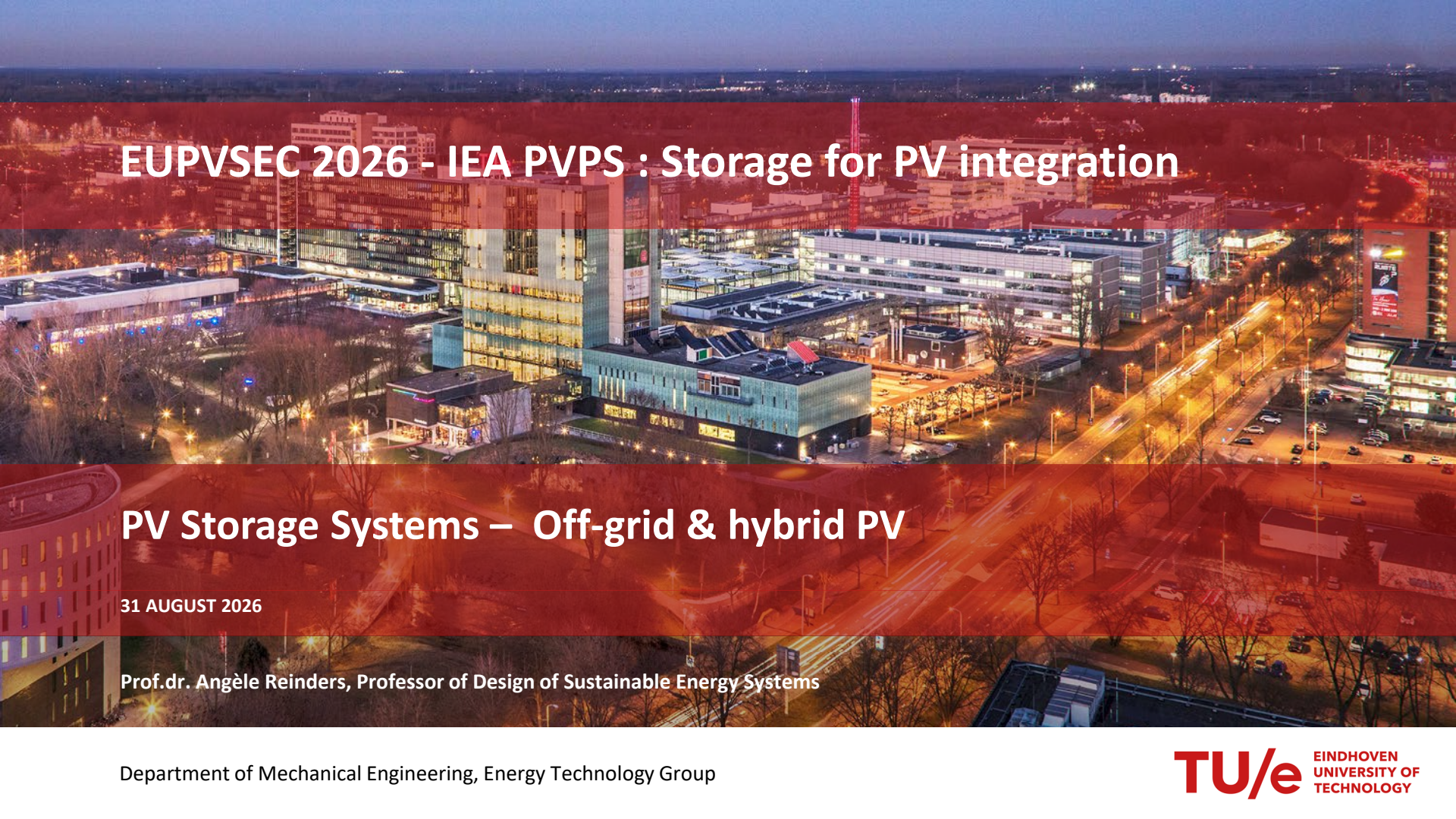


An aerial night photograph of a city, likely Eindhoven, with a prominent red semi-transparent overlay. The city lights and building structures are visible through the red tint. The text is overlaid on the upper portion of the image.

EUPVSEC 2026 - IEA PVPS : Storage for PV integration

PV Storage Systems – Off-grid & hybrid PV

31 AUGUST 2026

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Department of Mechanical Engineering, Energy Technology Group

Contents

- Why storage is useful?
- Storage overview
- Off-grid PV & hybrid systems
- Integrated PV
- Some conclusions and recommendations

Why storage?

Many reasons:

Renewables integration

Demand side management

- Load shifting (a)
- Peak shaving (b)
- Valley filling (c)

Reliability in weak grids

UPS / back-up power supply

Off-grid PV applications

Product integrated PV

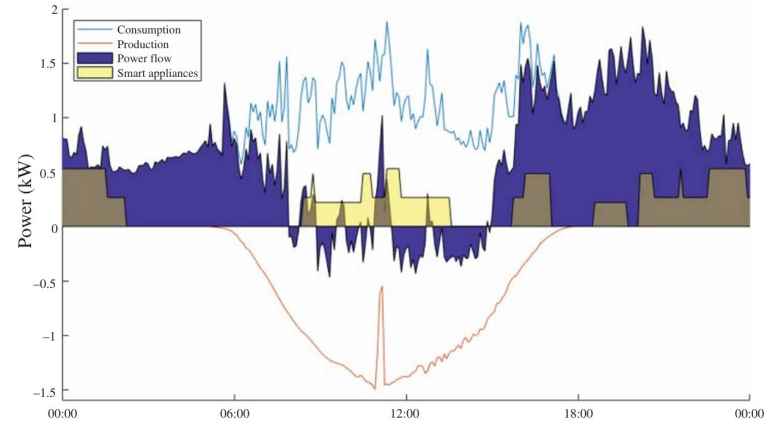
Vehicle integrated PV

Supporting EV penetration

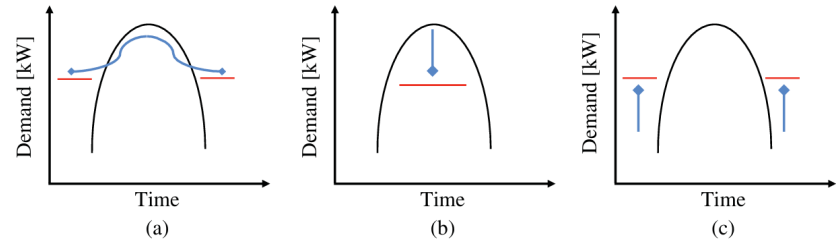
Increased self-consumption

Increased self-sufficiency

Enhancing power quality

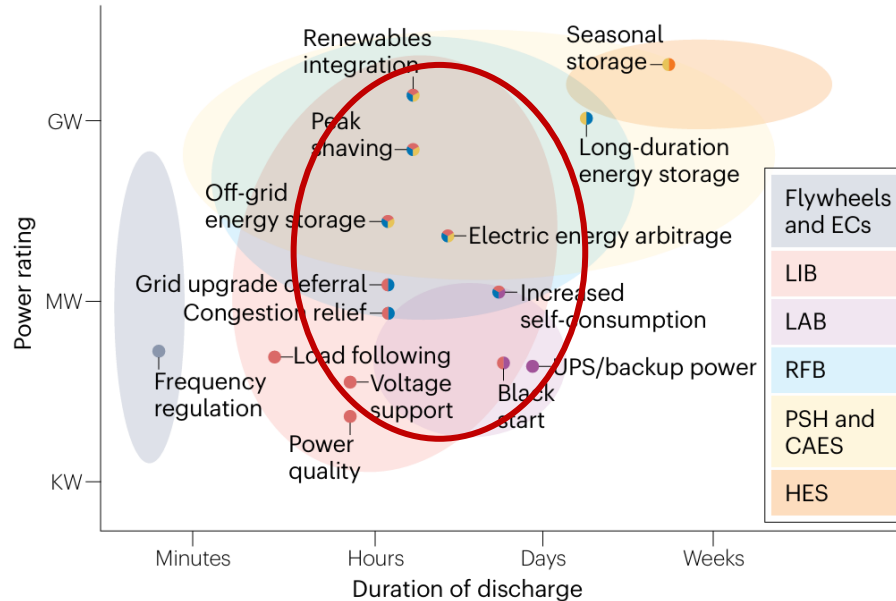


Energy consumption (blue line), energy production by PV modules (red line), and power flow (blue area) for a household with a photovoltaic (PV) system in the Netherlands, Photovoltaic Solar Energy, Chapter 27, Wiley, 2024



Storage overview

Storage technologies that can be applied in combination with PV



Source: Jiang et al., Nature reviews clean technology, 2026

EC: electrochemical capacitors
LIB: Lithium-ion batteries
LAB: Lead-acid batteries
RFB: Redox flow batteries
PSH: Pumped storage hydropower
CAES: Compressed air energy storage
HES: Hydrogen energy storage

Battery technologies compared

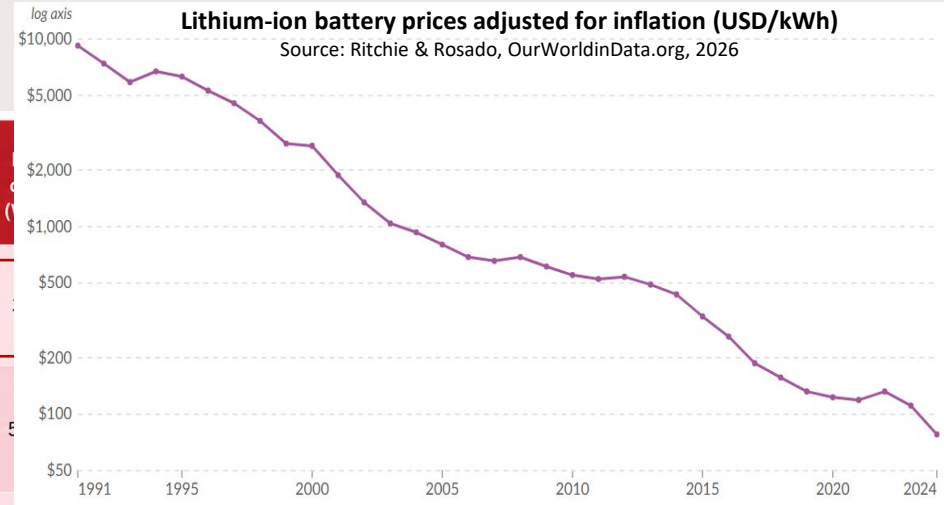
Battery	Strengths	Limitations	Cost (US\$ per kWh)	Cycle life (cycles)	Safety levels (1–10)	Energy density (Whkg ⁻¹)	Round-trip efficiency (%)	Operating temperature (°C)	Recyclability	Manufacturing readiness levels (1–10)
LAB	Low cost, high safety, high recyclability	Short cycle life	50–200	300–1,000	9	30–50	75–85	–20 to 50	High	10
Ni–MH	High safety	High cost and high self-discharge	200–600	1,500–4,000	9	50–100	80–90	–40 to 50	Medium	10
Zn ion	Low cost, high safety	Short cycle life, low technological maturity	50–250	500–2,000	9	50–100	80–90	–40 to 50	High	7
Li ion	High energy density and high efficiency	Poor safety	50–300	1,500–10,000	6	160–200	85–95	–10 to 60	Low	10
Na ion	No resource constraints, high energy density and high efficiency	Poor safety	50–400	500–4,000	6	100–160	80–90	–20 to 60	Low	9

LAB: Lead Acid Battery, MH: Metal-Hydride

Adapted from source: Jiang et al., Nature reviews clean technology, 2026

Battery technologies compared

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Off-grid PV & Hybrid systems

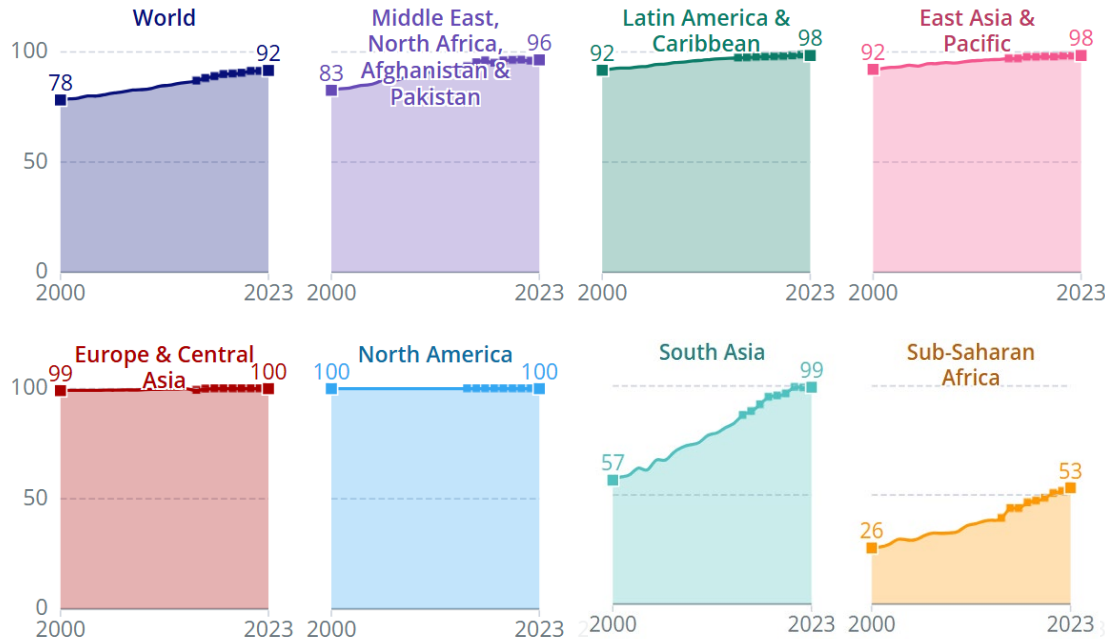
Off-grid PV & hybrid systems are PV systems that can be autonomously operated; usually they contain batteries.

Different application domains with different objectives:

- Remote electrification > providing electricity where access to the grid is lacking
- Integrated PV > providing electricity through PV integrated in surfaces of things
- UPS / Back-up systems > reliably providing electricity in case of sudden grid failure (blackout)
- Space applications > providing electricity where access to the grid is lacking

Off-grid PV driven by lack of electricity access

People with access to electricity, by region (% of population)



655 million people world-wide lack access to electricity and the majority of them lives in Sub-Saharan Africa
Most of those without access to electricity live in rural areas.

1.6 billion people have unreliable access to electricity

560 million people benefit from off-grid solar solutions

Sources: World Bank Group, 2026, <https://data360.worldbank.org/en/atlas/electricity-access/?lang=en#c6>
IEA, IRENA, UN, World Bank Group, WHO, 2026, [655 million people still living without electricity underscore urgent need to deliver on universal energy access target - News – IEA](#)
Gogla, 2026, <https://gogla.org/>

Classification table of off-grid PV-battery applications



	class 1		class 2		class 3		class 4
Typical application	Parking meter, streetlamp, cigarette automat		solar lantern, Pico PV, SHS, garden shed		Hybrid system mountain hut or village supply		PV – diesel big village supply
location	Moderate zone	(Sub-) tropical zone	Moderate zone	(Sub-) tropical zone	Moderate zone	(Sub-)tropical zone	worldwide
Typical PVp size	10- 100 Wp	5 - 50 Wp	1 - 500 Wp	1 - 250 Wp	1 kWp – 1 MWp	0,5 kWp - 0,5 MWp	0,2 -10 MWp
Typical battery size	20 – 500 Wh	15 – 250 Wh	10 – 2000 Wh	5 -1000 Wh	20 – 200 kWh	10 – 500 kWh	0,1 - 5 MWh
Final yield = Daily solar consumption/ PVp	0,25 – 0,75	0,5 – 1,5	1 - 2	2 – 4	1 - 2	1,5 – 4	1,5 – 4
Capacity ratio: Usable battery energy/PVp	2 - 4	4 – 7	3 - 6	3 – 12	2,5 – 4	5 – 8	0,1 – 2
solar fraction	100 %	100 %	100 %	100 %	30 - 80 %	80 - 100 %	< 40 %
Autonomy time	5 - 7 days	3,5 – 7 days	1 – 2 days	1,5 – 3 days	0,5 – 2 days	1 – 2 days	0,01 - 5 hours

Source: Rosenfeld, S., Mhanna, J., Bopp, G., Müller, M., Trittler, S., Stortz, F., Geze, N., Martell, C., Ortiz, J., Rodden, P. (2025). Stortz, F. (Ed.), Li-Ion Battery Systems in Off-Grid Applications (Report No. T18-04:2025). IEA PVPS Task 18.

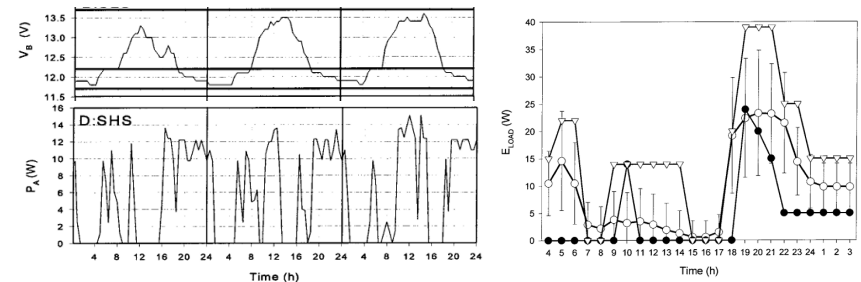
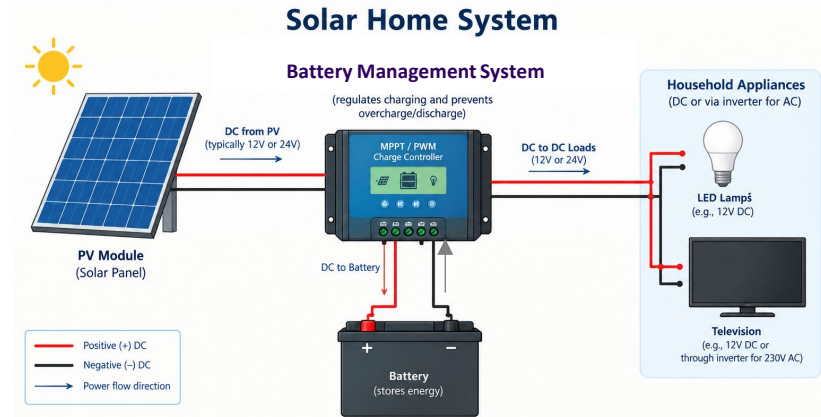
Solar home systems

Solar home systems (SHS) generally consist of a PV module (10–500 Wp) and a battery (5-2000 Wh), along with a battery management system (BMS). SHSs provide electricity for

- lighting
- refrigeration
- television, radio and
- access to the Internet.

System autonomy of 1 to 3 days depending on climate.
Performance ratio: 40-60%

Also applicable for water pumping, educational facilities (lighting, laptops), health clinics, telecommunication and community centers.



Left: Measured voltage and load pattern and Right: Typical load patterns derived from user surveys, SHSs with 80 Wp PV module and 1200 Ah battery in Indonesia, Reinders et al., SRER, 1999

Solar lanterns

Solar lanterns also called “Pico PV” consist of:
PV cells or a mini-PV module from 0,3 to 5 Wp,
Battery in the range of 1,5 Wh to 15 Wh,
LEDs at 40 to 150 lumens,
and electronics (sometimes in combination with phone charger)
meant to provide light for several hours each day (2h-8h).
Trends: automation, digitalization, sustainability

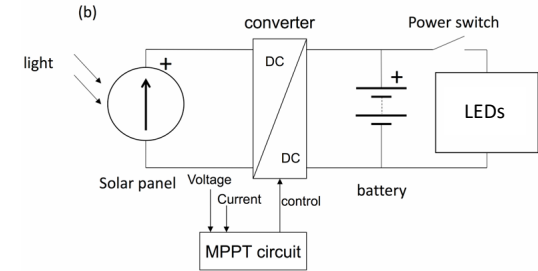
Products shown from database VeraSol (since 2020) supported by the World Bank Group’s Lighting Global program, IKEA Foundation and others, see:
<https://www.lightingglobal.org/>



Safer, affordable,
healthier, reliable



EUPVSEC 2026 IEA PVPS Storage for PV integration



Simple scheme for a solar lantern



Hybrid systems

Hybrid systems generally consist of a PV array (1 kWp to 10 MWp) a diesel genset, eventually wind turbines and a battery bank (0,1-500 MWh), along with a battery management system (BMS), providing electricity for

- residential homes
- village
- small industry
- hospitals

System autonomy of 0,5 to 3 days depending on climate.

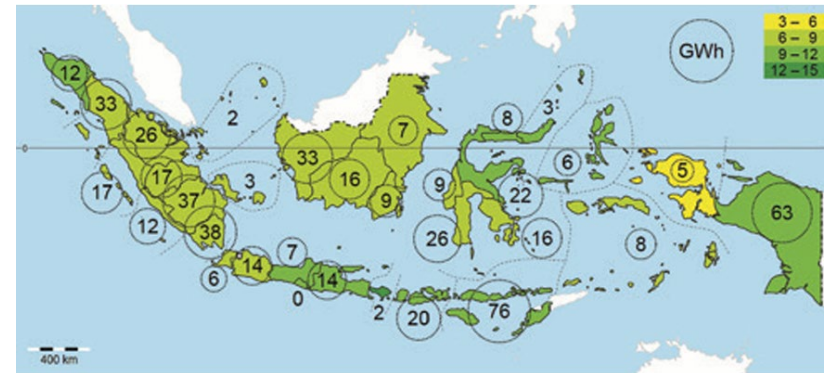
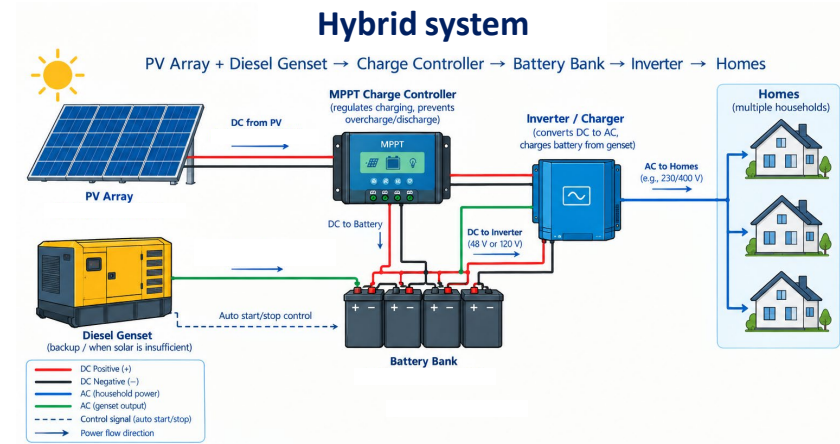
Motivation:

Lower OPEX as compared to diesel gensets

Less dependence on fuel deliveries at remote locations

Lower CO₂ emissions thanks to fuel savings, and

next step: mini-grid and connection to the electricity grid.



Difference in LCOE in cents/kWh between electricity produced by diesel gensets and hybrid PV systems in Indonesia (in circles: potential in GWh/year).

Hans Veldhuis, PhD thesis, 2015

Integrated photovoltaics (IPV)

IPV refers to solar-power-generating PV components that are inherently integrated into the design of objects, including products, structures, buildings, and automotive parts, instead of being simply added or retrofitted on top of the existing surfaces of conventional products¹.

Usually IPV contains batteries, but little is known about their

- Performance,
- User interaction,
- Reliability
- Sustainability
- and durability

In general IPV reduces CO₂ emissions of products and enhances their autonomy of functioning.

Even though users complain about batteries' functioning in IPV most of the research and developments are directed towards optimizing PV performance, not on assessing battery performance.

1) Angèle Reinders et al. Nature Energy, 2026



Georgia Apostolou,
PhD thesis

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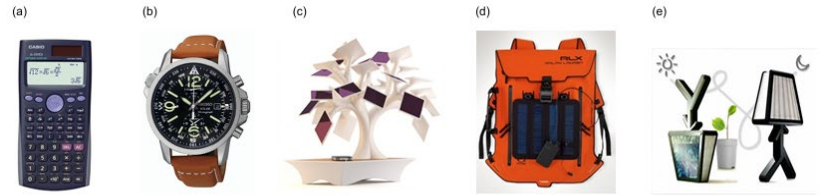
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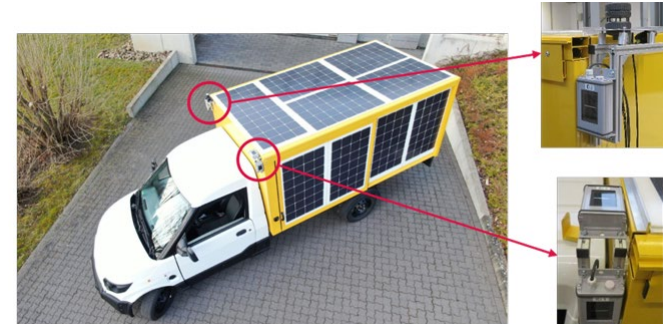
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1) Angèle Reinders et al. Nature Energy, 2026



Lighting condition	PV technology	Product's Power consumption	PV product size	Battery shape	Battery technology
Indoor	a-Si	<1 W	Thin/small	Button cell battery	Li-ion
Mixed: Indoor and Outdoor			Thick/large	AA, AAA	Alkaline, NiMH, NiZn
Outdoor	c-Si, m-Si			Li-ion batteries (cylindrical, prismatic or pouch cells)	Li-ion
Indoor	a-Si	>1 W	Thin/small	Button cell/custom made Li-ion batteries	Li-ion
Mixed: Indoor and Outdoor			Thick/large	AA, AAA	Alkaline, NiMH, NiZn
Outdoor	c-Si, m-Si			C, D, Li-ion (cylindrical, prismatic or pouch cells)	Alkaline(D), NiMH(C, D), Li-ion



Source:
Neel Patel's
PhD thesis,
2025

Image: ISFH

Some conclusions and recommendations

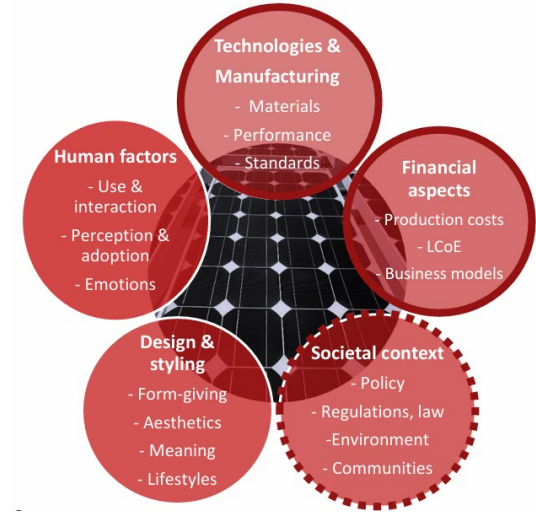
In off-grid PV, hybrid PV and integrated PV applications many different types of batteries are applied with a broad range of battery capacity, voltage, size and other specifications.

Main emphasize so far is on PV performance, not on battery performance, battery reliability or proper PV-battery system sizing

There is little data or in-depth knowledge regarding batteries in off-grid PV applications. The PV sector needs to improve experiences with the interaction between PV cells, modules and systems with batteries.

Batteries have not only a technical context, but also a financial, environment, user interaction, and regulatory context. A design-oriented approach could be useful here.

By looking at experiences with electrification in remote areas in emerging economies, we can learn a great deal about the performance, reliability, and sustainability of batteries in practice!



Innovation flower, Reinders, 2012-2026

Thank you for your attention!