

Challenges of Renewable Energy Integration in Clean Energy Systems

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AALBORG UNIVERSITY
DENMARK

Aalborg University, Denmark



**Established in
1974**
22,000 students
2,300 faculty



**PBL-Aalborg
Model
(Problem-based
learning)**



**THES 2025 (SDG's)
No. 9 globally**

**USNEWS 2025
Engineering
No. 27 globally
No. 2 in Europe
No. 19 in Electrical Engineering**

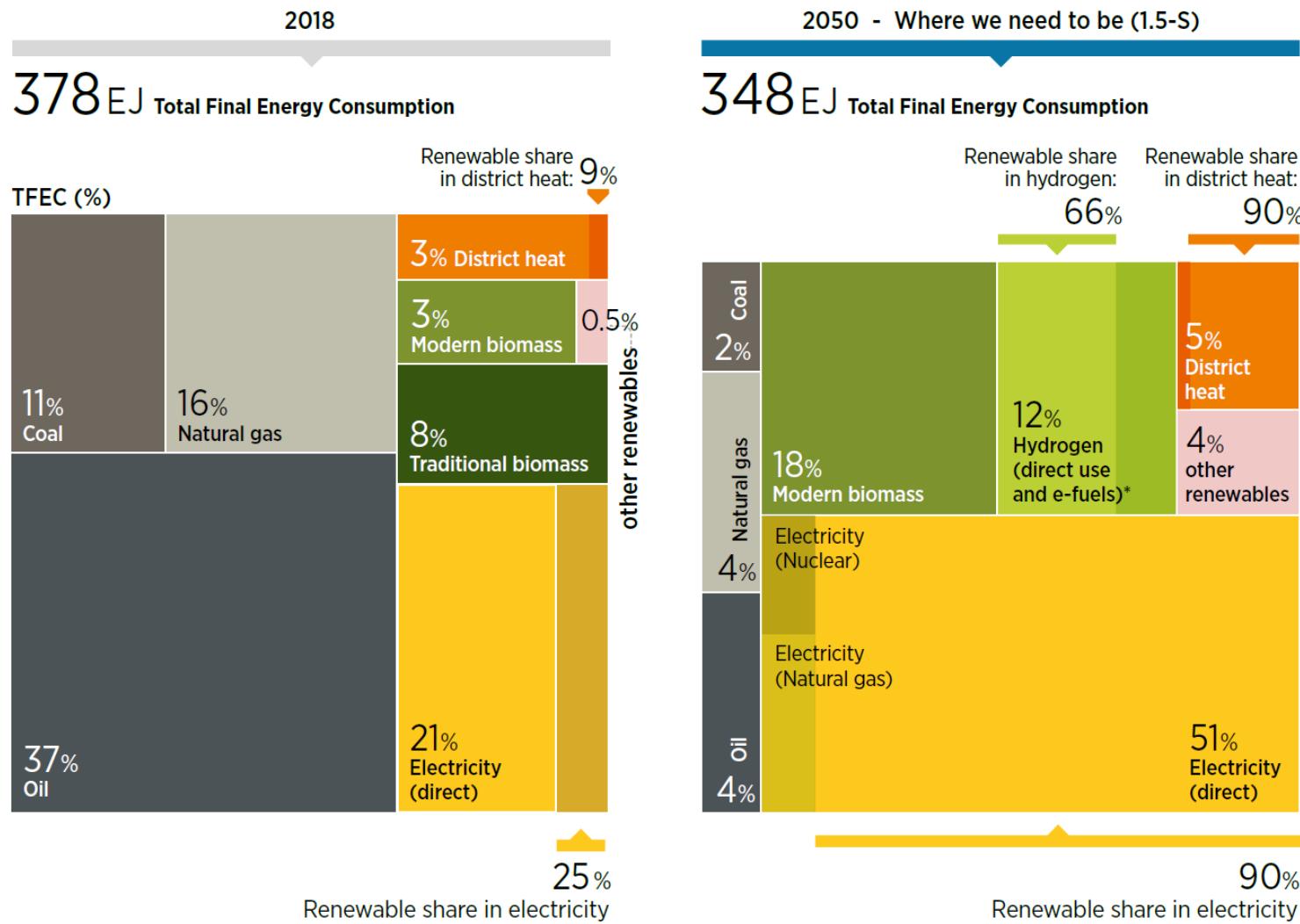
Source:
<https://www.usnews.com/education/best-global-universities/engineering>

SUSTAINABLE DEVELOPMENT GOALS



WORLD TRANSFORMATION (FROM IRENA)

ENERGY TRANSITION



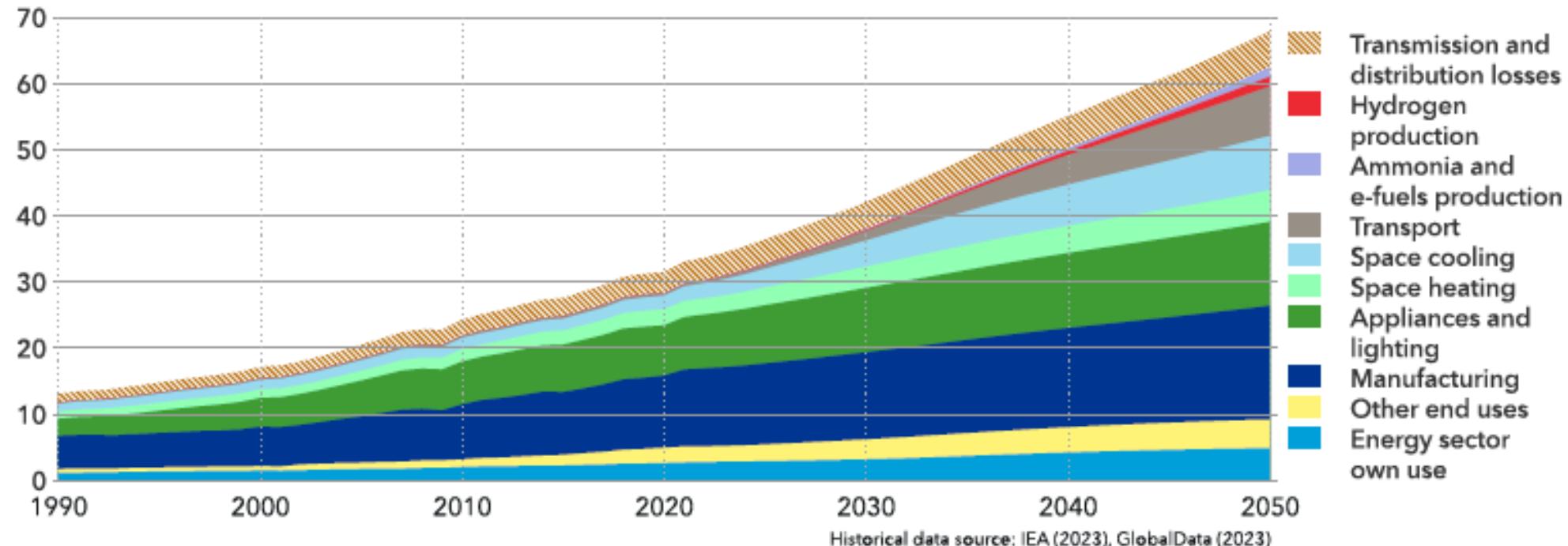
Source: (IRENA, 2021a).

World Electricity Consumption (1990-2050)

FIGURE 1.1

World annual electricity demand by segment

Units: PWh/yr



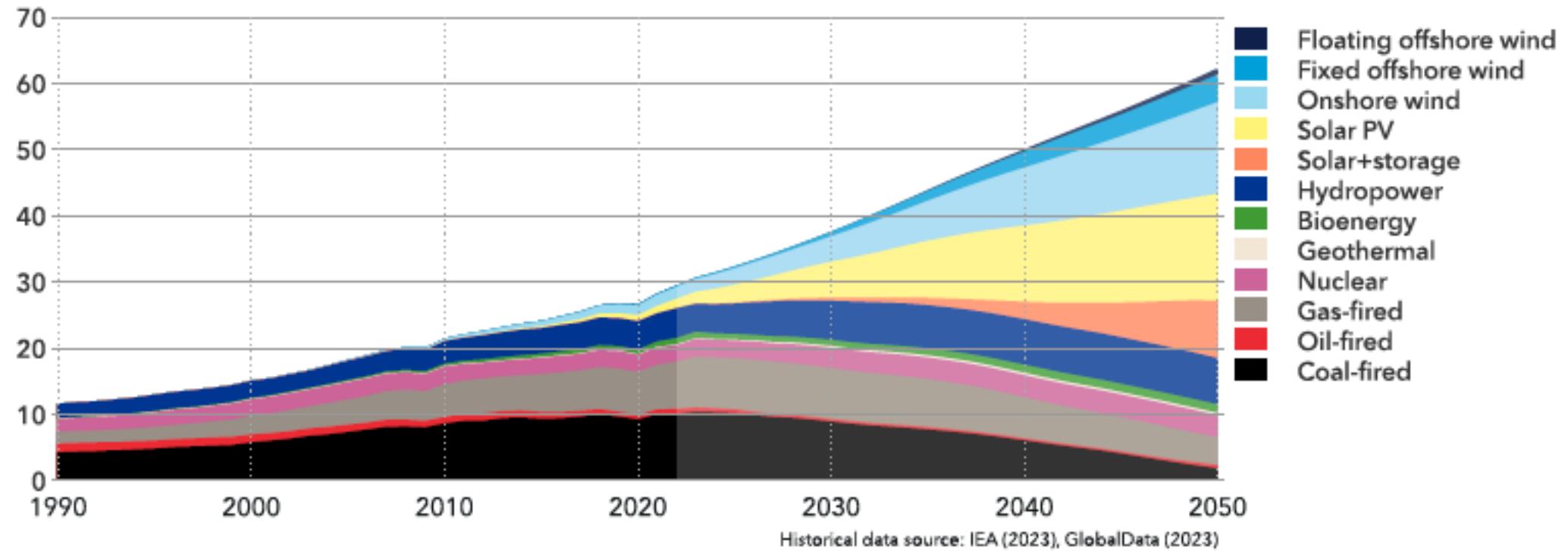
DNV : Energy Transition Outlook – New Power Systems 2024

Electricity generation Distribution (1990-2050)

FIGURE 1.5

World grid-connected electricity generation by power station type

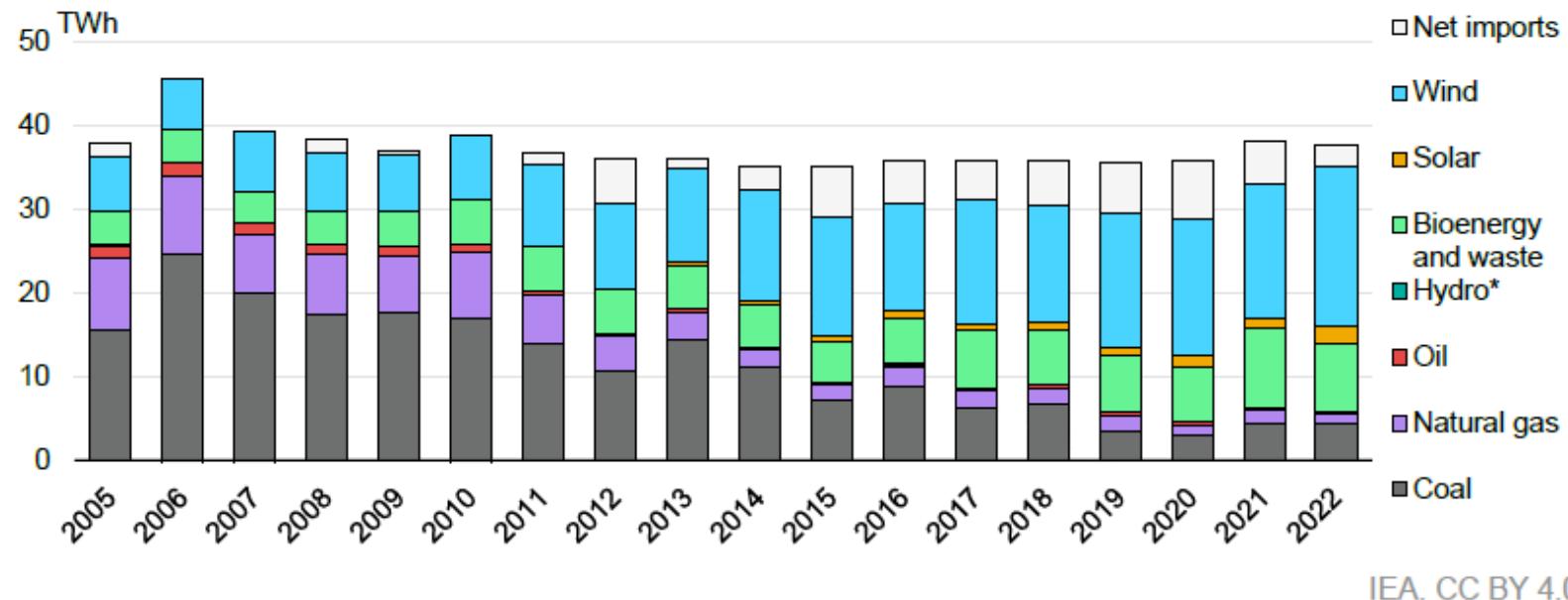
Units: PWh/yr



DNV : Energy Transition Outlook – New Power Systems 2024

Electricity generation in Denmark (2005-2022)

Figure 9.1 Electricity generation by source and net imports in Denmark, 2005-2022



* Hydro is not visible on this scale and represented 0.02 TWh in 2022.

Source: IEA (2023), [World Energy Balances](#).

IEA. CC BY 4.0.

Wind Power in Denmark has large growth in the past 30 years

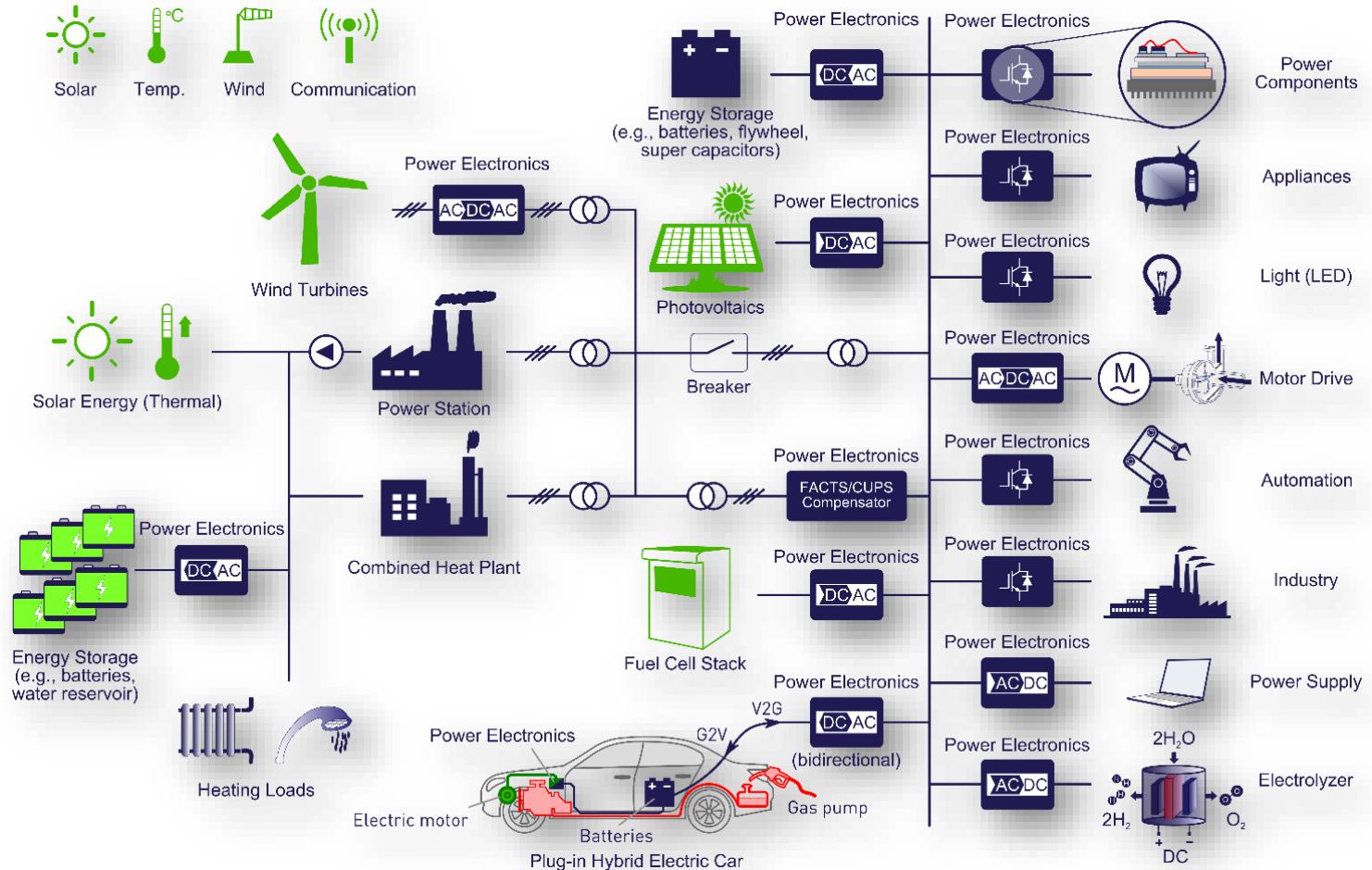
(Source: International Energy Agency, <https://www.iea.org/countries/denmark>)

POWER ELECTRONICS APPLICATIONS

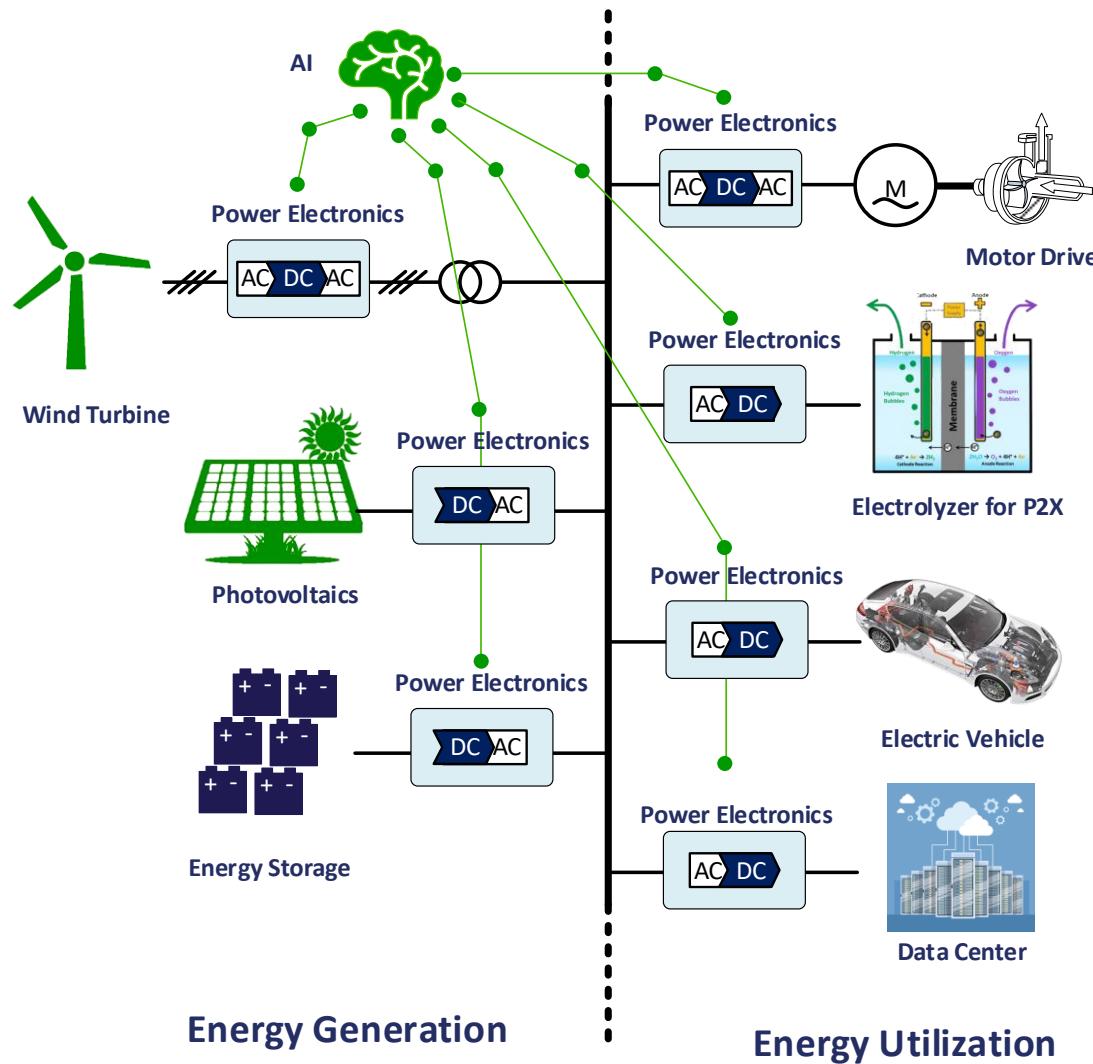
KEY ROLE

- Production
- Distribution
- Consumption
- Control

...Everywhere!



KEY AREAS OF EVOLUTION TODAY



Key Drivers

- Energy efficiency
- Cost of energy
- Life cycle cost
- Predictive maintenance
- Time-to-market

Key Trends

- Product + service
- Data + physics
- Digitalization

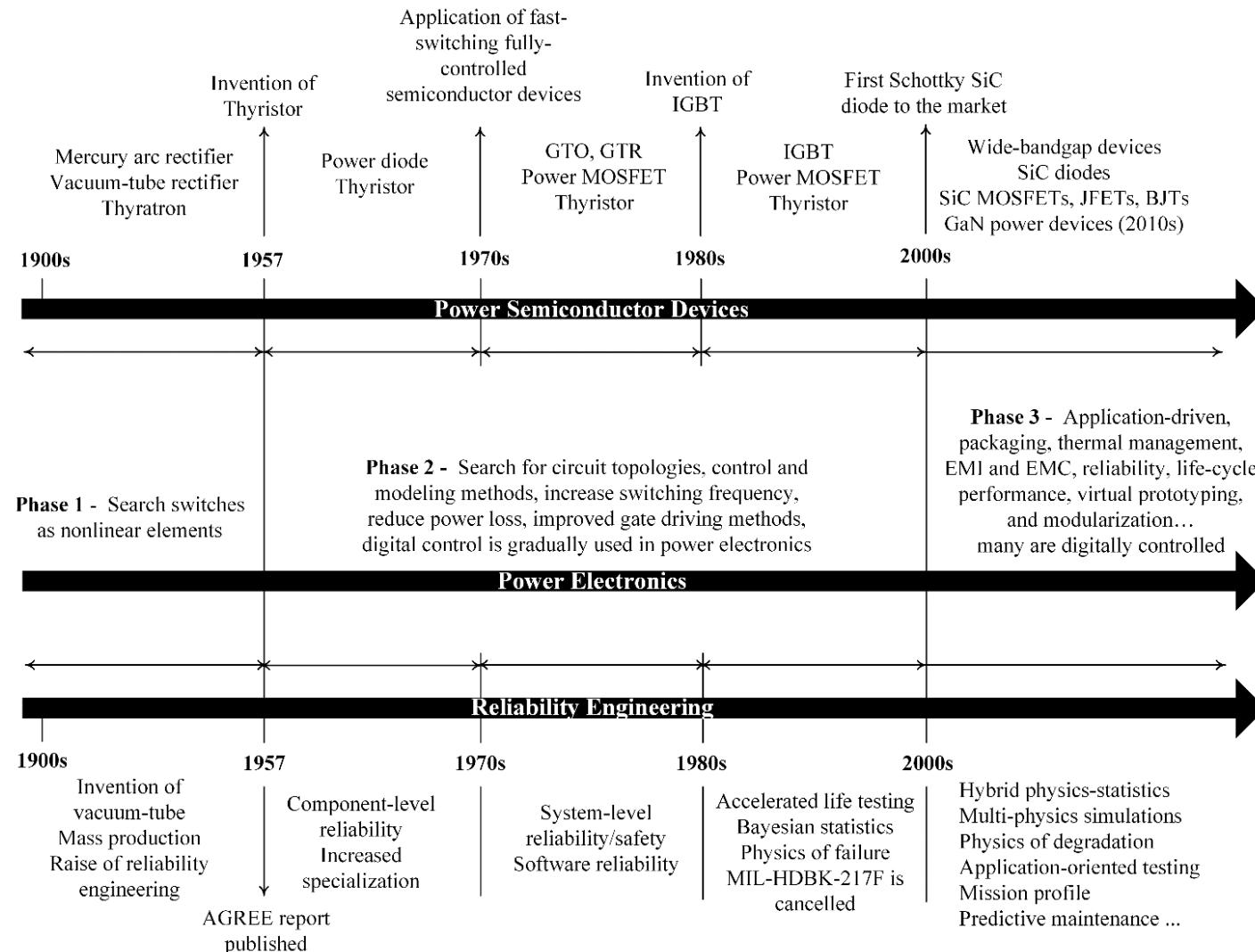
Emerging Areas

- Renewables
- Transportation
- Energy Efficiency
- Power-2-X
- Data-centers
- Grid infrastructure
- Storage
- Automation/Industry 5.0
- Defense
- Energy Access
- Artificial Intelligence
- Independence
- Sustainability

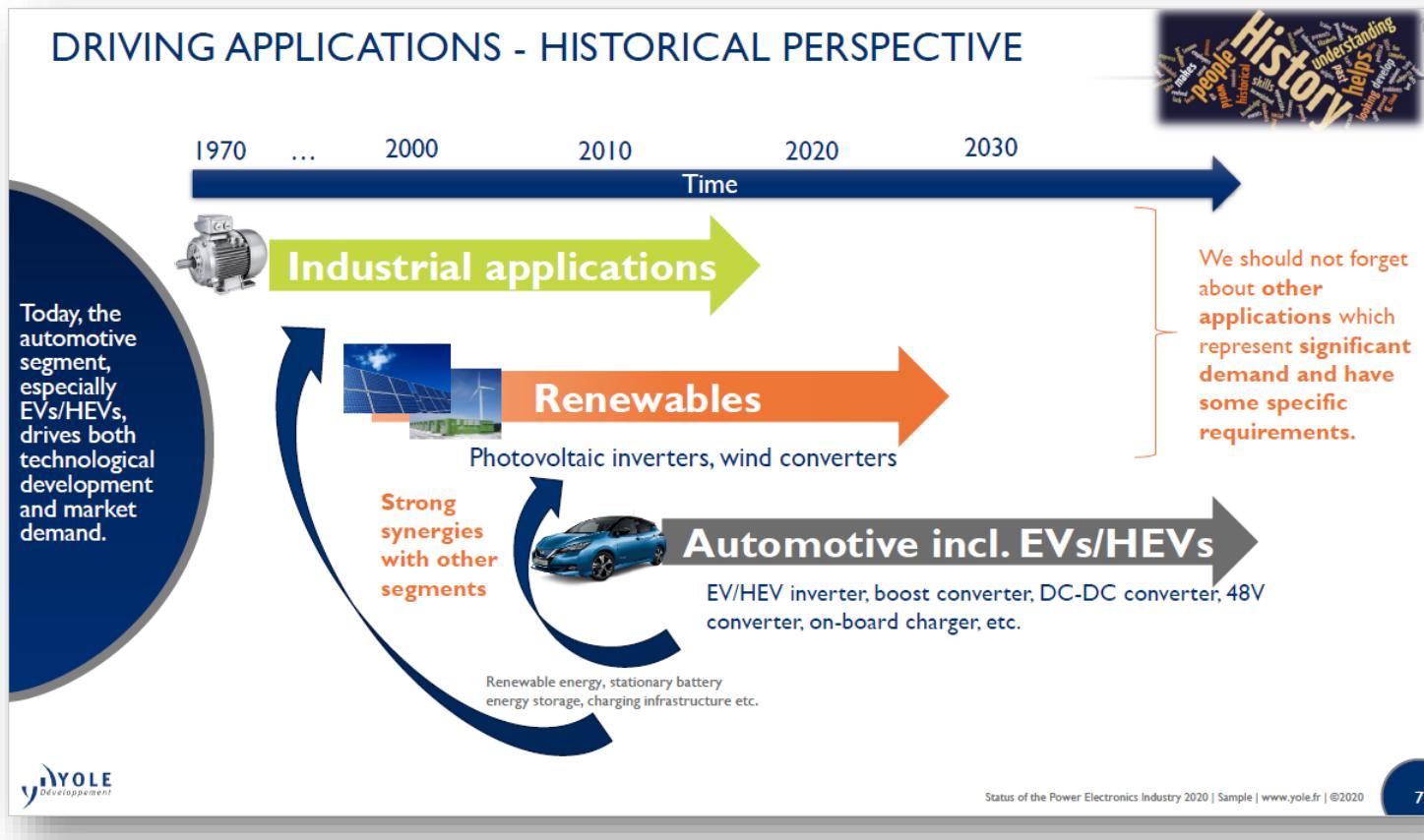
POWER ELECTRONICS DEVELOPMENT

MILESTONES

- Components
- Converters
- Systems
- Reliability



Driving Global Applications (last decades)



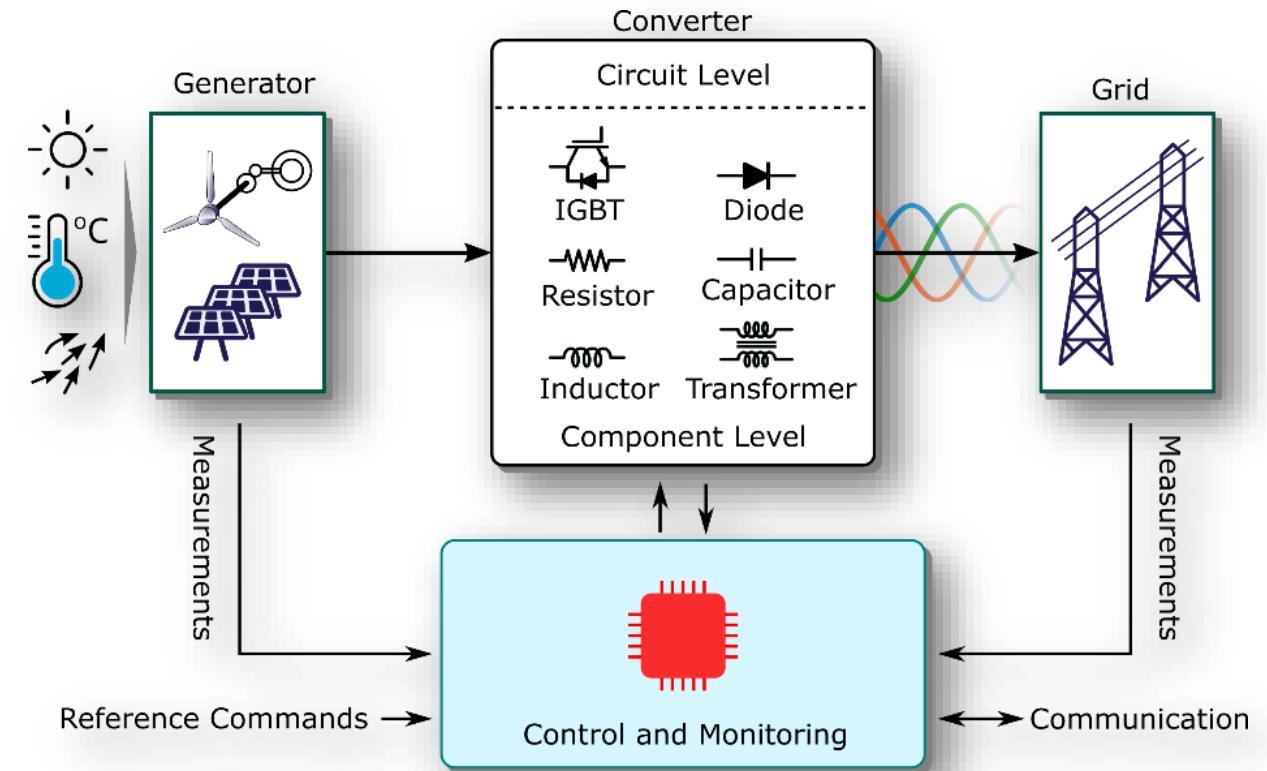
- Automotive segment is expected to drive the next decade development in Power Electronics

Source: Status of the Power Electronics Industry 2020, Yole Développement

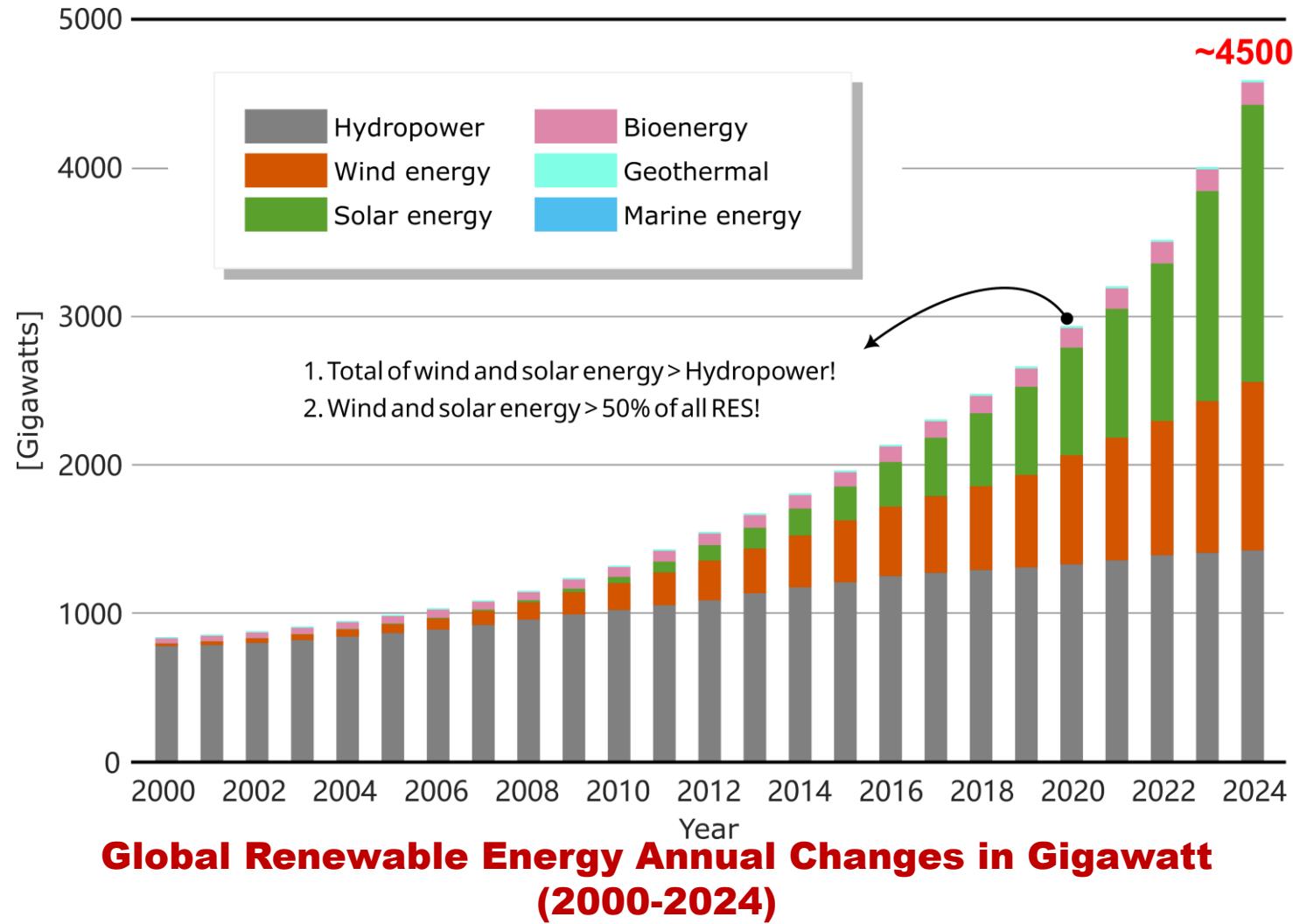
RENEWABLE ENERGY SYSTEM

OVERVIEW

- Various Demands for Grid-Connected Converters
 - GENERATION Power optimization (energy relying on ambient conditions)
 - CONVERSION
 - Reliable and secure power supply
 - Efficiency, cost, volume, etc.
 - Active & reactive power controllability
 - Fault handling capability
 - Communication
 - ...
 - LOAD/GGRID



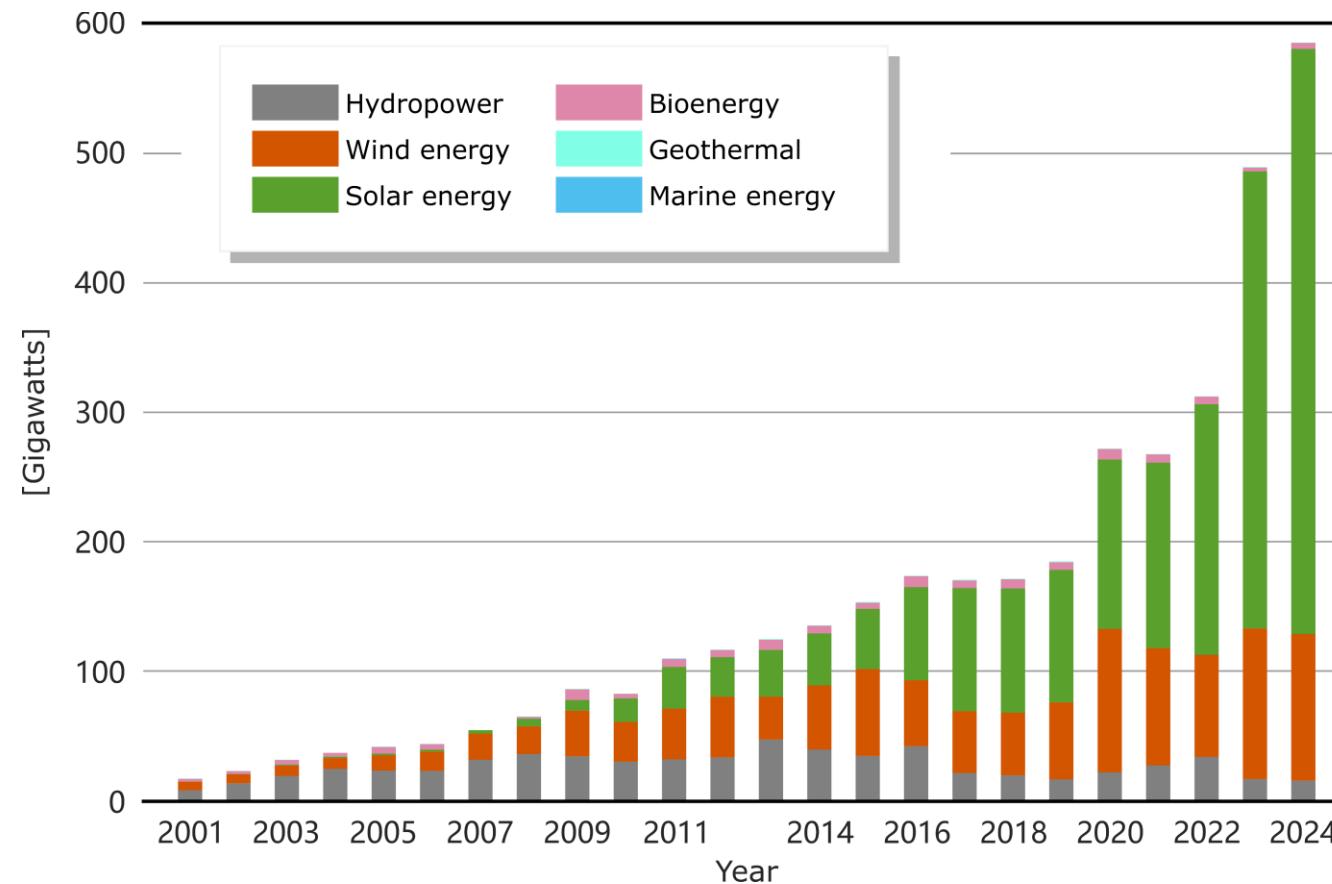
State of the Art – Renewable Evolution



(Source: IRENA, "Renewable capacity statistics 2024", <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>)

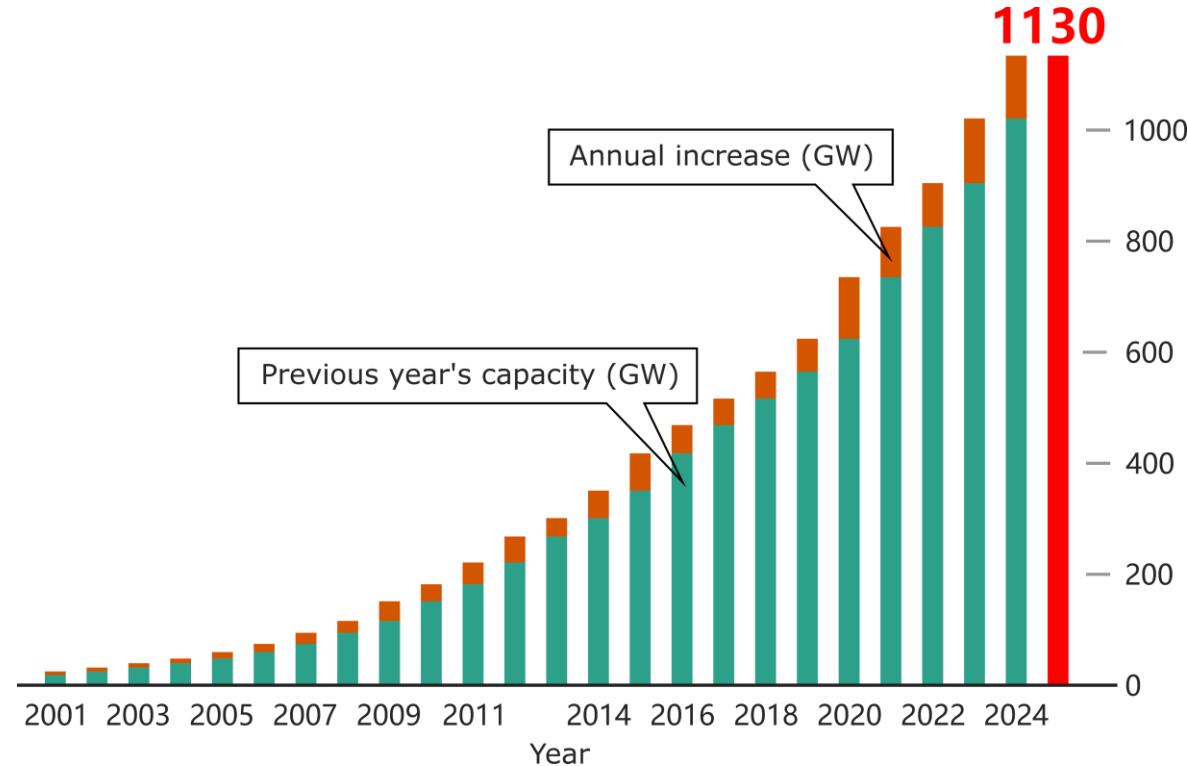
STATE-OF-THE-ART DEVELOPMENT

GLOBAL RES ANNUAL CHANGES



(Source: IRENA, "Renewable capacity statistics 2024", <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>)

State of the Art Development – Wind Power



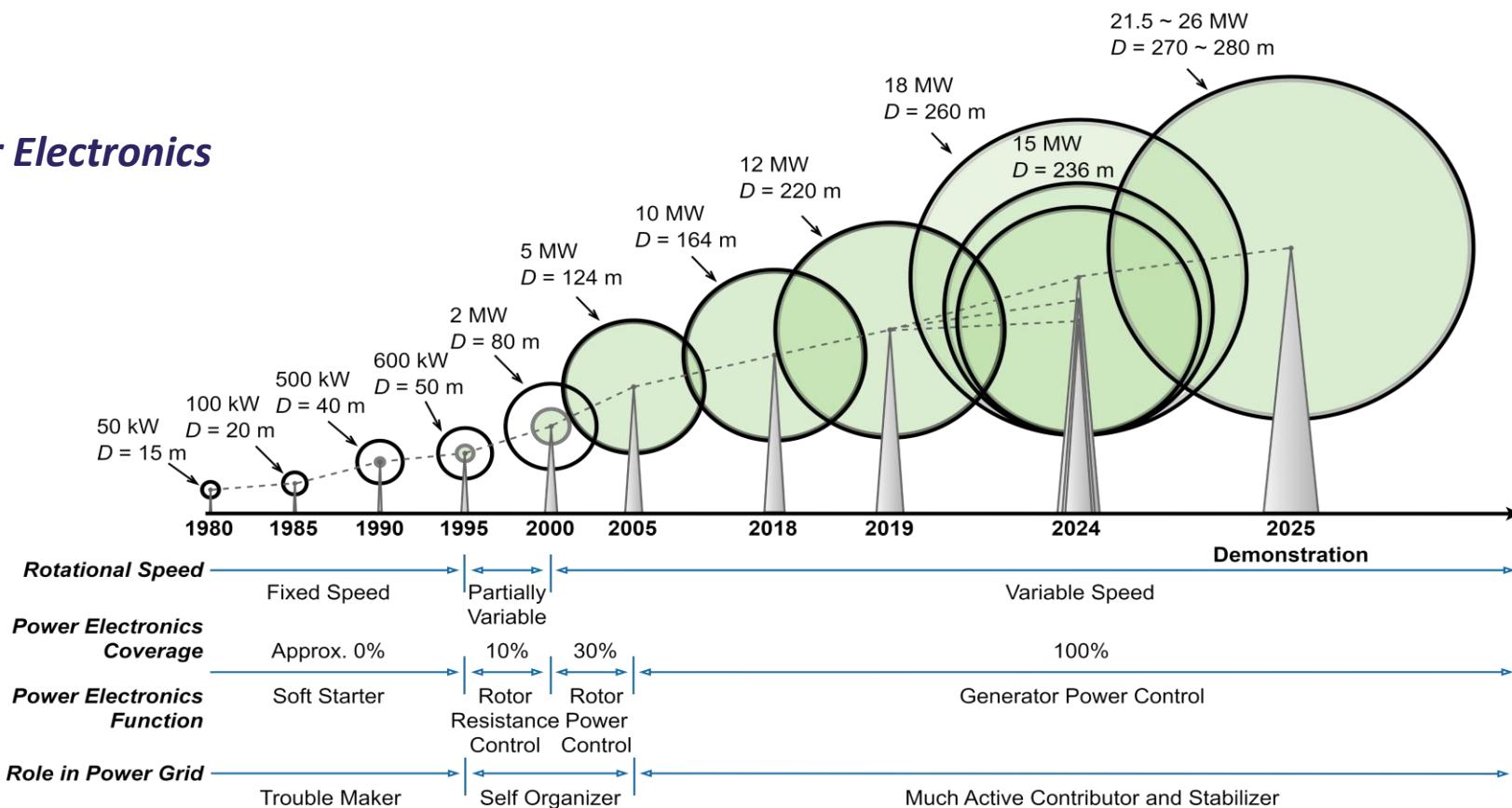
Global installed wind capacity (until 2024): **1020 GW**, 2024: **110 GW**

(Source: IRENA, "Renewable capacity statistics 2024", <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>)

STATE-OF-THE-ART DEVELOPMENT

WIND POWER

Enabled by Power Electronics



Global installed wind capacity (until 2024): **1020 GW**, 2024: **110 GW**

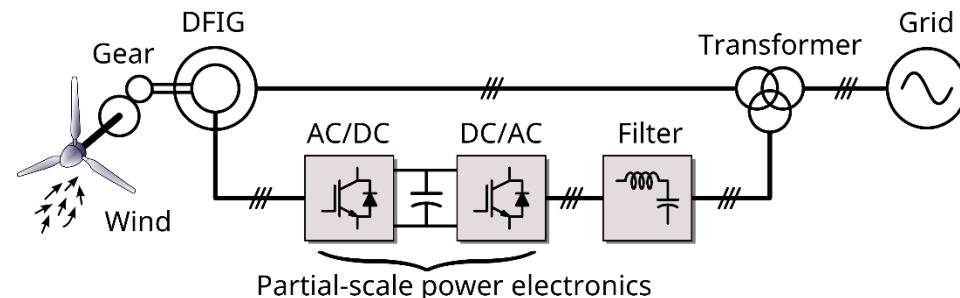
- Larger individual size (average 5 MW, up to 6-12 MW, +15 MW).
- More power electronics involved (up to 100 % rating coverage).

(Source: IRENA, "Renewable capacity statistics 2023", <https://www.irena.org/Publications/2023/Mar/Renewable-capacity-statistics-2023>)

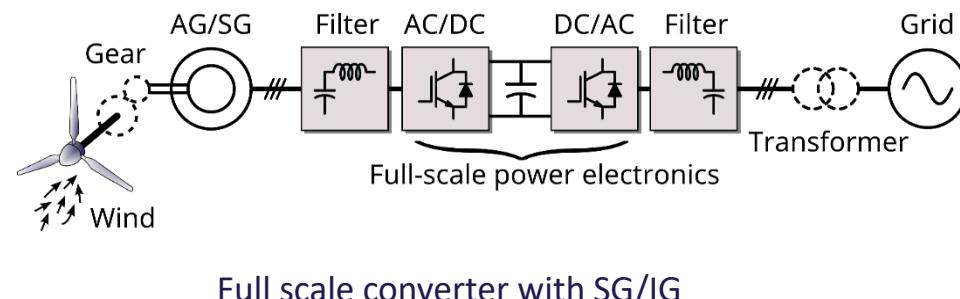
POWER CONVERTER CONFIGURATIONS

WIND TURBINE SYSTEM

Concept and Configurations



- ▶ Variable pitch – variable speed
- ▶ Doubly Fed Induction Generator
- ▶ Gear box and slip rings
- ▶ $\pm 30\%$ slip variation around synchronous speed
- ▶ Power converter (back to back/ direct AC/AC) in rotor circuit
- ✓ State-of-the-art solutions

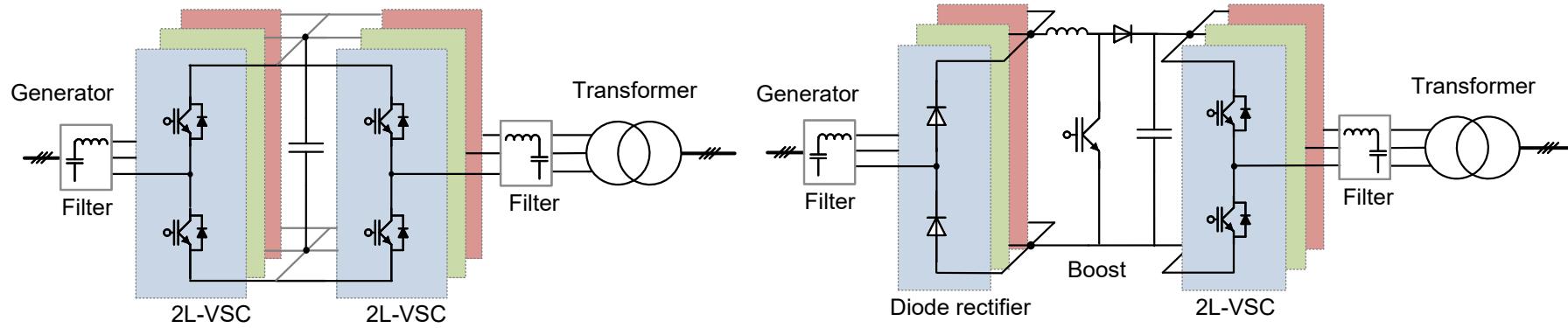


- ▶ Variable pitch – variable speed
- ▶ Generator
 - Synchronous generator
 - Permanent magnet generator
 - Squirrel-cage induction generator
- ▶ With/without gearbox
- ▶ Power converter
 - Diode rectifier + boost DC/DC + inverter
 - Back-to-back converter
 - Direct AC/AC (e.g. matrix, cycloconverters)
- ✓ State-of-the-art and future solutions

POWER CONVERTER CONFIGURATIONS

WIND TURBINE SYSTEM

Topologies under low voltage (<690V)



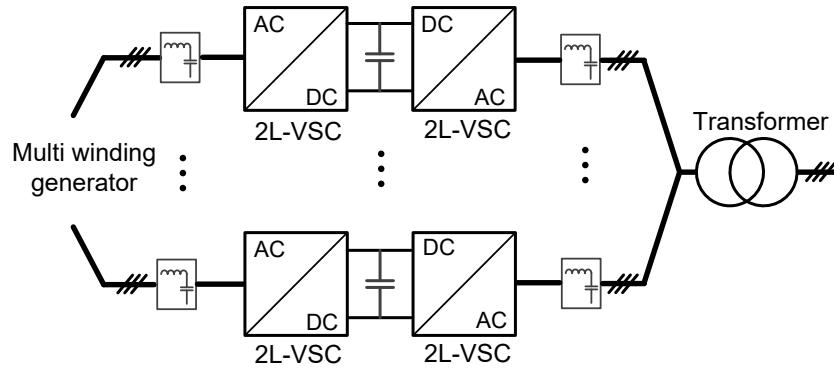
Back-to-back two-level VSC

- Proven technology
- Standard power devices (integrated)
- Decoupling between grid and generator (compensation for non-symmetry and other power quality issues)
- High dv/dt and bulky filter
- Need for major energy-storage in DC-link
- High power losses at high power (switching and conduction losses) → low efficiency

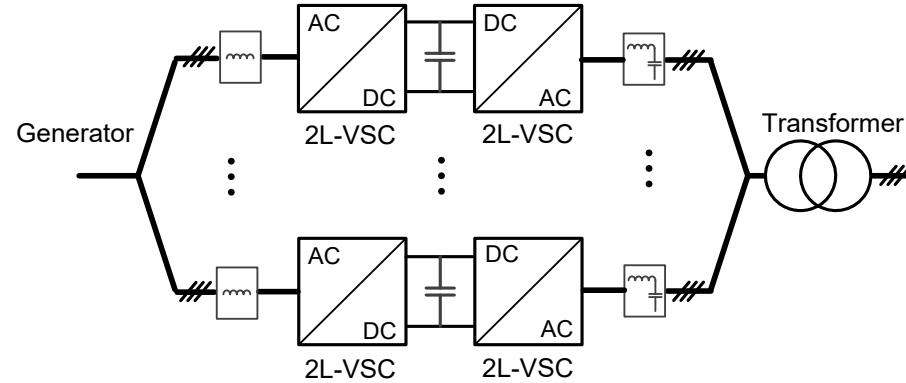
Diode rectifier + boost DC/DC + 2L-VSC

- Suitable for PMSG or SG.
- Lower cost
- Low THD on generator, low frequency torque pulsations in drive train.
- Challenge to design boost converter at MW.

Solution to extend the power capacity (Multi-MW)



Variant 1 with multi-winding generator.



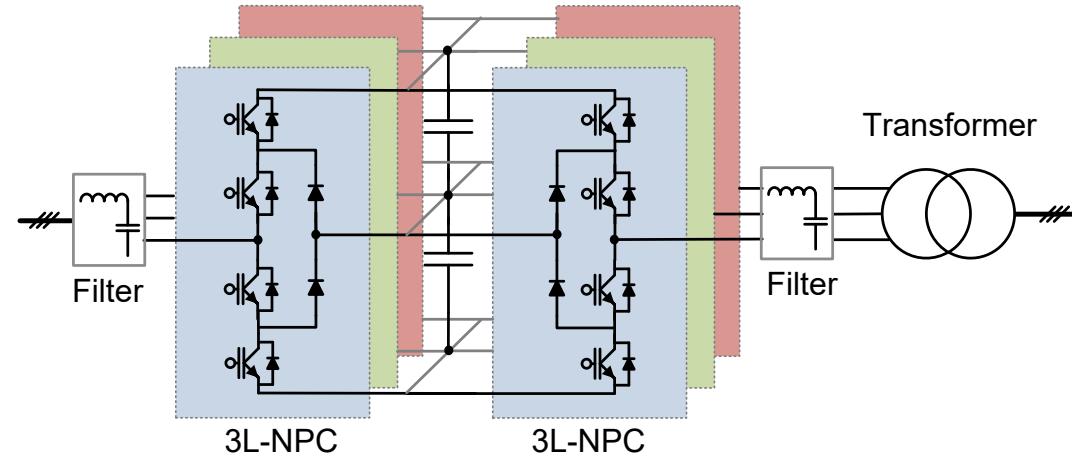
Variant 2 with normal winding generator

Parallel converter to extend the power capacity

- State-of-the-art solution in industry (>3MW)
- Standard and proven converter cells (2L VSC)
- Redundant and modular characteristics.
- Circulating current under common DC link with extra filter or special PWM

Multi-level converter topology – 3L-NPC

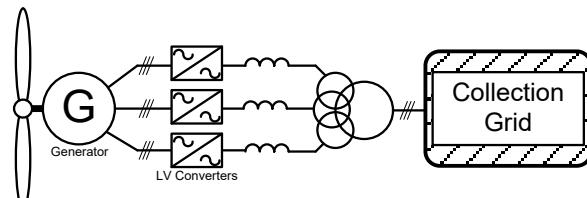
Topology above 690V



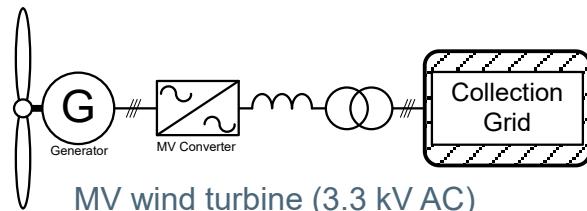
- Most commercialized multi-level topology.
- More output voltage levels → Smaller filter
- Higher voltage, and larger output power with the same device rating
- Possible to be configured in parallel to extend power capacity.
- Unequal losses on the inner and outer power devices → derated converter power capacity
- Mid-point balance of DC link – under various operating conditions.

Future generation of HV wind turbine

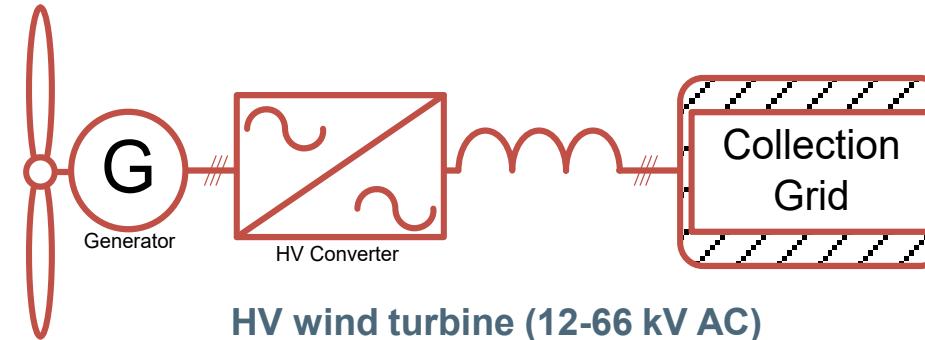
- **Features:**
 - Transformer-less operation
 - Low cooling system requirements
 - Less copper required
- **Challenges:**
 - Reliable insulation systems
 - Short circuit protection
 - Safety



LV wind turbine (0.69 kV AC)



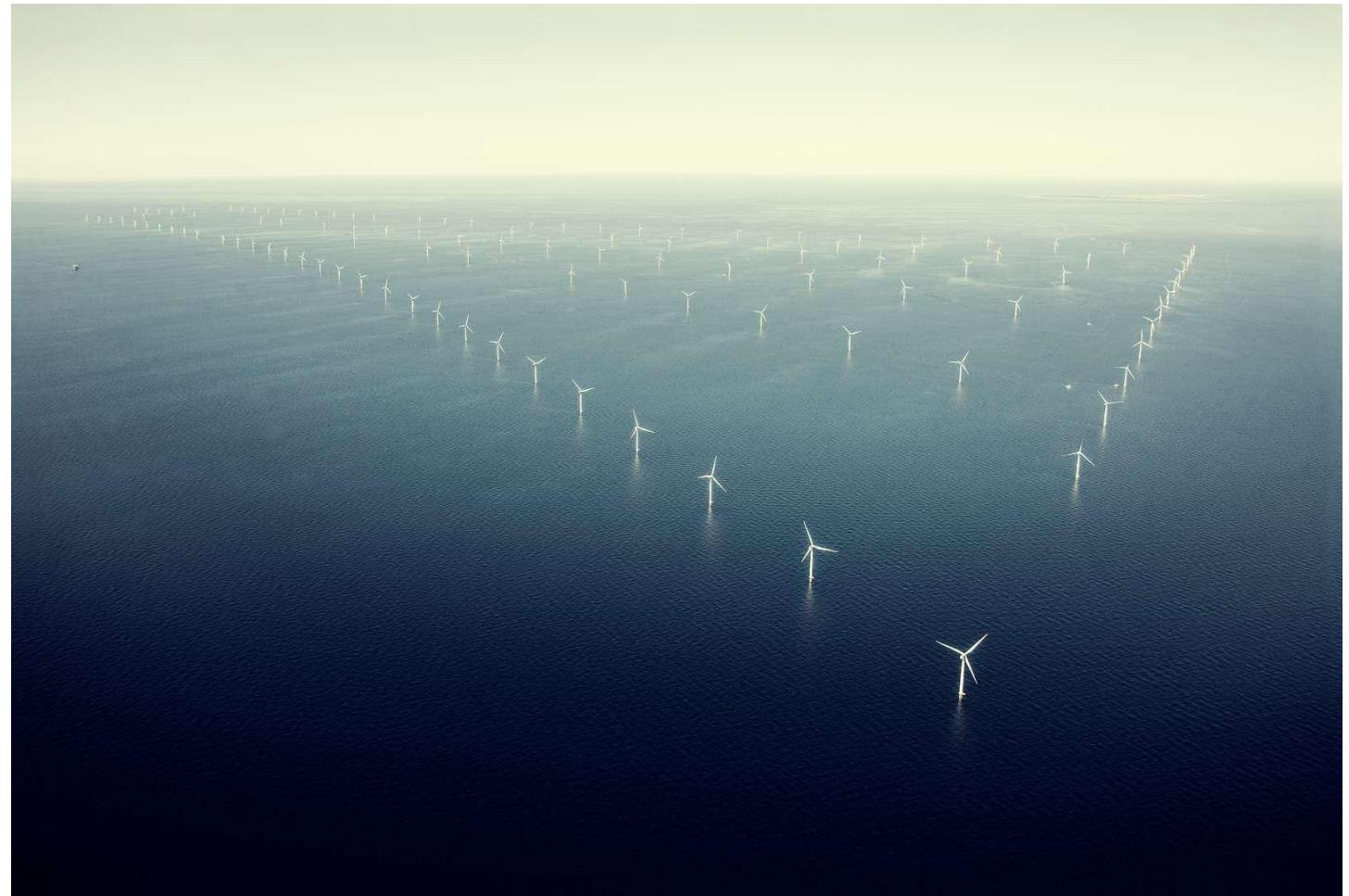
MV wind turbine (3.3 kV AC)



HV wind turbine (12-66 kV AC)

WIND POWER SYSTEMS

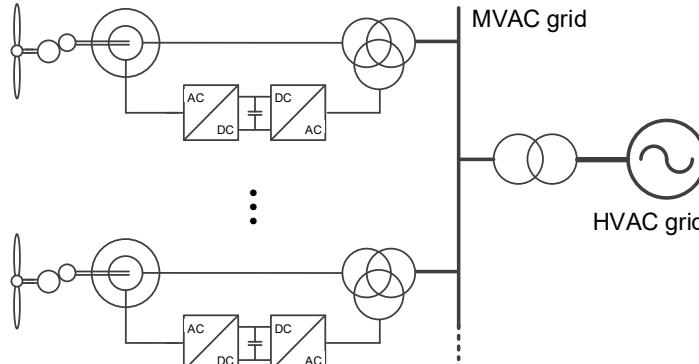
400 MW OFFSHORE –
TOWARDS +GW



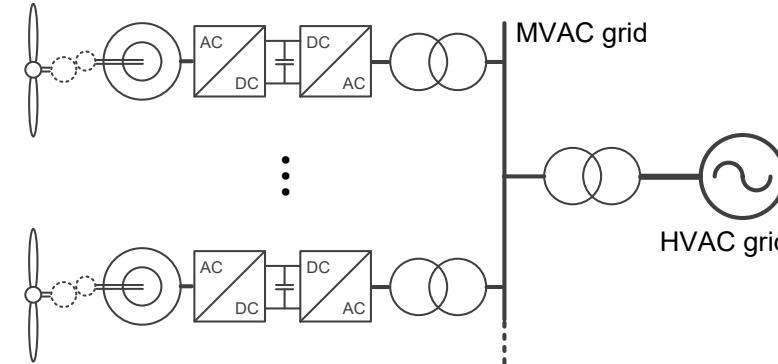
Anholt-DK (2016) - Ørsted

Wind farm with AC and DC power transmission

HVAC power transmission

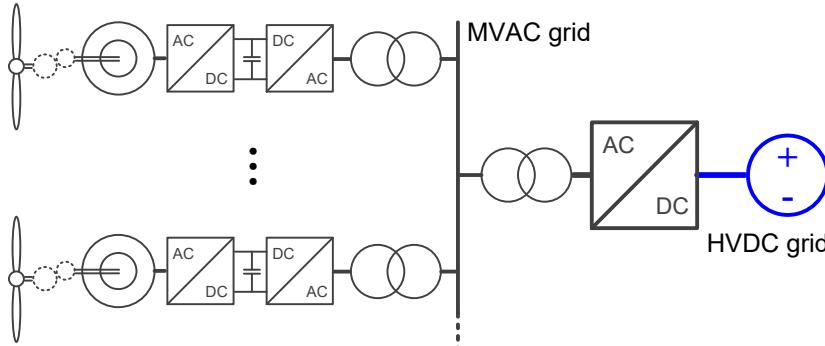


Partial-scale converter system

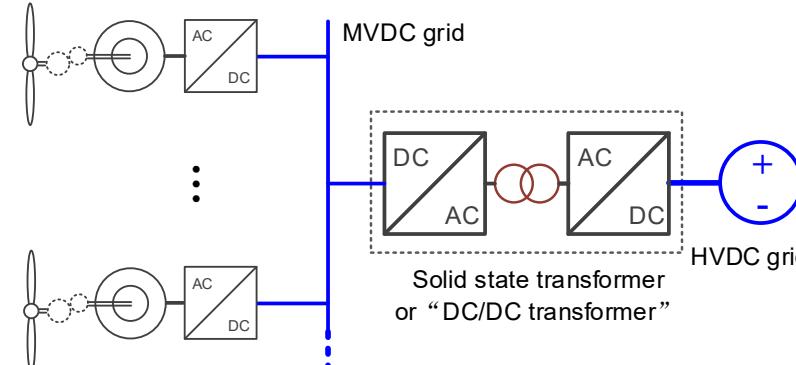


Full-scale converter system

HVDC power transmission

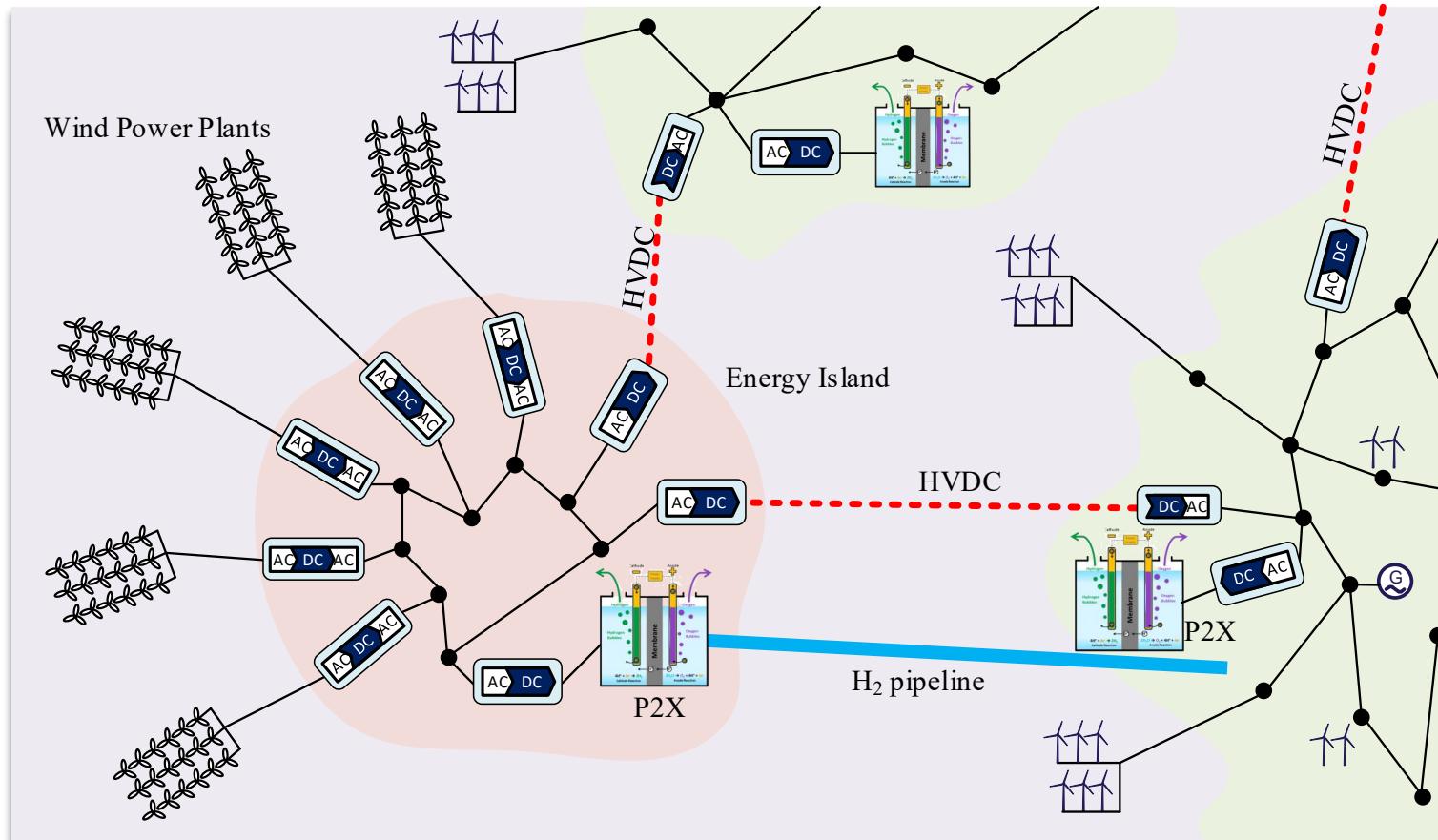


DC transmission grid



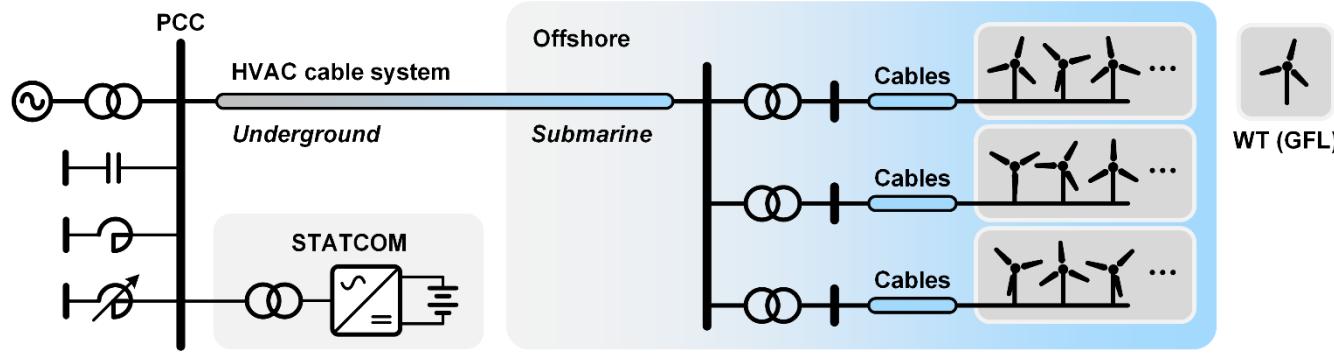
DC distribution & transmission grid

Concept of Offshore Energy Islands



- **Bornholm Energy Island** will serve as a hub for offshore wind farms off the coast supplying 3 GW of energy.
- An **Artificial Island in the North Sea** will serve as a hub for offshore wind farms supplying 3-4 GW of energy, with a long-term expansion of 10 GW.

Wind farm with STATCOM



STATCOM provides dynamic reactive power compensation, which helps to meet grid codes at the onshore PCC (e.g., voltage stability, FRT, harmonics)



An application example:

- Westermost Rough Offshore Wind Farm, UK
- 35×6 MW WTs (210 MW)
- ABB PCS6000 STATCOM ($\pm 25 \times 2$ MVA)
- Switched shunt reactor (50 MVA)
- 20 km cables (8 km submarine)

(Source: ABB, "Application note, ABB STATCOMs help fulfill the Grid Code of the Westermost Rough offshore wind farm, UK." https://library.e.abb.com/public/01ef81bd23194aa79d699a72f6ccd21a/ABB_Westermost_reference_STATCOM.pdf)

Sustainability of Renewable Technology (From Vestas)

Key Sustainability Figures V163-4.5 MW™

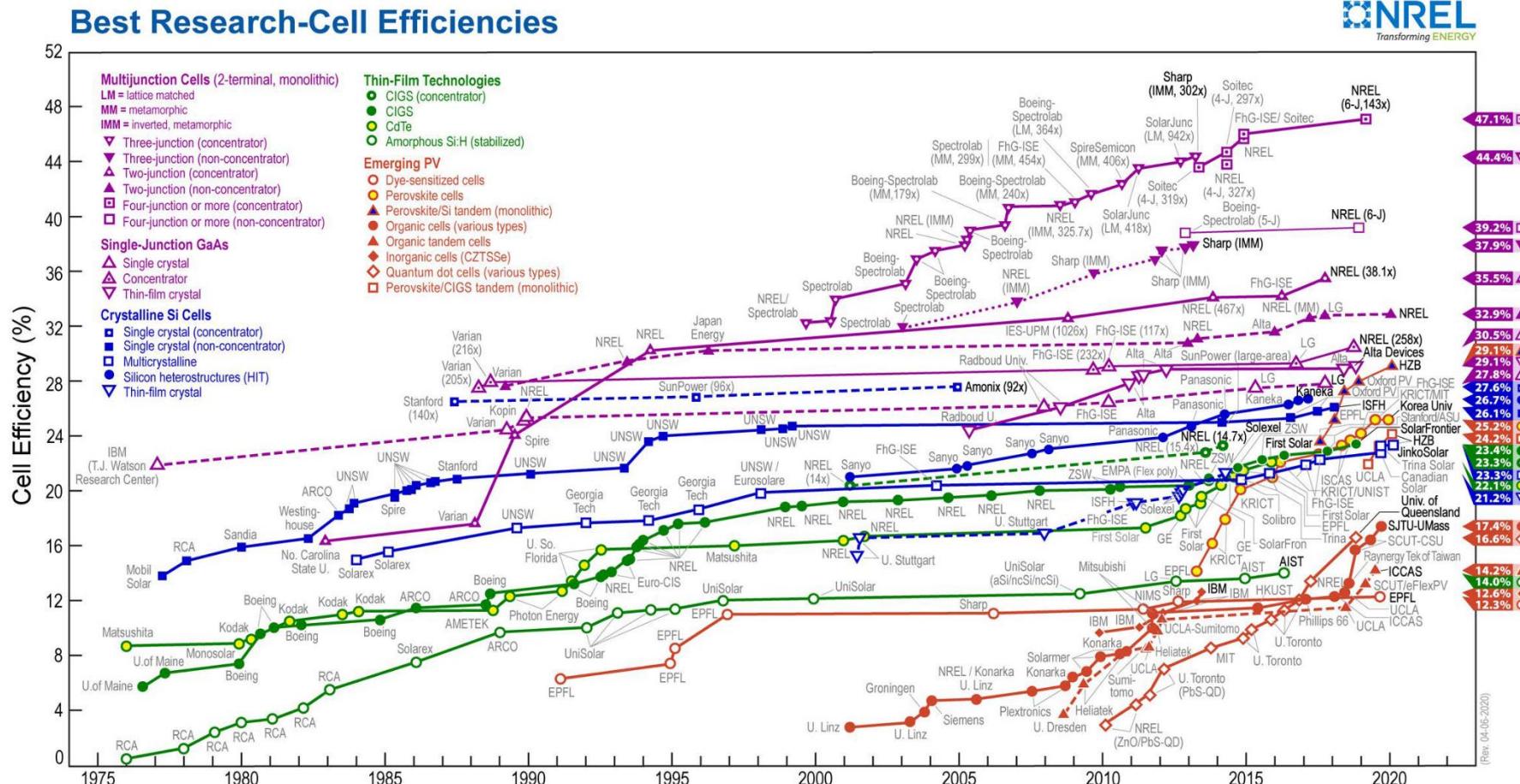


Wind plant specifications	
Wind turbine model	V163-4.5 MW™
Power rating	4.5 MW
Lifetime	20 years
Hub height	98 metres
Wind Class	IEC 5
Wind Speed	7.9 m/s
Annual Energy Production	22032 MWh
Foundation type	Low ground water level (LGWL)
Plant size	99 MW
Plant location	United States
Production location	Global average



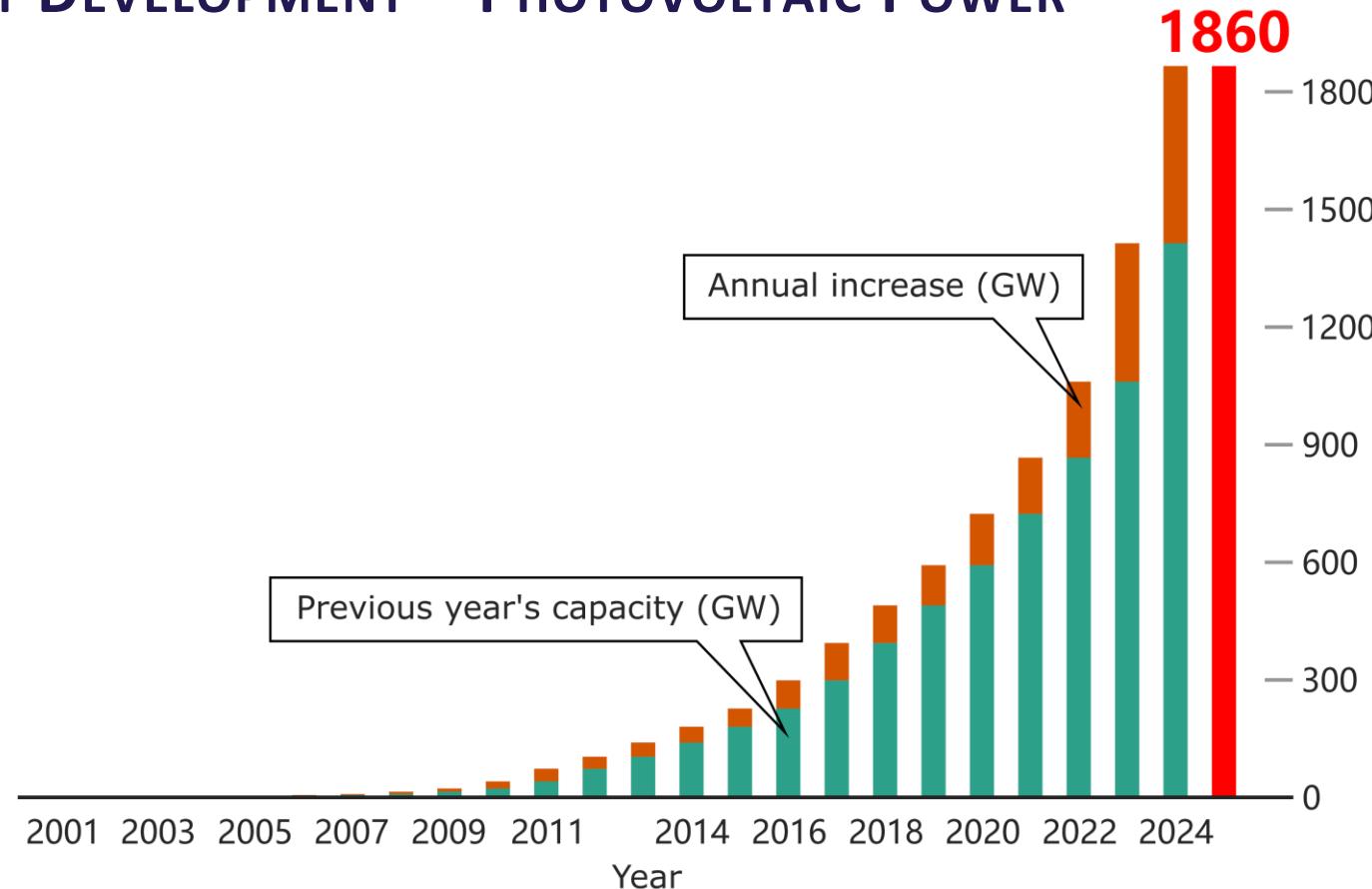
STATE-OF-THE-ART DEVELOPMENT

PV CELL TECHNOLOGIES



National Renewable Energy Laboratory, <https://www.nrel.gov/pv/cell-efficiency.html>

STATE-OF-THE-ART DEVELOPMENT – PHOTOVOLTAIC POWER



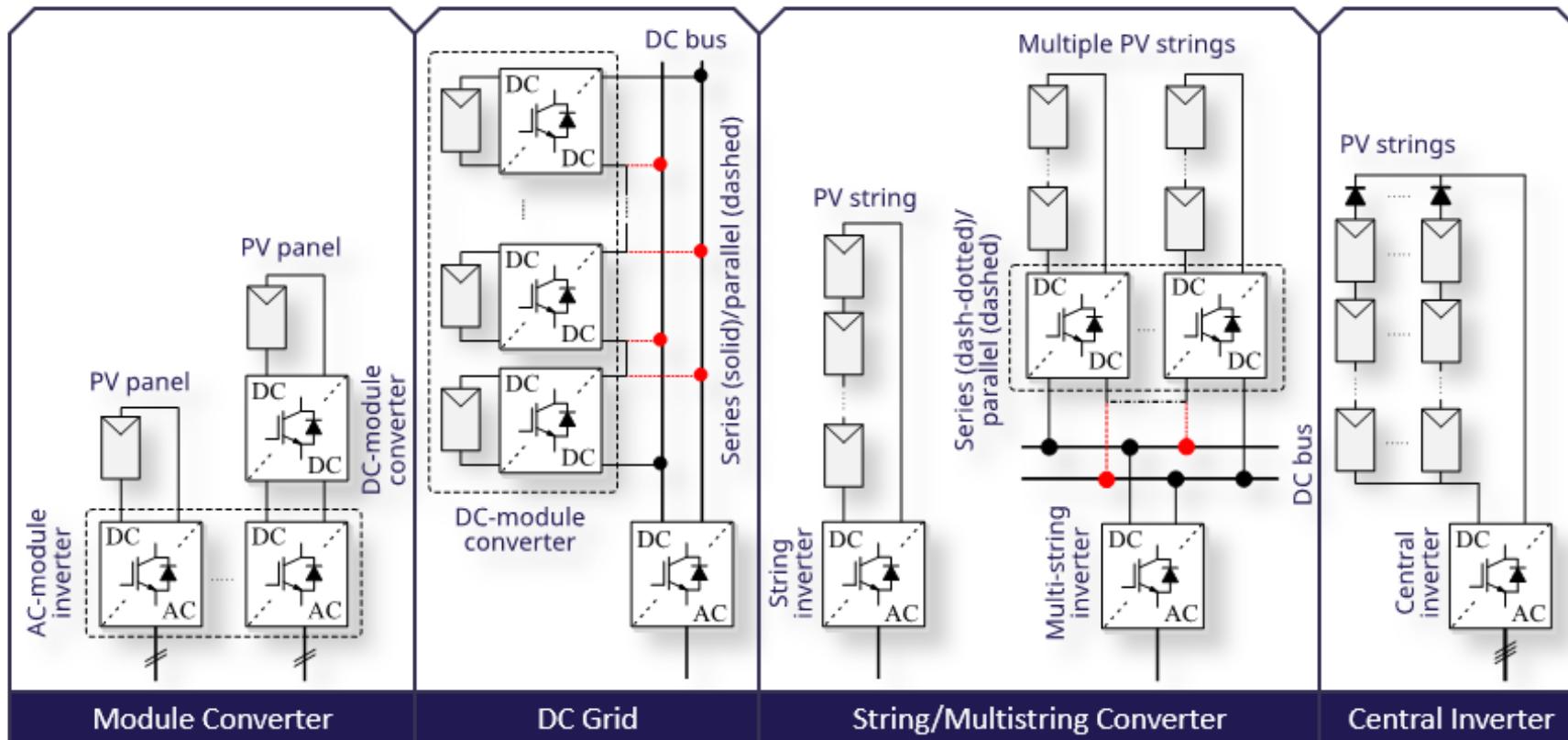
Global installed solar PV capacity (until 2024): **1420 GW**, 2024: **440 GW**

(Source: IRENA, "Renewable capacity statistics 2024", <https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024>)

POWER CONVERTER CONFIGURATIONS

PV INVERTER

Overview



- Single-phase
- Hundreds watts
- Small systems

- DC grid → AC grid
- Single-/three-phase
- Several kilowatts
- Small systems / residential

- Single-/three-phase
- 1~30 kW applications
- Residential/commercial

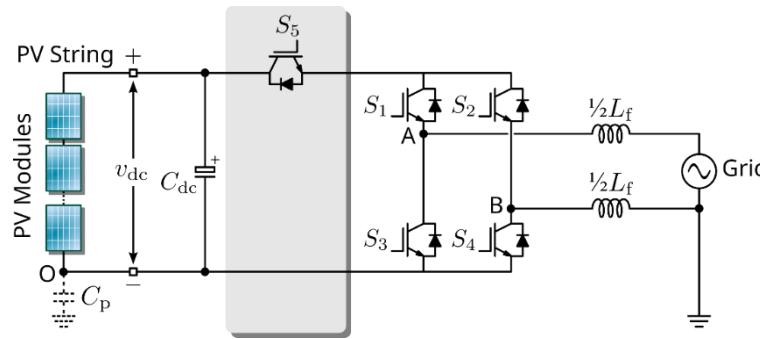
- Three-phase
- 30~ kW
- Commercial / utility-scale

POWER CONVERTER CONFIGURATIONS

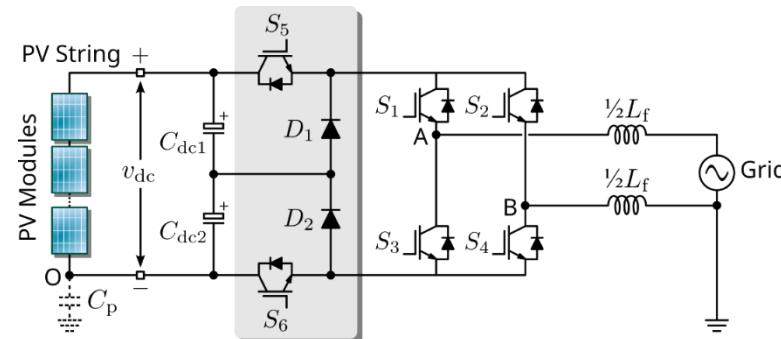
PV INVERTER

Transformer-less String Inverters

H5 Transformerless Inverter (SMA)



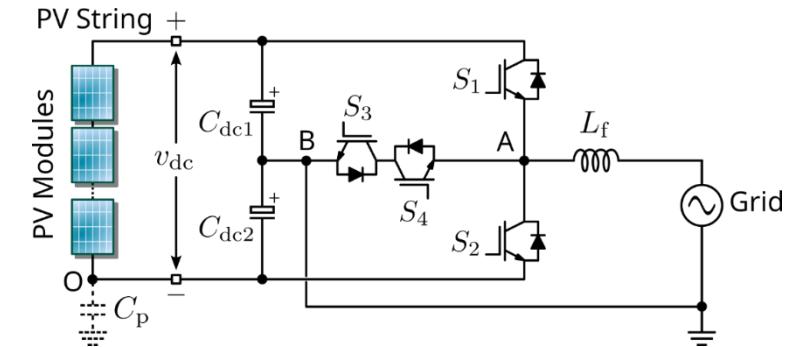
H6 Transformerless Inverter (Ingeteam)



- Efficiency of up to 98%
- Low leakage current and EMI
- Unipolar voltage across the filter, leading to low core losses

- High efficiency
- Low leakage current and EMI
- DC bypass switches rating: $V_{dc}/2$
- Unipolar voltage across the filter

Neutral Point Clamped (NPC) converter for PV applications



- Constant voltage-to-ground → Low leakage current, suitable for transformer-less PV applications.
- Less filtering effort

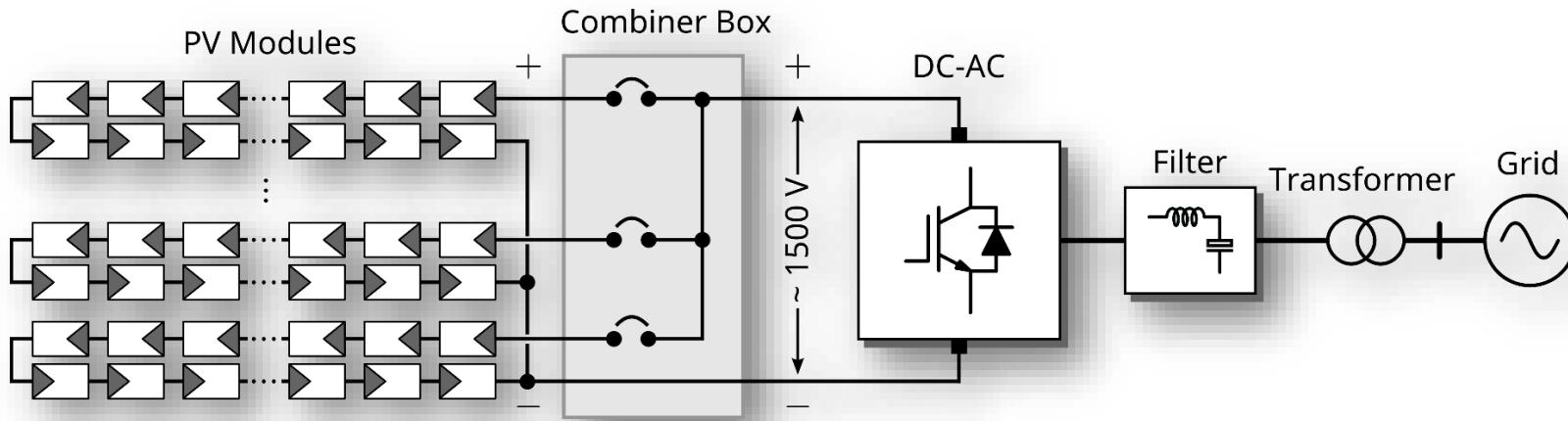
M. Victor, F. Greizer, S. Bremicker, and U. Hubler, U.S. Patent 20050286281 A1, Dec 29, 2005.

R. Gonzalez, J. Lopez, P. Sanchis, and L. Marroyo, "Transformerless inverter for single-phase PV systems," IEEE TPEL, 2007.

P. Knaup, International Patent Application, Publication Number: WO 2007/048420 A1, Issued May 3, 2007.

1500-V DC PV System

A mainstream solution!

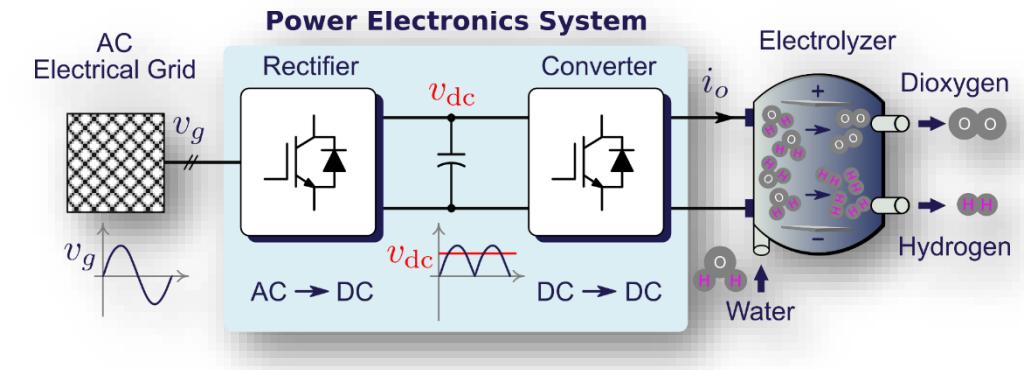
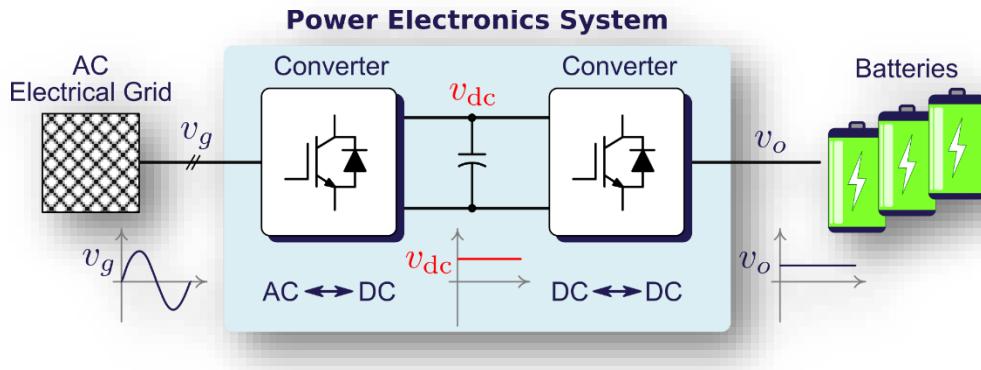
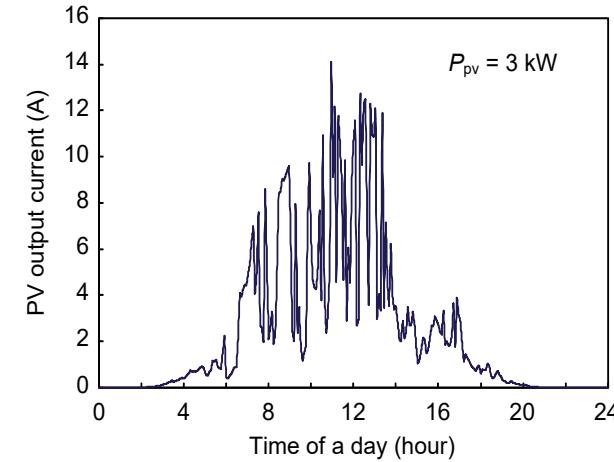


- Decreased requirement of the balance of system (e.g., combiner boxes, DC wiring, and converters) and Less installation efforts
- Contributes to reduced overall system cost and increased efficiency
- More energy production and lower cost of energy
- **Electric safety and potential induced degradation**
- **Converter redesign – higher rating power devices**

ENERGY STORAGE – SYSTEM INTEGRATION

WEATHER DEPENDENT VARIABILITY

Matching the inherent **weather-dependent variability** of renewable energy generation with the load demand in modern power systems and the smart grid remains a major challenge. This general problem benefits of great attention and sustained research programs with emphasis on both **power electronics** and **energy storage** devices and systems.

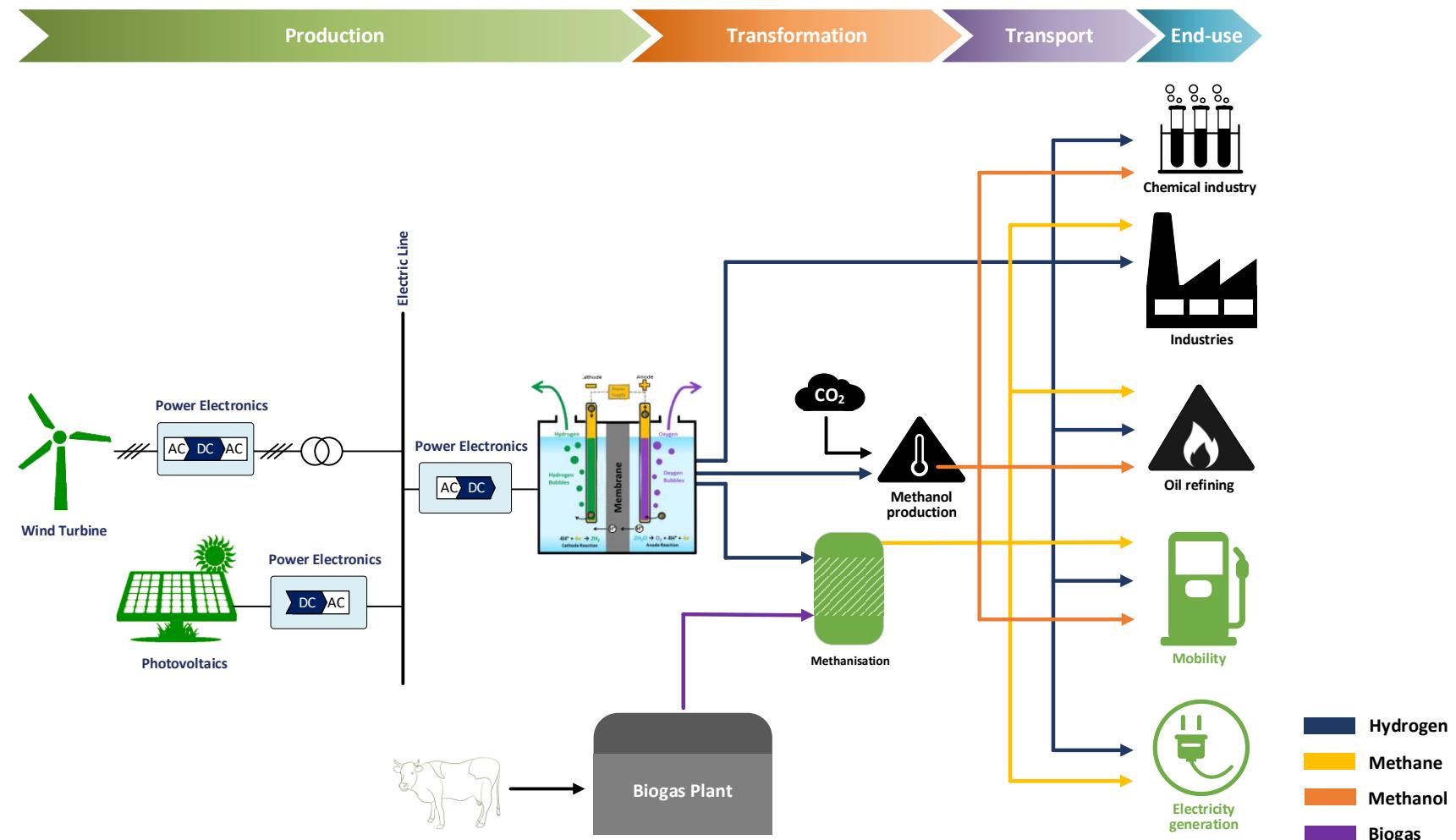


STATE-OF-THE-ART DEVELOPMENT

POWER-TO-X

Enabled by Power Electronics

- Green Hydrogen is key to reduce emissions

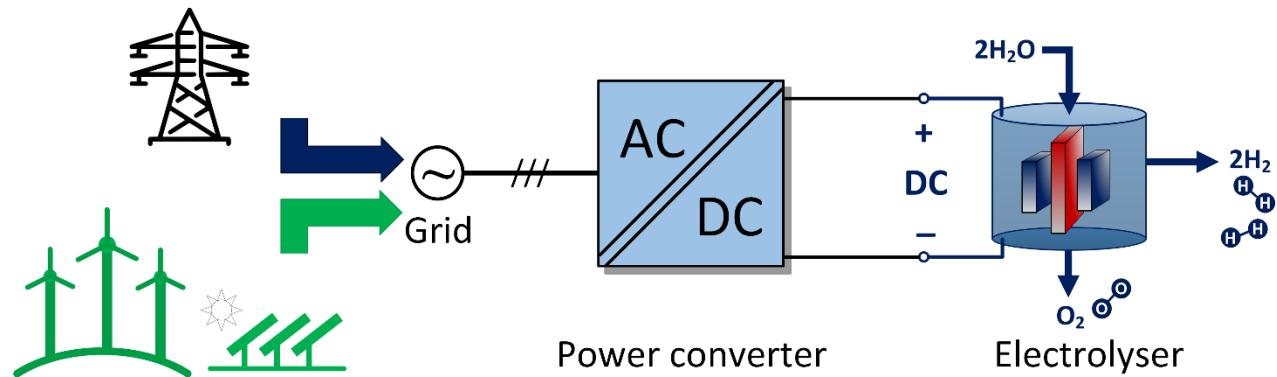


(Source: Chen, M., Chou, S. F., Blaabjerg, F. & Davari, P. Overview of Power Electronic Converter Topologies Enabling Large-Scale Hydrogen Production via Water Electrolysis. *Appl. Sci.* 12, 2022.

POWER CONVERTER SPECIFICATION

ELECTROLYSIS (HYDROGEN PRODUCTION)

General Requirements



Requirements

- Input Voltage: 0.4 – 35 kV
- Output Voltage: 350 – 1000V
- Output Current: 1- 15 kA
- Output Power: 0.1 – 15 MW
- Galvanic Isolation
- Controllability: Output Current/Voltage
- PF > 0.9
- THDi:
 - < 30% (small systems)
 - < 5% (large systems)

Challenges!

- High efficiency (> 98%)
- Load dependent THDi & PF
- Scalability
- Large size (multi-pulse transformers)
- Reliability
- 15% < Output power < 100%

(Source: Chen, M., Chou, S. F., Blaabjerg, F. & Davari, P. Overview of Power Electronic Converter Topologies Enabling Large-Scale Hydrogen Production via Water Electrolysis. *Appl. Sci.* 12, 2022.

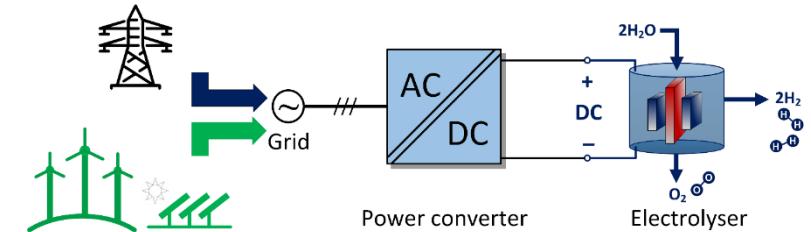
POWER CONVERTER SPECIFICATION

ELECTROLYSIS (HYDROGEN PRODUCTION)

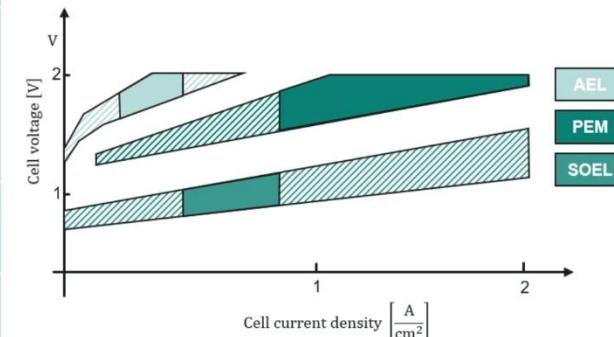
Technologies

Electrolyzer technologies

	Alkaline	PEM	SOEC
Technology	Alkaline	Proton Exchange Membrane	Solid Oxide Electrolyzer
Market share	75%	20%	5%
Operating temperature	Ambient – 120°C	Ambient – 90°C	600-800°C
Load dynamics	Weak	Good Allows high power and current density	Medium High operation temperatures
Efficiency ¹⁾	53-70%	62-74%	75-79%



Electrical cell characteristics



public

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Infineon Proprietary

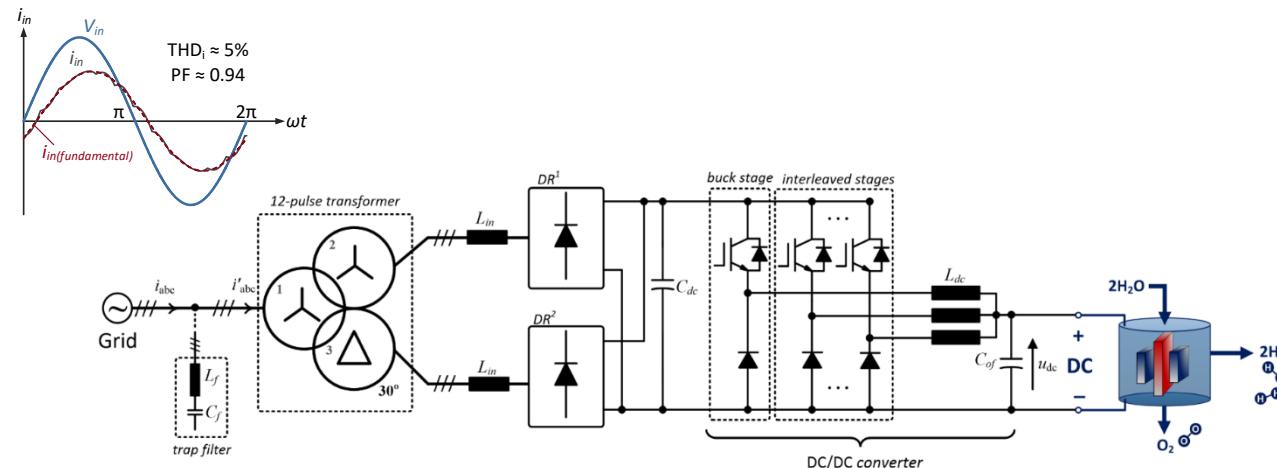
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(Source: Chen, M., Chou, S. F., Blaabjerg, F. & Davari, P. Overview of Power Electronic Converter Topologies Enabling Large-Scale Hydrogen Production via Water Electrolysis. Appl. Sci. 12, 2022.

POWER CONVERTER TOPOLOGY

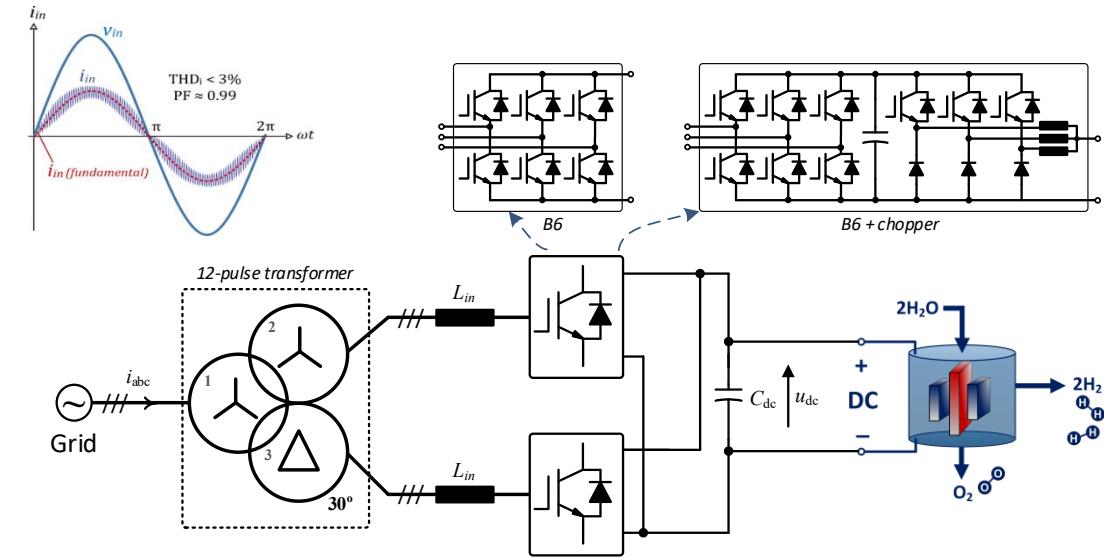
ELECTROLYSIS (HYDROGEN PRODUCTION)

Diode Rectifier with Multiple Chopper (12-DRMC):



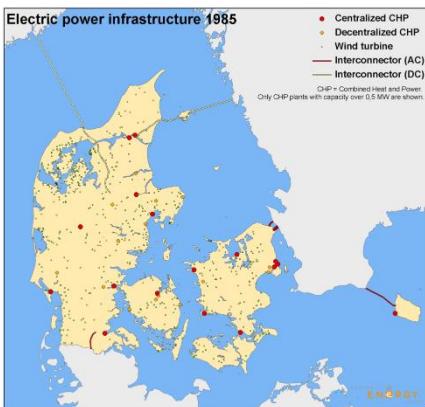
- + Low complexity
- + Reliable
- + Moderate efficiency
- + High power factor
- + Input current quality improvement
 - Adding trap filters
 - Using 18-pulse, 24-pulse transformers

- Bulky transformer
- Bulky DC-link capacitor (for ripple reduction)
- Not scalable for different stack sizes
- Adding trap filter further increase size and loss



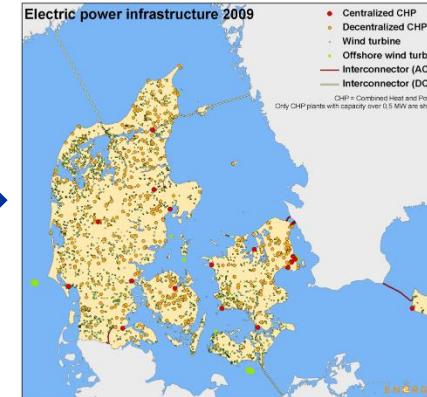
- + Either boost or buck capability
- + Moderate power density
- + THD < 5%
- + PF ≈ 0.99
- High control complexity
- Efficiency (lower than passive methods)
- Bulky Transformer
- High component counts

TRANSITION OF POWER SYSTEM



(Source: Danish Energy Agency)

from **Central to De-central** Power Generation



(Source: Danish Energy Agency)



Source: <http://electrical-engineering-portal.com>

from **large synchronous generators** to
more power electronic converters

**Towards 100% Power
Electronics Interfaced**

Integration to electric grid
Power transmission
Power distribution
Power conversion
Power control



Source: <http://media.treehugger.com>



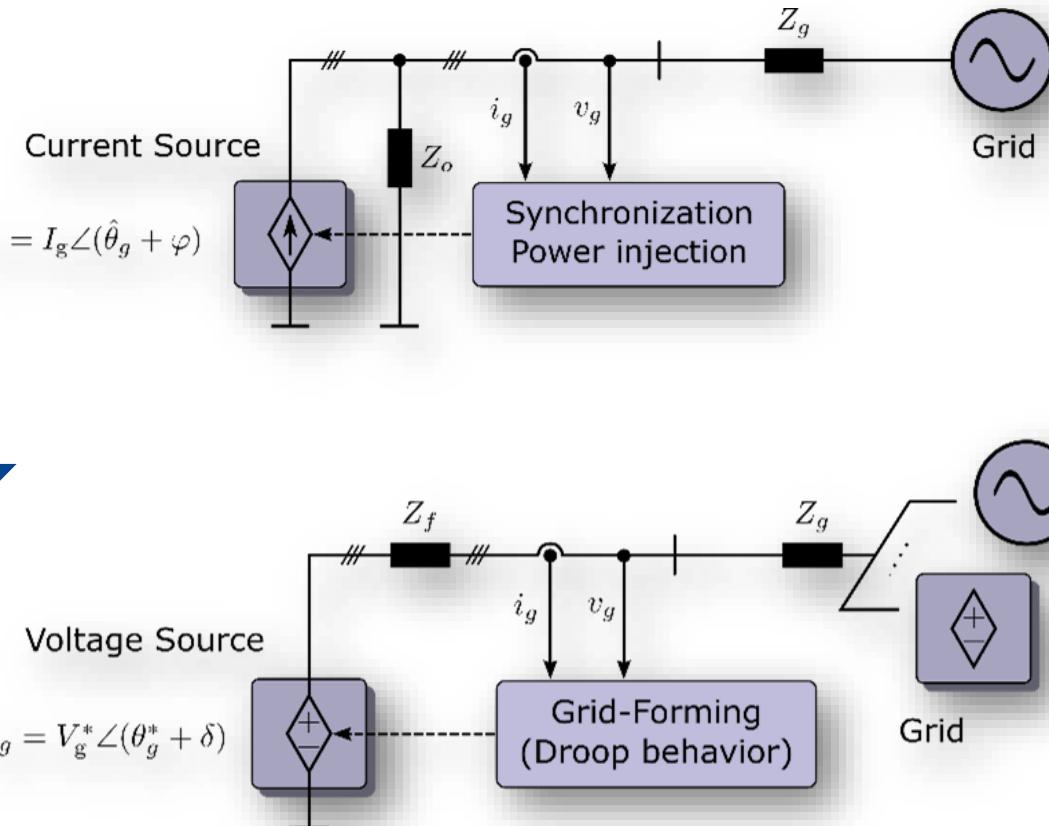
Source: www.offshorewind.biz

RENEWABLE INTEGRATION – GRID OPERATION

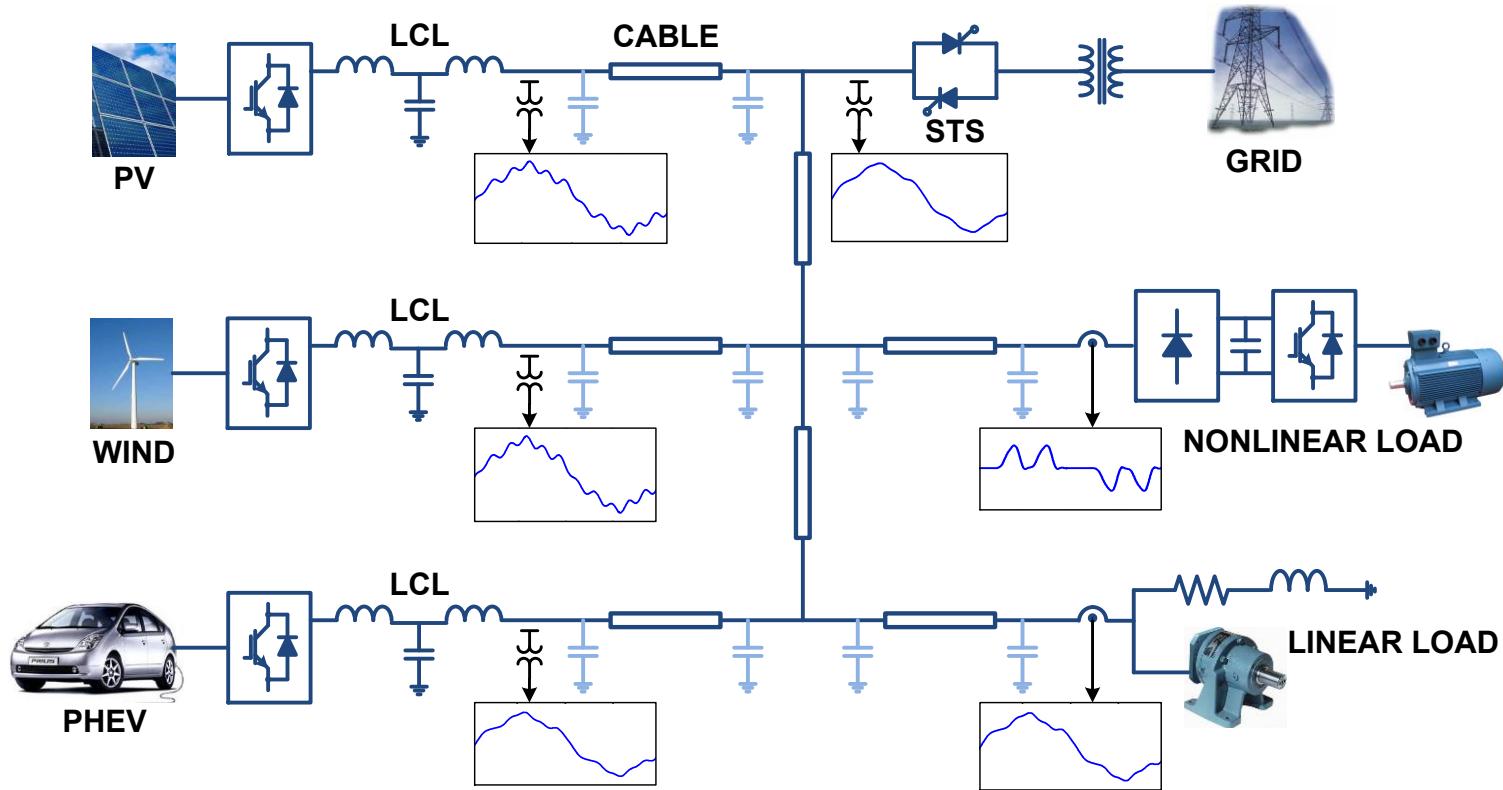
SYNCHRONOUS GENERATORS ARE PHASED OUT

- From Grid-Following to Grid-Forming
 - ▷ Droop control
 - ▷ Virtual synchronous generator/machine
 - ▷ Virtual oscillator control
 - ▷ Power synchronization
 - ▷ ...

Make Power Converters
Have/Emulate Characteristics of
Synchronous Generators

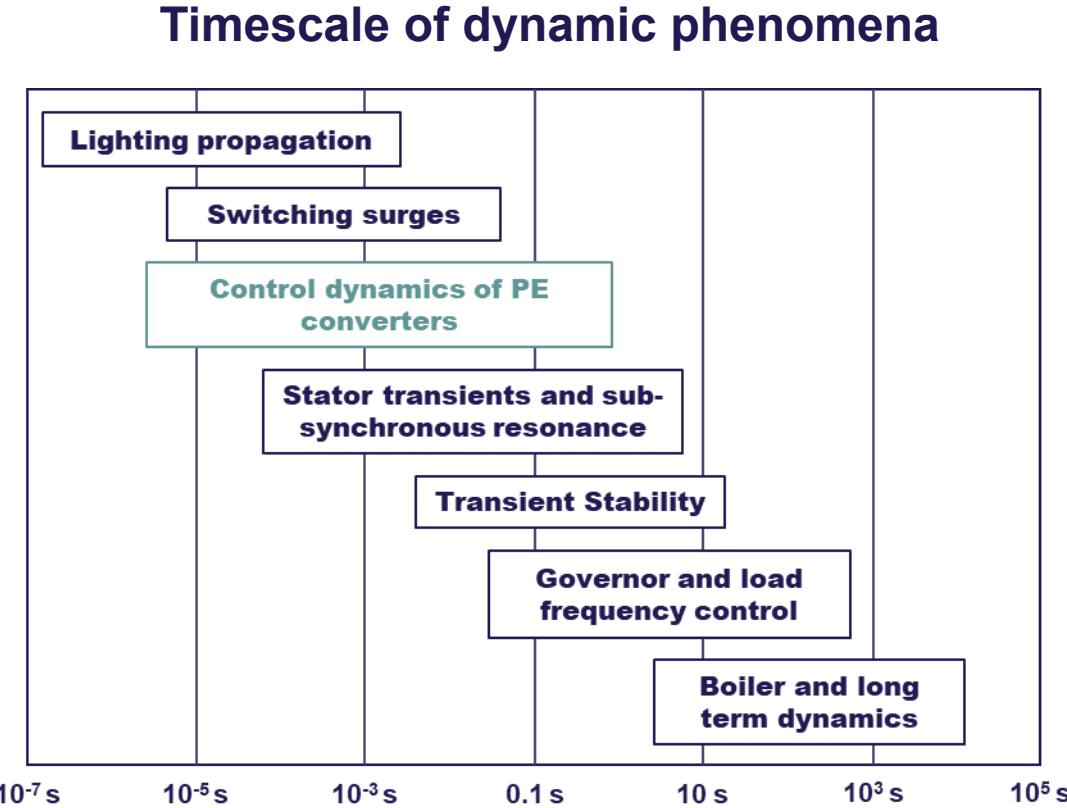
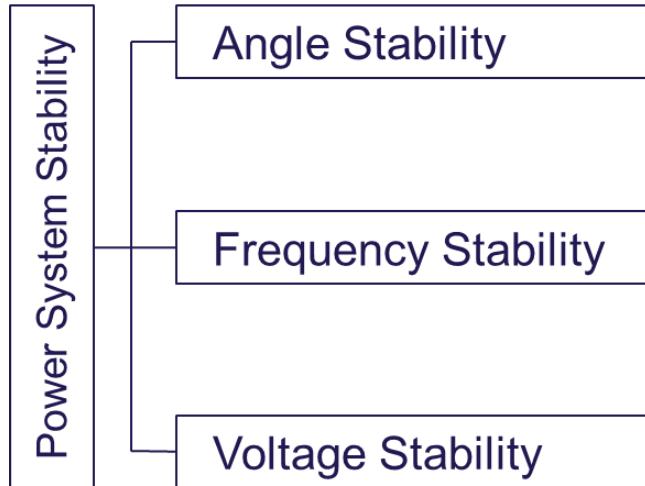


Power Electronic Based Power System Stability



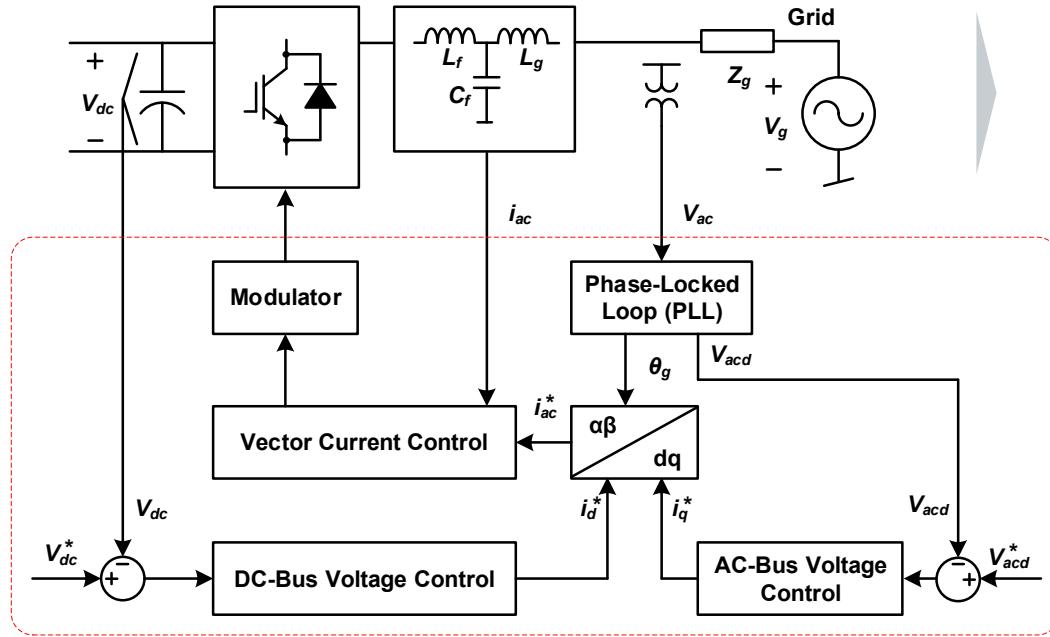
- ▶ **Multiple resonance** frequencies in LCL-filters and power cables
- ▶ **Dynamic coupling** of multiple converters through the grid impedance
- ▶ Interactions of harmonic and inter-harmonic components - **harmonic instability**

Power Electronic Based Power System Stability



Grid-Converter Interaction

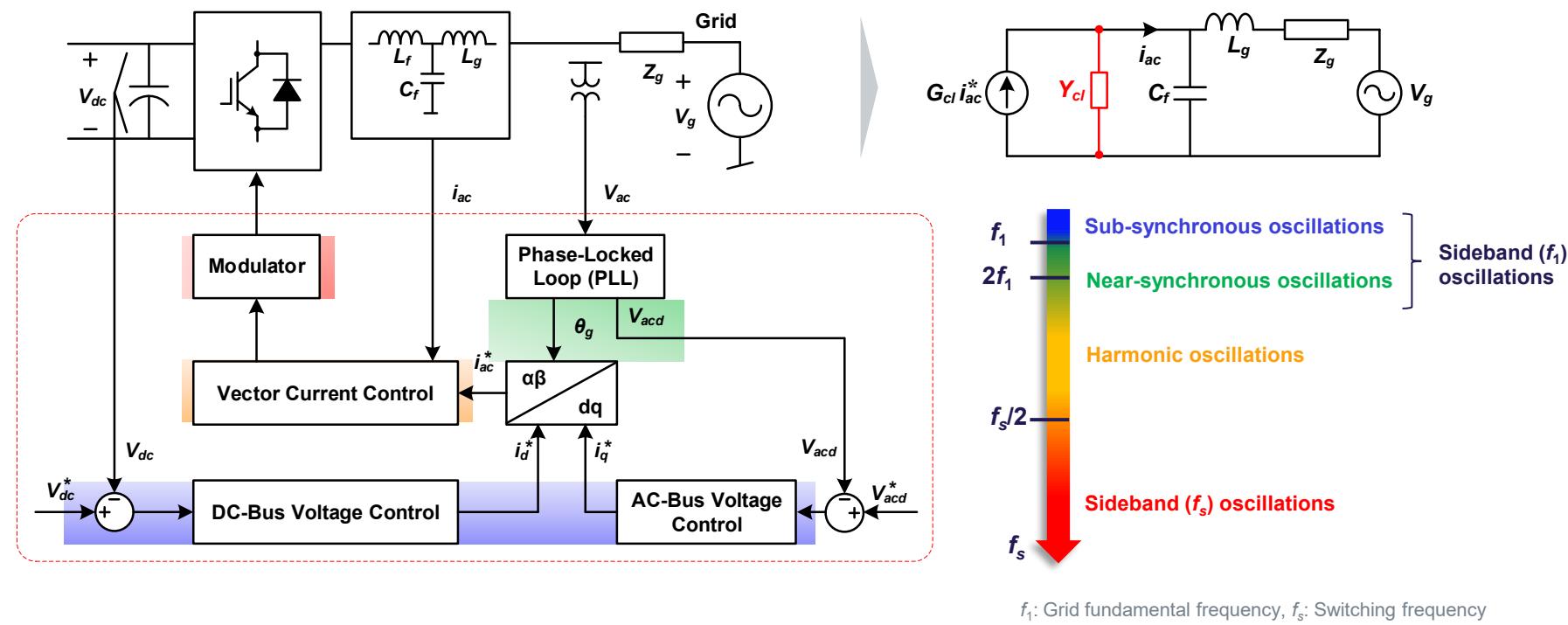
Negative damping induced by converter controllers



- $\text{Re}\{Y_o\} > 0$: stable, yet under-damped
- $\text{Re}\{Y_{cl}\} = 0$: resonant, zero damping
- $\text{Re}\{Y_{cl}\} < 0$: unstable, negative damping

Grid-Converter Interaction

Mapping from control loops to instability phenomena



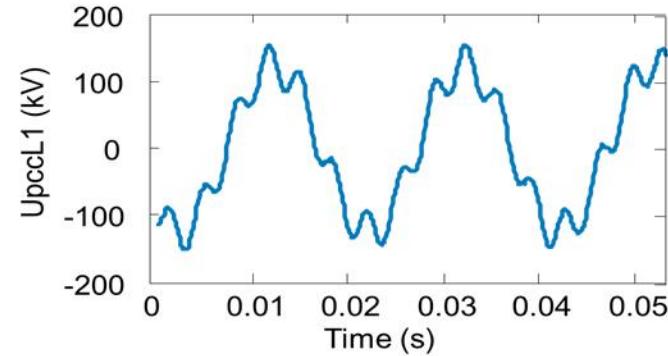
Wind Power Plants - Converter based Power Systems

Cross-frequency coupling and interactions – world's first HVDC+wind



VSC-HVDC + Offshore Wind^[1]

- 2-level VSC + Type-3 wind turbine
- 290 Hz resonance @ +200 MW
- Active damping with VSC-HVDC



Rätselhafter Defekt legt größten Windpark lahm

Seit M
still. t
bezahl
DER SPIEGEL 35/2014

DER SPIEGEL 35/2014

Ökostrom
Knall auf hoher See

Die Alte Auschweiz

Störung legt Windpark BARD Offshore 1 weiter lahm

Beim Windpark BARD Offshore 1 vor der Nordseeinsel Borkum gibt es eine Panne nach der anderen. Seit März steht der Windpark still. "Die Störungen zu beheben, zieht sich länger hin, als es allen Beteiligten lieb ist", sagte Mathias Fischer, Sprecher des Netzbetreibers Tennet. Noch immer suchen Experten des Windparkbetreibers Ocean Breeze Energy, des Elektronikkonzerns ABB und von Tennet nach der Störungsursache. Erst im September können die 80 Anlagen von BARD 1 voraussichtlich wieder Strom liefern.

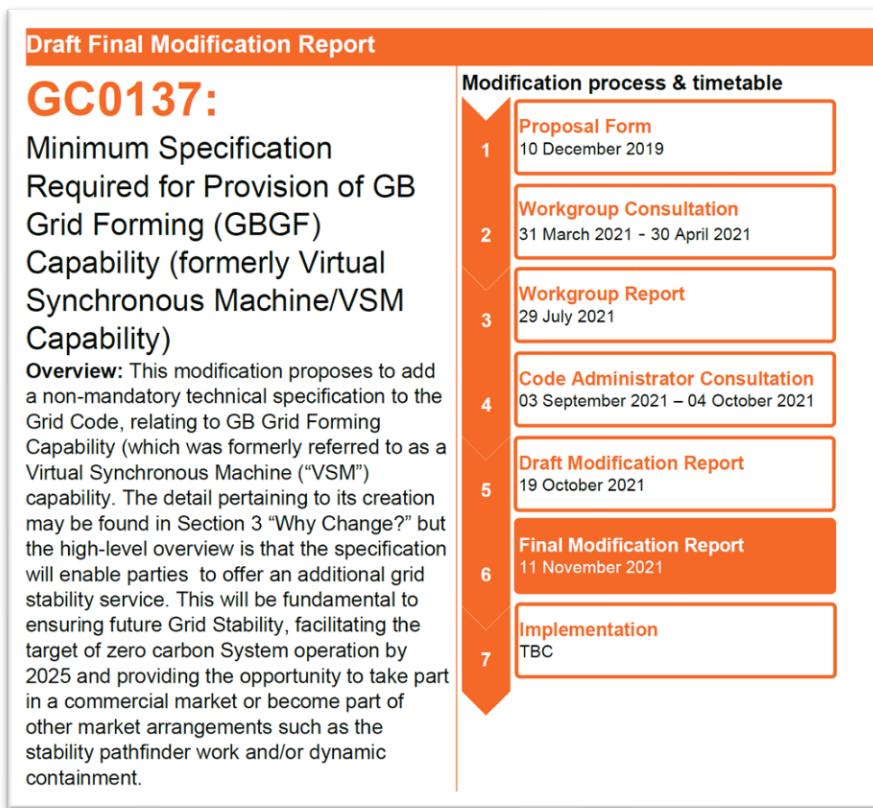
Schutzabschaltungen wegen "schmutzigem Strom"

Seit März liefert der Windpark BARD Offshore 1 keinen Strom mehr. (Archivbild)

M. Larsson, "Harmonic resonance and control interoperability analysis of HVDC connected wind farms," *IEEE eT&D*, Aalborg, 2017.

Grid Codes on GFM Capability

Minimum Specification Required for Provision of GB Grid Forming Capability



Comparison of Converter Technology

Capability	GBGF-S	GBGF-I	Conventional
Phase Based Phase Jump Power in one cycle	Yes	Yes	No
RoCoF response Power	Yes	Yes	No
Damping Power	Yes	Yes	Yes
Operate in Synchronism with the System	Yes	Yes	Yes
Contribution to Fault infeed	Yes - High	Yes - As specified	Yes - Limited
Avoids producing current harmonics > 5 Hz	Yes	Yes	No

GBGF: Great Britain Grid Forming

GBGF-I: GB Grid Forming Inverter – As defined in the Grid Code Glossary and Definitions

GBGF-S: GB Grid Forming Synchronous – As defined in the Grid Code Glossary and Definitions

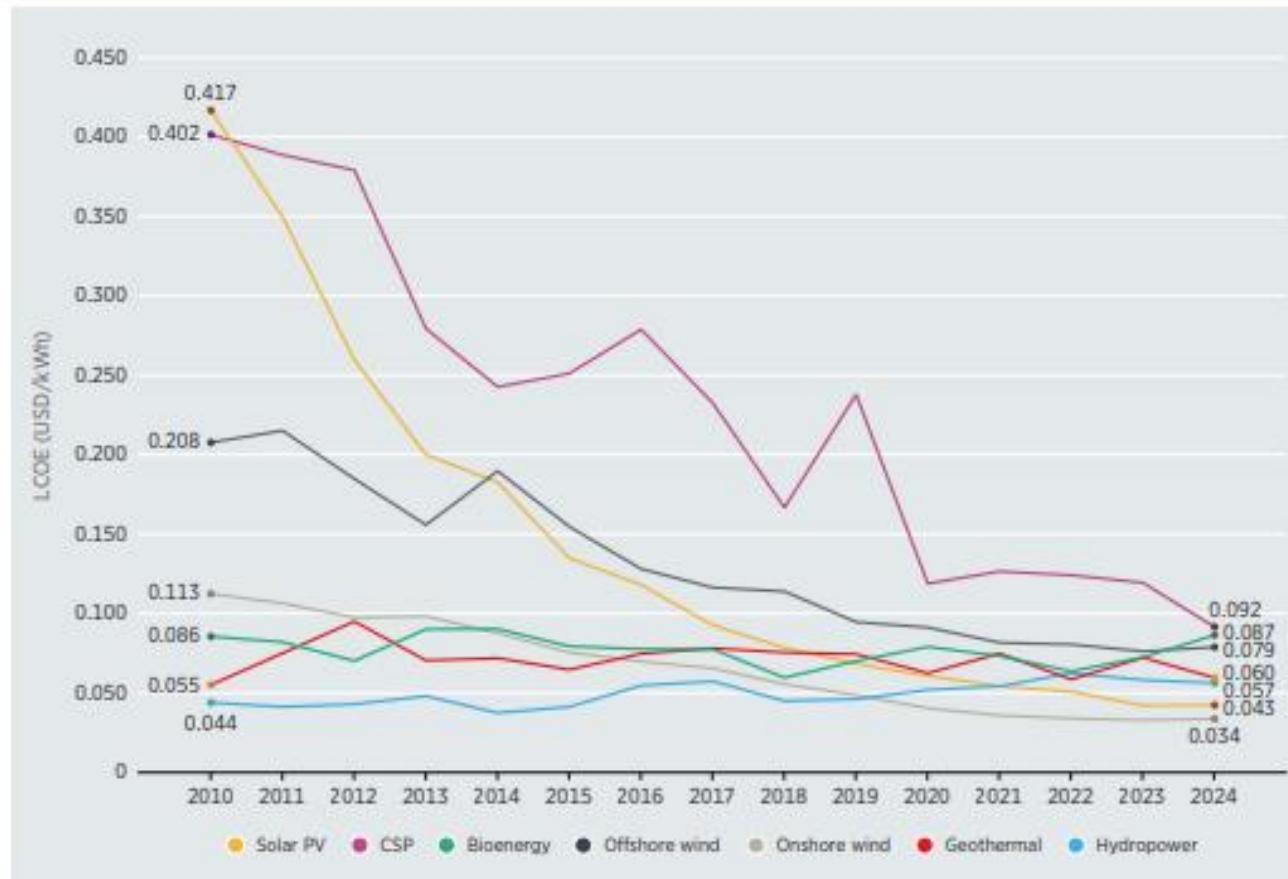
For the avoidance of doubt GBGF-I includes VSM0H converters

[1] "The Grid Code," National Grid ESO, Issue 6, Revision 16, Jan. 2023. [Online]. Available: <https://www.nationalgrideso.com/document/274186/download>.

COST OF ENERGY - RENEWABLES

STATUS TODAY

Figure S1 Renewable energy LCOE decline, 2010-2024



Notes: CSP = concentrated solar power; kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; USD = United States dollar.

https://tecsol.blogs.com/files/irena_tec_rpgc_in_2024_2025.pdf

COST OF ENERGY

APPROACHES TO REDUCE COE

$$COE = \frac{C_{Cap} + C_{O\&M}}{E_{Annual}}$$

C_{Cap} – Capital cost

$C_{O\&M}$ – Operation and main. cost

E_{Annual} – Annual energy production

Approaches	Important and Related Factors	Potential
Lower C_{Cap}	Production / Policy	+
Lower $C_{O\&M}$	Reliability / Design / Labor	++
Higher E_{annual}	Reliability / Capacity / Efficiency / Location	+++

Reliability is an Efficient Way to Reduce COE

– Lower $C_{O\&M}$ & Higher E_{Annual}



SUMMARY – POTENTIALS AND CHALLENGES

- We will be an electrical based society
- Power Electronics has a long track record – Enabler to the Grid
- Many emerging application areas – connected to the Grid
- Solar and Wind power competitive with fossil today
- Grid-following/Grid forming – how to do in large scale power systems?
- Storage is coming into system solutions – how to scale that enough ?
- Stability of Power Electronics Dominated grid ? We need scalable and reliable solutions.
- More reliable power electronics as well as sustainable/recyclable !
- Power-to-X - how to do it more effectively ?
- E-Transportation – use it in the integration of renewables
- And we need a lot of Engineers in eg. Electrical, Electronic, Mechanical, Mechatronics, AI, Material

Thank you!



Aalborg University
AAU Energy

www.energy.aau.dk

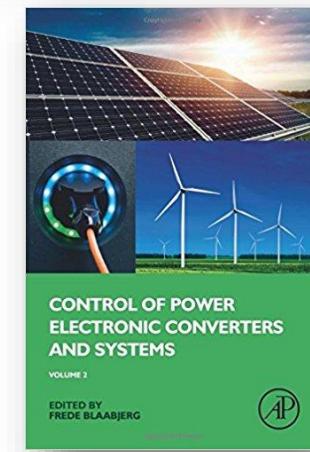
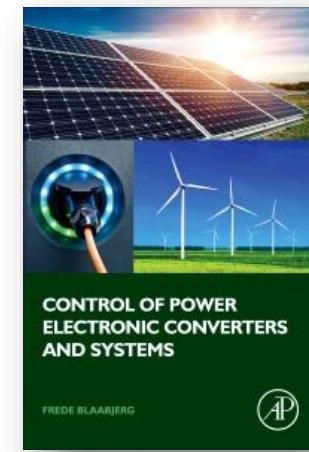
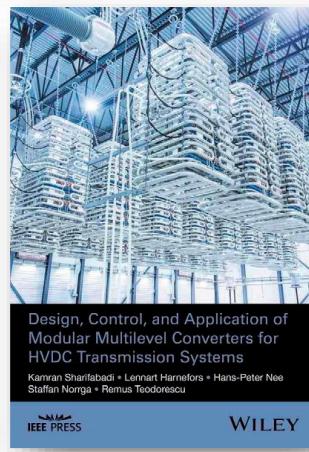
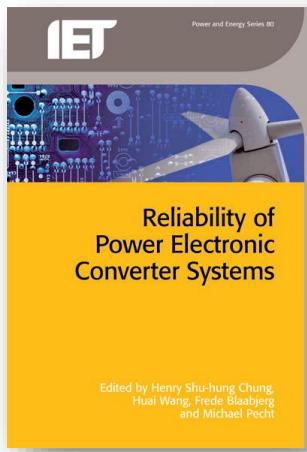
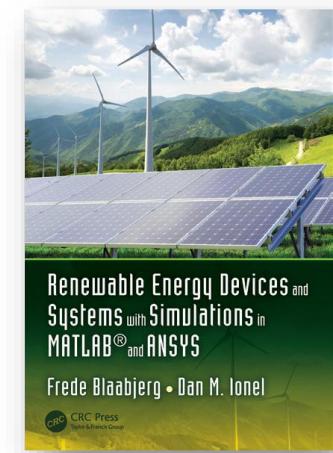
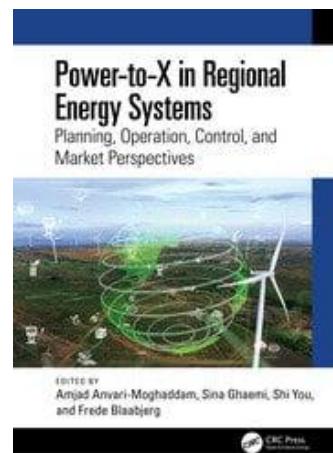
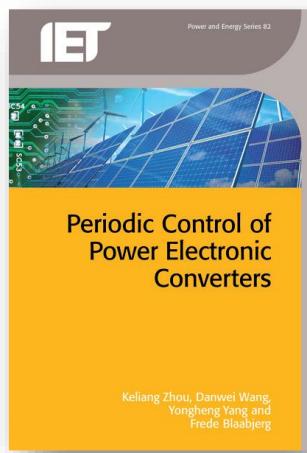
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