Design-driven research on photovoltaic technologies – Solar integration in buildings, mobility and our environment

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1. Introducing myself

Angèle Reinders (prof.dr.)

Professor of Design of Sustainable Energy Systems, Energy Technology and Fluid Dynamics Group, Fac. of Mechanical Engineering, Eindhoven University of Technology, the Netherlands, 2018 – present

Associate Professor, Dept. of Design Production and Management, Fac. of Engineering Technology, University of Twente, 2002 - present

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Professor of Energy Efficient Design, Fac. of Industrial Design Engineering, Delft University of Technology, Delft, 2010 – 2017

Visiting Research Fellow, Center for Urban Energy & Hydro One, Toronto, Canada, 2013-2014

Assistant Professor, Dept. of Design Engineering, Fac. of Industrial Design Engineering, Delft University of Technology, Delft, 2001

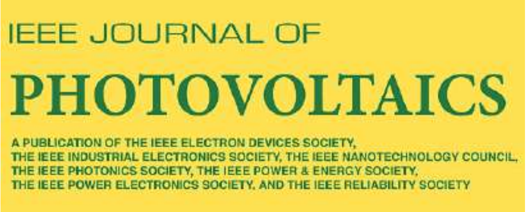
Consultant, World Bank, ASTAE: Asia Sustainable and Alternative Energy Program, Washington DC, USA, 2000

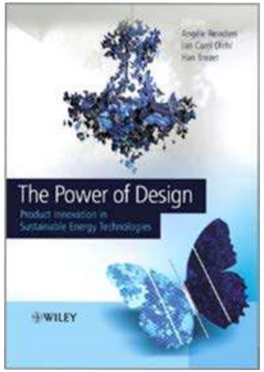
PhD in ‘Performance Analysis of Photovoltaic Solar Energy Systems’, Dept. of Science, Technology and Society, Fac. of Chemistry, Utrecht University, 1999

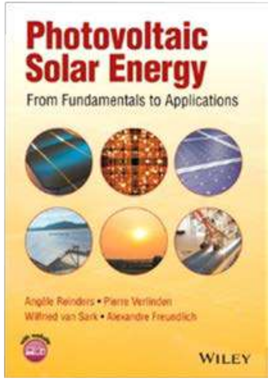
Master in Experimental Physics, Utrecht University, the Netherlands, 1993

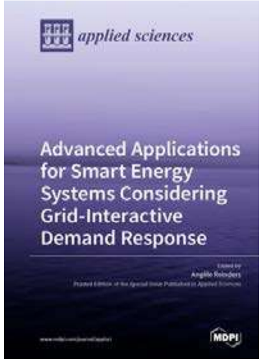
My present research topics

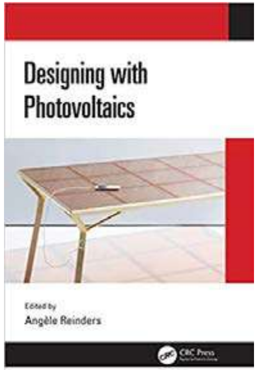
- Data analysis and simulations of PV systems
- Solar powered electric mobility with EVs
- Building integrated (solar) energy systems
- PV-powered hydrogen infrastructures
- Luminescent solar concentrators
- Distributed energy systems with RETs



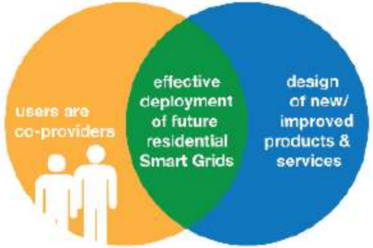


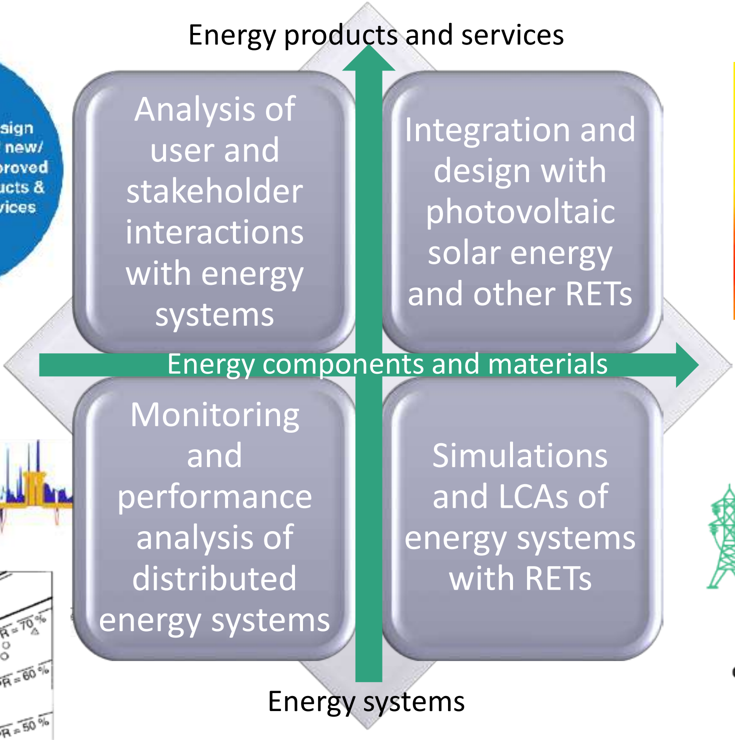


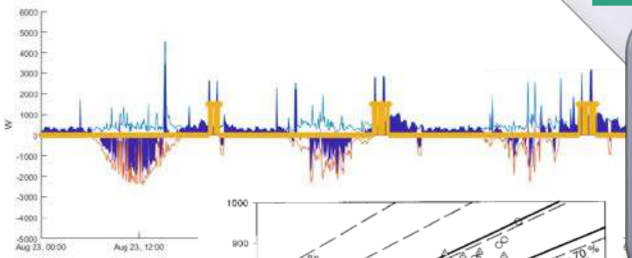


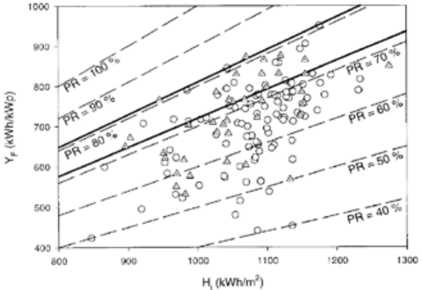


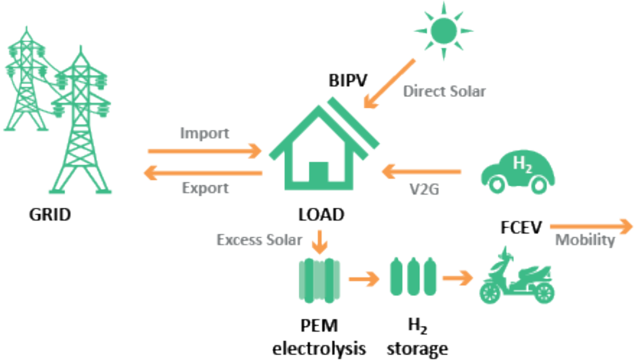
MY RESEARCH FRAMEWORK



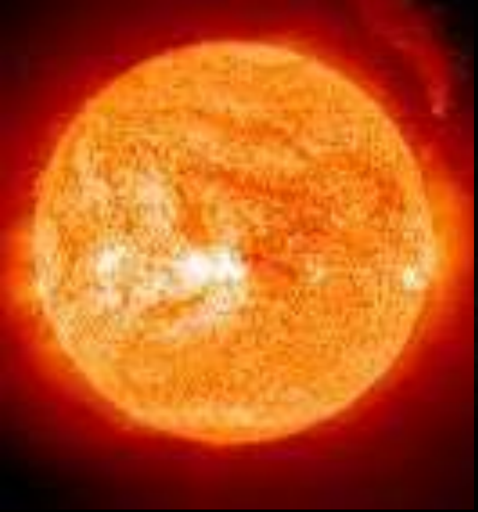


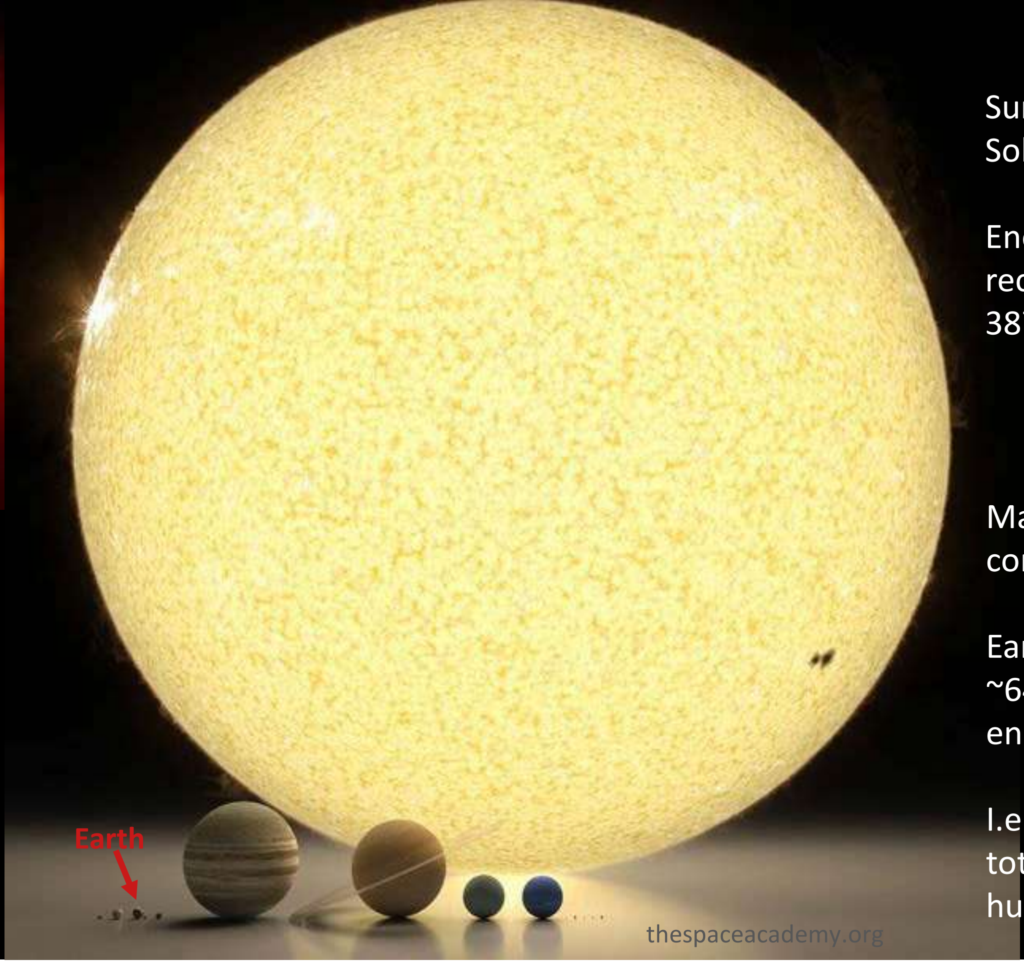






Integration potential of solar technologies





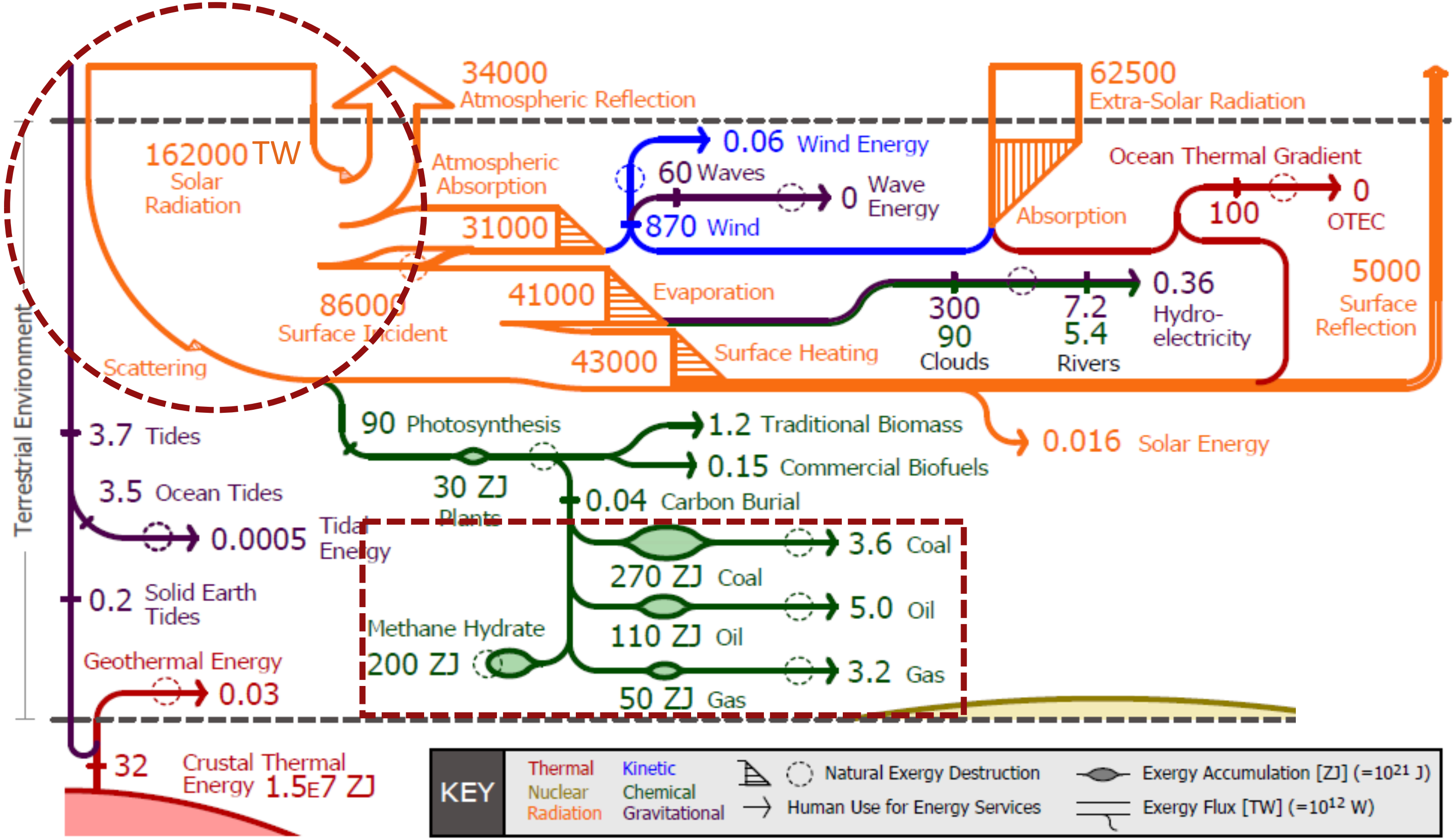
Surface temperature: ~5800 K
Solar radiation: ~3.9 x 10^{26} W

Energy (extraterrestrially) received by Earth: 3870 ZJ/yr

Mankind's energy consumption: ~600 EJ/yr

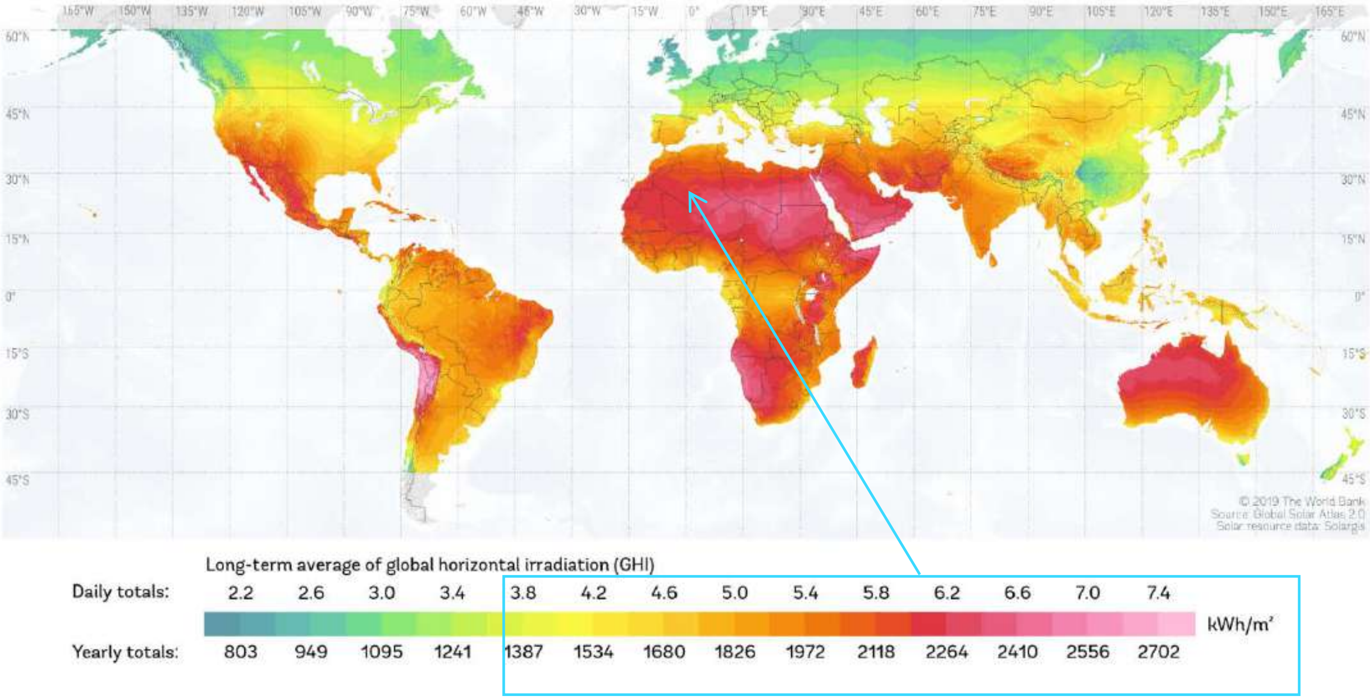
Earth receives every year ~6450 times its human energy use from the Sun.

I.e. in approx. 1,5 hour the total amount of yearly human energy use!



Source: Adapted from Global Climate & Energy Project, Stanford University https://gcep.stanford.edu/research/exergy/resourcechart.html

Terrestrial irradiation is globally distributed



Easily determine irradiance on any location with EU's PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM: https://re.jrc.ec.europa.eu/pvg_tools/en/

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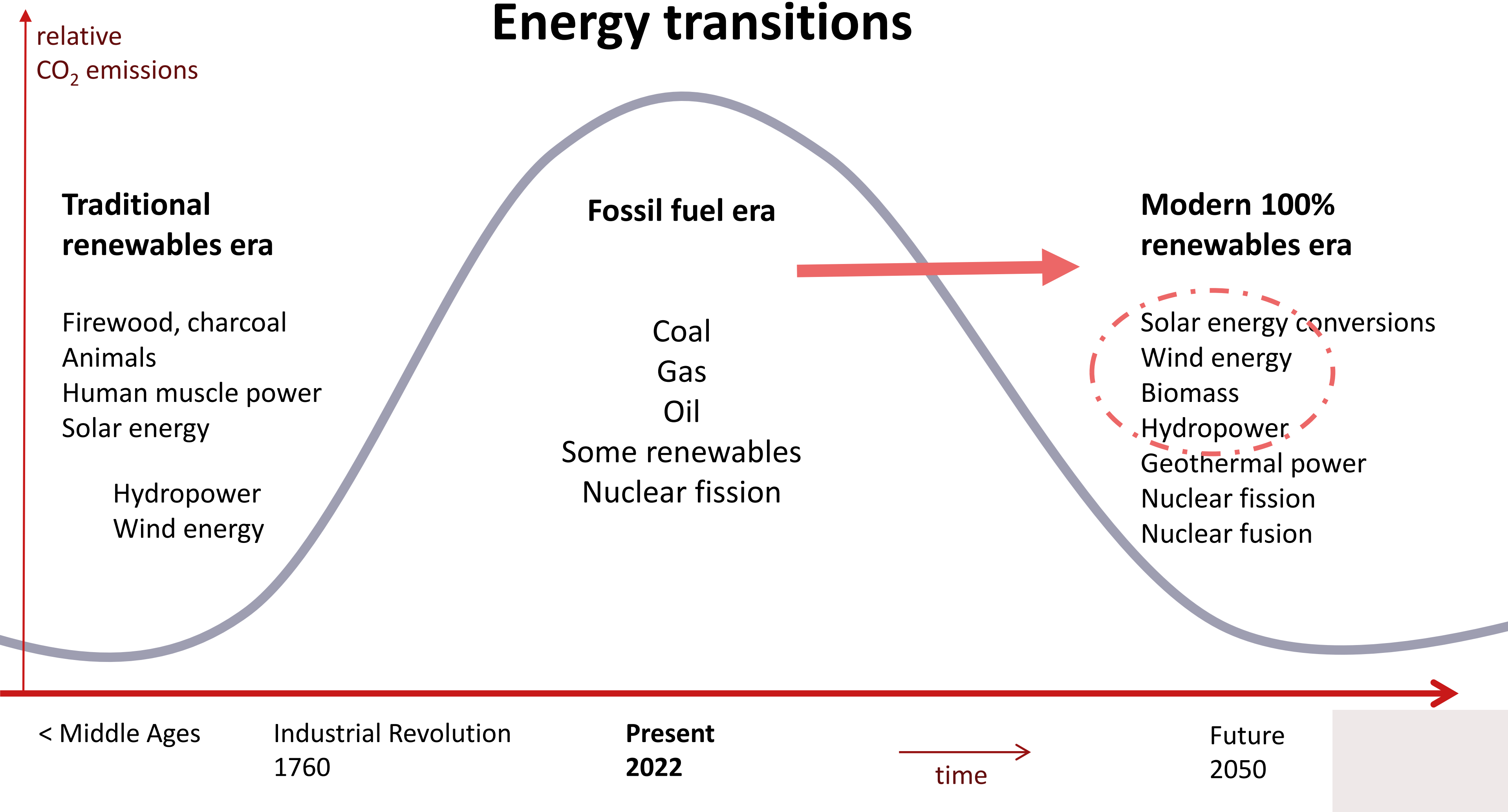
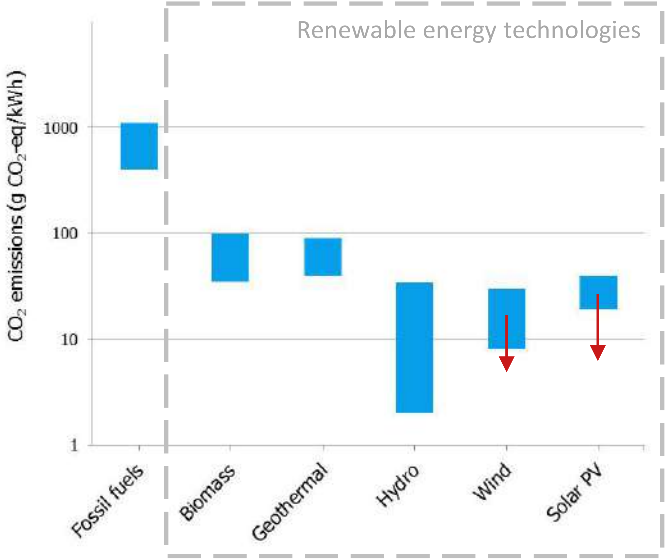
Energy transitions



Renewable energy to mitigate climate change

Energy that is derived from natural processes that are replenished at a higher rate than they are consumed with significantly low CO_2 emissions (IEA)



Comparison of CO_2 emissions of various energy technologies (Reinders, Verlinden, van Sark & Freundlich, 2017)

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Energy transition in the Netherlands

According to the National Climate Agreement (Klimaatakkoord)

By 2030: 70% of all electricity should originate from sustainable sources (2021: 33%), and 27% of all energy (2021: 12%)

By 2050: National CO_2 emissions should be reduced by 95%; almost all energy supply should be sustainable;

-the Netherlands should have a CO_2 emission-free electricity system;

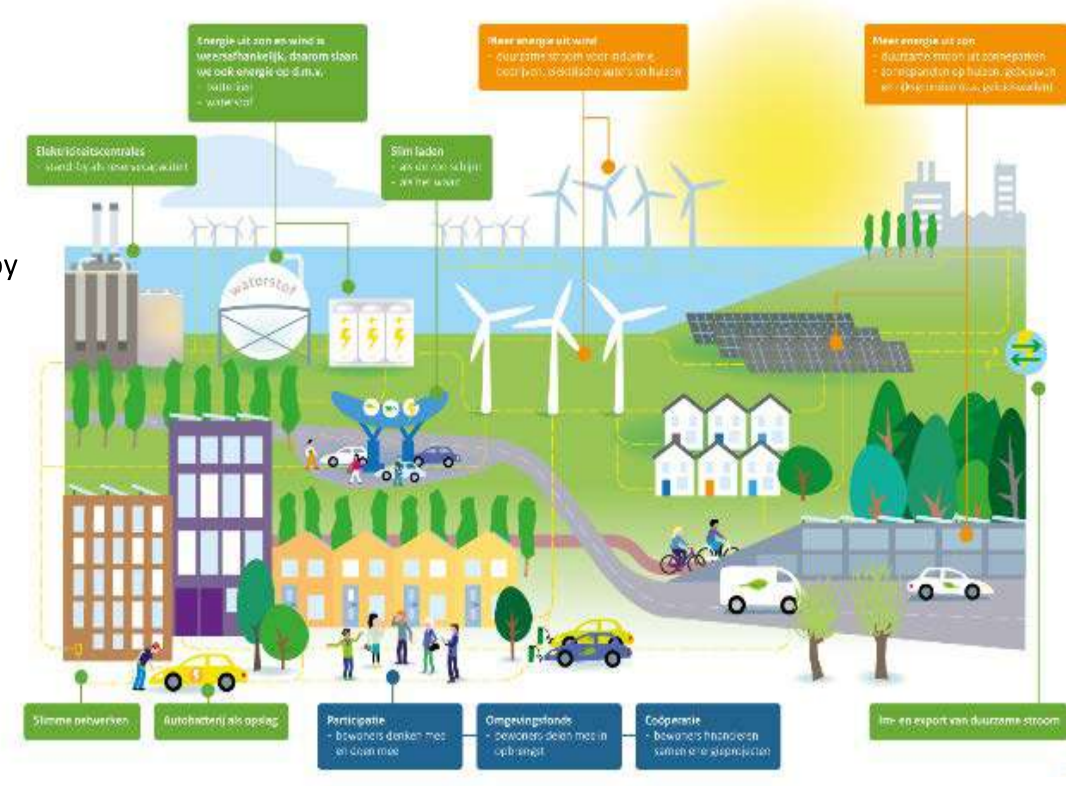
-7 million households and 1 million utility buildings must be natural gas-free;

-mobility must be emission-free in the Netherlands;

-Industry and agriculture will be climate neutral.

By 2020: all new buildings (in the EU) should be net-zero energy buildings.

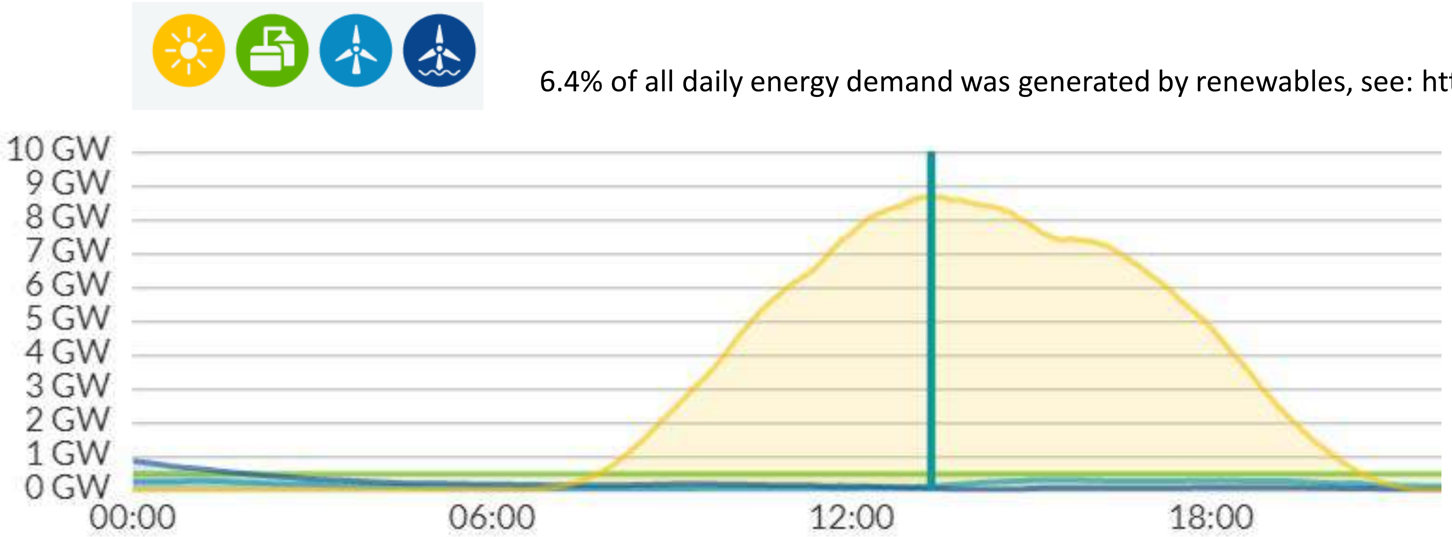
See: https://www.klimaatakkoord.nl/

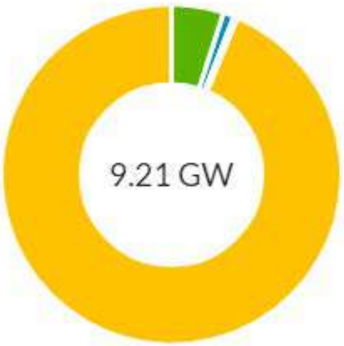


(Infographics from Klimaatakkoord, 2019)

Yesterday in the Netherlands

6.4% of all daily energy demand was generated by renewables, see: https://energieopwek.nl/





A possible route to achieve a higher share of solar energy supply

Renewable Energy + **Design** = **Renewable Energy Transition**

Renewable Energy: producing and using energy in a way that "meets the needs of the present without compromising the ability of future generations to meet their own needs"

Design: "the human capacity to shape and make our environment in ways without precedent in nature, to serve our needs and give meaning to our lives"

Renewable Energy Transition: the long-term, structural transformation of a society which is mainly based on fossil fuel conversions to a decarbonized one with a high share of sustainable energy

Solar energy, technologies and their application context

Electricity

- Photovoltaic (PV) effect in semiconductor materials: silicon, III-V compounds, chalcogenides etc. Concentration irradiance.
- PV systems: intermittency can be partially handled by grid, and demand management, otherwise additional storage is required

Infrastructures

Buildings

Transport

Challenge for large-scale use:

daily and seasonal storage ; integration

Thermal energy

- Heat transfer through various (fluid) media by absorption, conduction, convection and radiation. Short term storage in system.
- Eventually combined with PV technologies (PVT) and/or heat engine (CSP).

Infrastructures

Buildings

Challenge: seasonal storage ; integration

Fuels

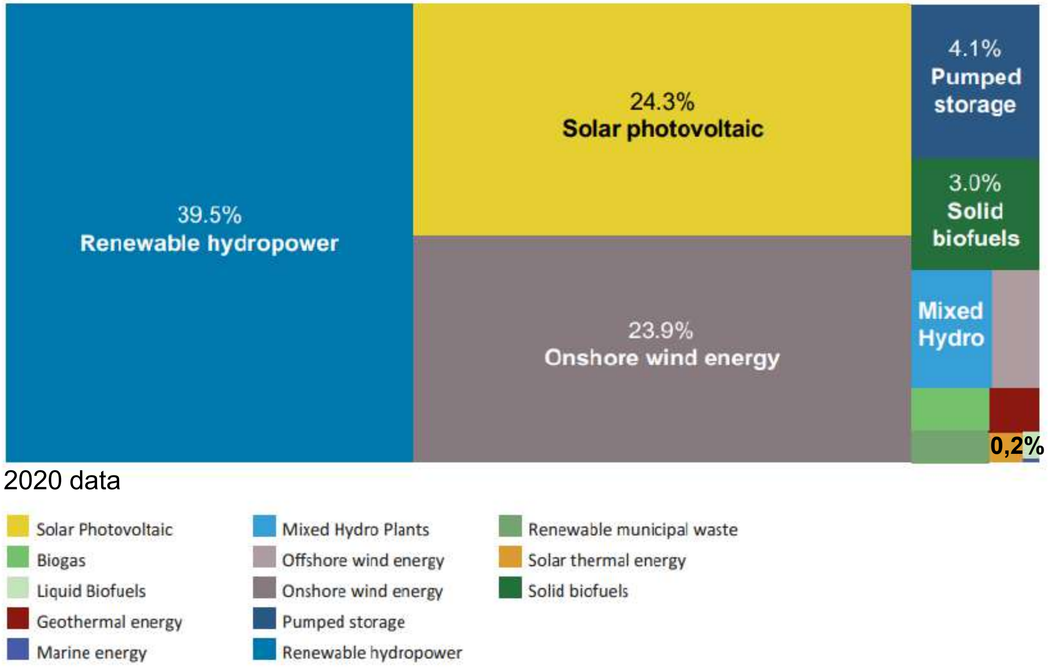
- Solar fuels: hydrogen, methane and ammonium, etc. Produced by: Electrolysis using PV electricity or photochemical processes using solar heat as an input
- Fuel itself is the storage means

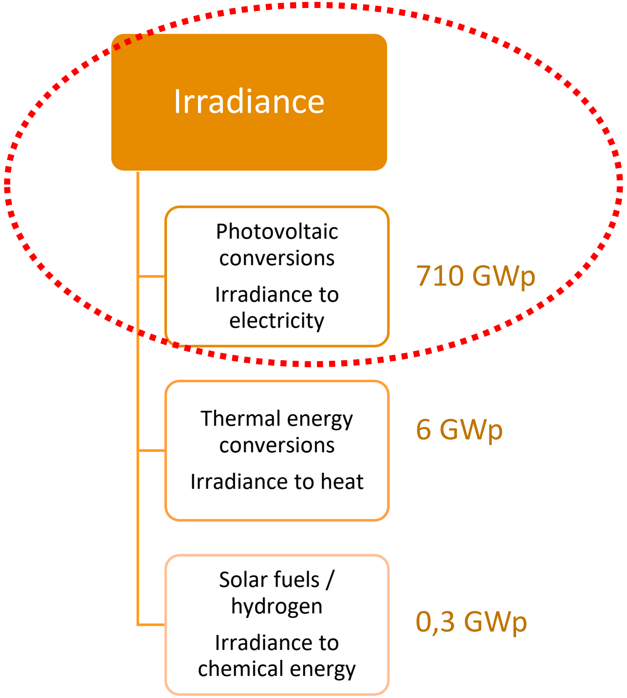
Infrastructures

Transport

Challenges: TRL of technologies, cost compared to fossil fuels ; integration

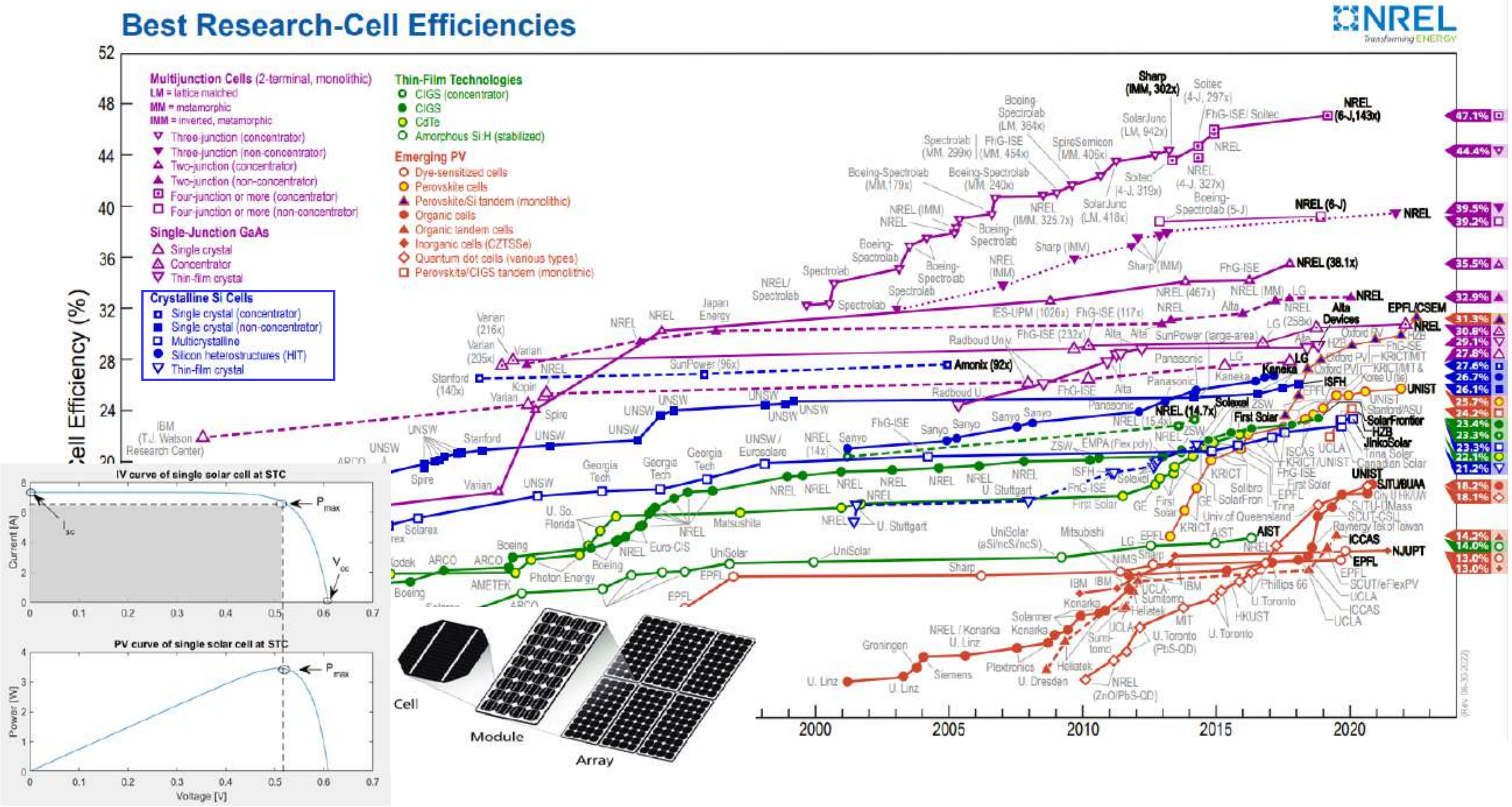
Installed capacity





Sources: Irena, https://www.irena.org/, data for the year 2020, total installed capacity ~2800 GWp
and, IEA, https://www.iea.org/data-and-statistics/charts/global-installed-electrolysis-capacity-by-technology-2015-2020

Photovoltaic technologies are very diverse



https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies-rev220630.pdf

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Growth of photovoltaics

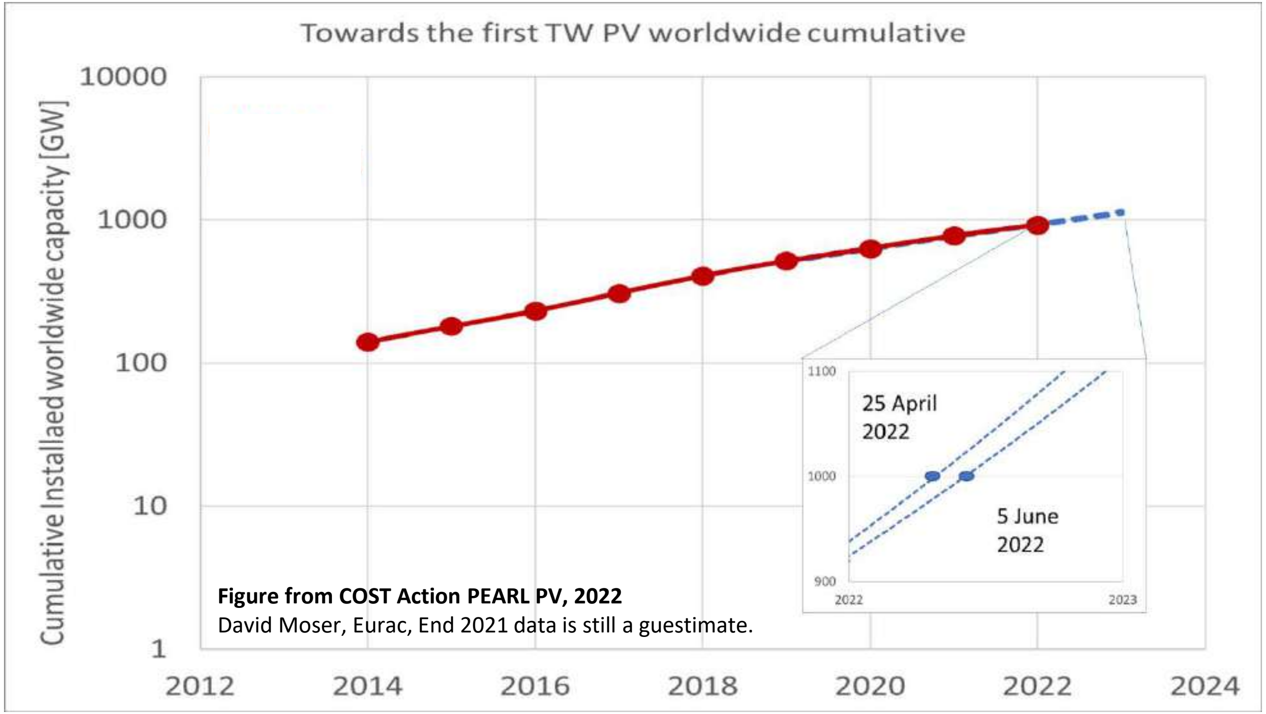
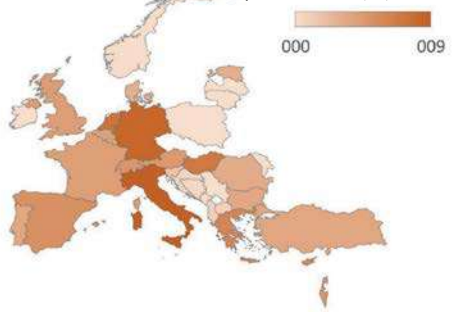
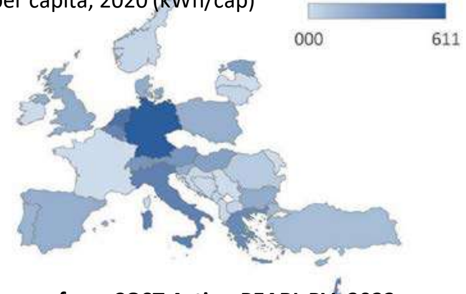


Figure from COST Action PEARL PV, 2022
David Moser, Eurac, End 2021 data is still a guestimate.

Share of PV in the electricity mix, 2020 (%)



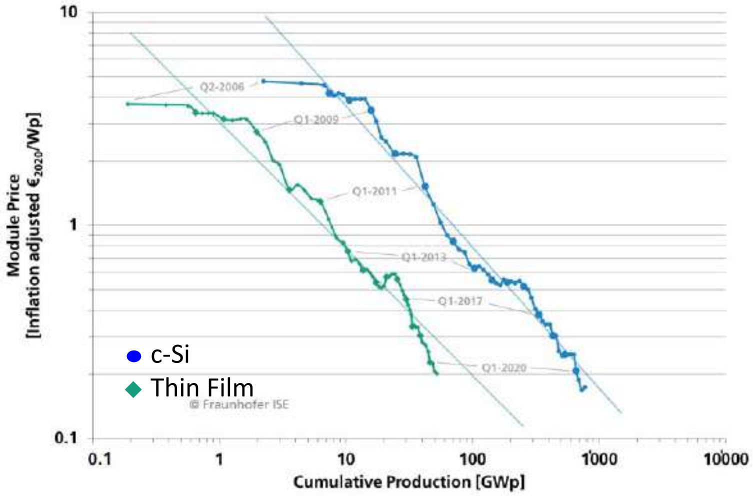
Average annual PV electricity produced per capita, 2020 (kWh/cap)



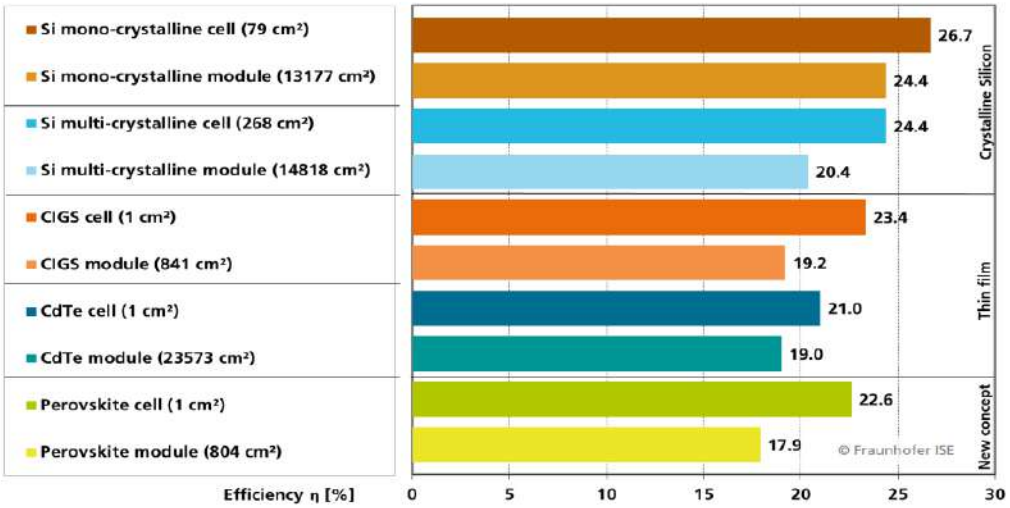
Figures from COST Action PEARL PV, 2022

Present status of photovoltaic technologies

Higher efficiency, lower costs has been the leading innovation trajectory for PV so far, with success! (Photovoltaics Report, FhG ISE, 2022)



Data: from 2006 to 2010 estimation from different sources :
Navigant Consulting, EUPD, pvXchange; from 2011: IHS. Graph: PSE GmbH 2021
Price learning curve for all PV module technologies; each time the cumulative production doubled, the price went down by 24 % for the last 39 years.



Data: Green et al.: Solar Cell Efficiency Tables (Version 59), Progress in PV: Research and Applications 2021. Graph: PSE Projects GmbH 2021, Date: November 2021

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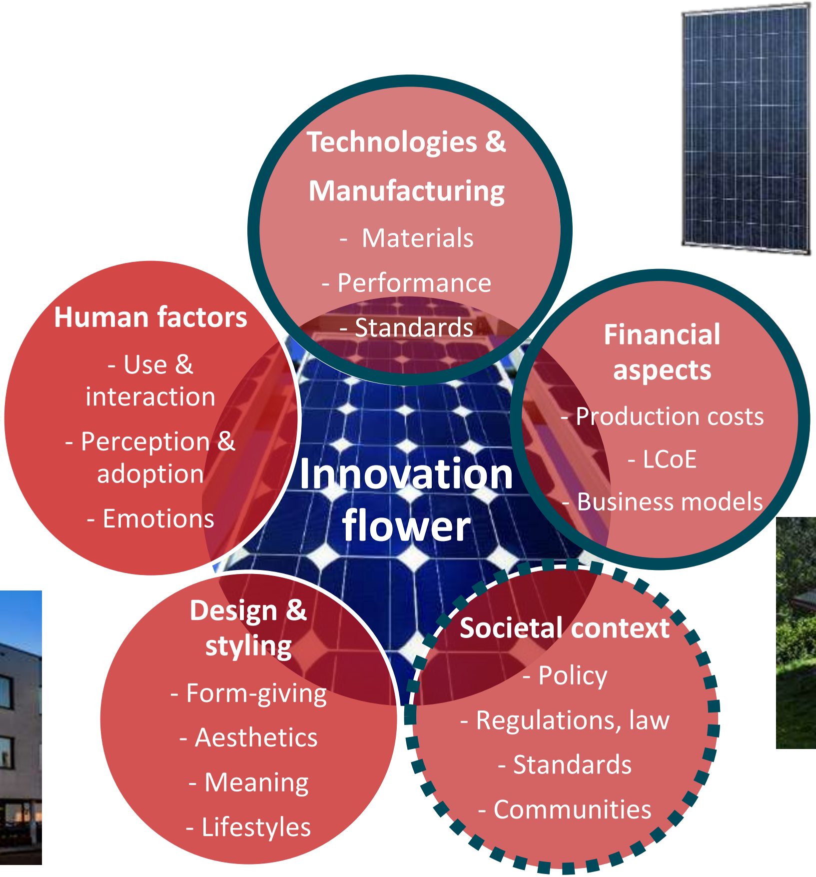
Next step: integration of photovoltaics

Virtue of blue
DeMakersVan



30 MW PV system, SunPort Delftzijl, NL

Solid Grey

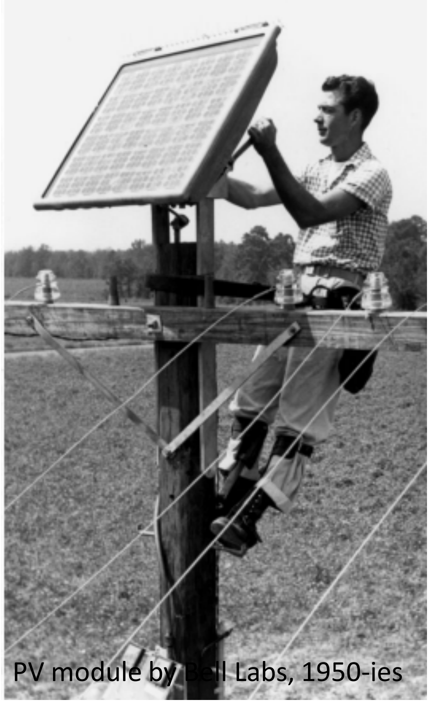
Sion Sono Motors

Kuipers building, Helmond, NL

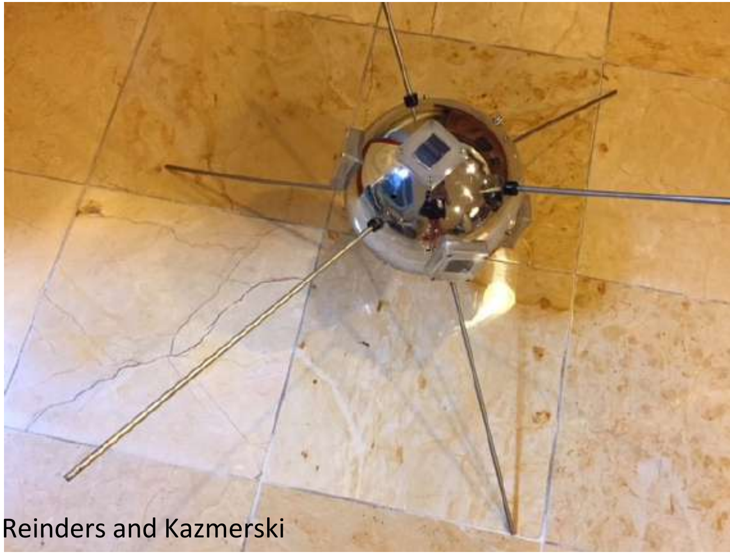
Brunner-Bapst House, solarchitecture.ch

Source: A.H.M.E. Reinders et al. The Power of Design, 2012-2022

How it all started

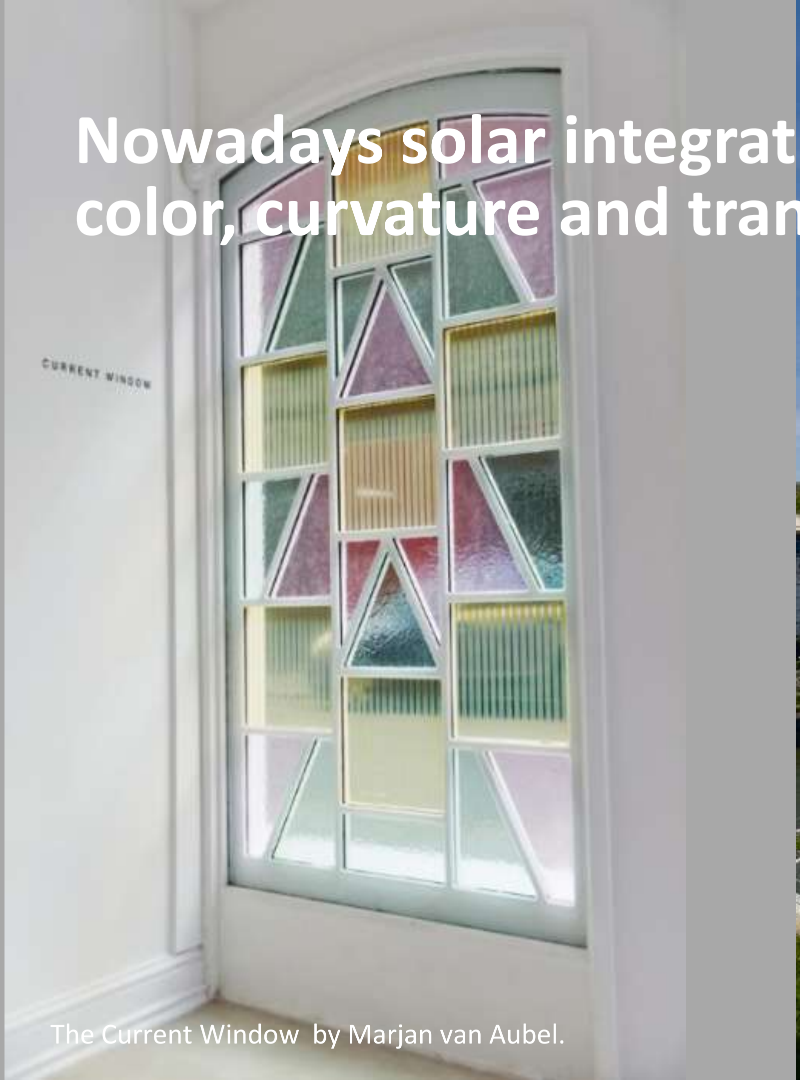


PV module by Bell Labs, 1950-ies

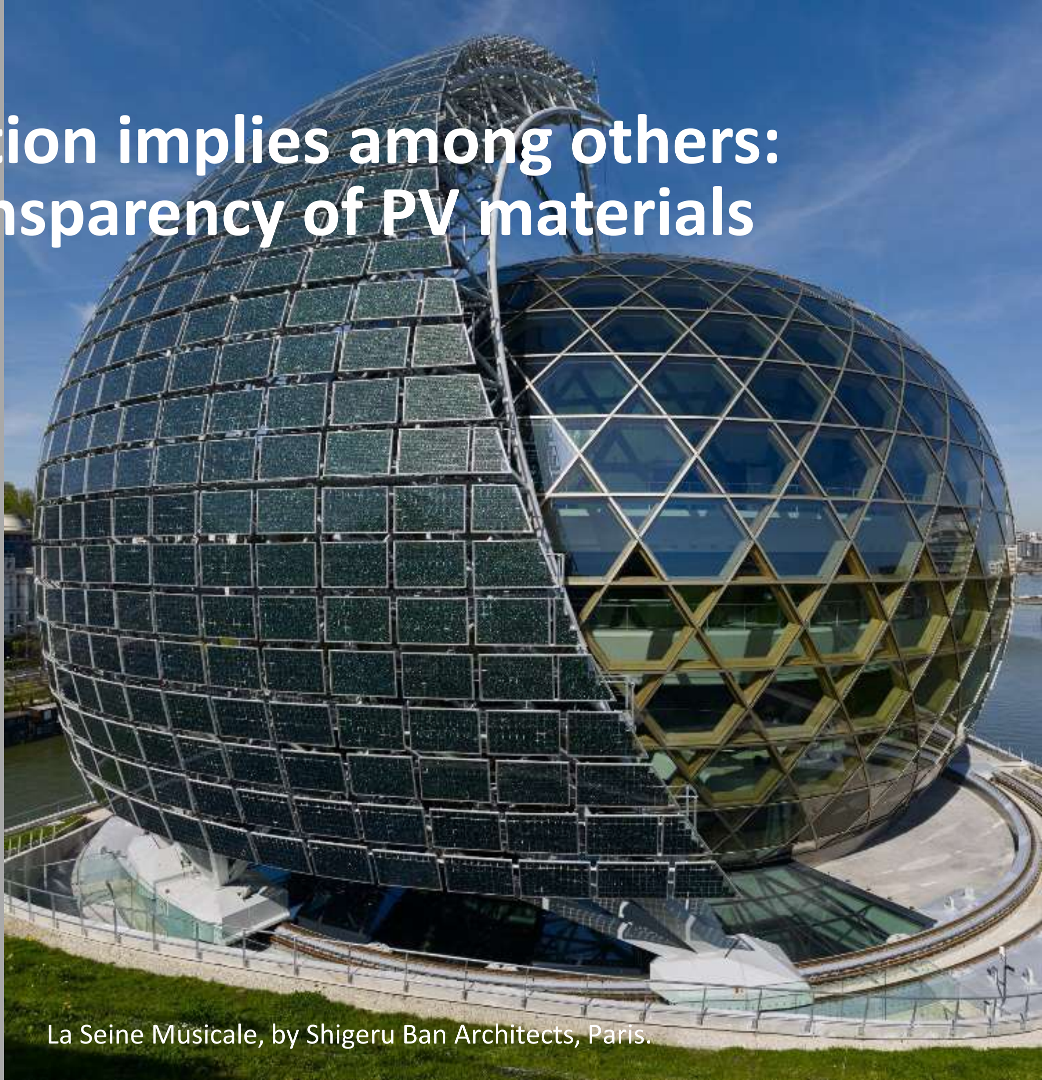


Photo's from Chapter 2 of Desiging with Photovoltaics, Reinders and Kazmerski

Nowadays solar integration implies among others: color, curvature and transparency of PV materials



The Current Window by Marjan van Aubel.



La Seine Musicale, by Shigeru Ban Architects, Paris.

Solar integration: effects on landscapes

A 30 MW PV system, SunPort Delftzijl, Netherlands

Solar integration: effects on landscapes


PV plant in the shape of pandas

Solar integration: effects on landscapes

PV plant in Andalusia, Spain

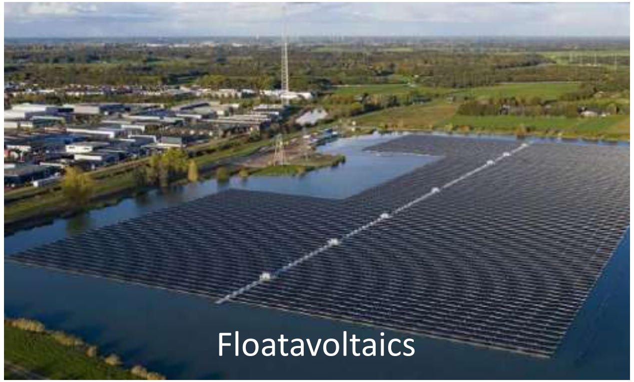
Agrovoltaics by Rsun, France

Solar integration: effects on landscapes

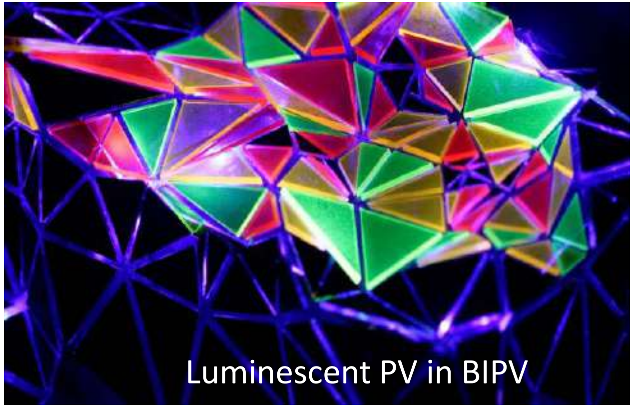
Floating PV system, ABB, Lac des Toules, the Swiss

Solar integration in buildings, mobility and environment


Building integrated PV: BIPV


Floatavoltaics


Vehicle integrated PV: VIPV


Luminescent PV in BIPV

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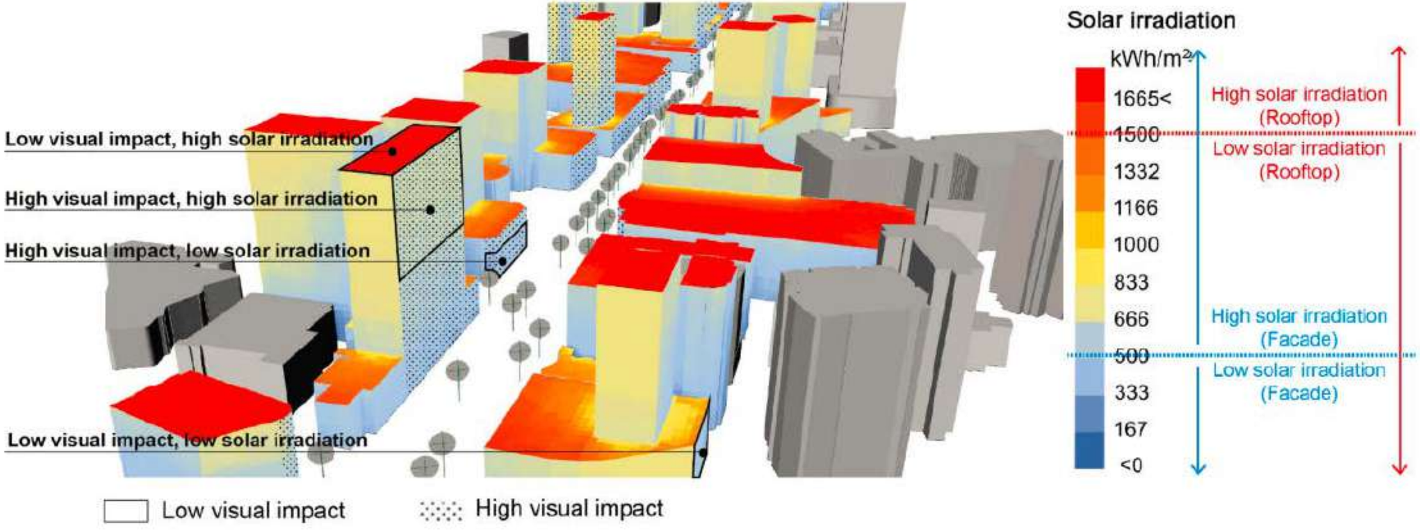
PV potential in the built environment

Given a specific built environment with objects such as buildings and vegetation, the available annual solar irradiance on surfaces such as roofs and facades and the visual impact of these surfaces determines the potential for PV applications.

Figure from Sun et al. Comprehensive feasibility assessment of building integrated photovoltaics (BIPV) on building surfaces in high-density urban environments, Solar Energy, Vol. 225,2021, Pages 734-746, https://doi.org/10.1016/j.solener.2021.07.060.

PV potential in the built environment



Visualisation results of a simulation of 3D annual solar irradiation for Orchard Street in Singapore showing different annual irradiation levels and classes of visual impact. Figure from Sun et al. , 2021.

PV potential in the built environment

Especially building surfaces with a **high visual impact** are suitable for **advanced Building integrated photovoltaic applications**:

Highly visible
Colored or
high-tech
with LEDs

Camouflage
Mimicking
existing
building
materials

Building integrated photovoltaics (BIPV)

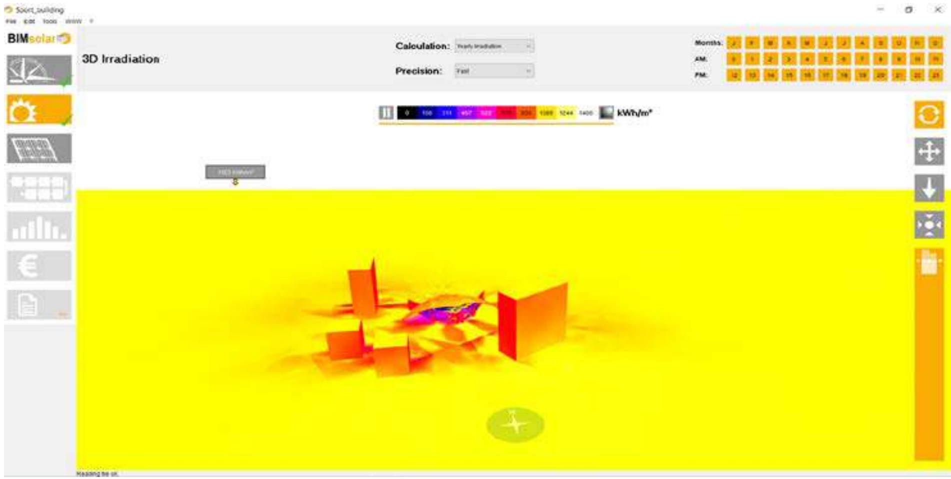
Definition: Building integrated photovoltaics (BIPV) are construction materials and components that include solar photovoltaic (PV) cells: they have a **dual functionality** as a power generator and a building component. A BIPV element must perform one or more additional functions in addition to generating electricity. Among others, and most notably:

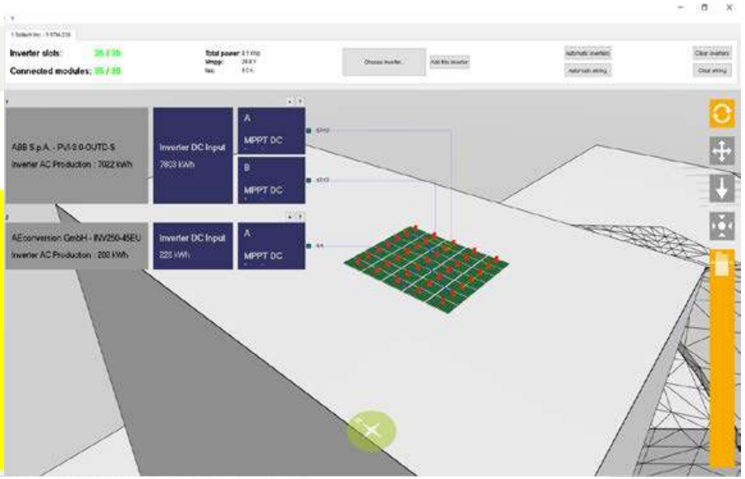
- mechanical rigidity or structural integrity;
- primary weather impact protection: rain, snow, wind, hail;
- energy economy, such as shading, daylighting, thermal insulation;
- fire protection;
- noise protection;
- separation between indoor and outdoor environments;
- security, shelter or safety.

Simulations of building integrated PV

BIPV applications can be simulated with BIM Solar, which can be downloaded through this link: https://www.bim-solar.com/en/download-bimsolar/

Software originated from a European project (KIC InnoEnergy) as an **interoperable platform in a BIM environment to estimate PV and BIPV potential**.





Research cases

(i) Performance: evaluation of a large fleet of PV systems in Europe
(ii) Reliability: failure assessments of PV modules
(iii) Environmental aspects: solar-powered electric mobility
(iv) Design features: luminescent solar concentrator photovoltaics

Performance: evaluation of a large fleet of PV systems in Europe

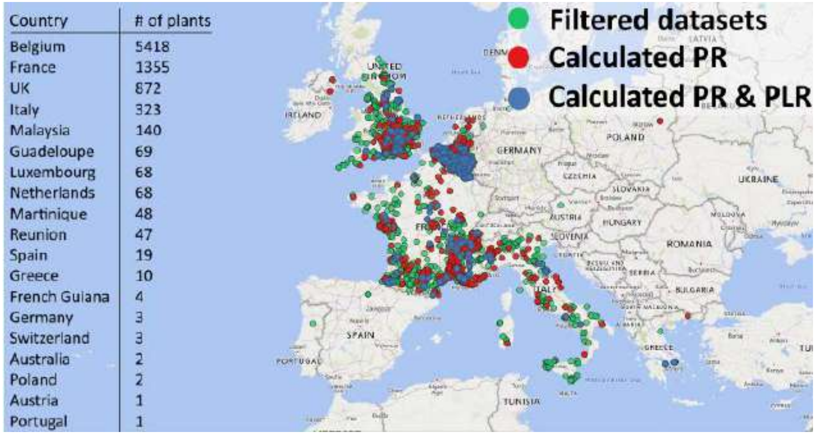
PV system performance

How well do PV technologies perform in reality?

Evaluation of long term system performance in the field: mainly small residential PV systems ~ 6 kWp
Total: 8400 PV systems, average life time: 30 months
Period of 2010 - 2016
Monitoring of power production at 10 minute basis

Research in framework of COST Action PEARL PV:
[Welcome - PEARL PV (pearlpv-cost.eu)](pearlpv-cost.eu)

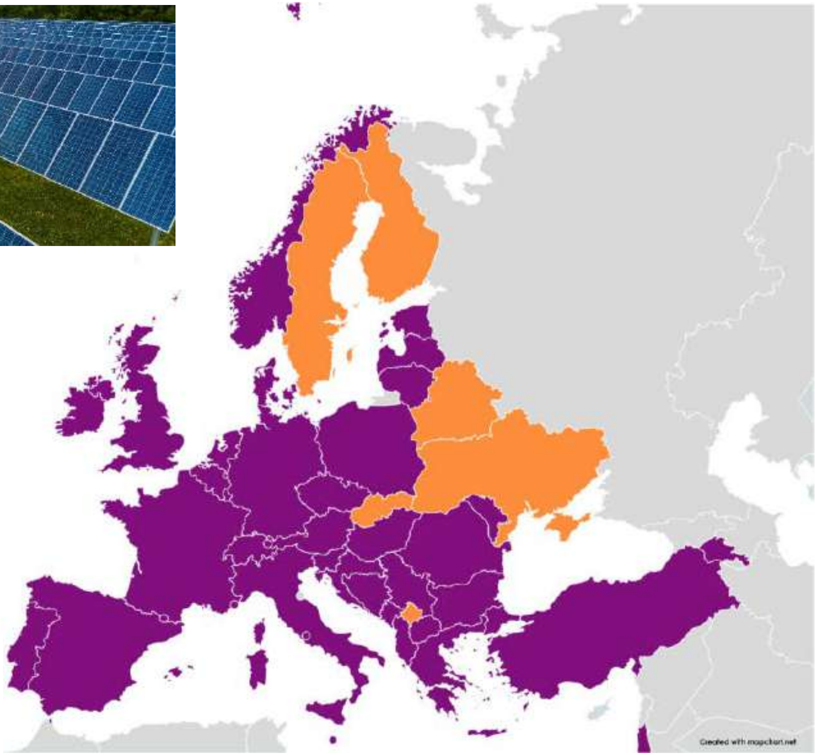

Picture: zonnefabriek.nl

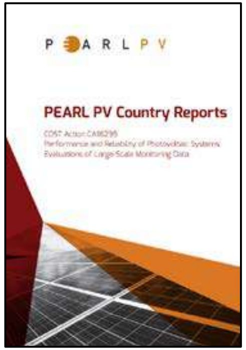


Country	# of plants
Belgium	5418
France	1355
UK	872
Italy	323
Malaysia	140
Guadeloupe	69
Luxembourg	68
Netherlands	68
Martinique	48
Reunion	47
Spain	19
Greece	10
French Guiana	4
Germany	3
Switzerland	3
Australia	2
Poland	2
Austria	1
Portugal	1

COST Action PEARL PV

Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data" (2017-2022): A COST Action an **European Research Network**





260 researchers in 38 European countries take part in COST Action PEARL PV by March 2022, indicated in purple. Not shown on this map, but participating, are the USA and Australia.

Activities in this network: Research and **Training Schools**, Seminars & Workshops, exchange programs by STSM grants & ITC conference grants

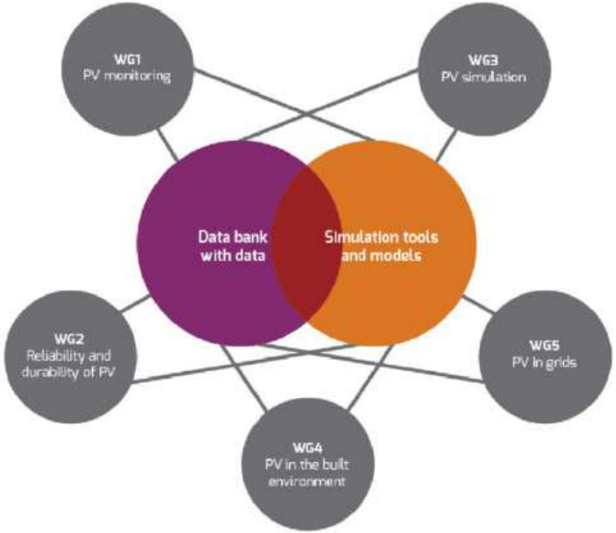
Aim **to collaborate** by country reports on the status of PV, **joint papers** and research proposals and a **shared data bank.**

Emphasis on inclusiveness regarding gender, age and inclusiveness target countries with resp. targets of 30% (females), 30% (early career researchers) and 50% (ITCs).

All information about PEARL PV can be found here: [Welcome - PEARL PV (pearlpv-cost.eu)](pearlpv-cost.eu)

Objectives of PEARL PV

To **improve** the **energy performance** and **reliability** of PV systems leading to (i) **lower costs** by a higher yield, (ii) a **longer lifetime** and (iii) a **reduction of perceived risk**; by analyzing data of the long time monitored long-term performance of PV systems and of their defects and failures.



More detailed objectives:

- To quantitatively determine the absolute influences of (i) components' rated performance, (ii) system design, (iii) installation type, (iv) operation and maintenance practice, (v) interactions with grids, (vi) geographic location and (vii) weather and climate conditions, on performance degradation over time and failure modes;

- To (i) improve the electrical design of PV systems, (ii) achieve optimal sizing via the use of simulation models, (iii) enhance expected system efficiency, (iv) ease maintenance, (v) achieve high reliability and (vi) demonstrate excellent durability.

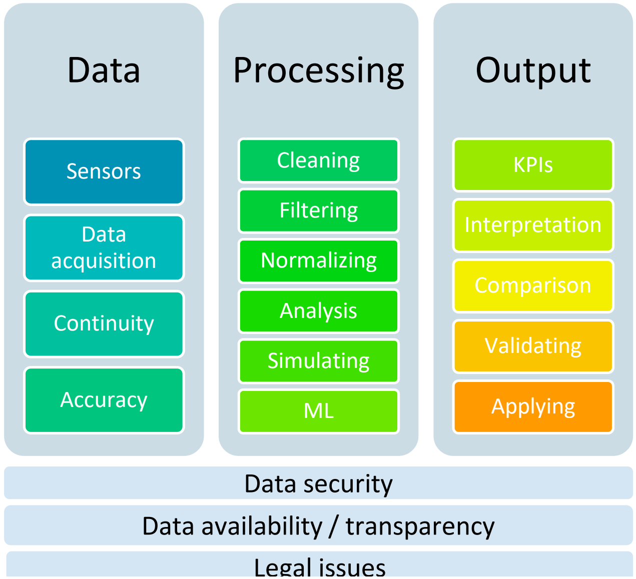
Research topics in COST Action PEARL PV

- Monitoring of PV systems
- Data analysis of PV systems

} Lots of data processing

- Reliability and durability of PV
- Simulations of PV systems
- Machine learning with PV data for
  - - Forecasting of energy production by PV
  - - Failure diagnostics and O&M processes
  - - Improved PV-grid interactions

Main application areas
- PV in grids
- PV in the built environment

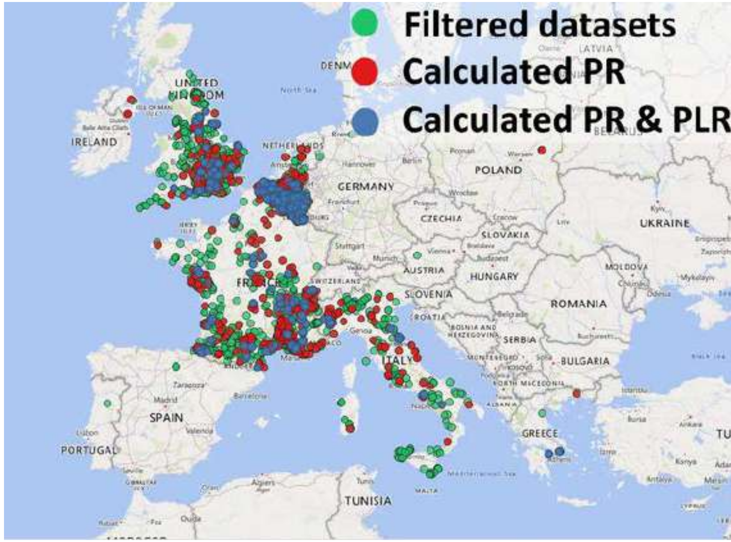


Performance analysis of large fleets of PV systems

Analysis of **~8400 PV systems with 10-minute recordings for 2010-2016** with mainly crystalline PV modules taken from data bank (data from Rbee Solar + ERA5 satellite data), with a focus on the determination of Performance and Ratio and Performance Loss Rate

Performance Ratio, PR: $PR = \frac{E_{AC}/Pnom}{H_{POA}/GSTC}$

where E_{AC} energy produced (kWh), P_{nom} nominal power (kWp) H_{POA} irradiation in plane of array (kWh/m^2), G_{STC}=1000 W/m^2



Performance Loss Rate, **PRL**:
change of system performance in time using three methods:
a) Seasonal and Trend decomposition using LOESS (STL),
(b) the Year-on-Year approach (YoY) and
(c) statistical clear-sky fitting.

Performance analysis and degradation of a large fleet of PV systems by Sascha Lindig, Julian Ascencio-Vasquez, Jonathan Leloux, David Moser and Angèle Reinders, Journal of Photovoltaics, 2021.

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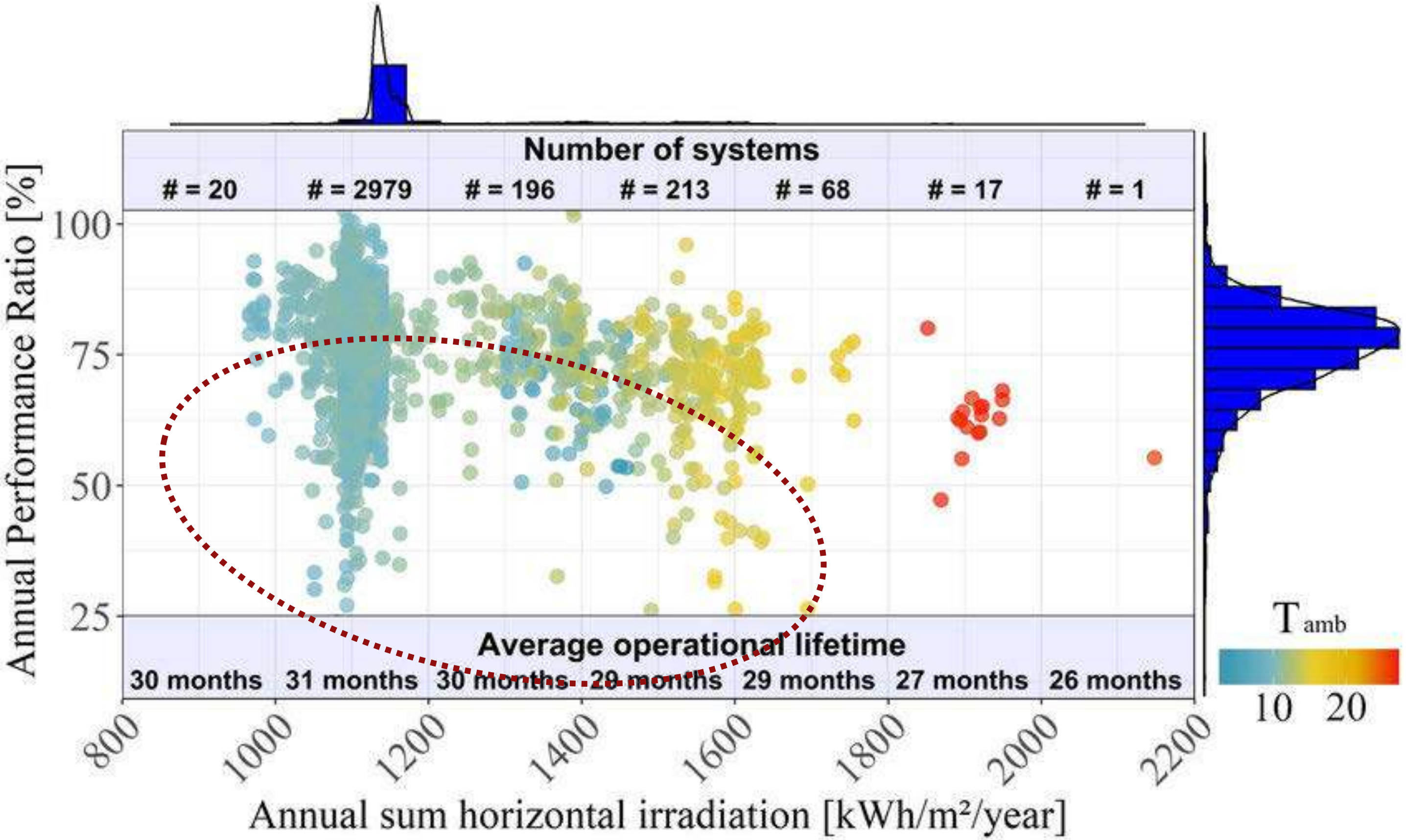
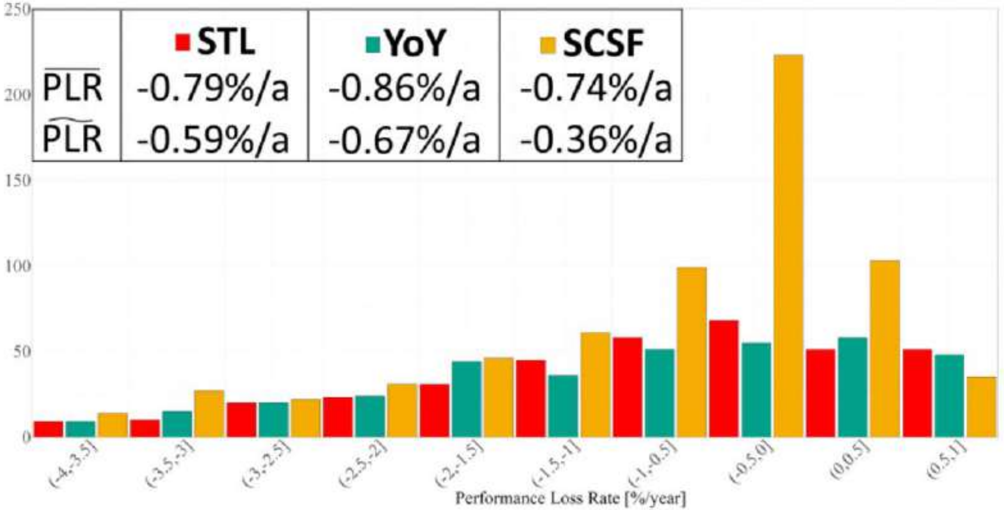
Performance analysis of a large fleet of PV systems



The annual mean performance ratio across all systems is **76.7%** and the average yield is **954.9 kWh/kWp** per year.

Performance Loss Rate

Performance loss rate distribution of Pearl-PV performance database; red: calculated with STL; turqouise: calculated with YoY; yellow: calculated with SCSF.



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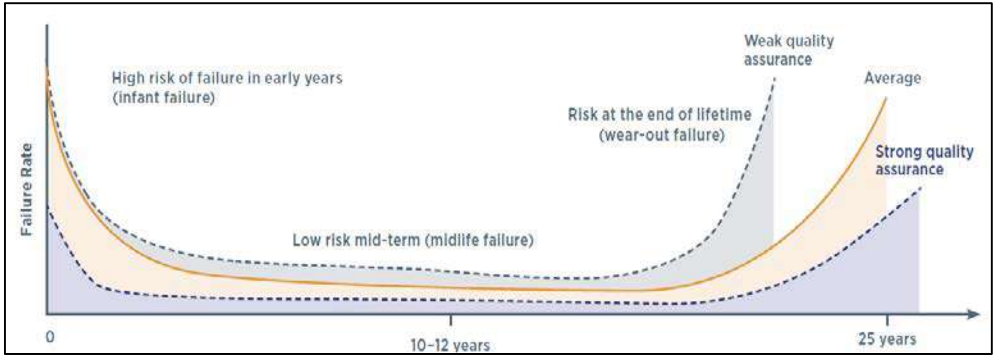
Reliability: failure assessments of PV modules

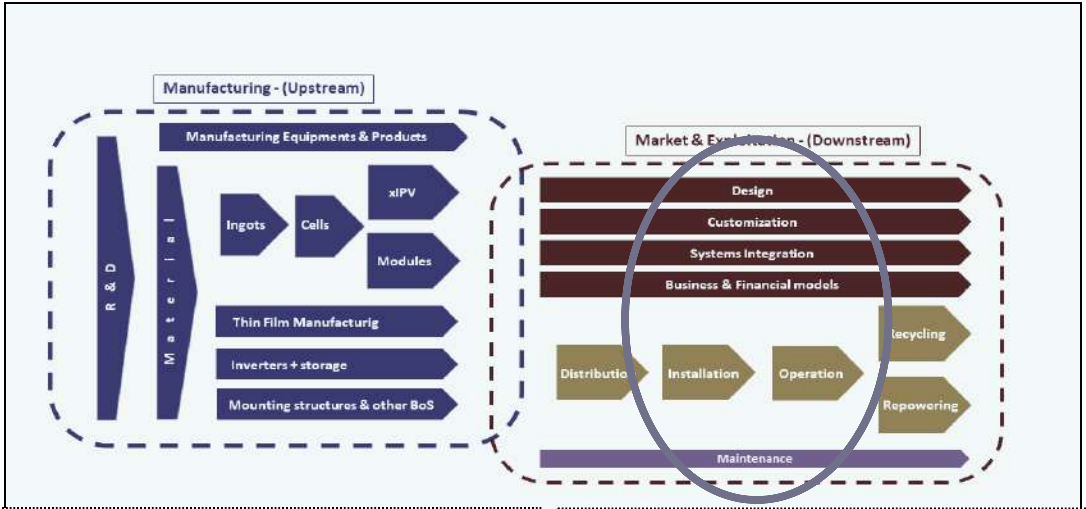
Why failure assessments of PV modules?

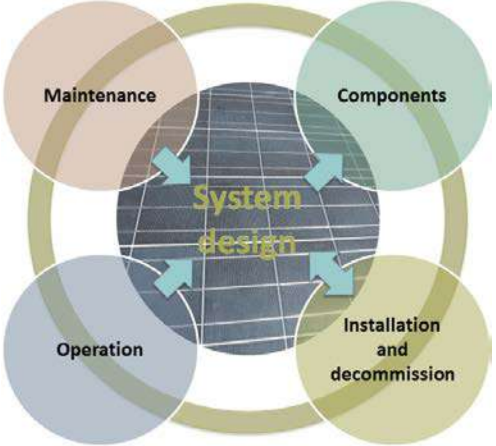
Failure assessments PV modules on the short and long run can
improve the **QUALITY,** i.e. **energy performance** and
reliability, of PV systems leading to
(i) **lower costs** by a higher yield, (ii) a **longer lifetime,** and, (iii) a **reduction of perceived risk.**



Moser, D., Azpilicueta, L., Salgado, A., Richter, A., Reinders, A., Bihler, F., Bosshell, F., Masson, G., Serra, G., Lin, J., Garreau-Iles, L., Cherradi, N., Moreth, R., Jahn, U. and Ekus, B., White paper on harmonized data collection from the field, SolarUnited Quality Initiative, 2019.

Context of failure assessments of PV modules





The **upstream part of the PV value chain** intends to play a major role in the improvement of the quality of PV components and installations: through new and improved production processes, the industry will contribute to increase the durability and reliability of PV systems.

For the **downstream part of the PV value chain** data acquisition is of fundamental importance not only for fast feedback within subsequent steps of the value chain but also between processes which are not directly linked, i.e. manufacturing and installation of components.

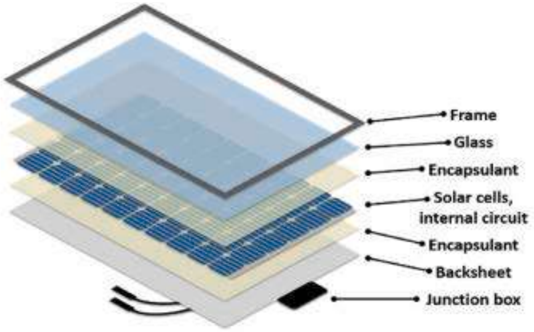
Understanding failure of PV modules

Why it is important? Understanding of stressors and their early detection can reduce their (long term) impact on stability of PV modules

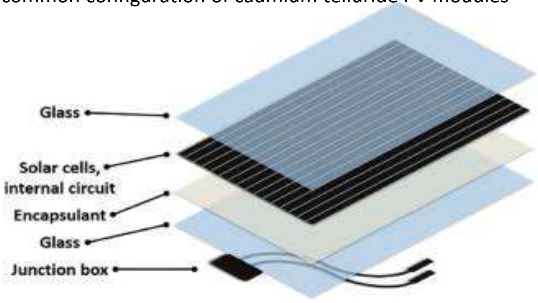
- Focus on mono- and multi-crystalline silicon, cadmium telluride, and copper indium gallium selenide PV, transferring this information to emerging low-cost technologies, i.e. perovskites.
- Reliability metrics and how reliability is measured.
- Main stress factors and how they influence module degradation
- Review of degradation and failure modes by individual modules' components

Aghaei, M., Fairbrother, A., Gok, A., Ahmad, S., Kazim, S., Kettle, J., Lobato, K., Oreski, G., Reinders, A.H.M.E., Schmitz, J., Yilmaz, P., Theelen, M., **Review of degradation and failure phenomena in photovoltaic modules**, Renewable and Sustainable Energy Reviews, Vol. 159, 112160, DOI: doi.org/10.1016/j.rser.2022.112160, 2022

common configuration of crystalline silicon PV modules



common configuration of cadmium telluride PV modules

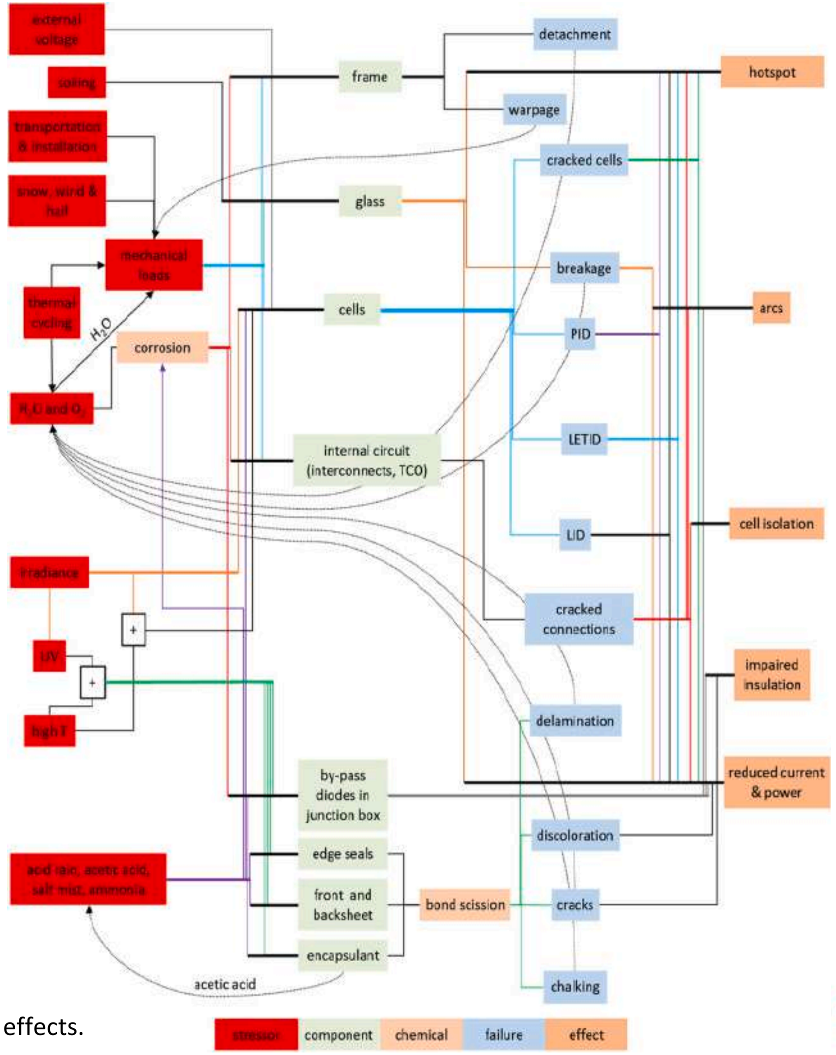


Failure modes of PV modules

Mixture of external and internal stress factors makes it difficult to uniquely identify:
-causes for failure and effects at the level of PV module output
-each failure in relation to effects and vice versa

Please notice that:
-external stress factors are related to environmental conditions
-internal stress factors related bill of materials of PV modules and processing related effects

Also important, please be aware that also inverter, electronics and other BOS can show failures, and hence affect the system performance.



Flow diagram representing the relationships between stressors, components, failures and effects.

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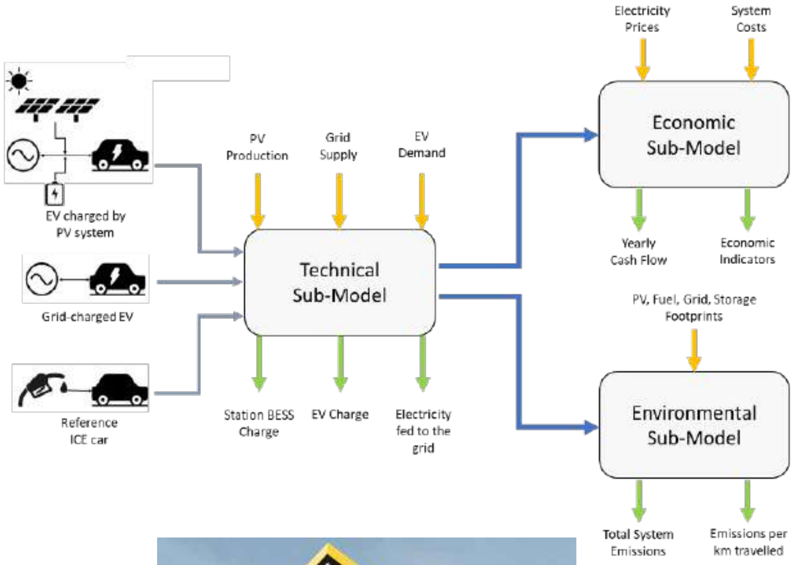
Environmental aspects: solar powered electric mobility

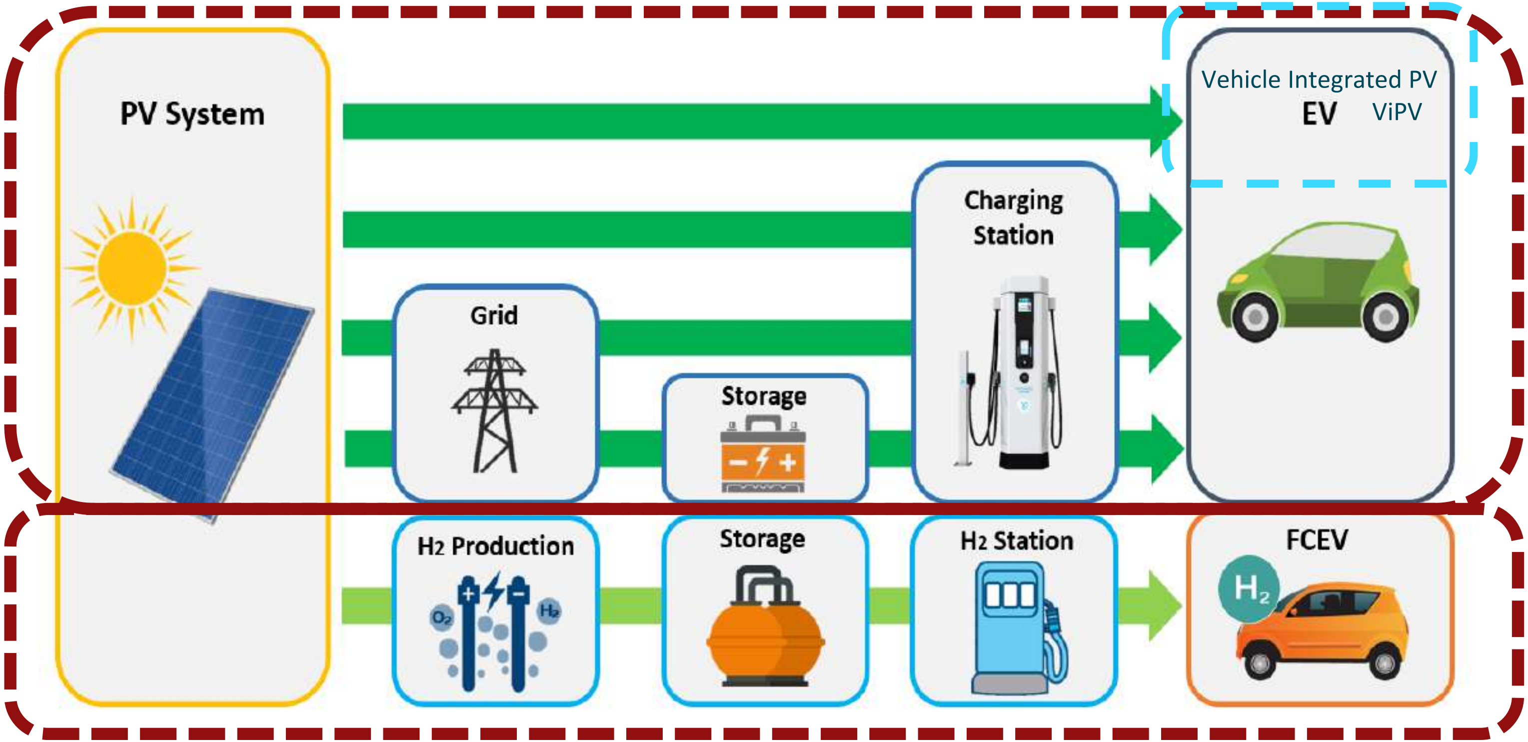
Solar powered electric mobility

Externally funded research (RVO-NL)
Asom: Association for solar mobility
IEA PVPS Task 17: PV for Transport

Research on charging of electric vehicles with solar power, environmental impact, financial aspects and energy balance.
-Simulations
-Monitoring
-Product design

- Vehicle integrated PV (VIPV)
- Solar charging stations
- PV in infrastructures





Adapted from Prof. Masafumi Yamaguchi, Int. Session, 2017 IEEE PVSC-44, Washington DC

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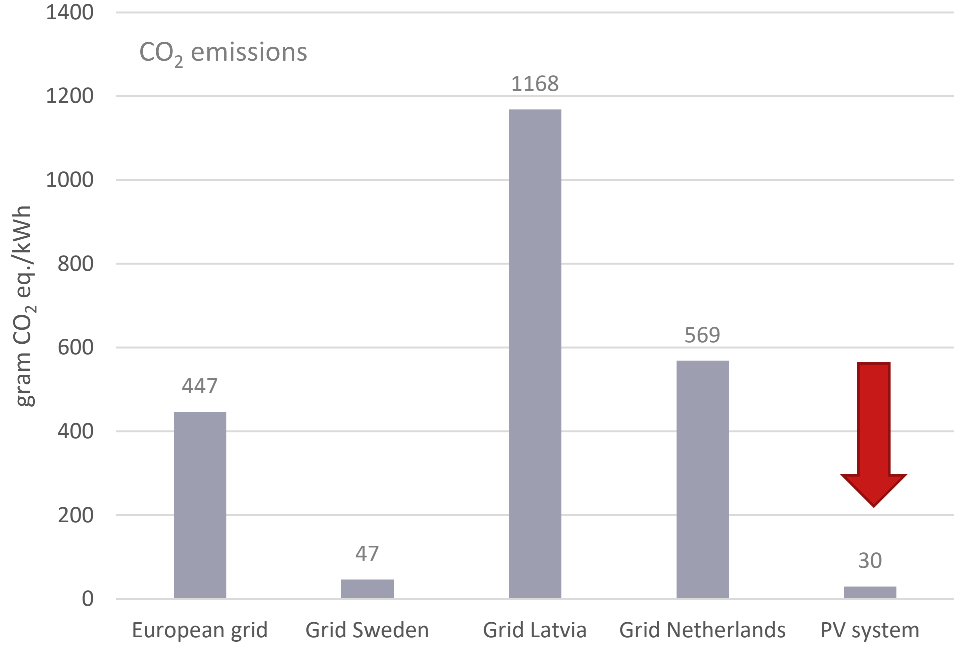
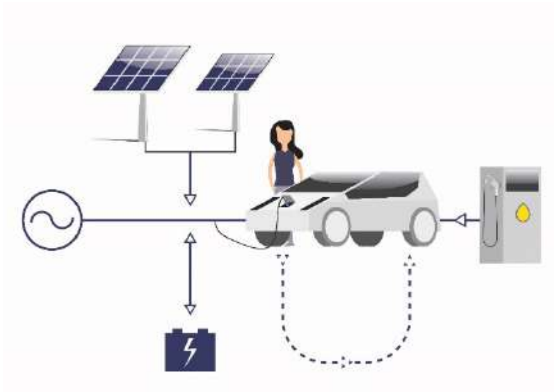
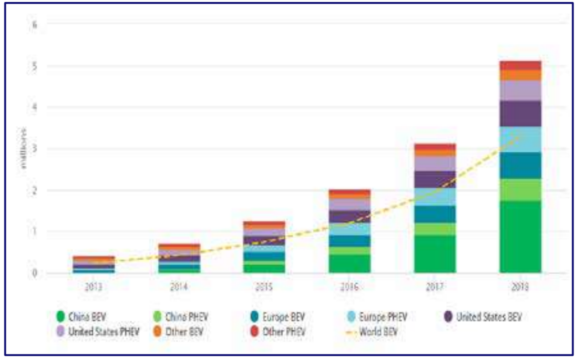
Design-driven research on PV-powered electric vehicles







Global uptake of EVs (IEA Global EV Outlook)

(PRE)Commercial VIPV'S design features

Vehicle-integrated Photovoltaic (VIPV)	/ PV nominal power	/ battery capacity	/ charging	/ drive range
Lightyear One (Lightyear)	Estimated 750 Wp, cells on vehicle roof, bonnet and rear	60 kWh	22 kW AC 60 kW DC	575 km SDR: 50 km/day
Sono Sion (Sono Motors)	Estimated 1.2 kWp, cells on vehicle roof, bonnet, doors and rear	35 kWh	11 kW AC 50 kW DC	225 km SDR: 34 km/day
Solar O, L, R and A (Hanergy)	Estimated 0.8 – 1.5 kWp depending on model, cells on vehicle roof and bonnet	n.a.	na.a.	350 km SDR: 80 km/day
Sonata (Hyundai) *	Estimated 200 Wp, cells on vehicle roof	9.8 kWh	3.3 kW AC	SDR: 1300 km/year
Revero (Karma Automotive) *, +	200 Wp, cells on vehicle roof	21 kWh	6.6 kW AC 40 kW DC	SDR: 80 km/day
Solar Prius (Toyota) *	860 Wp, cells on vehicle roof, bonnet and rear	8.8 kWh	3.3 kW AC	SDR: 50 km/day

SDR: 'Solar drive range' gained with the energy from the integrated PV cells
* Vehicle with hybrid powertrain, range shown in table is electric-only.
+ Commercially available at the time of writing

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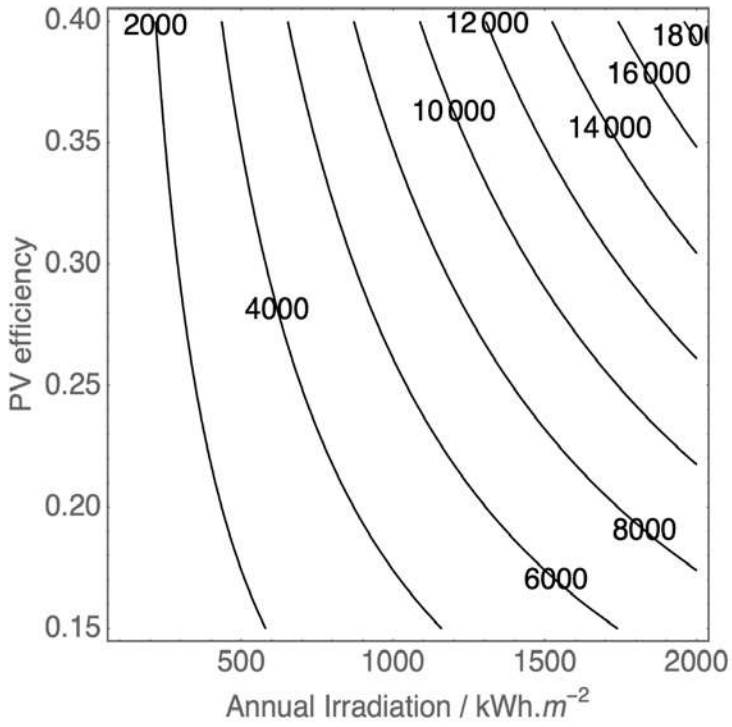
SOLAR DRIVE RANGE - IRRADIATION - PV EFFICIENCY



The maximal annual solar drive range, **D_{max}**, in kilometers of an PV powered EV (VIPV) can be simply estimated – by excluding major energy losses such as drag, rolling resistance and electrical losses – by:

$D_{max} = (A_{EV} * H * \eta_{PV}) / E_{EV}$

where

H is the annual irradiation (in kWh/m^2)

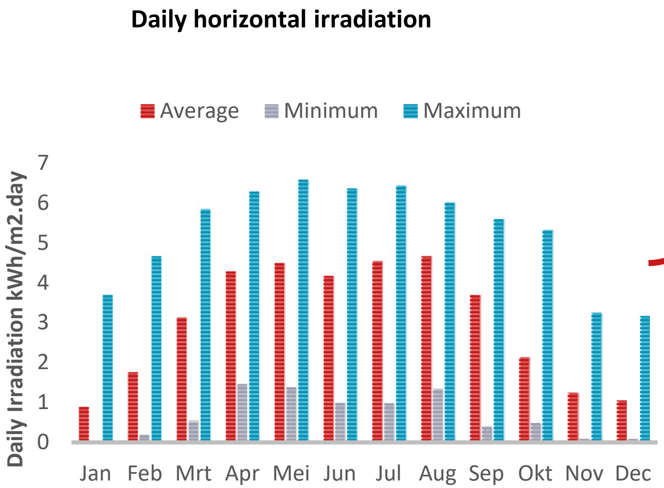
η_{PV} the PV system efficiency (unitless)

A_{EV} the maximum available area for the integration of PV cells, here A_{EV} = 4 m^2

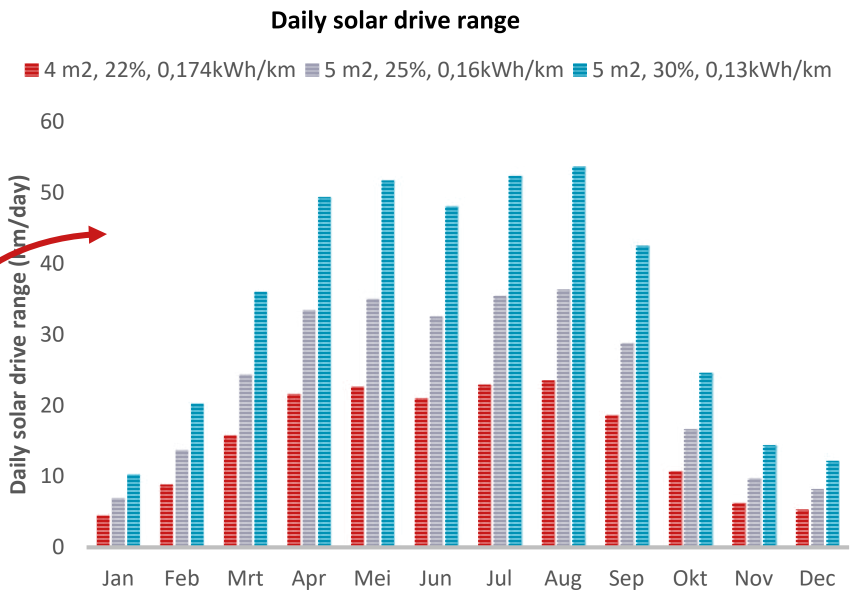
E_{EV} the EV's energy consumption, where E_{EV} = 0.174 kWh/km

DAILY DRIVE RANGE

The **average daily solar drive range** in kilometers is given by the same equation.
Graphs for the Netherlands with different values for A_{EV} the maximum available area for PV cells, η_{PV} the PV system efficiency, and E_{EV} the EV's energy consumption,



(data from PVGIS, 2016)



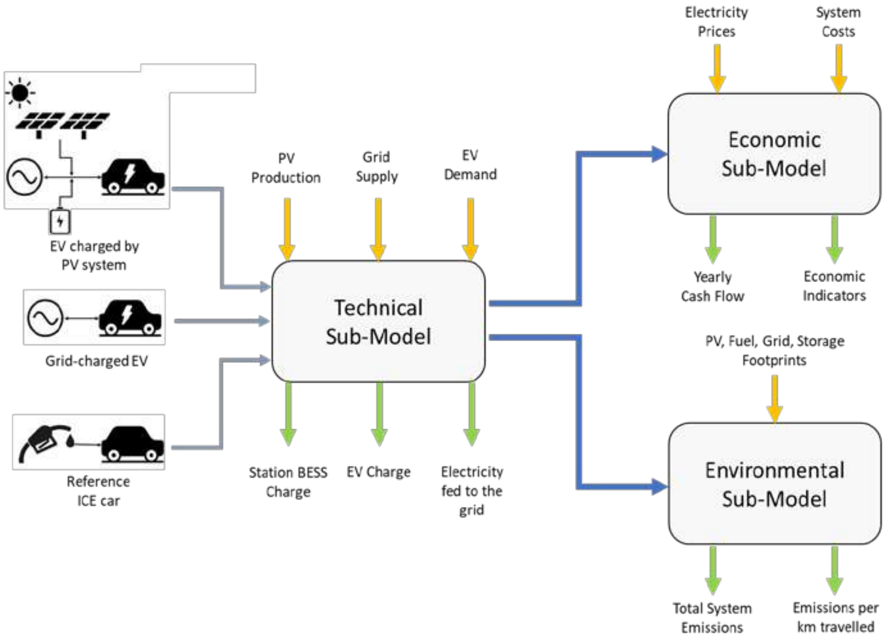
INTERDISCIPLINARY MODELLING OF SOLAR CHARGING STATIONS FOR EV'S

Decision-based time step model.

Grid-connected solar PV charging station with battery energy storage system (BESS) and a battery powered EV.

Results compared with grid-only charging and an ICE car with identical features as the EV.

Can be applied to any location in the world.



PV Production:
kWh/kWp time-series extracted from PVGIS software (online freeware EU: https://re.jrc.ec.europa.eu/pvg_tools/en/)
EV is modelled as a Nissan Leaf:
30 kWh battery, 0,174 kWh/km energy consumption by EV

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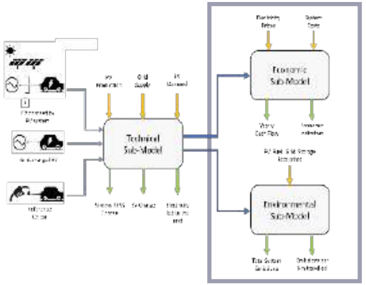
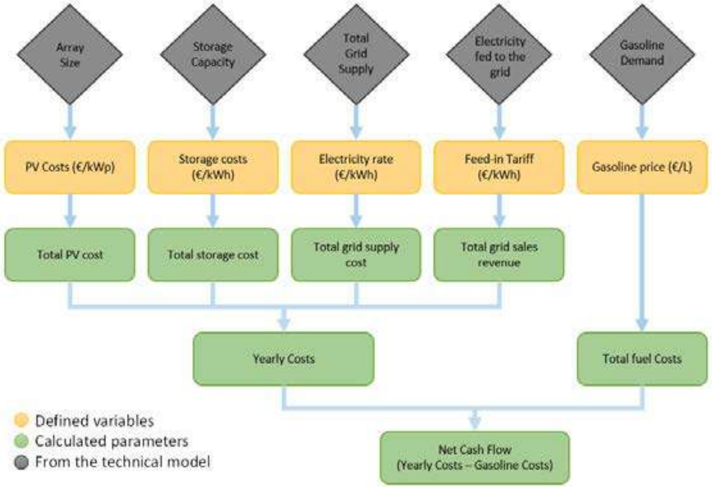
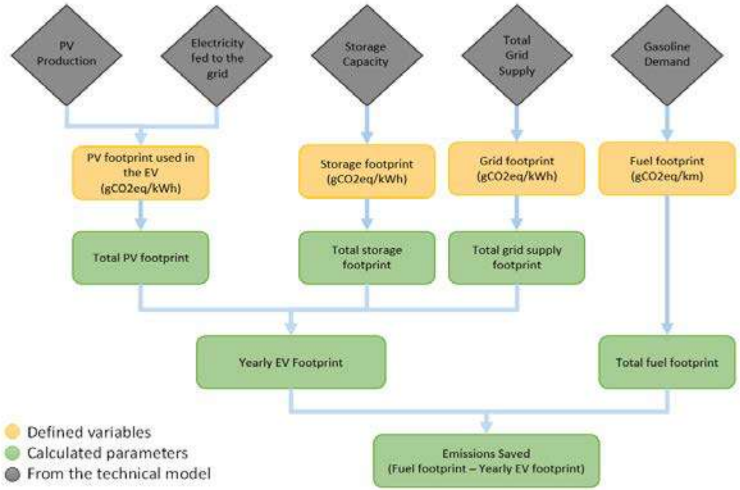
Economic Model: Cash flow analysis + Economic Indicators (NPV, payback time, etc.)

Environmental Model: Total CO_2 emissions, emissions per km driven







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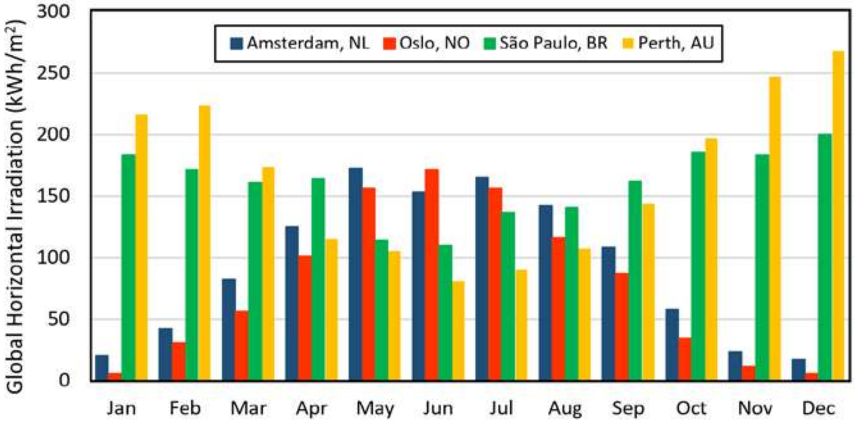
MODELLING APPROACH

Four scenarios:

- 100% PV
- 75% PV + 25% Grid
- 50% PV + 50% Grid
- 100% Grid

In six cities around the world
- San Francisco, US
- Guangzhou, China
- Perth, Australia
- São Paulo, Brazil
- Amsterdam, The Netherlands
- Oslo, Norway



Location	Coordinates	Optimal Tilt Angle	GHI [kWh/m²]	In-plane Irradiation [kWh/m²]
San Francisco, US	37.78, -122.42	35°	1810	2110
Guangzhou, CH	23.13, 113.26	21°	1430	1490
Perth, AU	-31.95, 115.86	0°	1965	2156
São Paulo, BR	-23.55, -46.63	26°	1694	1804
Amsterdam, NL	52.38, 4.90	38°	1065	1245
Oslo, NO	59.91, 10.74	44°	913	1131

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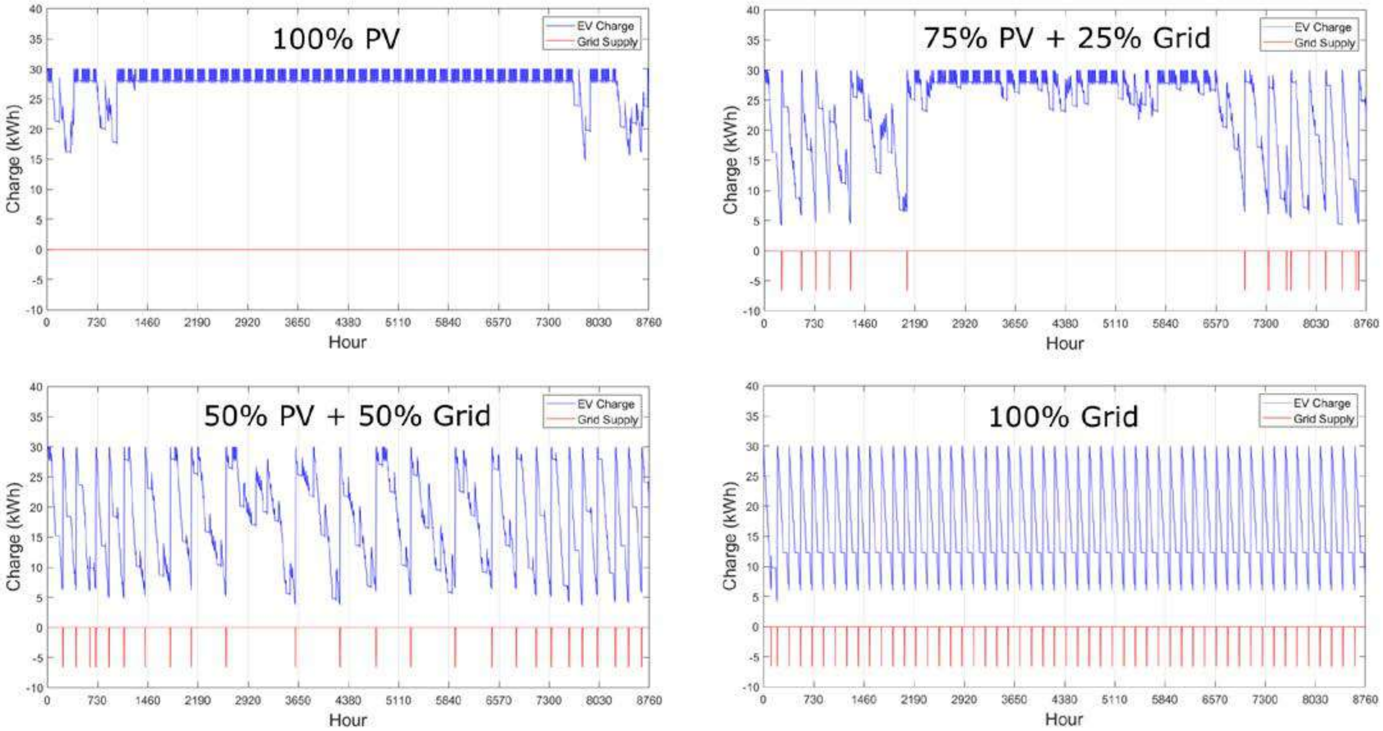
Input data for simulations

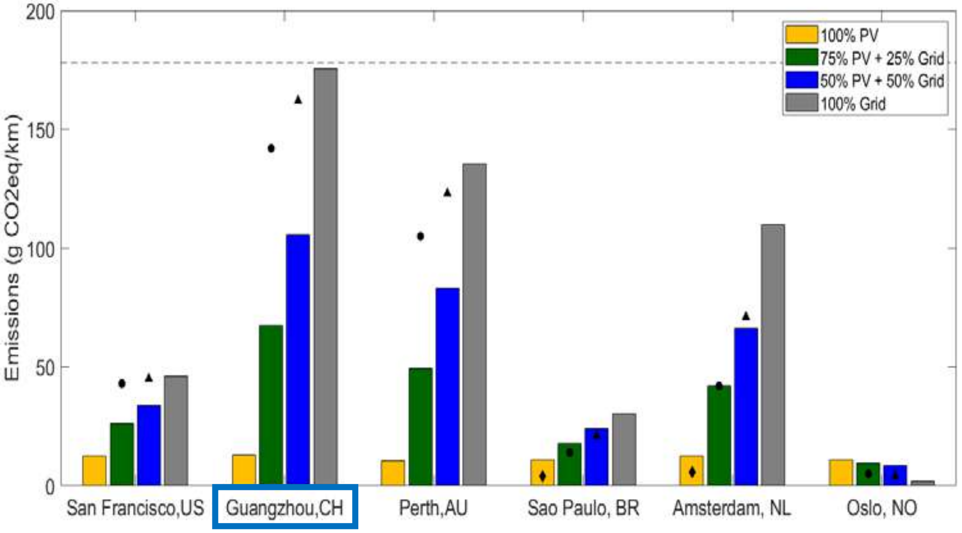
	San Francisco, US	Guangzhou, CH	Perth, AU	São Paulo, BR	Amsterdam, NL	Oslo, NO
Technical Submodel						
EV Battery Capacity (kWh)	30					
EV Charging Power (kW)	6.6					
EV Energy Consumption (kWh/km)	0.174					
EV Range (km)	172					
ICEV Efficiency (L/km)	0.072					
Avg. driving distance (km/day)	26	28	32	32	30	47
Yearly PV Degradation Rate	- 0.5%					
Economic Submodel						
Fuel Price (€/L)	0.9	0.93	0.88	1.03	1.72	1.72
Electricity Price (€/kWh)	0.14	0.06	0.18	0.15	0.21	0.13
Feed-in Tariff (€/kWh)	0.08	0.03	0.05	0.15	0.21	0.04
PV Cost (€/kWp)	1160	915	920	1520	1140	1140
Storage Cost (€/kWh)	890	890	750	920	880	880
Discount Rate	5%					
Environmental Submodel						
Grid Footprint (gCO2eq/kWh)	239	910	700	157	569	9
PV Footprint (gCO2eq/kWh)	21	26	19	21	29	33
WTW Gasoline Footprint (gCO2eq/km)	178					

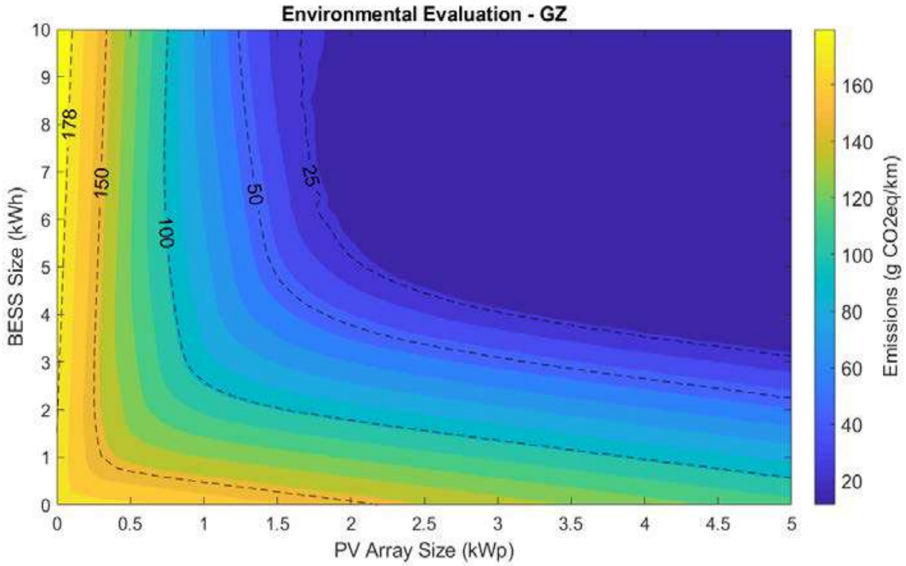
Example of results: EV charging in NL



EV charging by PV charging station (blue) and grid (red) in each scenario for the system located in the Netherlands (with 10 kWh BESS). Clockwise from top left: 100% PV ($A_{PV} = 5$ kWp), 75% PV + 25% Grid ($A_{PV} = 1.2$ kWp), 100% Grid, 50% PV + 50% Grid ($A_{PV} = 0.8$ kWp).

RESULTS: ENVIRONMENTAL ASPECTS





	San Francisco, US	Guangzhou, CH	Perth, AU	São Paulo, BR	Amsterdam, NL	Oslo, NO
Reference ICEV	12.08	13	13.94	21.93	14.87	14.87
100% PV	0.85 (7%)	0.94 (7%)	0.87 (6%)	0.91 (4%)	1 (7%)	1.33 (9%)
75% PV, 25% Grid	1.77 (15%)	4.92 (38%)	4.13 (30%)	1.5 (7%)	3.29 (22%)	1.17 (8%)
50% PV, 50% Grid	2.29 (19%)	7.72 (59%)	6.96 (50%)	2.01 (9%)	5.2 (35%)	1.03 (7%)
100% Grid	3.14 (26%)	12.84 **(99%)**	11.3 (81%)	2.52 (11%)	8.6 (58%)	0.21 **(1%)**

Total emissions in the first 10 years of operation (ton CO_2-equivalents)

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Further reading

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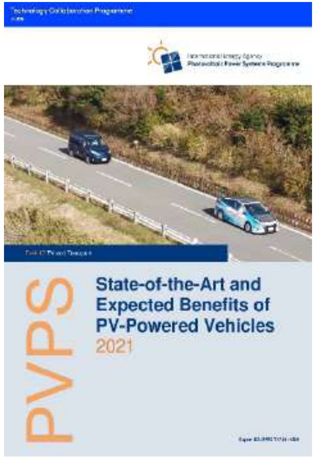
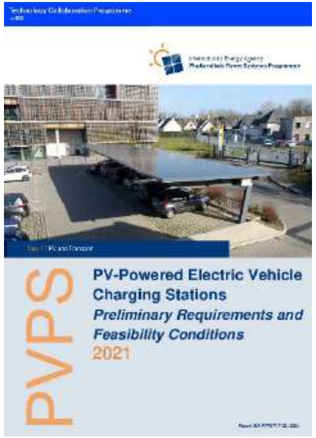
Sierra Rodriguez, A., de Santana, T., MacGill, I., Ekins-Daukes, N. J. and Reinders, A.H.M.E., A feasibility study of solar PV-powered electric cars using an interdisciplinary modeling approach for the electricity balance, CO_2 emissions, and economic aspects: the cases of The Netherlands, Norway, Brazil, and Australia, Progress in Photovoltaics: Research and Applications, Vol. 28, 517–532, 2020.





Further reading

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Aghaei, M., Zhu, X., Debije, M., Wong, W., Schmidt, T., Reinders, A., Simulations of Luminescent Solar Concentrator Bifacial Photovoltaic Mosaic Devices Containing Four Different Organic Luminophores IEEE Journal of Photovoltaics, 2022.

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Conclusions

From a physics perspective, energy radiated from the Sun to Earth is inexhaustibly, overly supplied: a large share of solar energy supply in the energy transition is hence technically feasible. Though the focus is on photovoltaics (PV) at present, thermal solar energy and chemical conversions will gain interest in the near future.

PV system performance is good, even in less sunny countries in Europe.

Better integration possibilities will be the next step for R&D of solar technologies: in cities, buildings and mobility. Therefore research is required that is focused on the optimization of performance, reliability, design features, environmental aspects.

Given their great design features, new PV technologies need to be further optimized by research.

Summarizing: many sunny opportunities however there's also still a lot of R&D work to do!

Acknowledgements

Special thanks to:
Xitong Zhu, Neel Patel, Olga Kanz Dr. Michael Debije, Dr. Reza Aghaei, dr. Alonzo Sierra, Amrita Raghoebarsing, Dr. Eli Shirazi, Sakthi Guhan and Martin Huijzer, as well as all former master students and former colleagues

All colleagues in COST Action PEARL PV and my collaborators at UNSW, Dr. Wallace Wong, Dr. Ned Ekins-Daukes and prof. Timothy Schmidt, as well as colleagues in IEA PVPS Task 17, NEB, ASOM and many others.