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PV Battery Power Plants
Status, Trends and Potentials

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www.ise.fraunhofer.de

Fraunhofer Institute for Solar Energy Systems ISE

At a Glance

Institute Directors:
Prof. Dr. Hans-Martin Henning
Prof. Dr. Andreas Bett

Employees: ca. 1400
Budget 2021: €116.7 million
Founded: 1981

Photovoltaics
- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Perovskite and Organic Photovoltaics
- Photovoltaic Modules and Power Plants

Energy Efficient Buildings

Solar Thermal Power Plants and Industrial Processes

Hydrogen Technologies and Electrical Energy Storage

Power Electronics, Grids und Intelligent Systems

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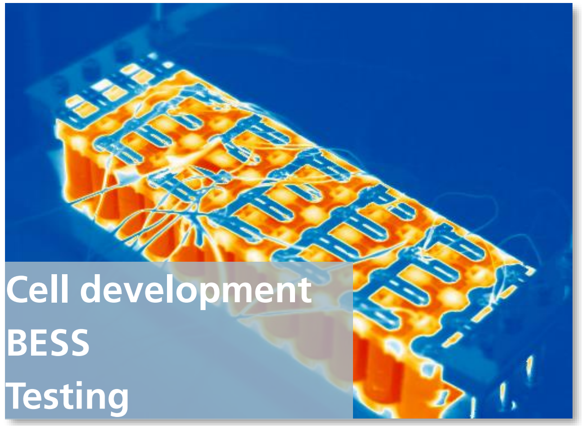
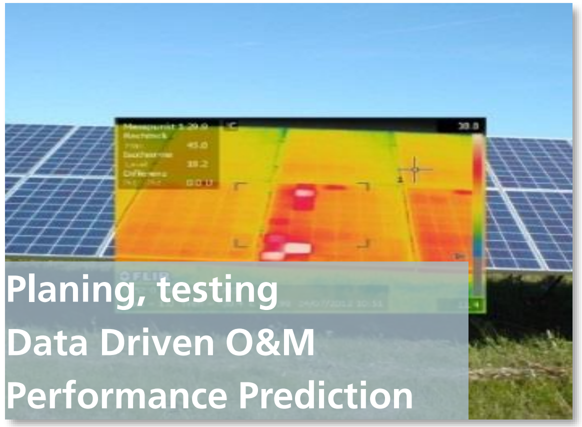
Power Solutions

PV Modules

Power Electronics



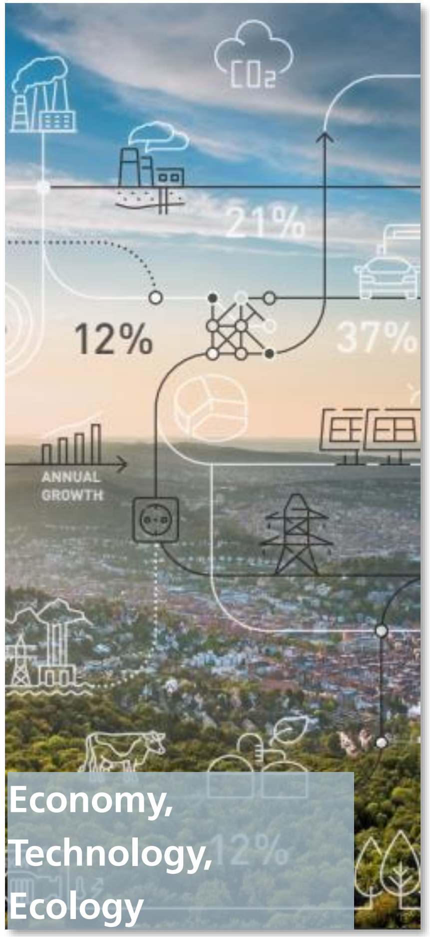
Electrical Energy Storage



PV Power Plants

Integrated PV

Intelligent Grid



Energy System

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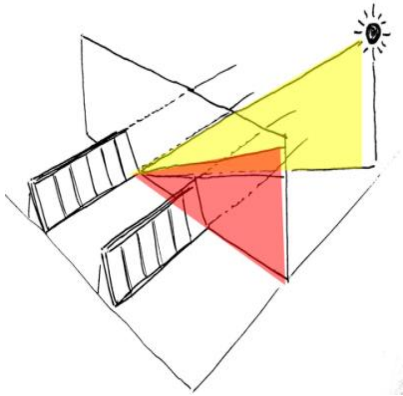
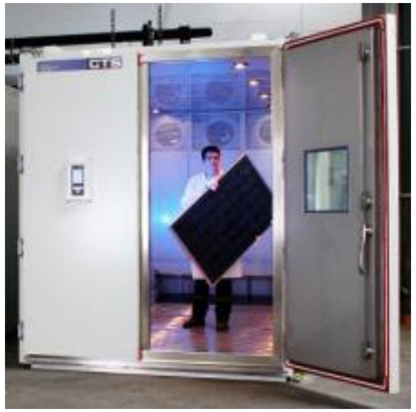
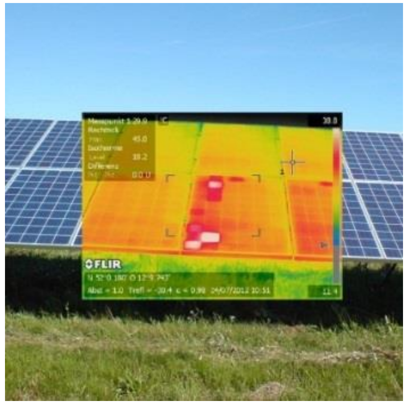
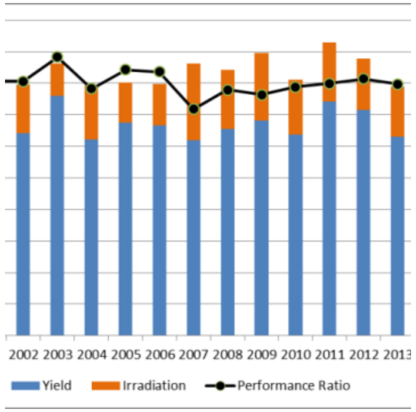
Services for Industry – PV Battery Power Plants









DEVELOPMENT

- Solar resource assessment
- GIS - site assessment
- Feasibility studies
- Design review and optimization, system simulations
- Life cycle analysis, ecology

ENGINEERING

- Yield assessment
- Glare assessment
- Module benchmarking
  - performance
  - reliability
- Outdoor Performance Lab
- Inverter testing

PROCUREMENT

- Representative module and other component sampling and checks
  - performance
  - reliability
  - benchmarking

COMMISSIONING

- Inspections and tests
  - visual inspection
  - IR/EL imaging
  - module/string power
  - performance
- failure analysis

Including bifacial tracker, integrated pv and pv-battery

OPERATION

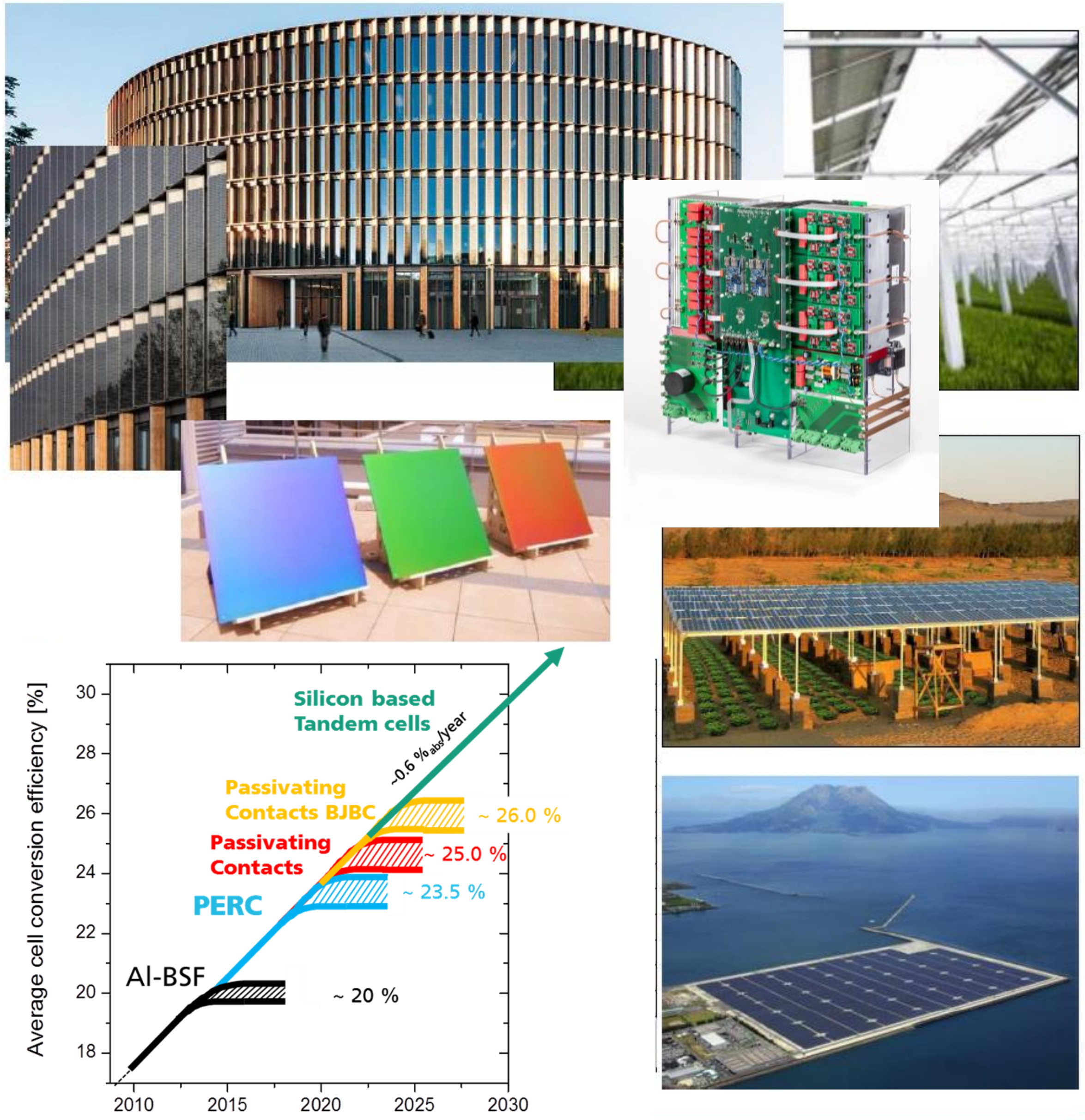
- performance analysis and monitoring
- digital twin simulation
- irradiance and power forecasting
- Root cause analysis for failures
- Power forecasting and predictive maintenance

Current Trends in photovoltaic plants

Integration, high efficiency, quality assurance

- **Photovoltaic** (PV) as the dominant power generation technology for the energy transformation

- Solutions:
  - Double use of **Surface Areas**
    Agrivoltaics, Floating-PV, Road-Integrated-PV, Building **Integrated PV**
  - **High Efficient Solar Cells and Modules**
  - High Efficient and cost reducing **power electronics** – eg novel medium voltage inverter
  - Quality assurance and data driven O&M
  - Integrating **PV battery plants**



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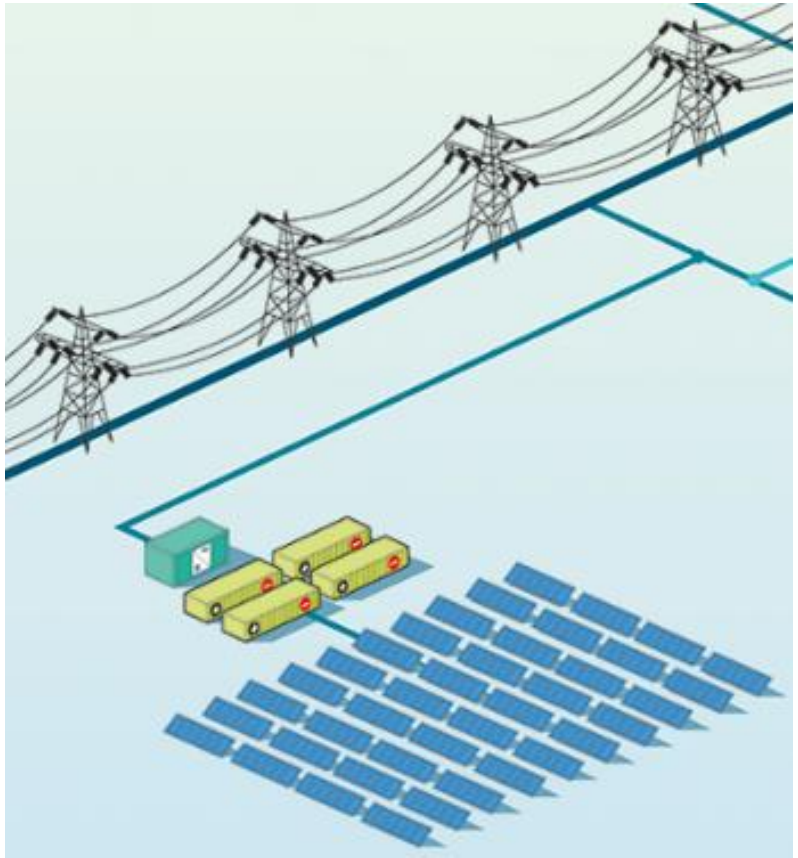
PV battery power plants – Motivation

Why are battery storage systems being integrated into PV power plants on the generation side?

Integration in »grid service markets«

- Fulfilling the local grid operator's requirements
  - Power output limits
  - Ramp rate control
  - Redispatch power
  - Reactive power balance
- Offering balancing power
  - Instantaneous reserve (»Fast Frequency Response FFR«)
  - Primary control reserve (»Frequency Containment Response FCR«)
  - Minute reserve / Secondary reserve (»automatic Frequency Restoration Reserve aFRR«)



https://www.ise.fraunhofer.de/en/key-topics/stationary-battery-storage.html

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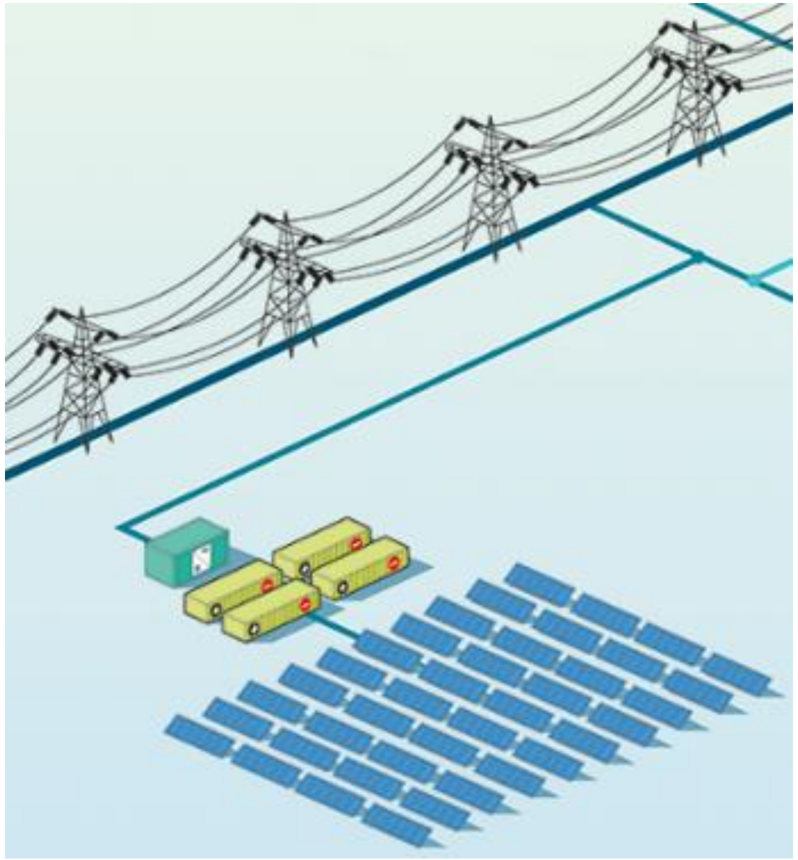
PV battery power plants – Motivation

Why are battery storage systems being integrated into PV power plants on the generation side?

Integration in »energy markets«

- Planning feed-in by means of FTM peak shaving and load following
- Delaying feed-in of PV power to times when prices are high to increase income from direct marketing (also particularly attractive in the context of local energy markets)
- Generating additional revenue by charging the battery storage system from the grid and subsequently discharging it to exploit the increasing differences in electricity prices (arbitrage trading)
- Integrating a larger amount of PV capacity where there is a limited connection with the grid and a fixed feed-in limit
- Implementing projects with higher PV capacities more quickly in cases where the expansion of the grid connection or transmission lines is delayed

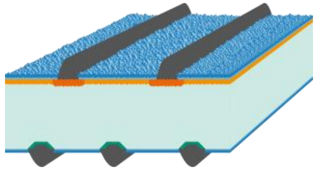


https://www.ise.fraunhofer.de/en/key-topics/stationary-battery-storage.html

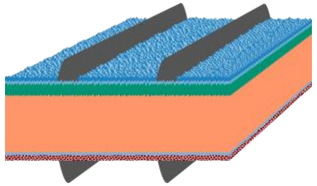
Current trends – Battery technologies

Industrial Solar Cells – PERC, TOPCon, SHJ

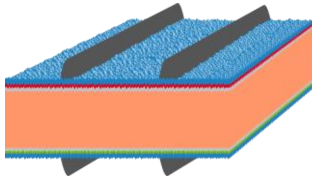
p-PERC
Passivated Emitter and Rear Cell



n-TOPCon
Tunnel Oxide Passivated Contact

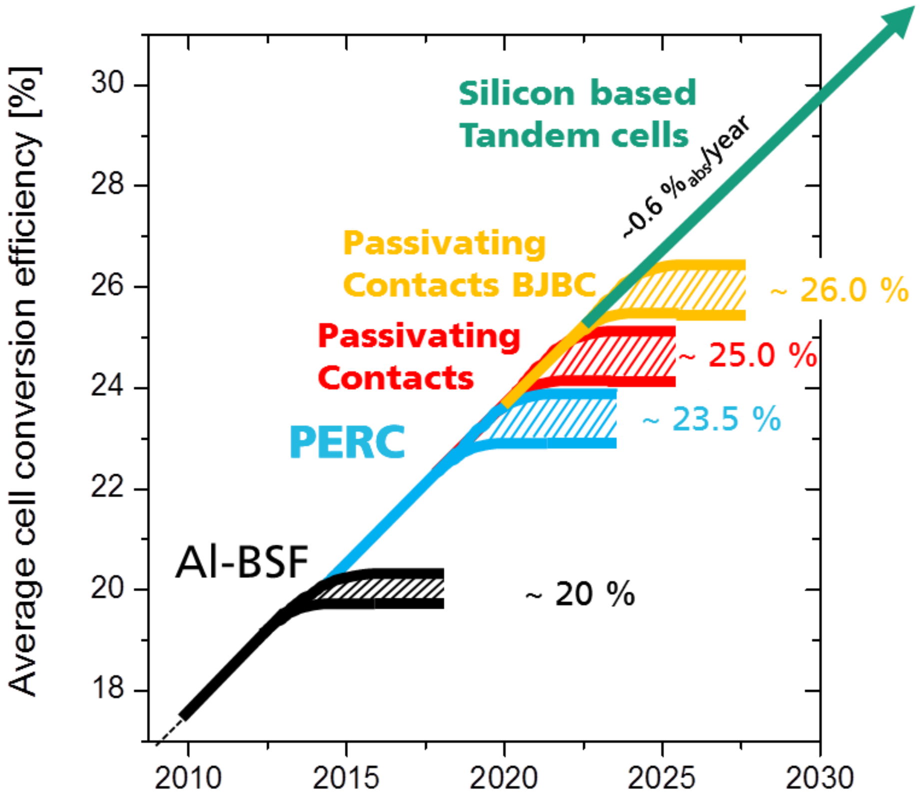


n-SHJ
Silicon Hetero Junction



Device	V_{OC} (mV)	j_{SC} (mA/cm²)	*FF* (%)	η (%)
PERC	690	41.1	80.7	**23.1***
TOPCon	714	41.4	81.7	**24.2***
SHJ	742	39.1	83.1	**24.2***

*Calibrated measurement at Fraunhofer ISE CalLab PVCells



M. Hermle et al., ETIP 2017

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Current trends – Battery technologies

Overview

	LNMC [1]	LFP [2]	NaS [3]	ZBS [4]	NIB [5]	VRFB [6]
Rated voltage of cell (V)	3.6	3.3	~ 2	~ 1.7	~ 3.1	~ 1.6
Gravimetric energy density (Wh/kg) at cell level	150 – 300	140 – ~ 200 [b]	100 – 250	40 – 80	135 – 140 [d]	15 – 50 (in relation to electrolytes)
Volumetric energy density (Wh/l) at cell level	200 – 850	200 – ~ 350	150 – 300	50 – 100	215 – 280	20 – 70 (in relation to electrolytes)
Typical operating temp. (°C)	0 – 45	0 – 45	300 – 340	-20 – 50	-20 – 60	5 – 50
Equivalent full cycles	1,000 – ~6,000 [a]	1,000 – ~10,000 [c]	7,000 – ~ 8,000	~ 20,000	2,000 – ~5,000 [e]	> 10,000
Calendar life (a)	10 – 20 [a]	10 – 20 [c]	≥ 20	> 25	~ 20 [e]	5 – 20
DC – DC Efficiency (%)	~ 90 – 98	~ 90 – 98	~ 70 – 85	75 – 80	Up to 97	60 – 75

(a): LNMC cells for stationary applications typically have average energy densities, giving them a higher cycling stability and a longer calendar life.

(b): Recent developments have enabled LFP batteries to reach gravimetric energy densities of around 200 Wh/kg.

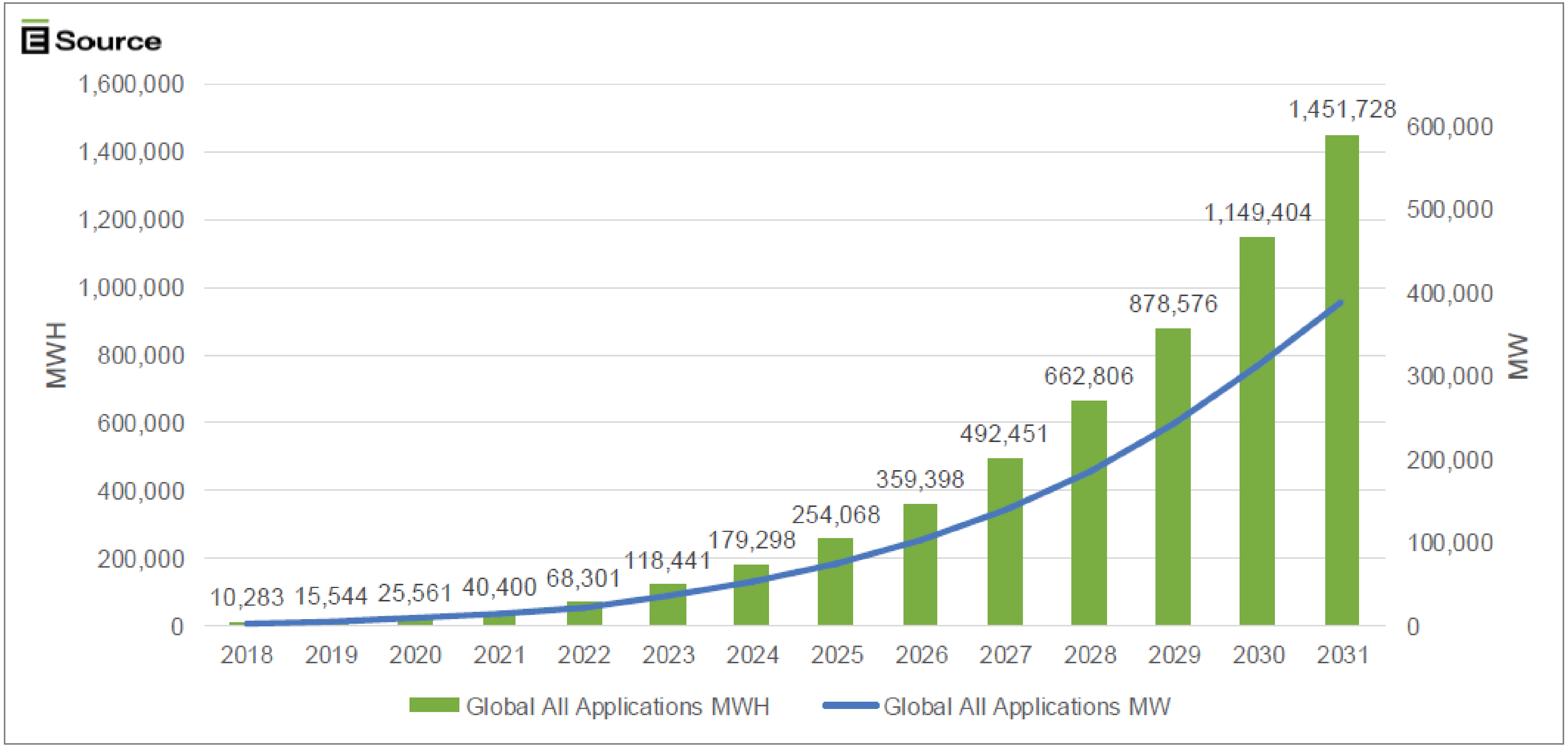
(c): In recent publications, suppliers of LFP battery storage systems have reported cycle numbers of around 10,000 and a calendar life of 20 years.

(d): Information from manufacturers indicates that they are also now aiming for 200 Wh/kg.

(e): Sodium-ion batteries are still a relatively new technology, meaning that the data on their cycle and calendar life should be viewed with a degree of uncertainty.

Current trends – System configurations

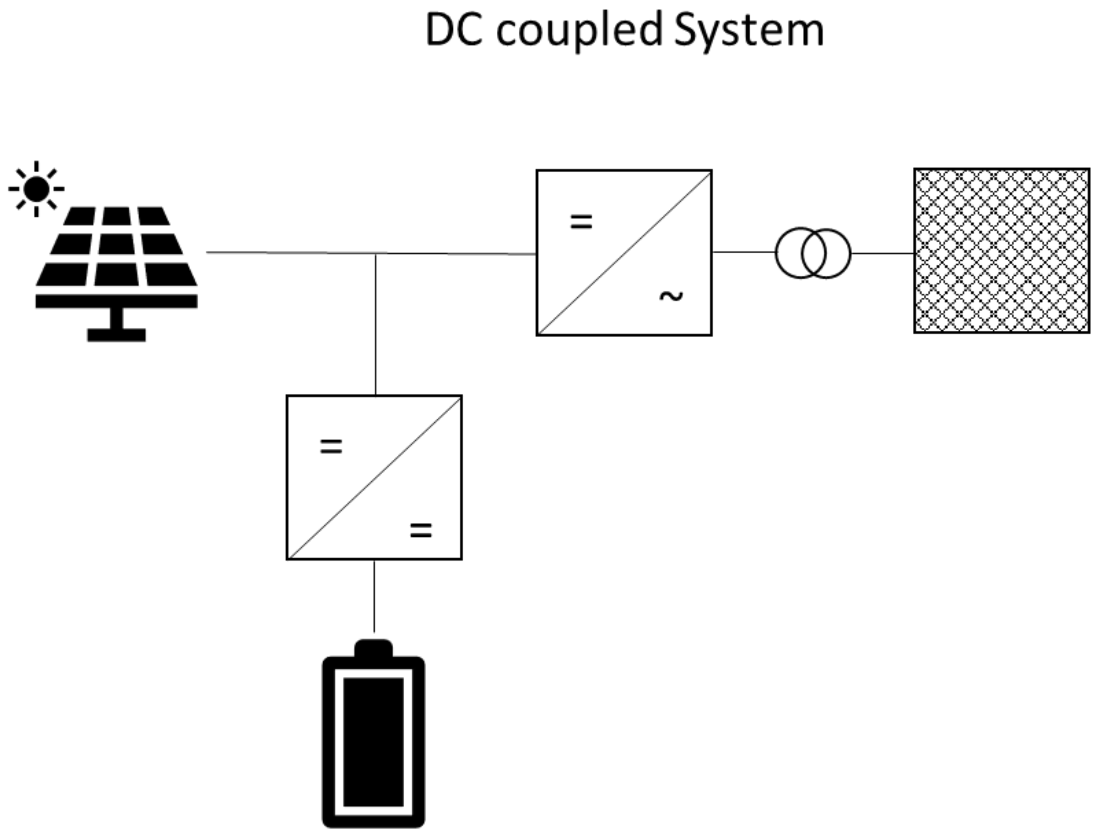
Capacity to power ratios are increasing

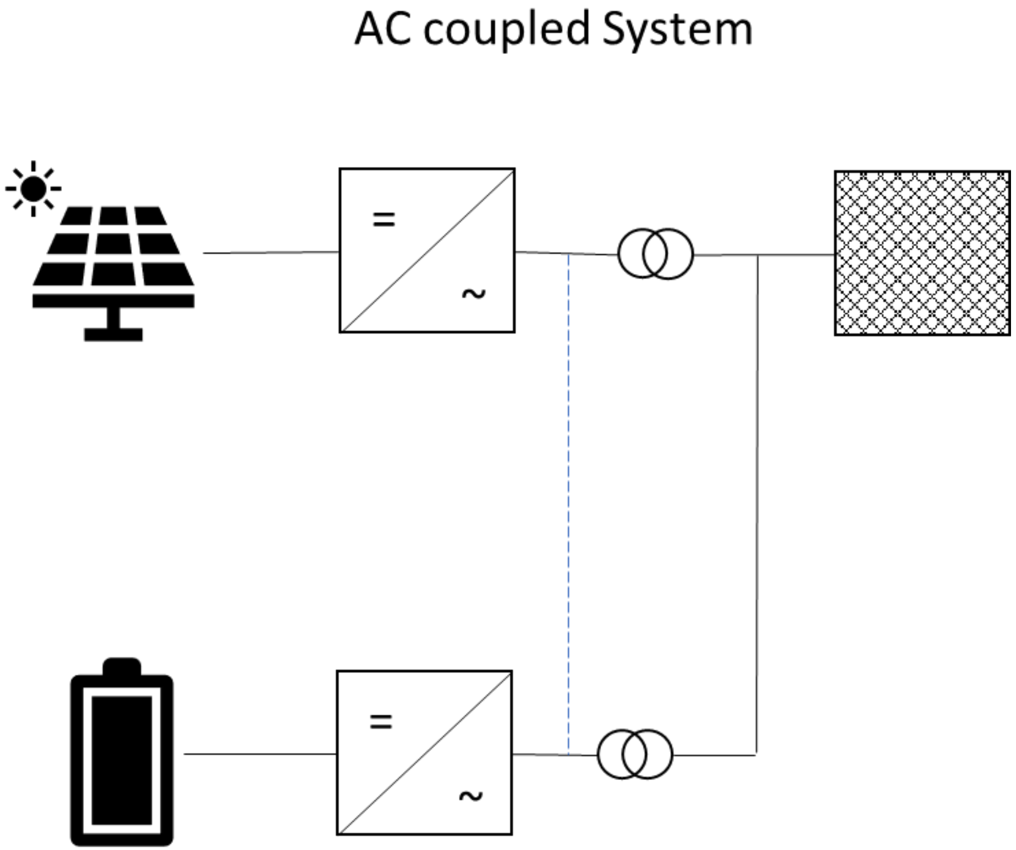


Source: S. Jaffe: The Tera-Watt Hour Age, 40th International Battery Seminar, Orlando, 2023.

Current trends – System concepts

DC versus AC coupled solutions





Current trends – Energy management

Forecast-based operating control strategies

Revenue stacking
- Participation at "grid services" markets
- Participation at "energy" markets

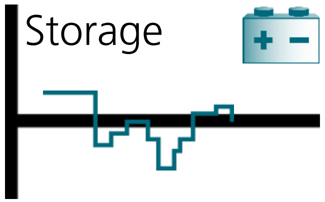
INPUT
- Weather forecast
- Demand forecast
- Price forecast
- State of charge
- Operating strategy

ENERGY MANAGEMENT

Software
(protocols, algorithms,
e.g. AI / deep learning)

Hardware
(computer, interfaces)

SCHEDULES



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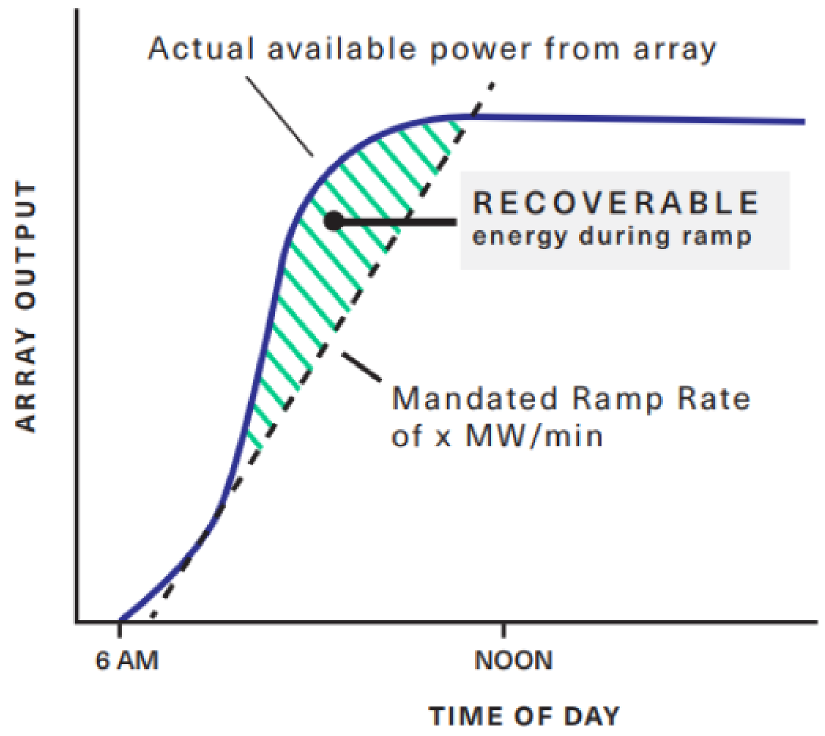
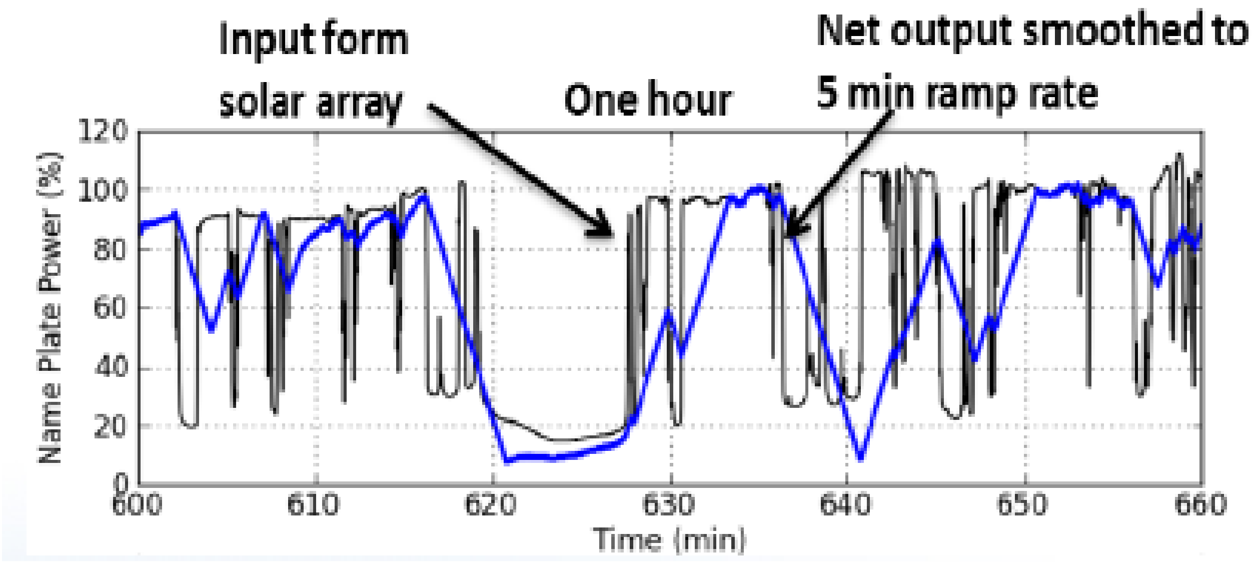
Potentials

Technical and financial added value through flexible operating modes

Ramp rate control





R. Mattar: DC-coupled plus storage, International Battery Seminar, Orlando ,2023.

Source: Increasing the Value of PV: Integration, NAATBatt Storage Workshop July 10, 2014.

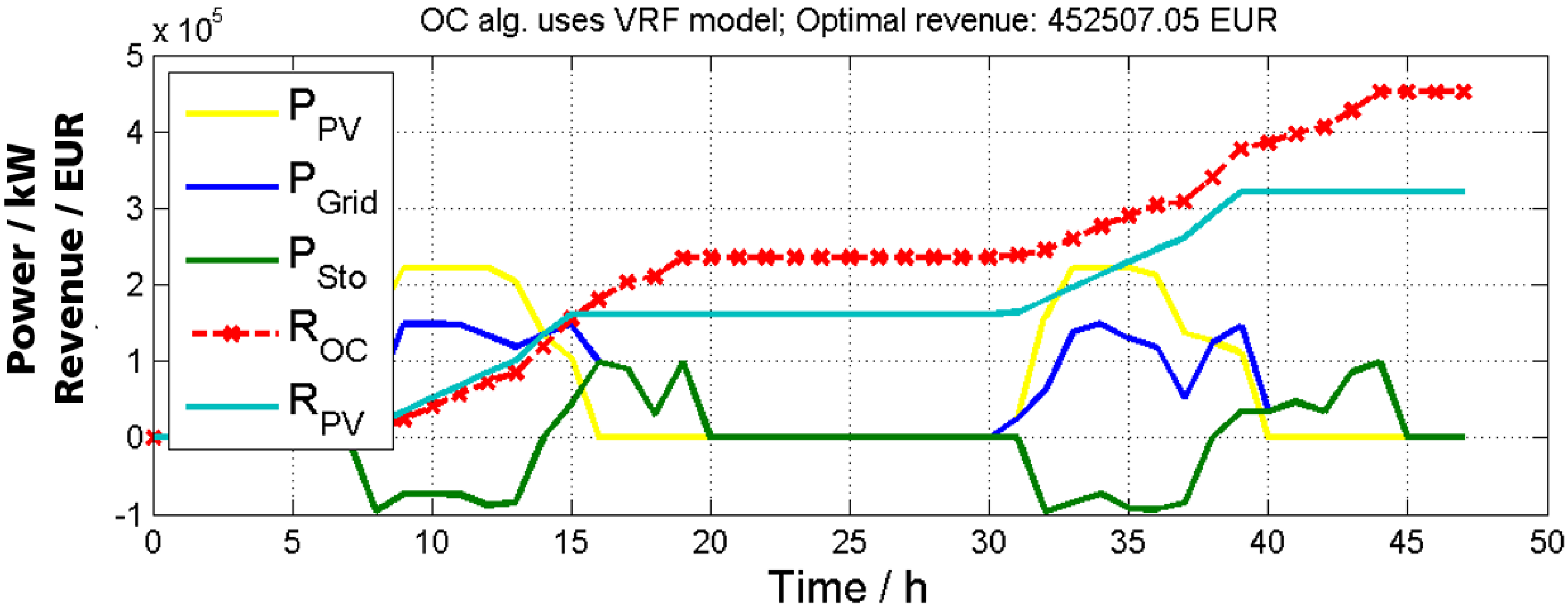
Potentials

Technical and financial added value through flexible operating modes

Energy time shifting

Optimal control problem: Maximization of the revenues

→ Optimal dispatch plan for the storage power

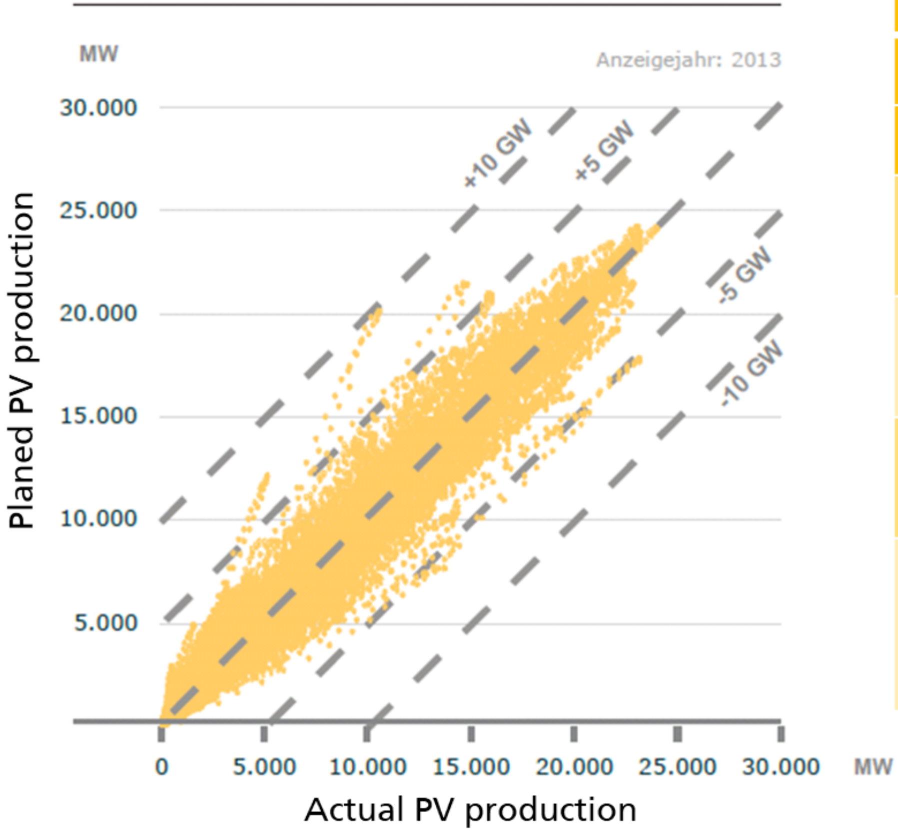


Potentials

Technical and financial added value through flexible operating modes

Deliver as forecasted

→ **Battery storage is the enabler**



Date	03.03.	03.04.
Time	13:15	12:30
GMT	+1:00	+1:00
Planed production	7.5 GW	19.7 GW
Actual production	13.7 GW	10.1 GW
Forecast error	-6.1 GW	+9.6 GW
Relative forecast error	-44.7 %	+94.8 %

Source: B. Burger, Fraunhofer ISE; Data: EEX Transparency Platform.

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PV battery power plants – Example: Energy time shifting

Germany PV power plant with battery – part of the innovation tender initiative

Innovation Tender Germany

25% of the installed capacity should be able to provide flexible operation power to stabilize the grid

2022 1200 MWp installed, typical ratios of storage capacity MWh to installed PV power MWp in the range of 0.25 to 0.6

Source:
https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Ausschreibungen/Innovation/BeendeteAusschreibungen/start.html;jsessionid=C40730490CA80D85737C817465E7808F

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PV battery power plants – Example: Energy time shifting

Germany PV power plant with battery – part of the innovation tender initiative

Project: Spitalhöfe (Pfaffenweiler) BayWaRe

PV installation: 7.2 MWp

Battery storage system: 4 MWh, lithium-ion

Coupling: AC

Best practices bio-diversity applied

Operation example: Storage load during lunchtime, feed in when demand is high – energy time shifting

Source: BayWaRe https://www.baywa-re.de/de/solar/solarpark-spitalhoefe#artenvielfalt

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PV battery power plants – Example: Delivered as forecasted

La Reunion a French oversea department and Island

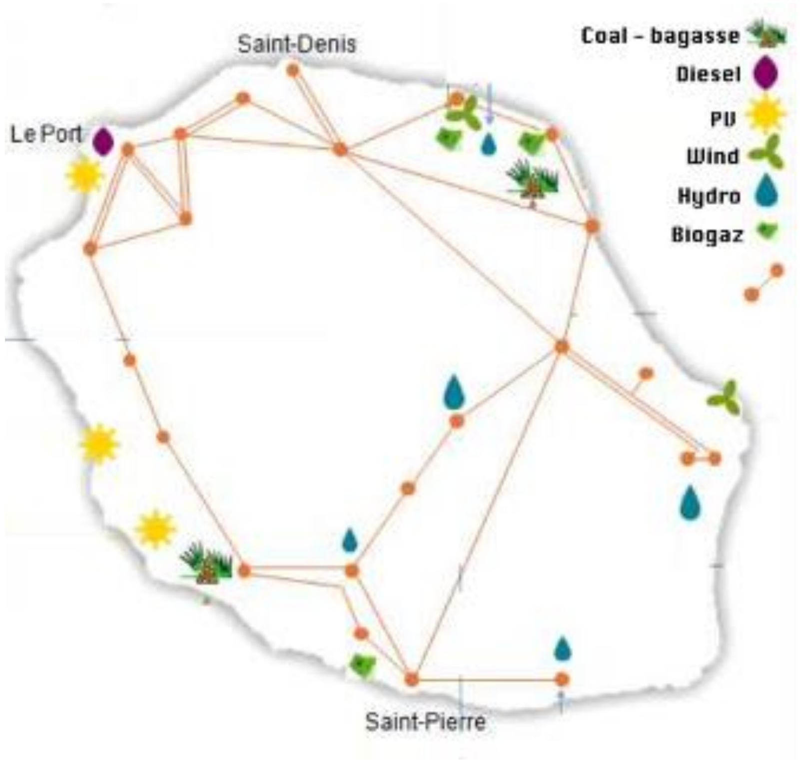


Fig. 3: Schematic diagram of La Reunion's electricity grid in 2022

Battery storage system and agrivoltaic plant in the French overseas department of La Réunion ©CPMR.

https://oer.spl-horizonreunion.com/ EU Project Twin Solar

PV battery power plants – Example: Delivered as forecasted

La Reunion a French oversea department and Island

Project: Les Cedres, Akuo

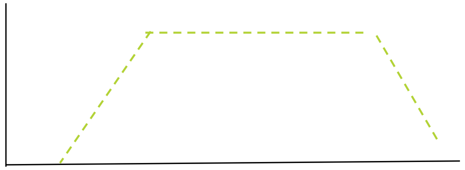
PV installation: 9 MWp

Battery storage system: 9 MWh, lithium-ion

Coupling: AC

Agrivoltaics allows effective dual land use

Operation example: Day ahead forecasting of trapezoidal ramp



Battery storage system and agrivoltaic plant in the French overseas department of La Réunion ©CPMR.

Source: CPMR and Akuo, https://akuocoop.com/fr/projets/5-les-cedres

TwInSolar

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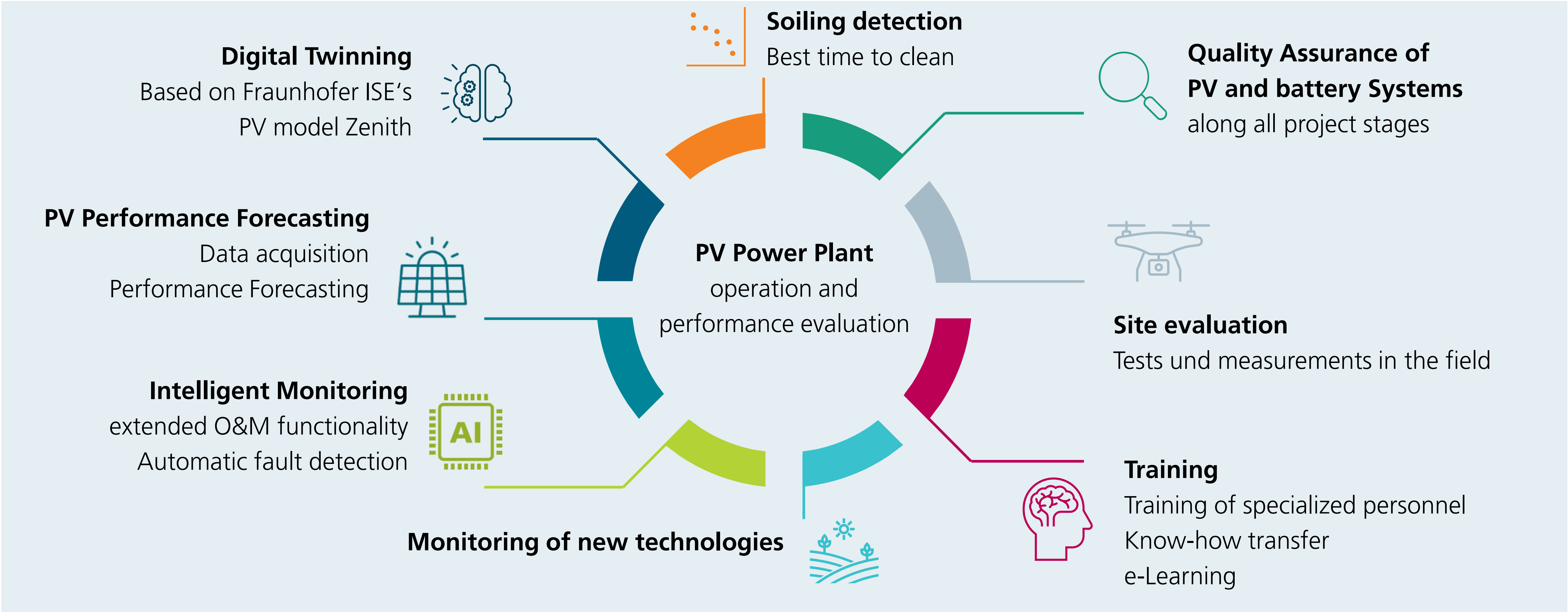
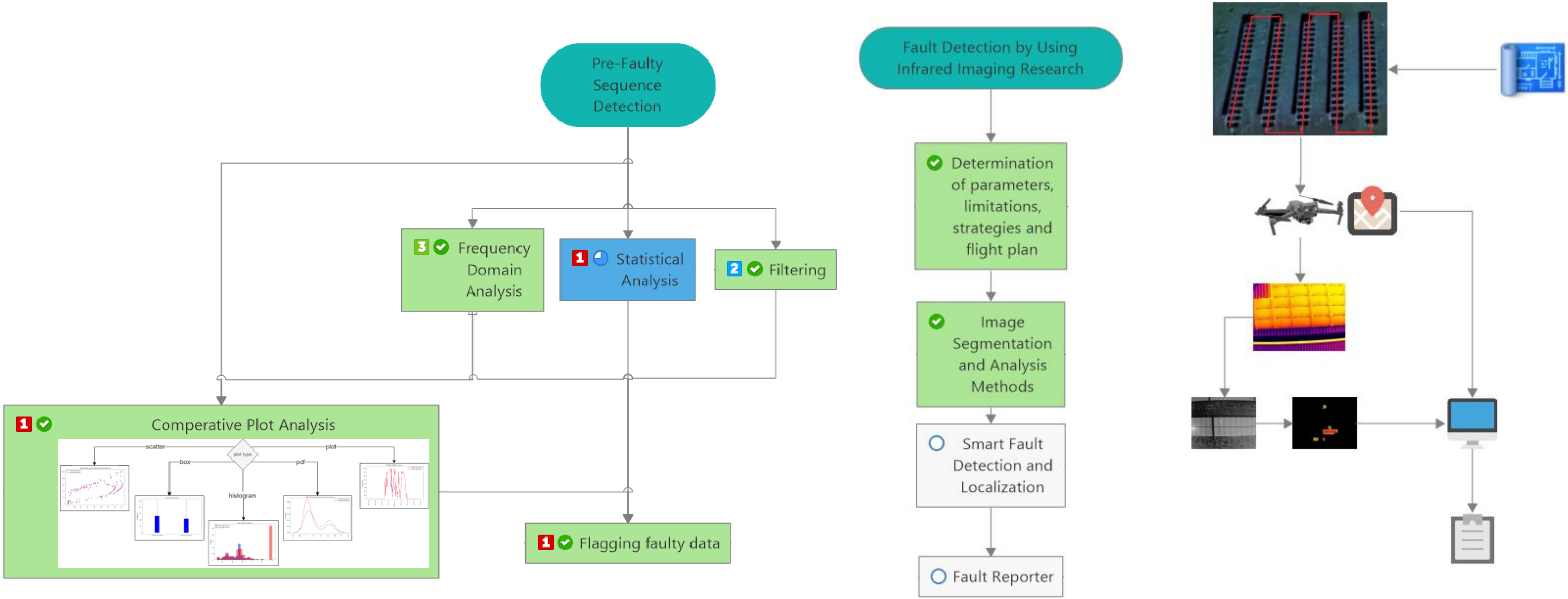
Operation and Maintenance of PV Battery Power Plants

Research topics



Operation and Maintenance– Collaboration with Ege University

Pre-faulty sequence detection and Smart Fault Detection and Localization



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Conclusions

1 **Battery storage systems are used in various applications**
→ Behind-the-meter: Home storage systems and C&I storage systems
→ Front-of-the-meter: District storage systems and utility-scale storage systems

2 **Front-of-the-meter battery storage systems**
→ World-wide: Impressive growth rates forecasted
→ Europe: Integration of battery storage in PV power plants is still lacking behind

3 **Integration of battery storage in PV power plants – Revenue stacking**
→ Participation in grid service markets
→ Participation in energy markets

4 **Technologies**
→ Batteries: It's a lot about lithium-ion, but it's not all about lithium-ion
→ Forecast-based energy managements are key for optimized operation

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Contact

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PV battery power plants – Spain

Example: PV power plant with a battery storage – hybrid power plant in Spain

Project: Gecama Hybrid, Enlight

PV installation: 200 MWp (Wind about 300 MW)

Battery storage system: 100 MW, lithium-ion

Coupling: AC

Operation example: The PV battery power plant will use the same grid connection point as the original wind project. This should enable the project's infrastructure (substations and transmission lines) to be used much more efficiently.

PV: 7.5 GWp installed in 2022 /Storage strategy

State funded innovation tender

Figure 3: Combination of battery storage, photovoltaics and wind power in Spain, ©Enlight

Source: https://enlightenergy.co.il/project/gecama-hybrid/ / www.boe.es/diario_boe/txt.php?id=BOE-B-2023-236 / https://www.miteco.gob.es/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf

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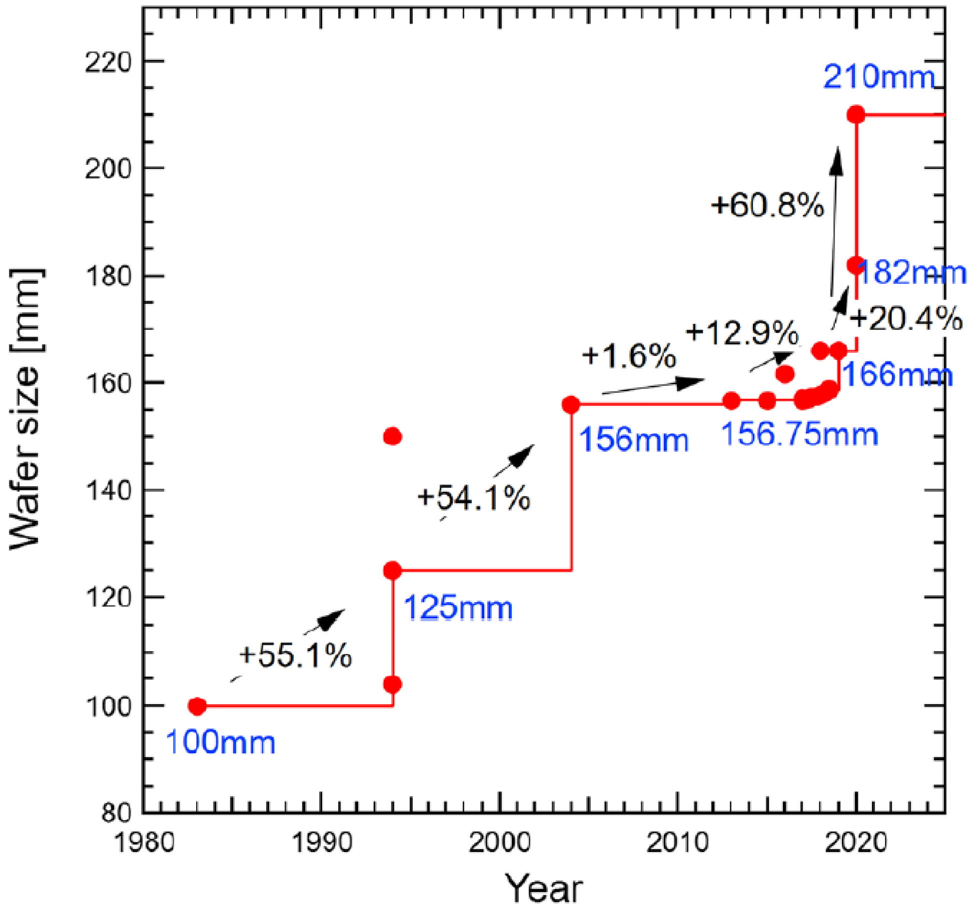
Entwicklung Photovoltaikindustrie
Wirkungsgrade Solarzellen

- Trend bei Wafer- bzw. Solarzellengröße folgt empirischem Gesetz „50% - 10 Jahre“
- **„50% - 10 Jahre“ Gesetz besagt, dass Wafergröße nur dann zu langfristigen Industriestandard wird, wenn Waferfläche um mehr als 50% zunimmt, neue Wafergröße bleibt etwa 10 Jahre am Markt**
- Trina Solar glaubt, dass 210 mm-Standard in den nächsten 5 bis 10 Jahren für die gesamte Branche gelten wird

→Einschätzung wird vom ISE geteilt, 210 mm wird vermutlich Standard

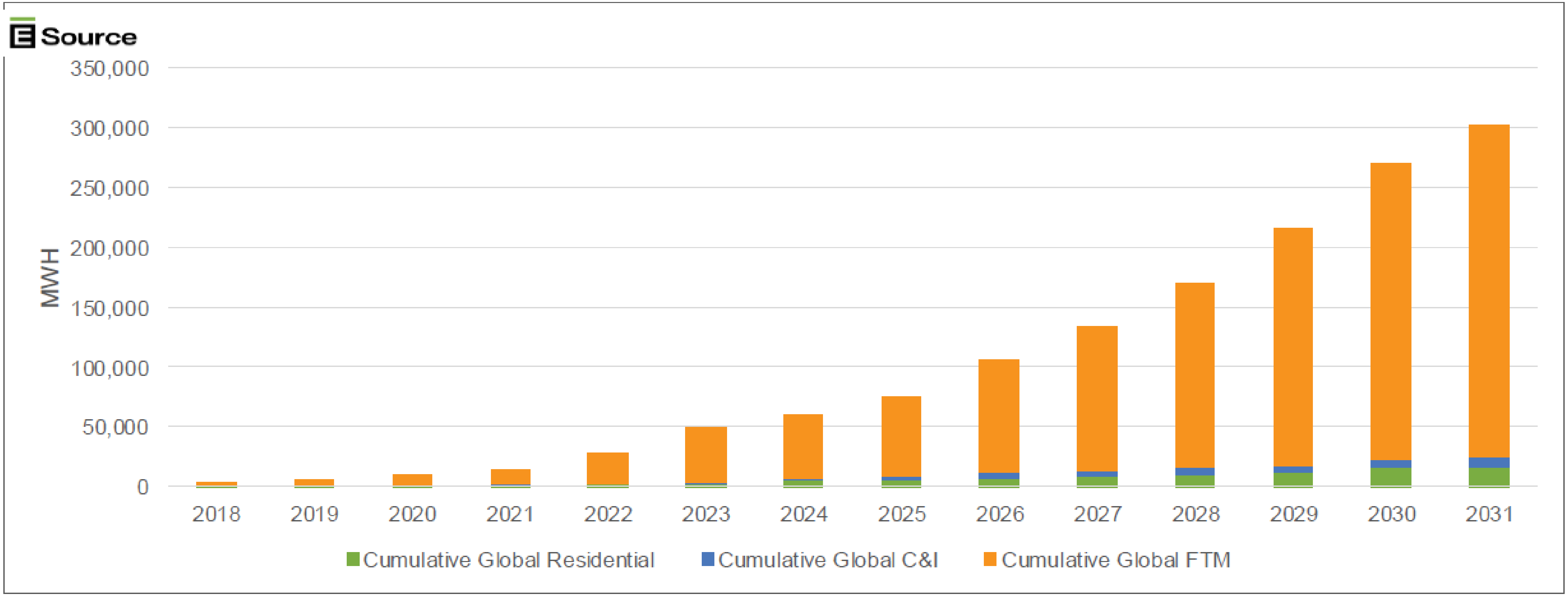


Y. Chen et al., Technology evolution of the photovoltaic industry: Learning from history and recent progress, Prog Photovolt Res Appl. 2022;1-11. doi:10.1002/pip.3626

Hagel, Bett et all; Photovoltaics at Multi-Terawatt Scale: Waiting is not an Option

Battery storage systems

Market trends: »Behind-the-meter« and »Front-of-the-meter«



Source: S. Jaffe: The Tera-Watt Hour Age, 40th International Battery Seminar, Orlando, 2023.