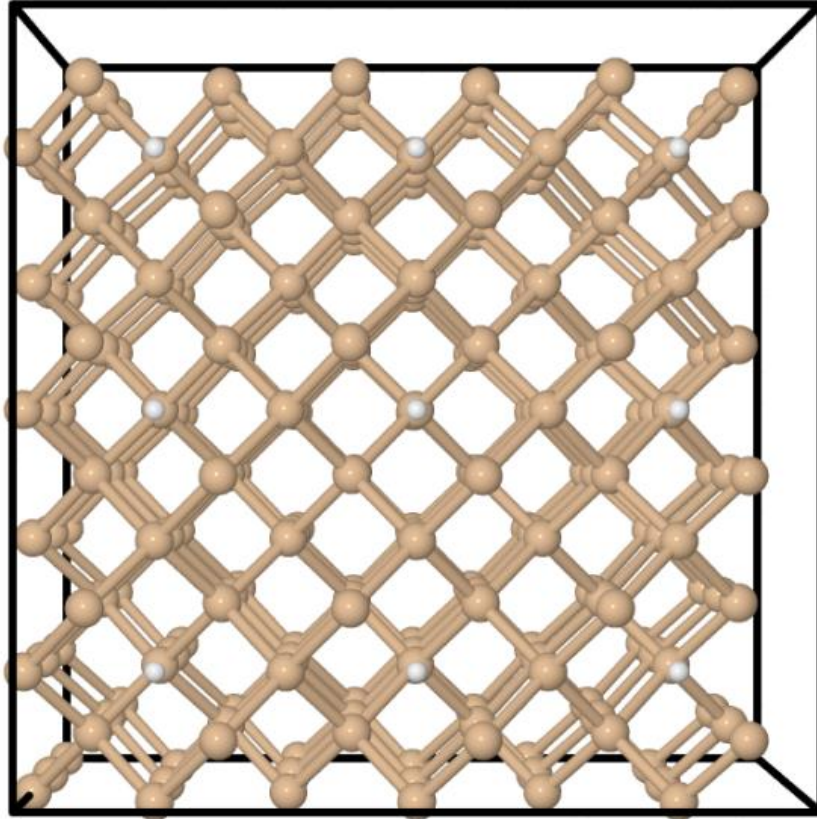
# PV onderzoek



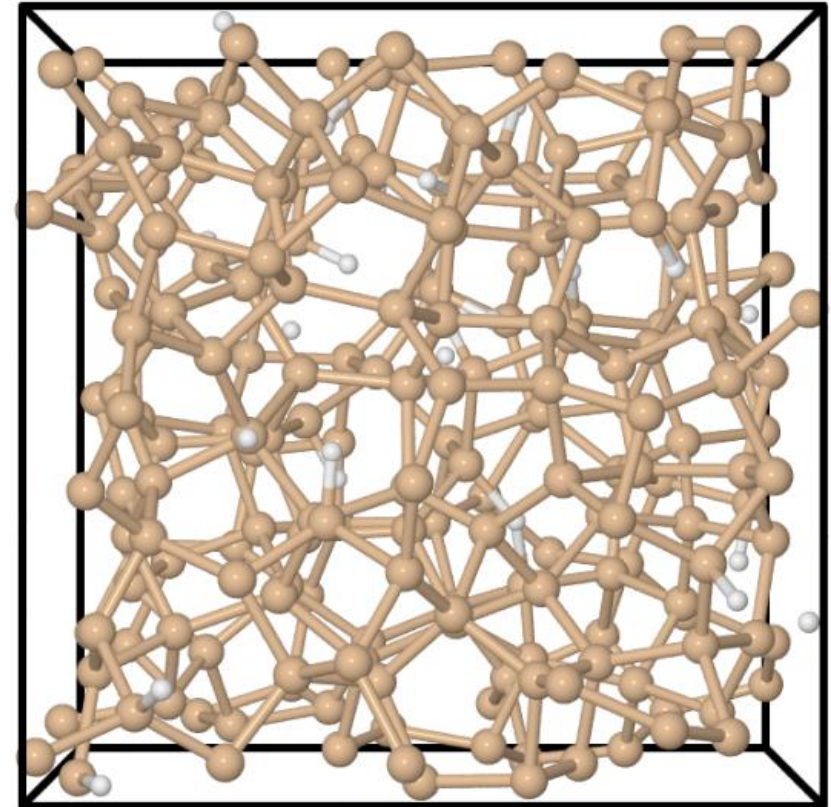




# Amorf silicium



Kristalijn silicium



Amorf silicium





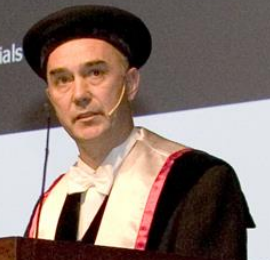
Advanced Semiconductor Analysis  
Software om zonnecellen te simuleren

'Solar Electricity'

Prof.dr.ir. M. Zeman

Vakgebied Photovoltaic Devices and Materials

11 december 2009



TU Delft

TU Delft



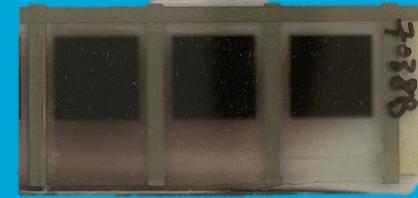
**TU Delft**  
**PV Technology**  
**Center**

Industrieel-compatibele  
infrastructuur



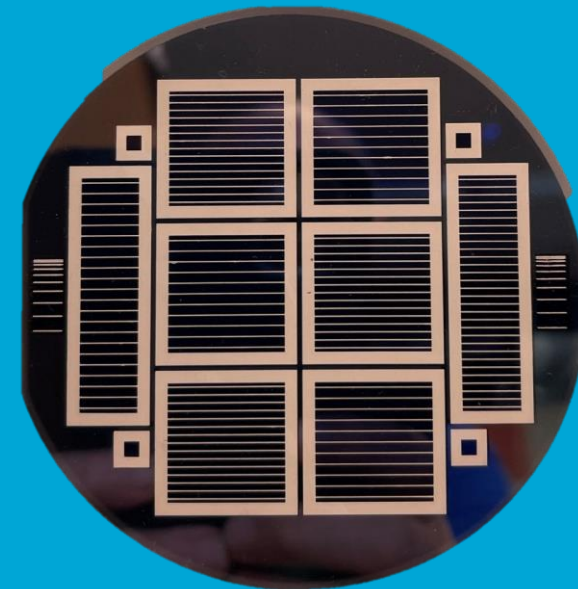


## Dunne-film silicium zonnecellen



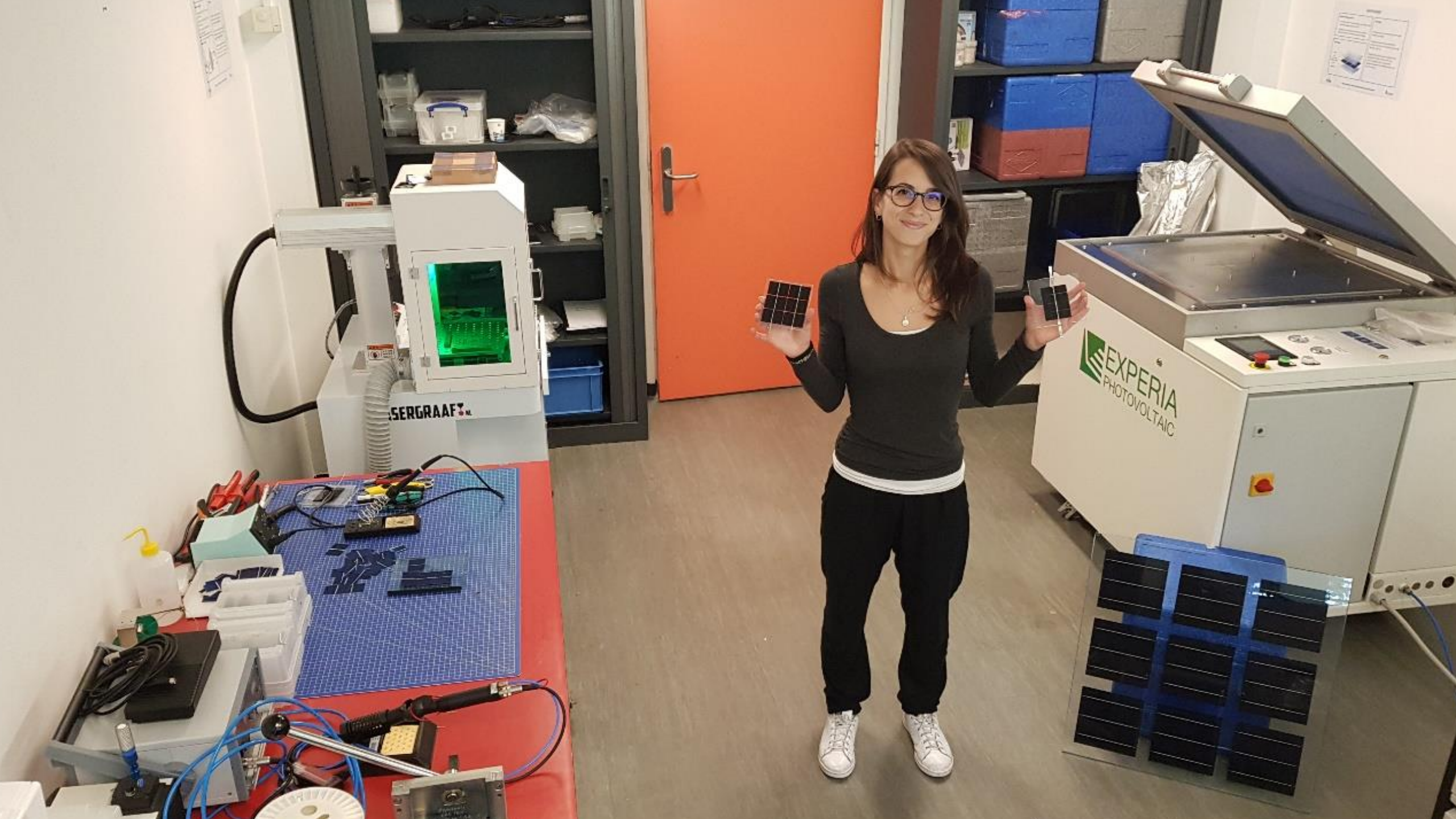
WR Initieel rendement > 14.8%  
Gestabiliseerd rendement 12.5%

## Kristallijn silicium zonnecellen



Rendement > 24%





SERGRAAF

EXPERIA  
PHOTOVOLTAIC

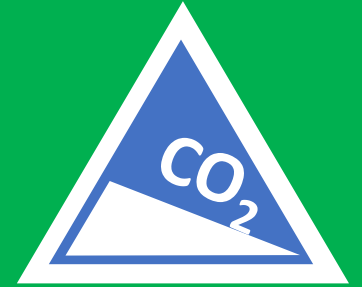




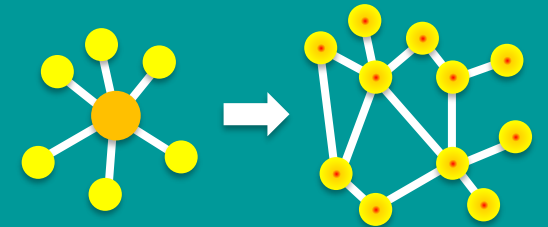
# Energietransitie

# Trends in energy sector

**Decarbonisation**



**Decentralization**



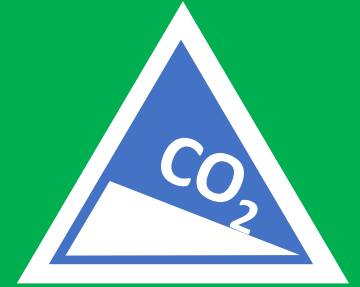
**Digitalization**



# Trends in energy sector

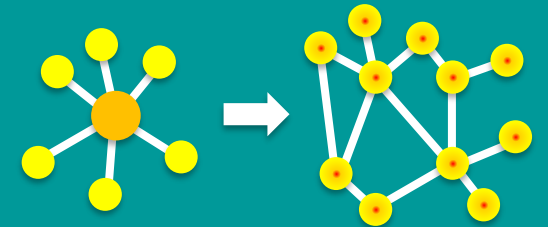
## Decarbonisation (defossilization)

- **From fossil fuels to renewable energy sources & storage**
- Energy efficiency (minimize conversion & transmission losses)
- Electrification of transport, heating and industrial processes



## Decentralization

- Location: From centralized to distributed power generation
- Control: From centralized to de-centralized management (prosumers)
- Decentralized energy management: security & **flexibility of supply**



## Digitalization

- Intelligent infrastructure (autonomous assets, sensors)
- Fast operational control
- New services and markets

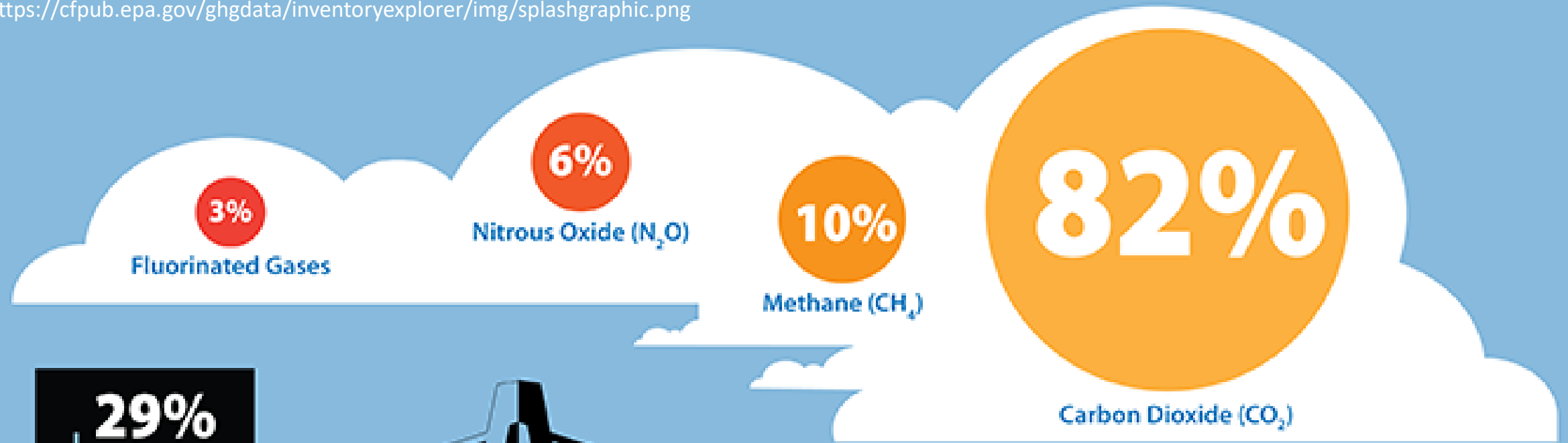


# Greenhouse gasses emissions

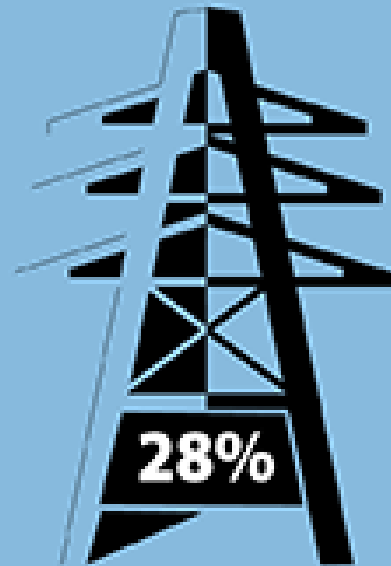
<https://cfpub.epa.gov/ghgdata/inventoryexplorer/img/splashgraphic.png>

U.S. Greenhouse Gas Emissions in 2017\*

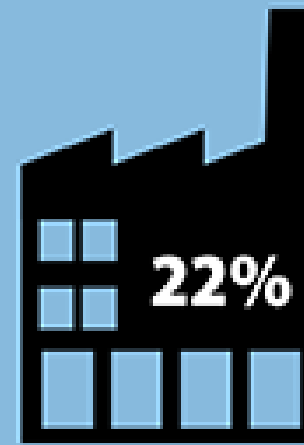
Total U.S. Greenhouse Gas Emissions by Economic Sector in 2017\*



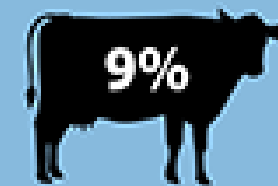
Transportation



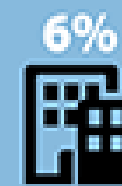
Electricity Generation



Industry



Agriculture



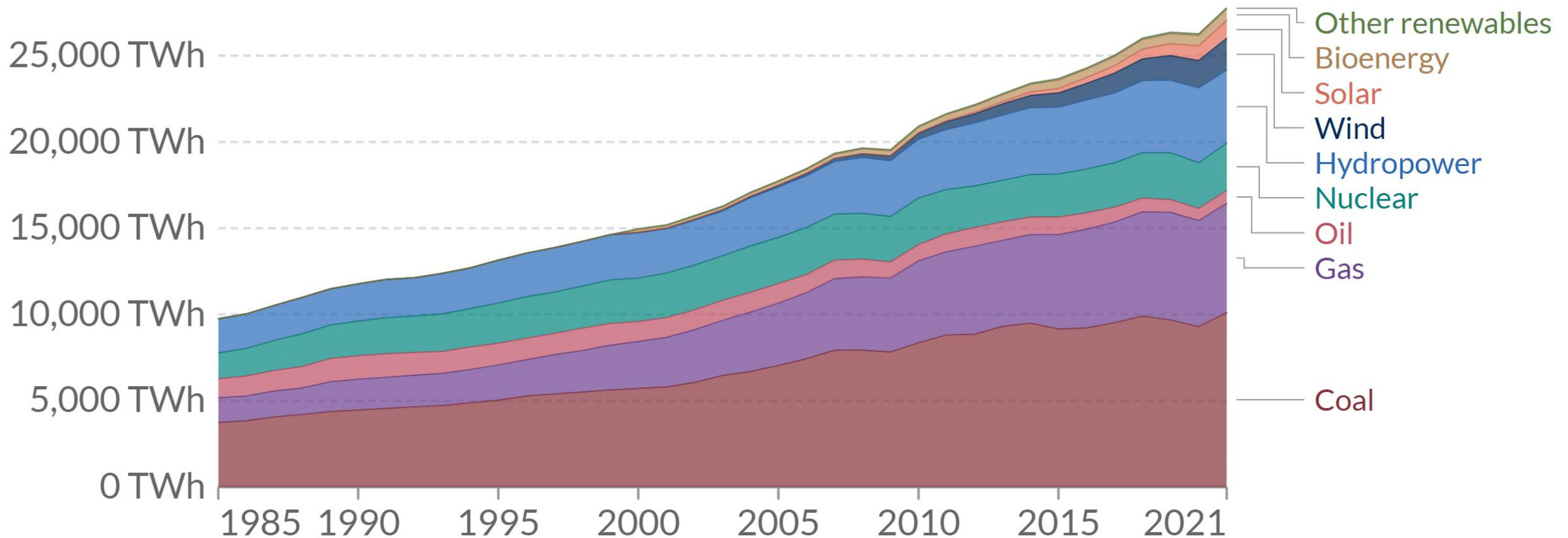
Commercial



Residential

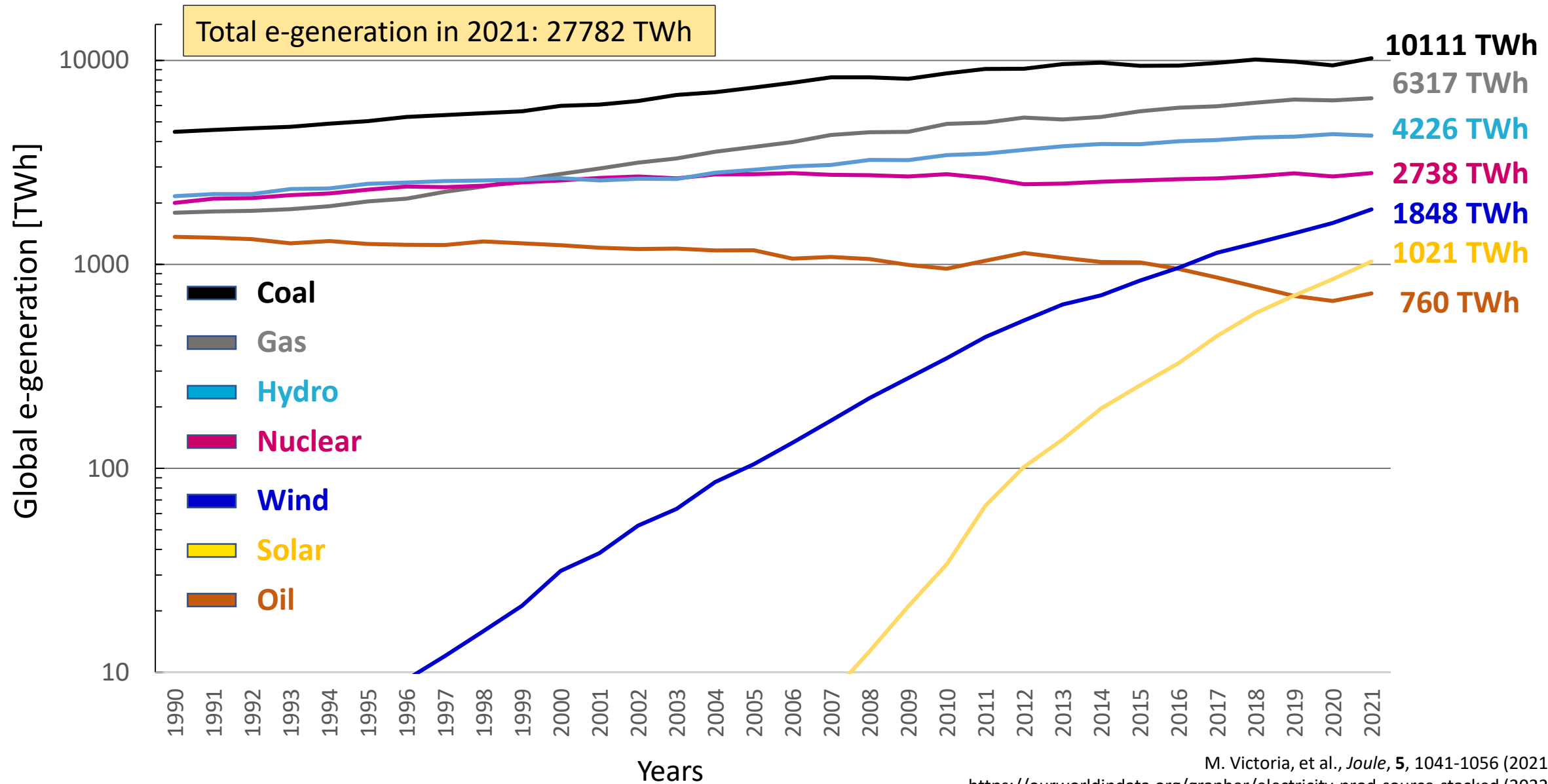
# Primary energy mix for electricity generation

World:

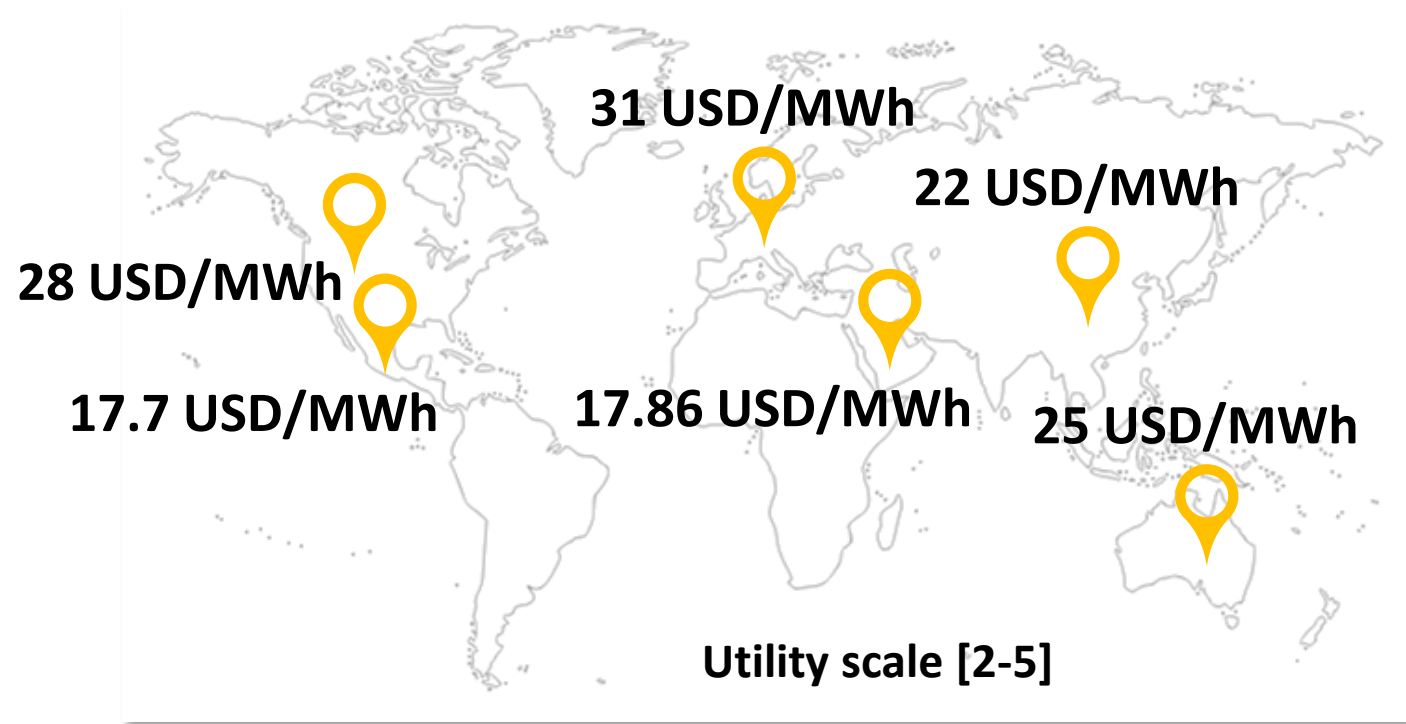
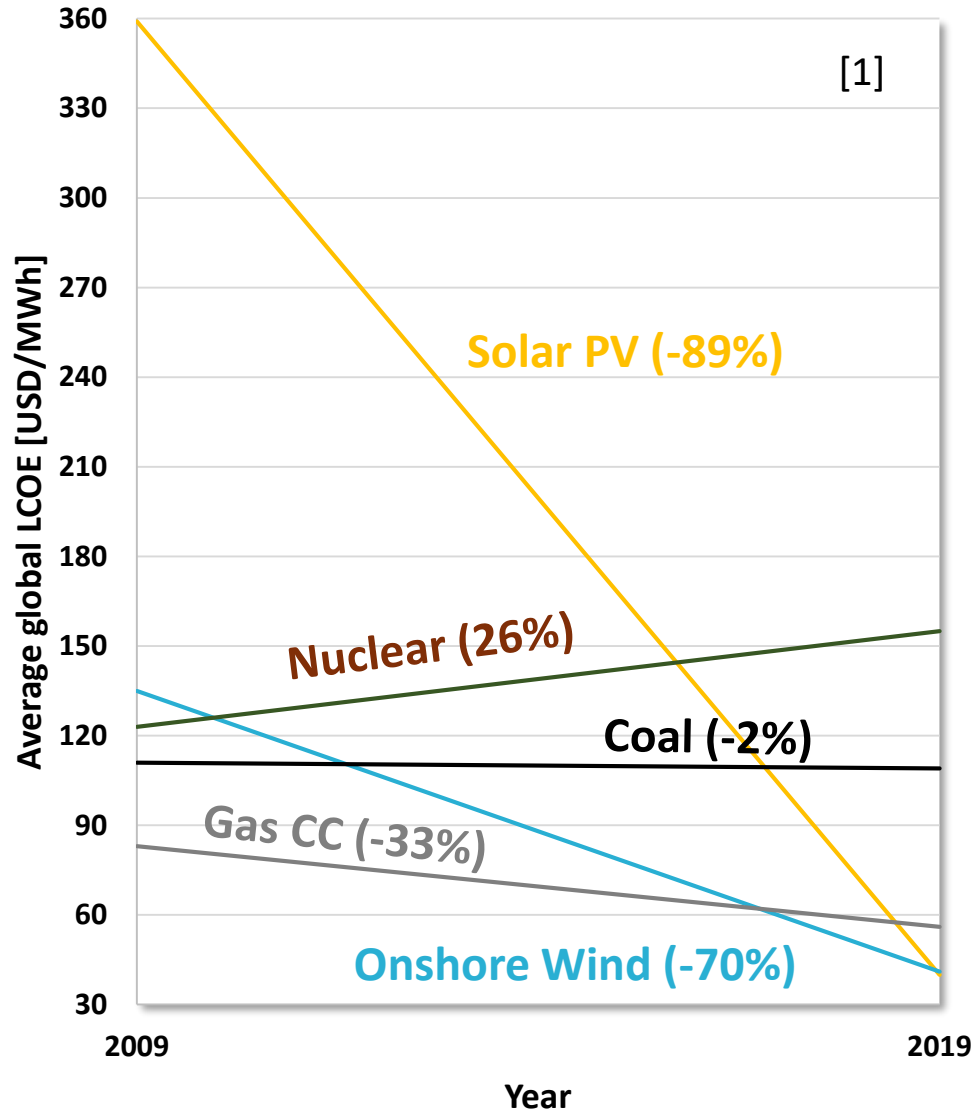




# Primary energy mix for electricity generation



# Levelized Cost of Electricity



[1] Elaborated from <https://ourworldindata.org/cheap-renewables-growth> (2022)

[2] <https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html> (2021)

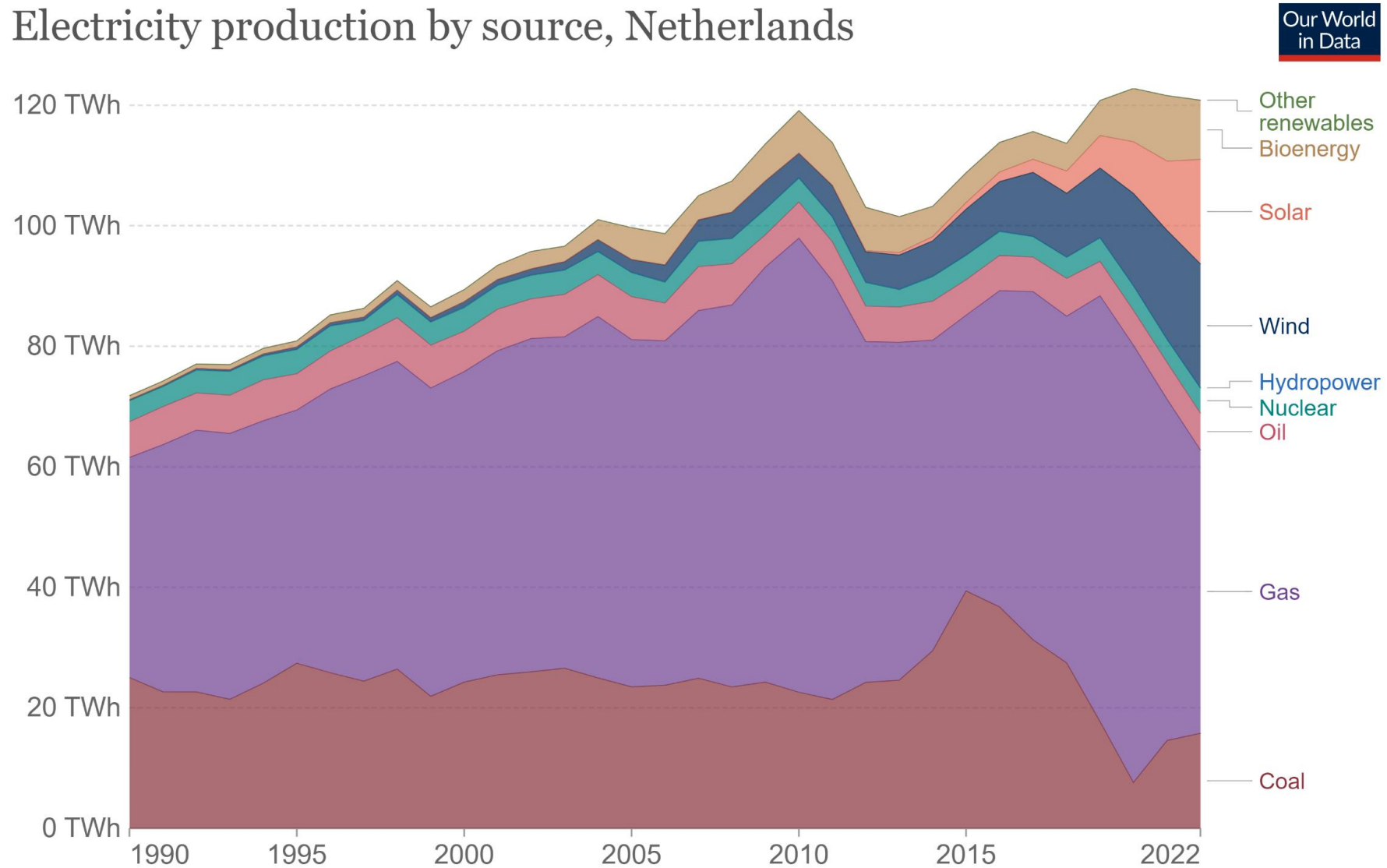
[3] <https://www.greentechmedia.com/articles/read/mexico-auction-bids-lowest-solar-wind-price-on-the-planet> (2017)

[4] <https://www.pv-magazine.com/2021/11/05/utility-scale-solar-reaches-lcoe-of-0-028-0-041-kwh-in-the-us-lazard-finds/> (2022)

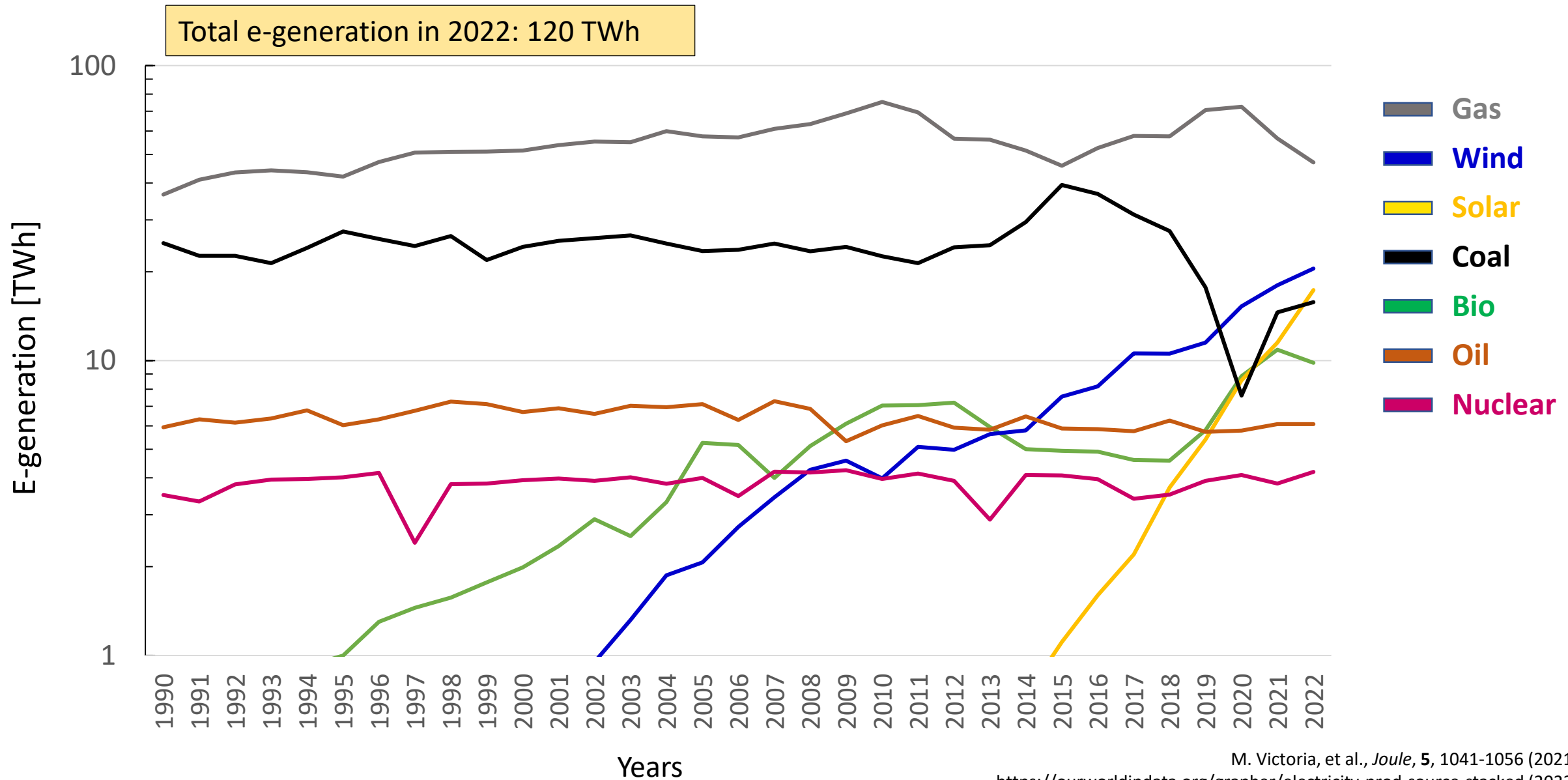
[5] <https://www.pv-magazine-australia.com/2021/12/17/csiro-report-reveals-renewables-remain-cheapest-new-build-power/> (2021)

# Primary energy mix for electricity generation

Electricity production by source, Netherlands



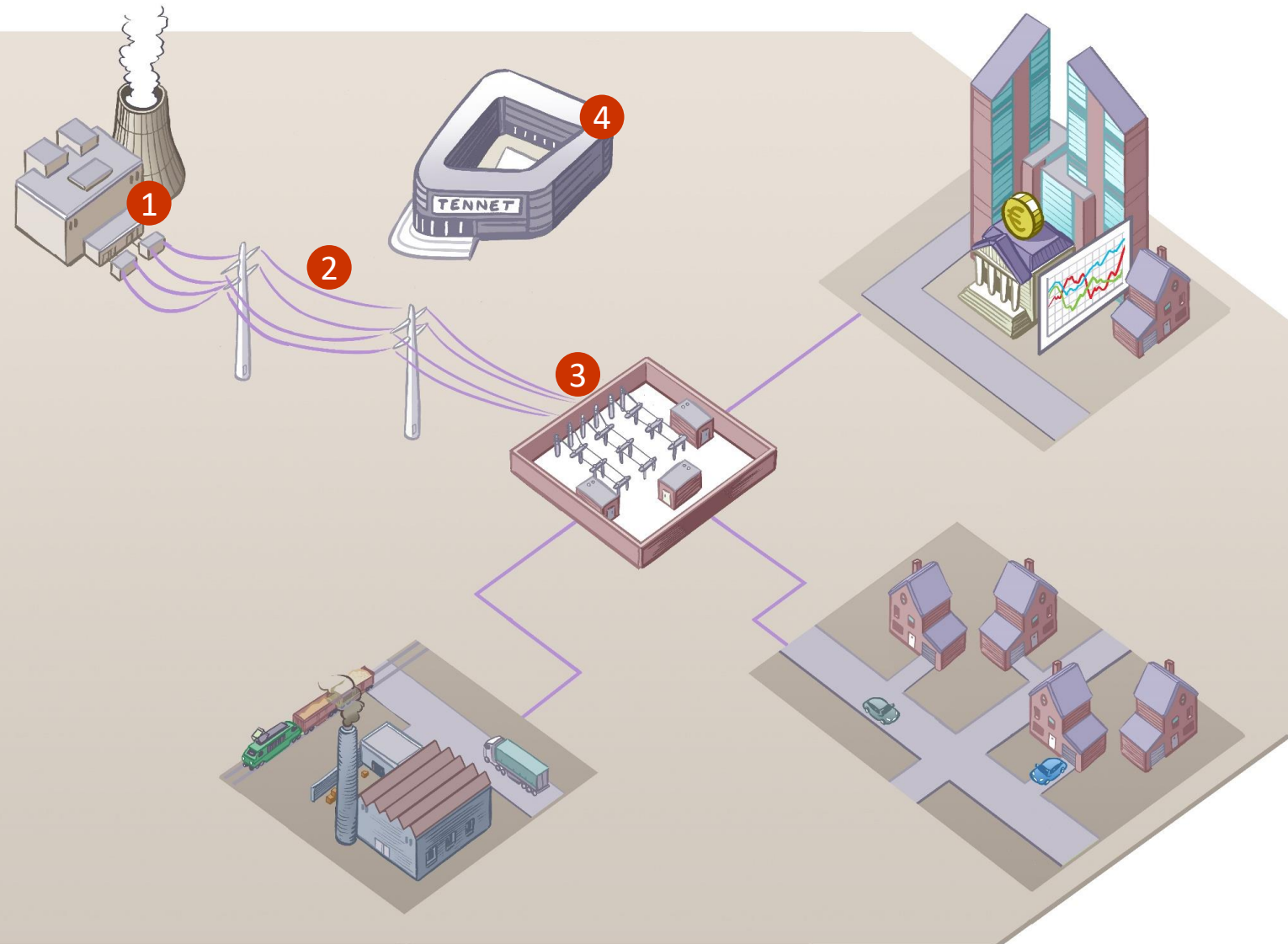
# Primary energy mix for electricity generation



# Integratie van hernieuwbare energiebronnen

# Traditional electrical energy system

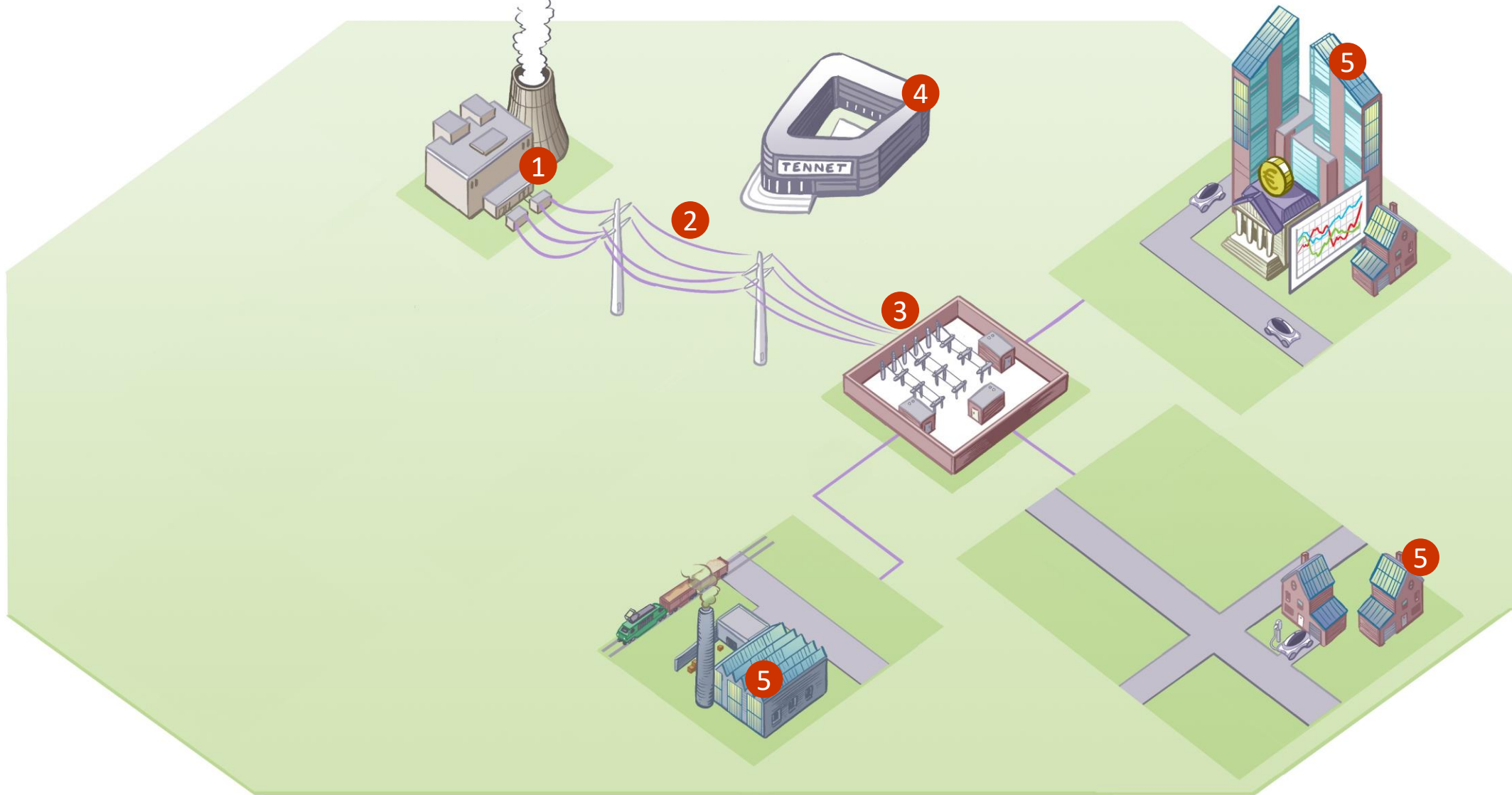
Basic principle: Balancing power demand and supply



- 1 Central power plant
- 2 HV Transmission
- 3 Substation
- 4 TSO

# Energy transition: Distribution level

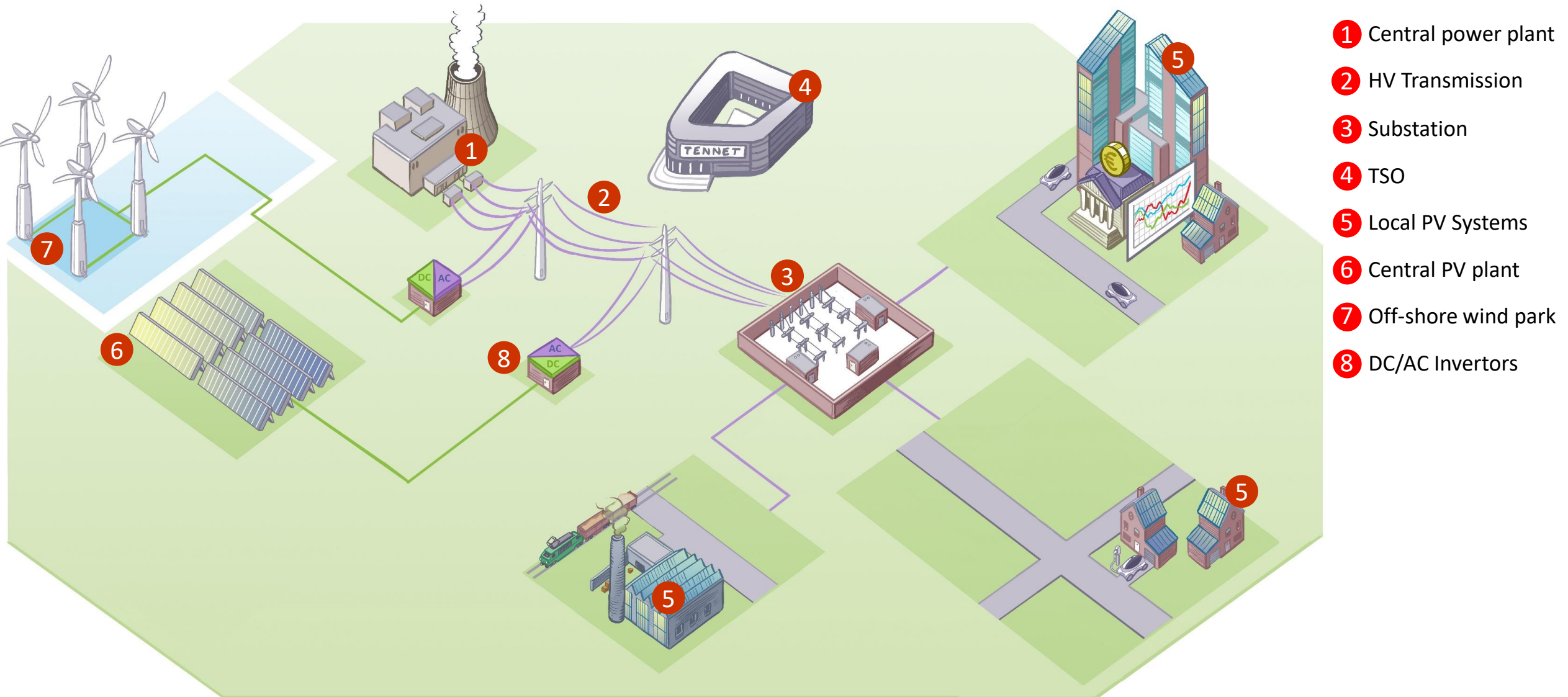
## Local distributed e-generation from RES



- 1 Central power plant
- 2 HV Transmission
- 3 Substation
- 4 TSO
- 5 Local PV Systems

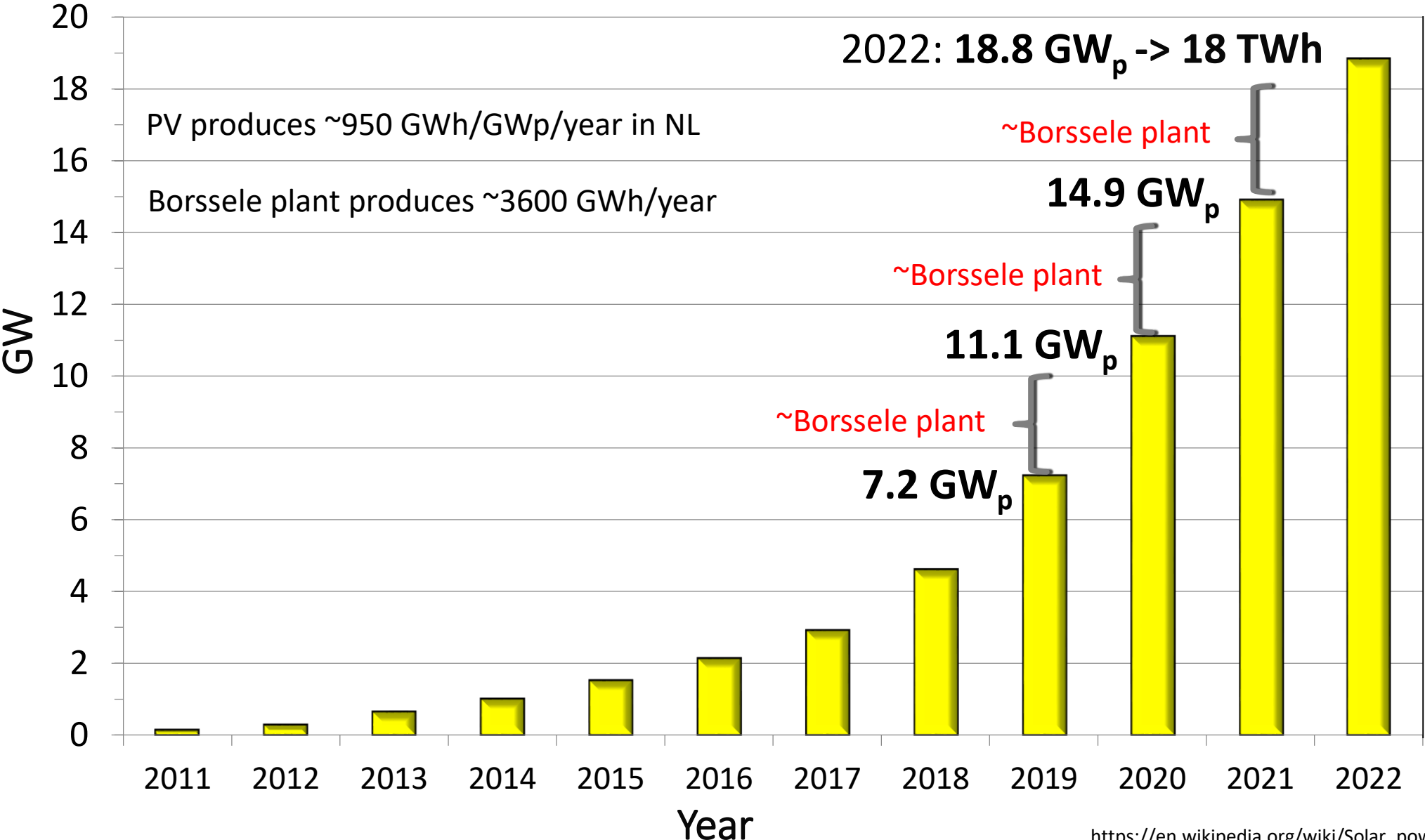
# Energy transition: Bulk e-generation

## Bulk e-generation from RES

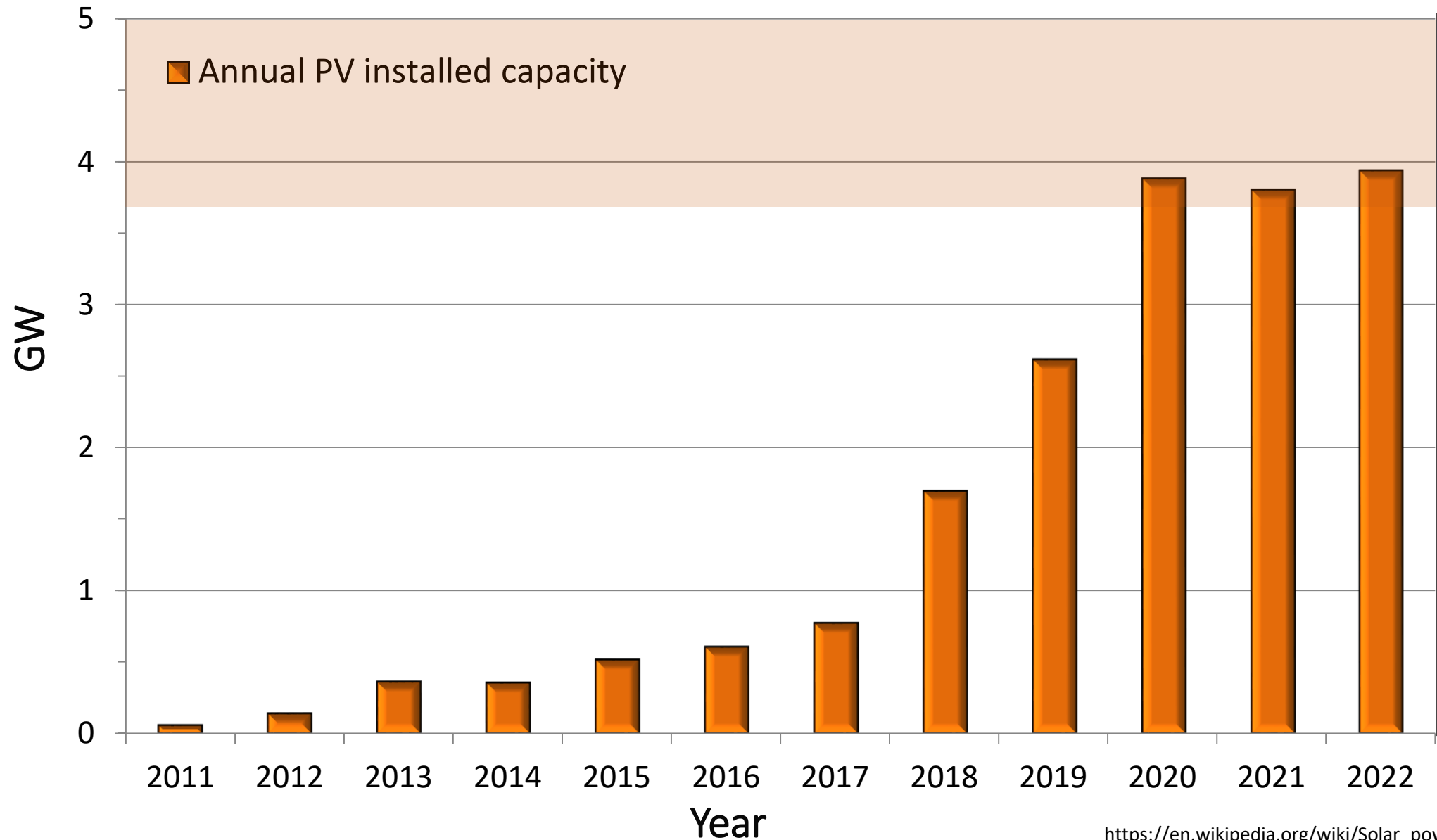




# Cumulatief geïnstalleerd PV vermogen in NL

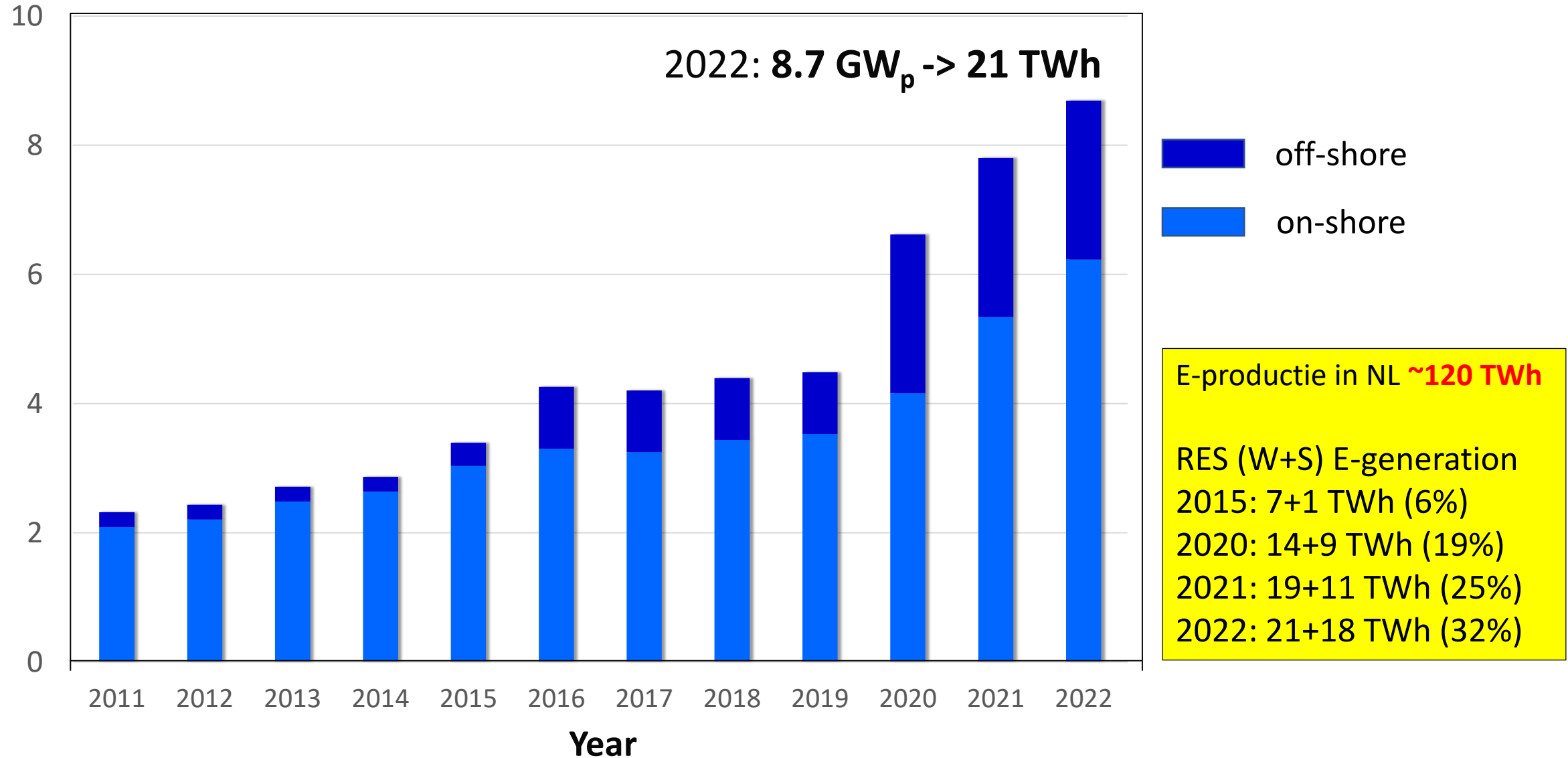


# Jaarlijks geïnstalleerd PV vermogen in NL



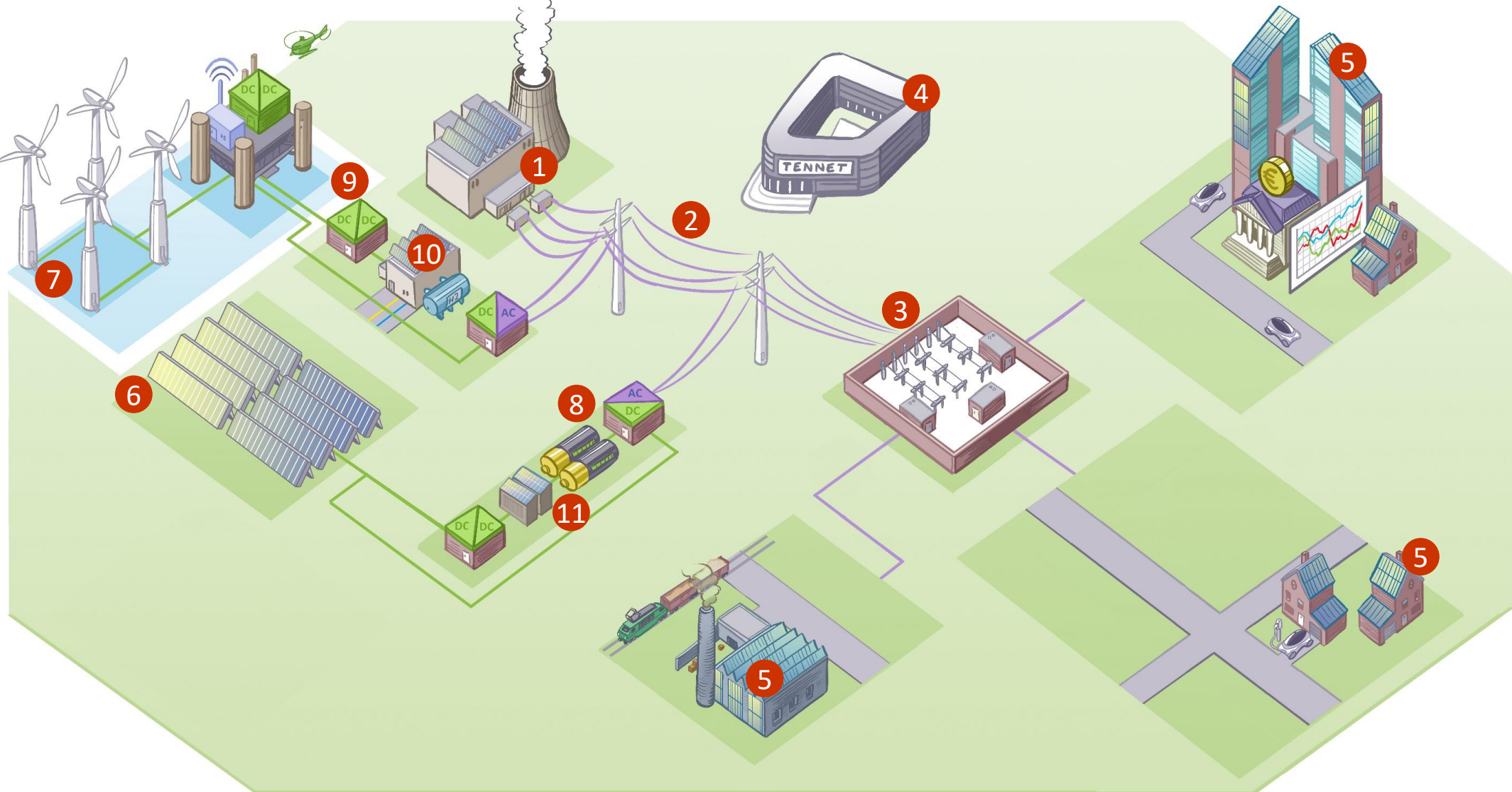
# Geïnstalleerd wind vermogen in NL

GW



# Energy transition: Flexibility of energy supply

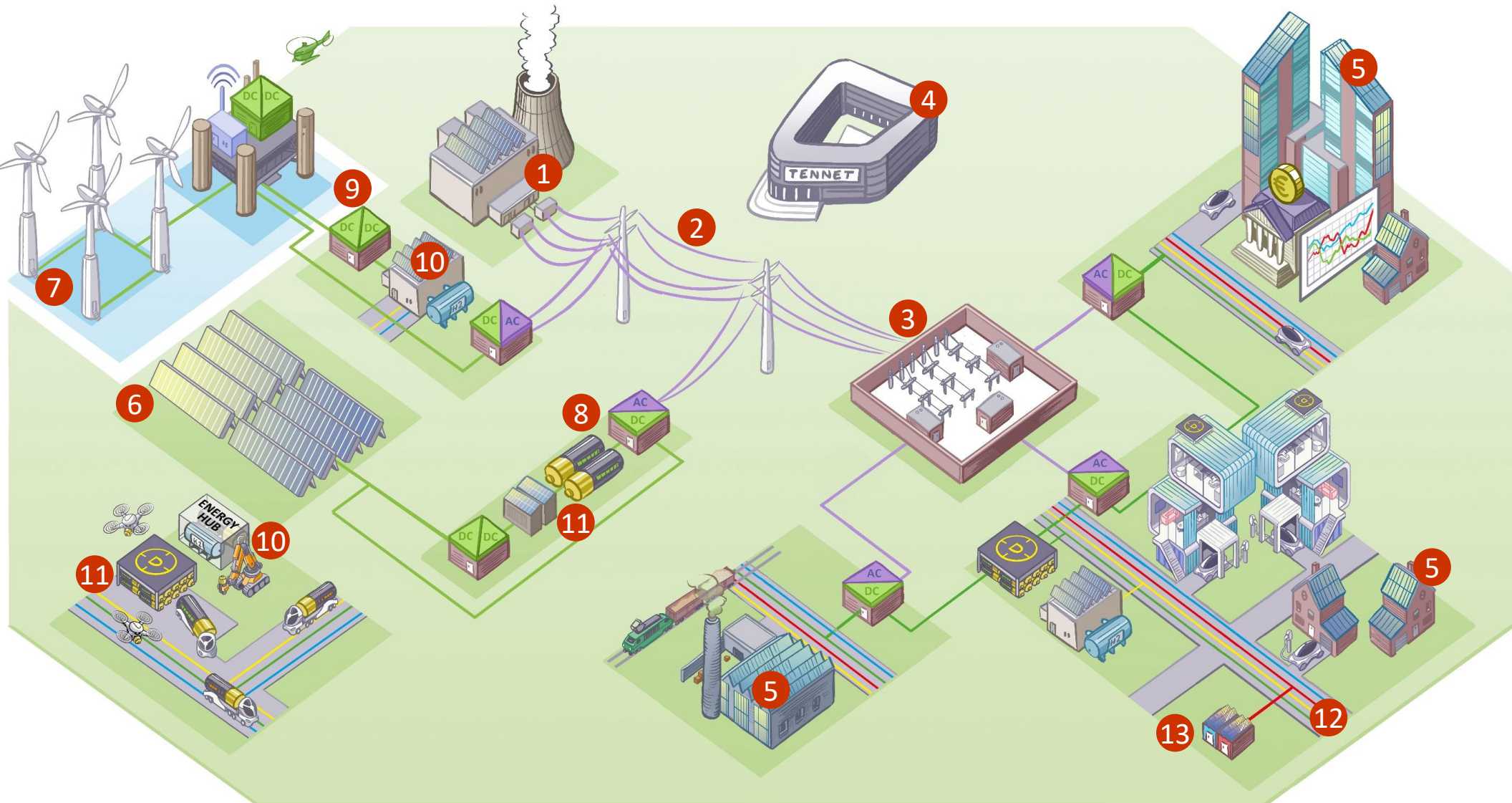
Increasing flexibility of supply by different energy storage options



- 1 Central power plant
- 2 HV Transmission
- 3 Substation
- 4 TSO
- 5 Local PV Systems
- 6 Central PV plant
- 7 Off-shore wind park
- 8 DC/AC Invertors
- 9 DC/DC Invertors
- 10 Power to gas (H<sub>2</sub>)
- 11 Battery storage

# Energy transition: Multi-commodity grids & hubs

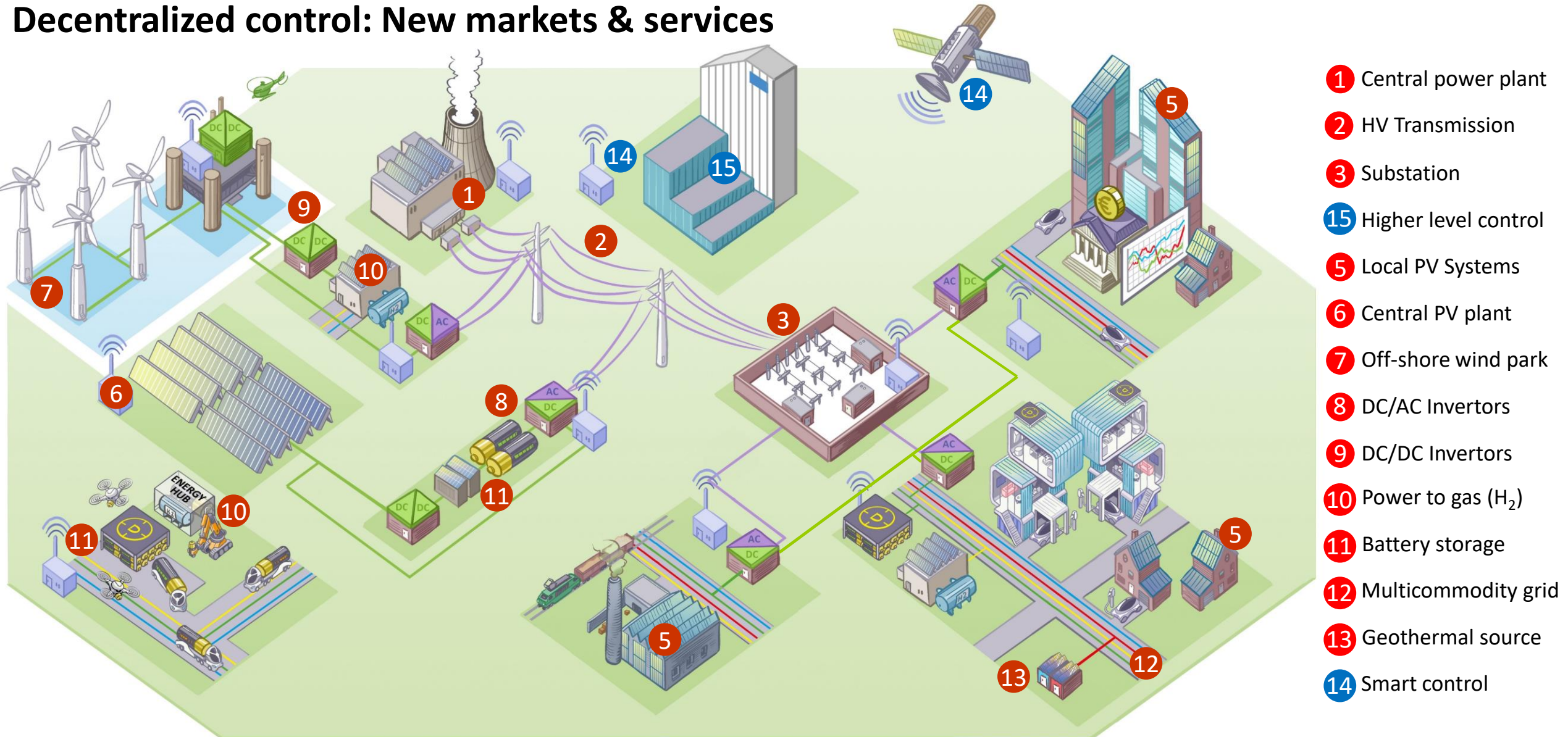
## Local energy systems with e-generators



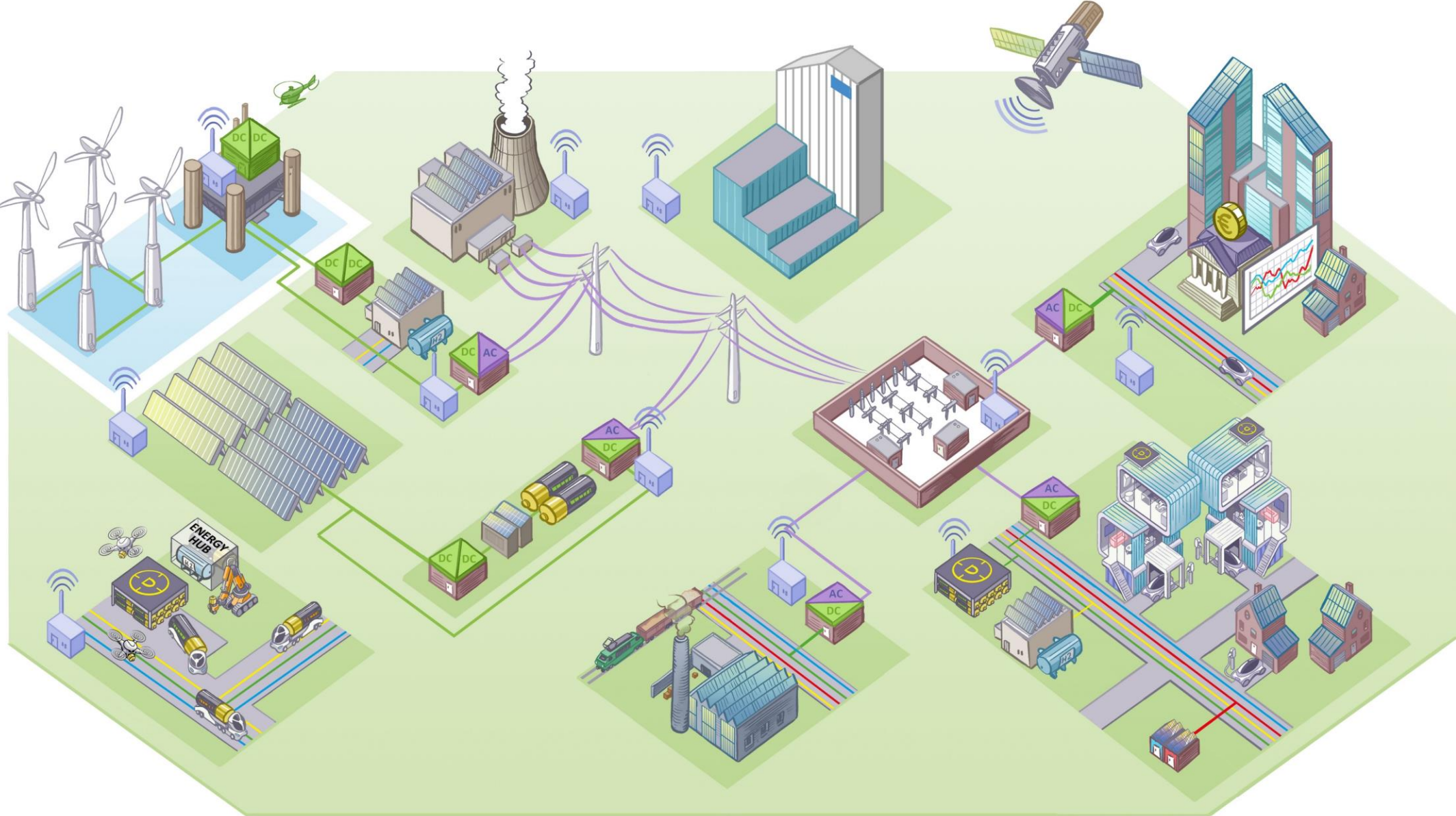
- 1 Central power plant
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- 5 Local PV Systems
- 6 Central PV plant
- 7 Off-shore wind park
- 8 DC/AC Invertors
- 9 DC/DC Invertors
- 10 Power to gas (H<sub>2</sub>)
- 11 Battery storage
- 12 Multicommodity grid
- 13 Geothermal source

# Energy transition: Intelligent monitoring & control

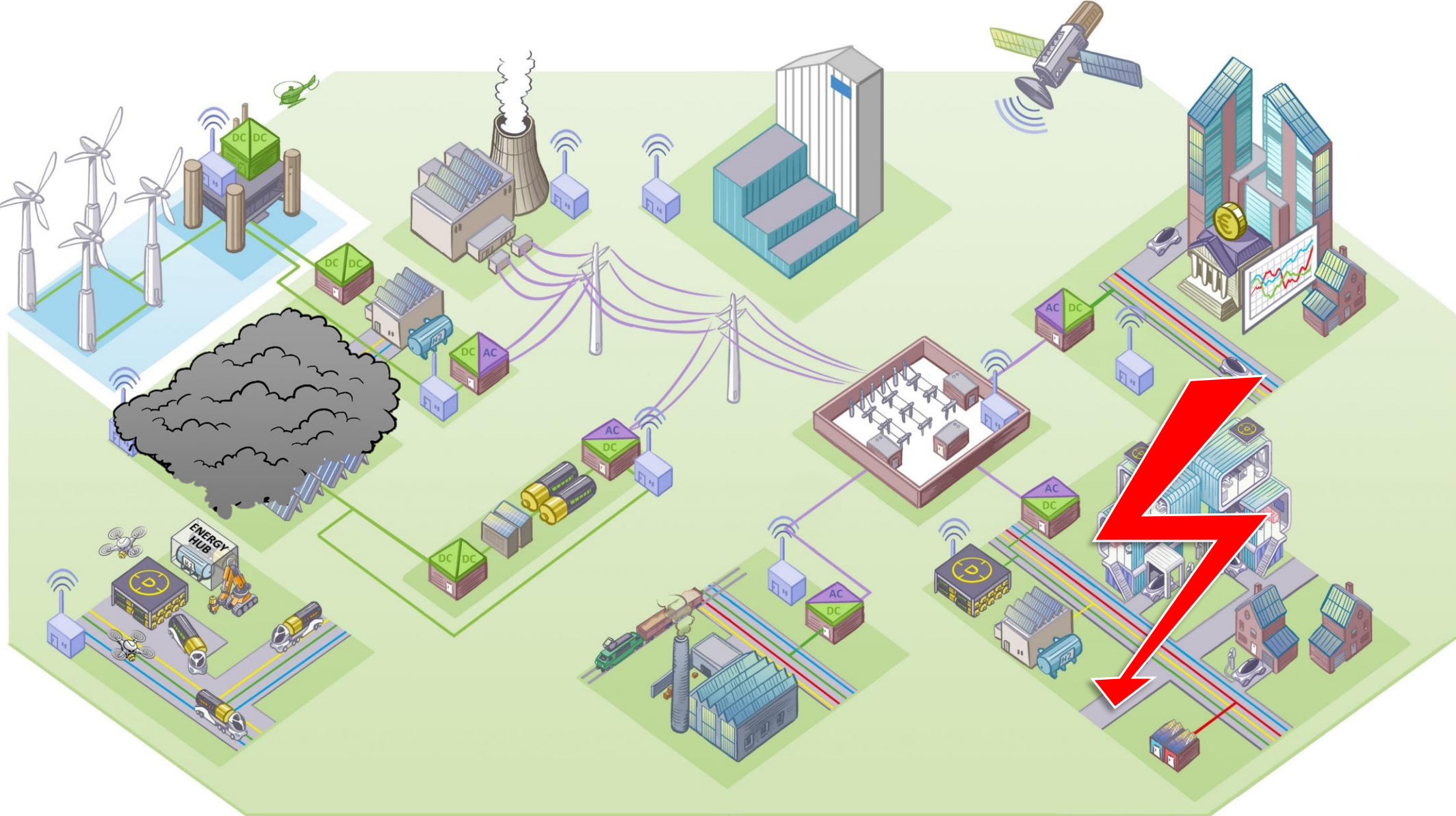
## Decentralized control: New markets & services



# Energy transition: Challenges



# Energy transition: Challenges



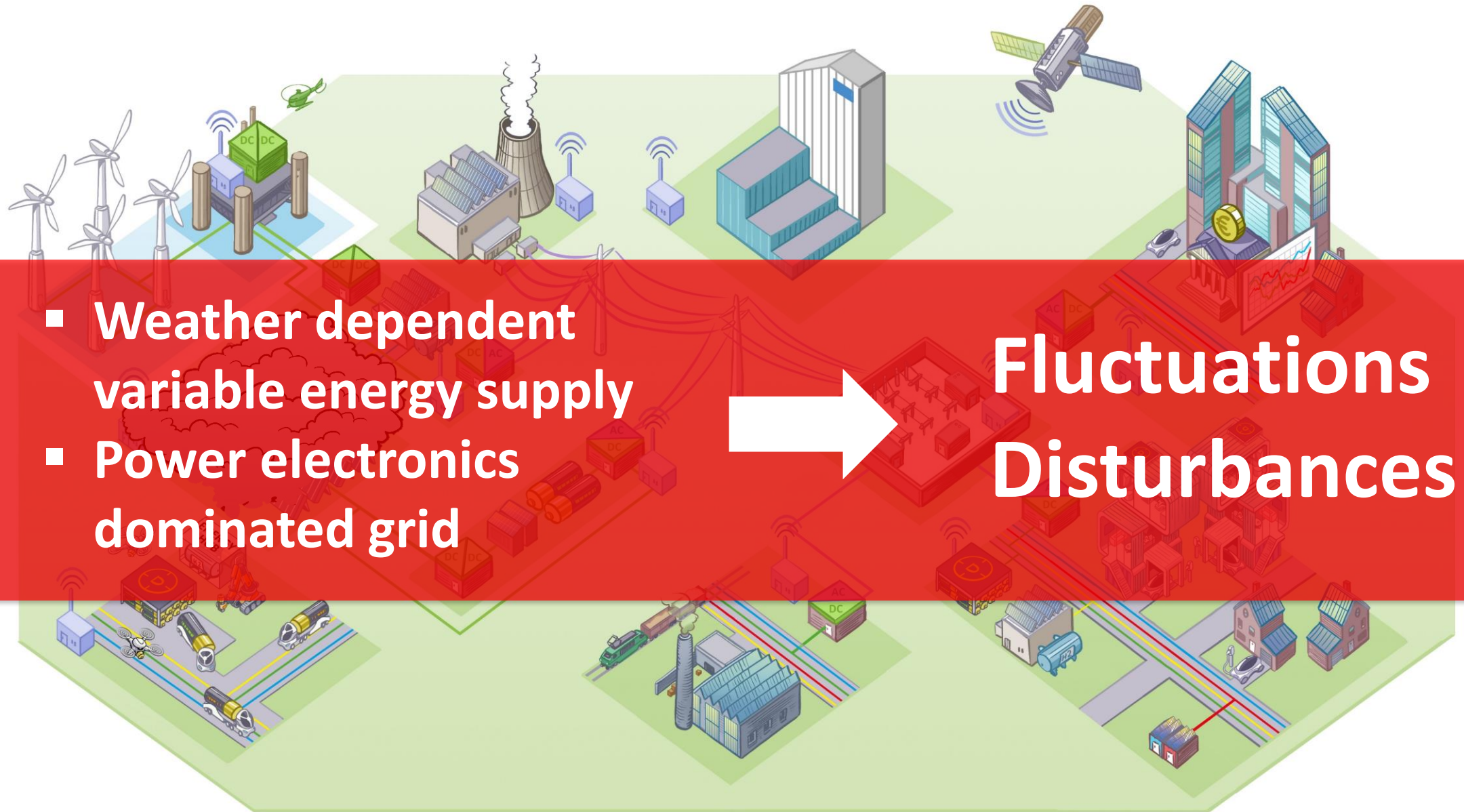


# Energy transition: Challenges

- Weather dependent variable energy supply
- Power electronics dominated grid



**Fluctuations  
Disturbances**



# Energy transition: Challenges



**Key issues:**  
Security of supply  
Dynamic stability  
Power quality

# Klimaatakkoord



## Klimaataakkoord



### Main goal:

Reduction of greenhouse gas emissions by 49% by 2030 compared to 1990

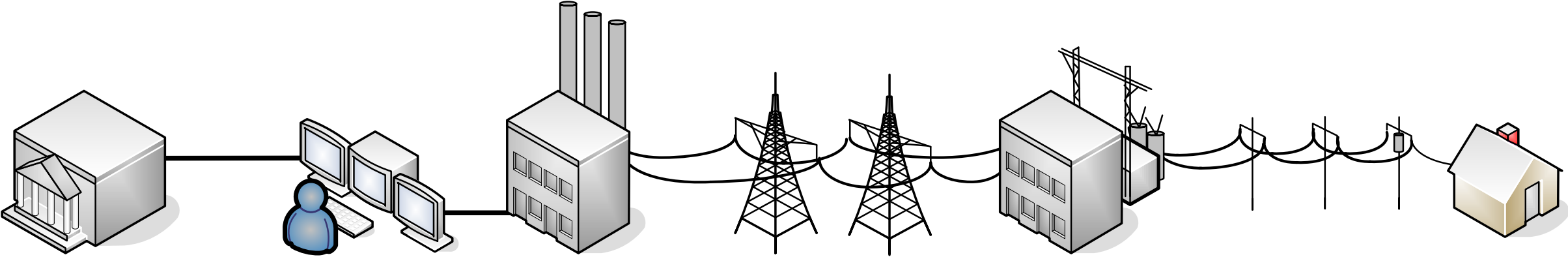
### Main impact:

Electricity sector of energy system

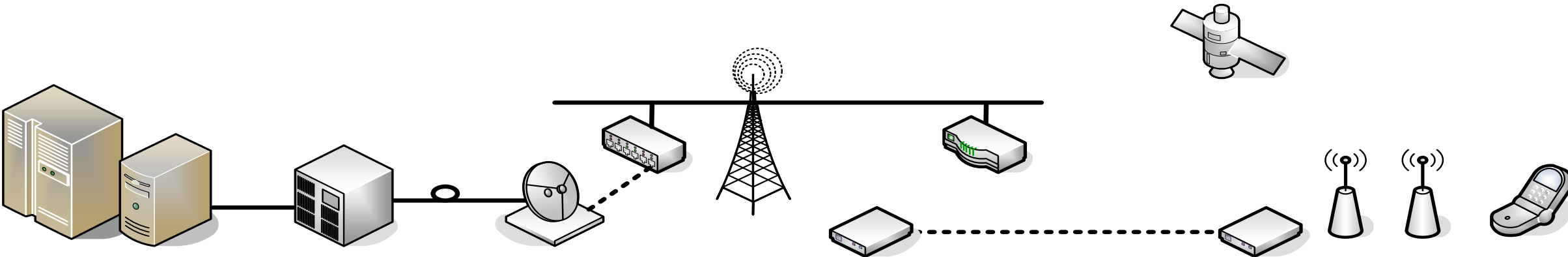
### Agreements 2030:

- **Total 84 TWh** (from 120 TWh) **in 2030** from renewable energy sources
- **70% of electricity production dependent on weather**

# Smart grid: Building and merging of two infrastructures



Electrical power infrastructure

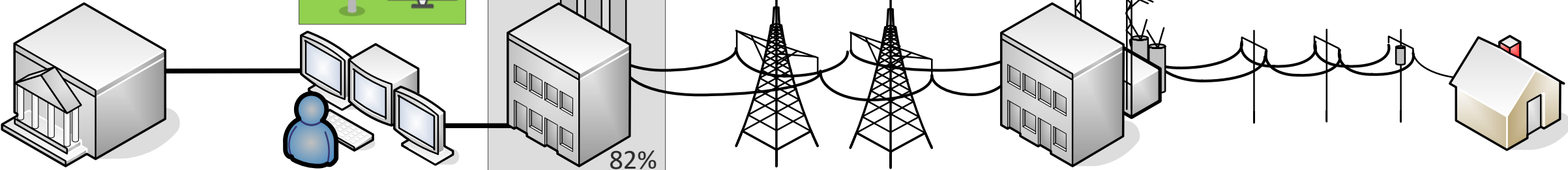
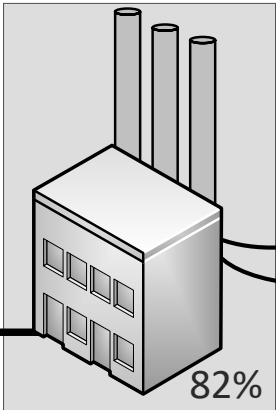
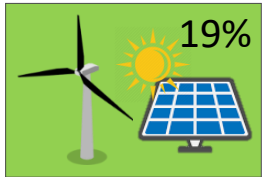


Measurement, Control and Communication infrastructure

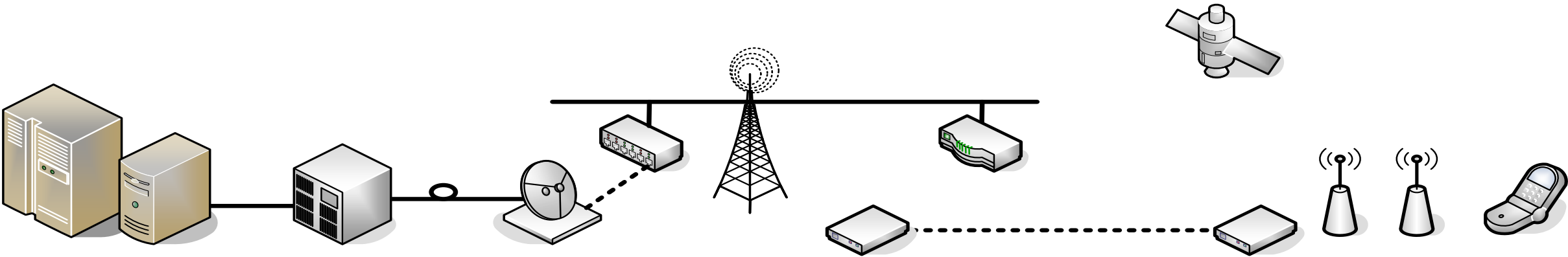
Bron: Prof. Riberio

# Smart grid: Building and merging of two infrastructures

2020



Electrical power infrastructure



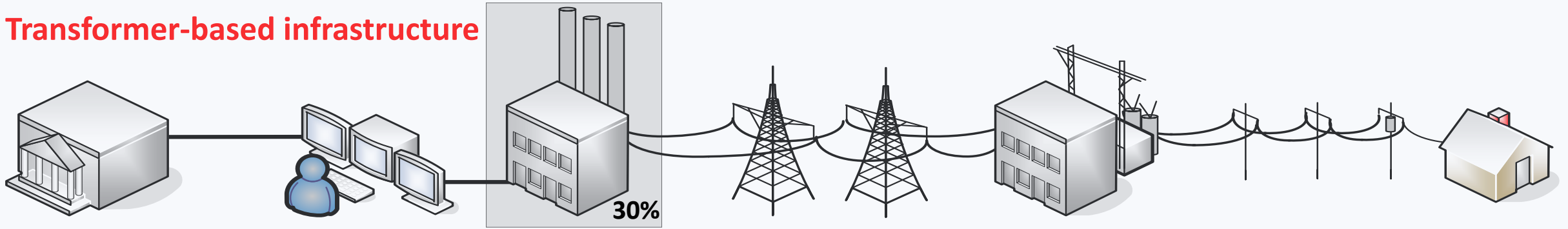
Measurement, Control and Communication infrastructure

Bron: Prof. Riberio

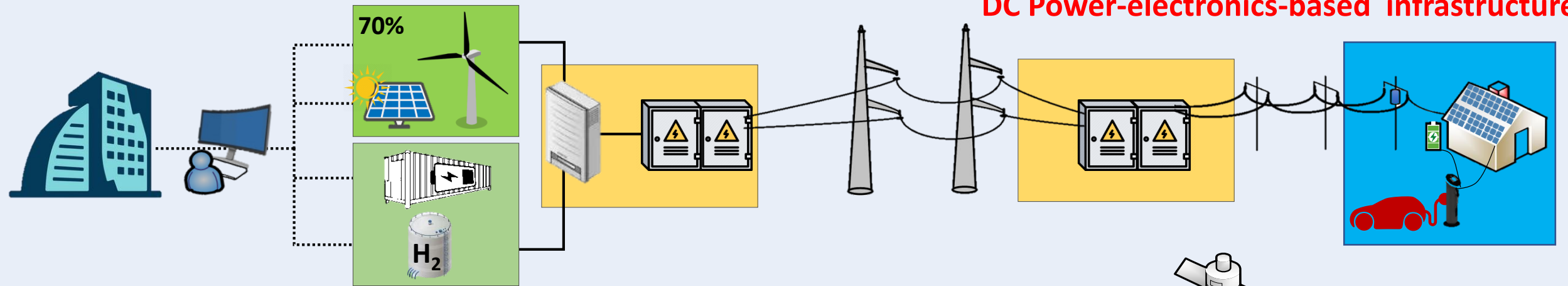
# Smart grid: Building and merging of **three infrastructures**

2030

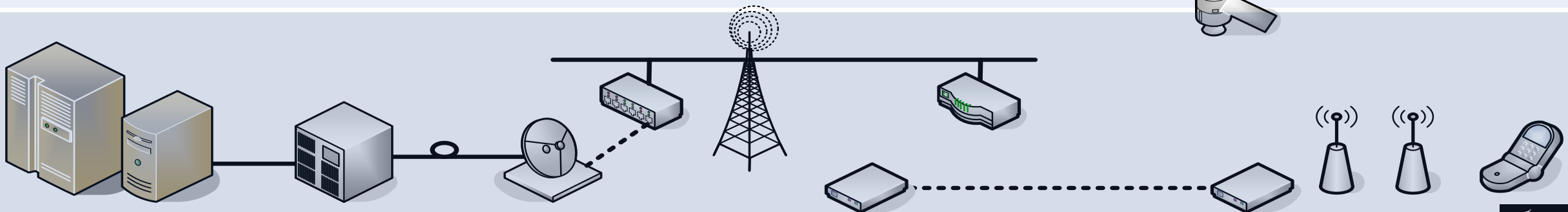
**AC Transformer-based infrastructure**



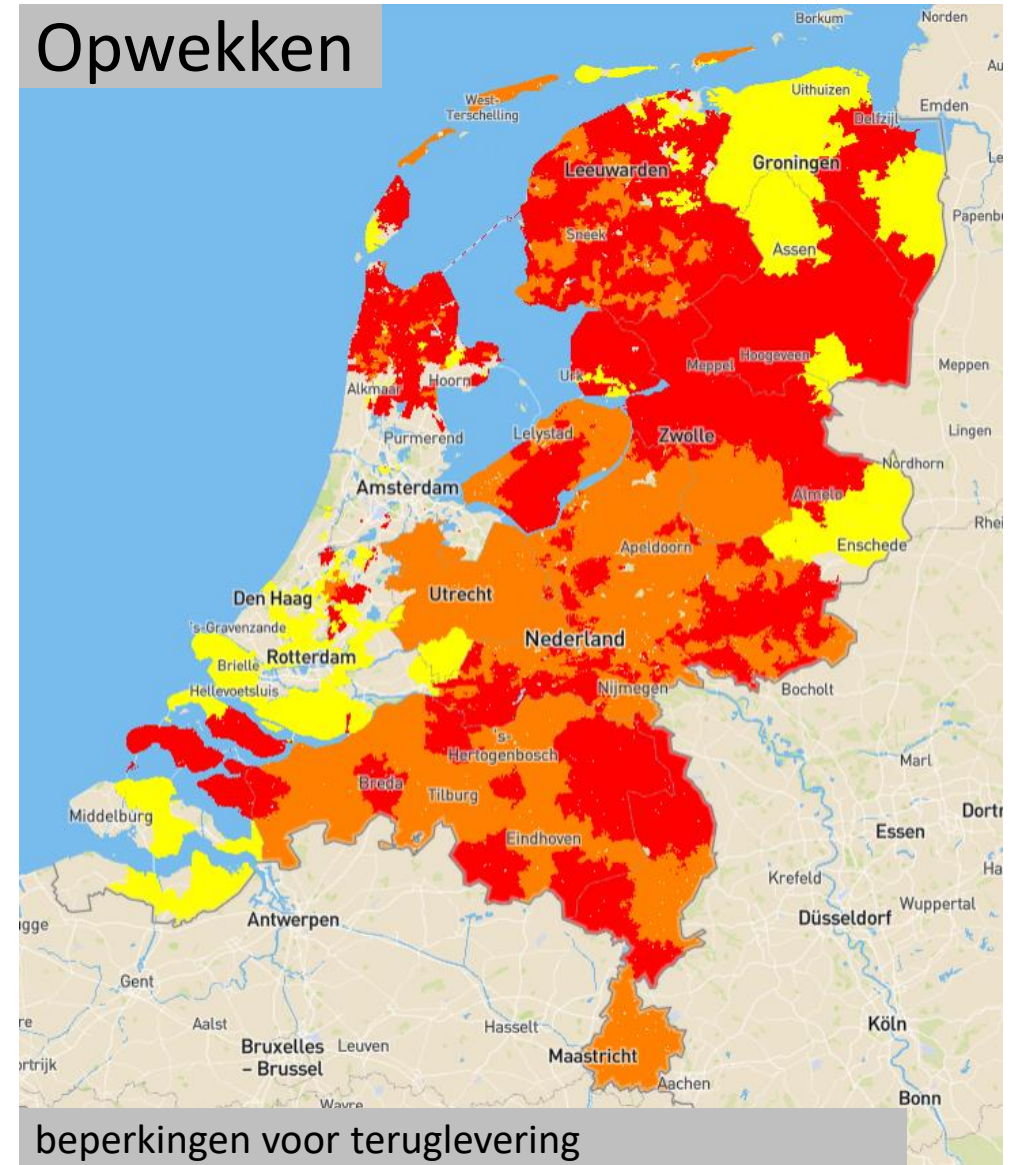
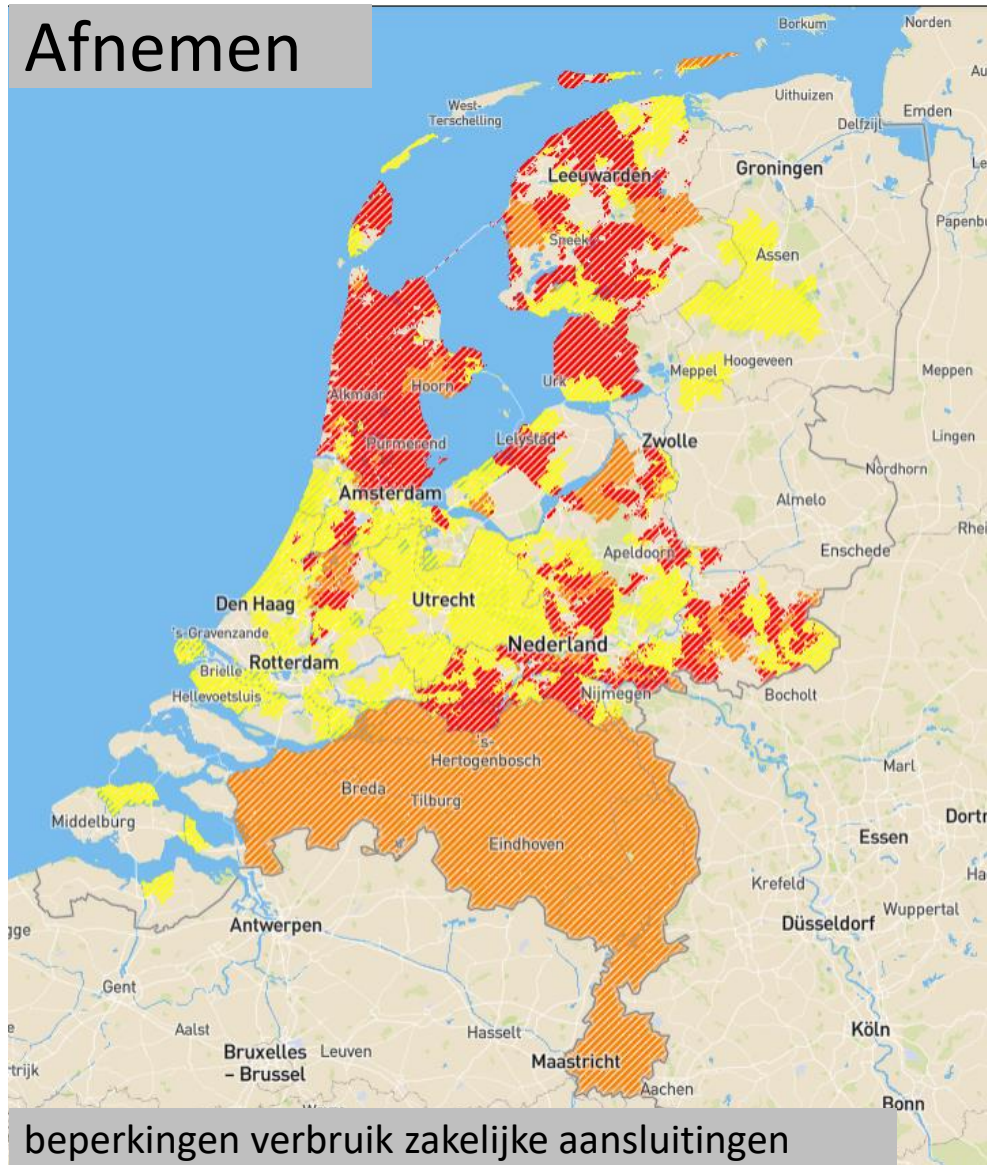
**DC Power-electronics-based infrastructure**



**Digital infrastructure (Measurement, Control and Communication)**



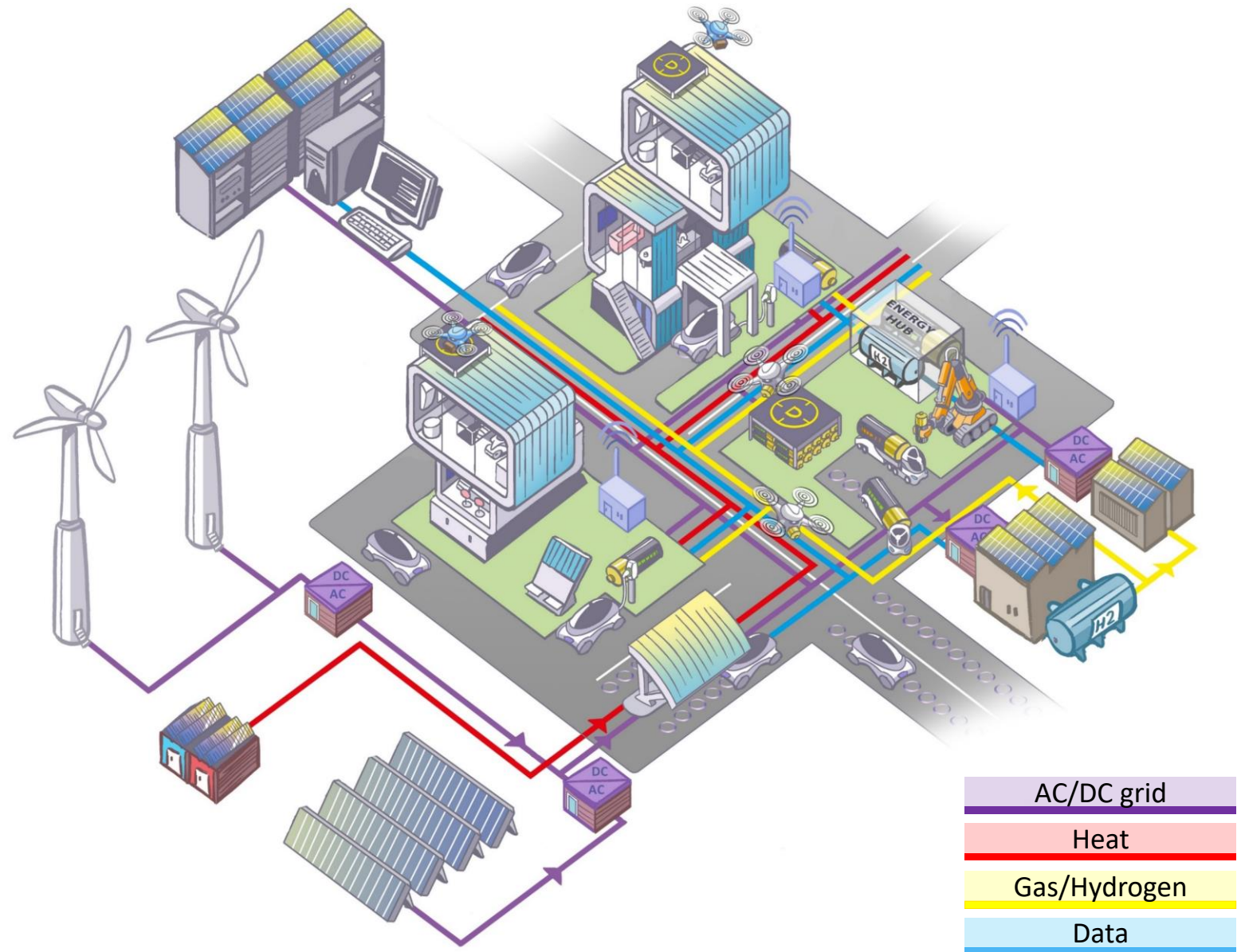
# Availability of network capacity





# Energy Hubs

- Optimal use of local renewable energy
- Management of energy conversion, storage and consumption
- Infrastructure, smart control



# ESP Lab



# Weg vooruit



Vlam van Prometheus

TU Delft

ENERGY

**DARE  
TO CHANGE**

**ENERGY**



We did it!