Introduction to Renewables

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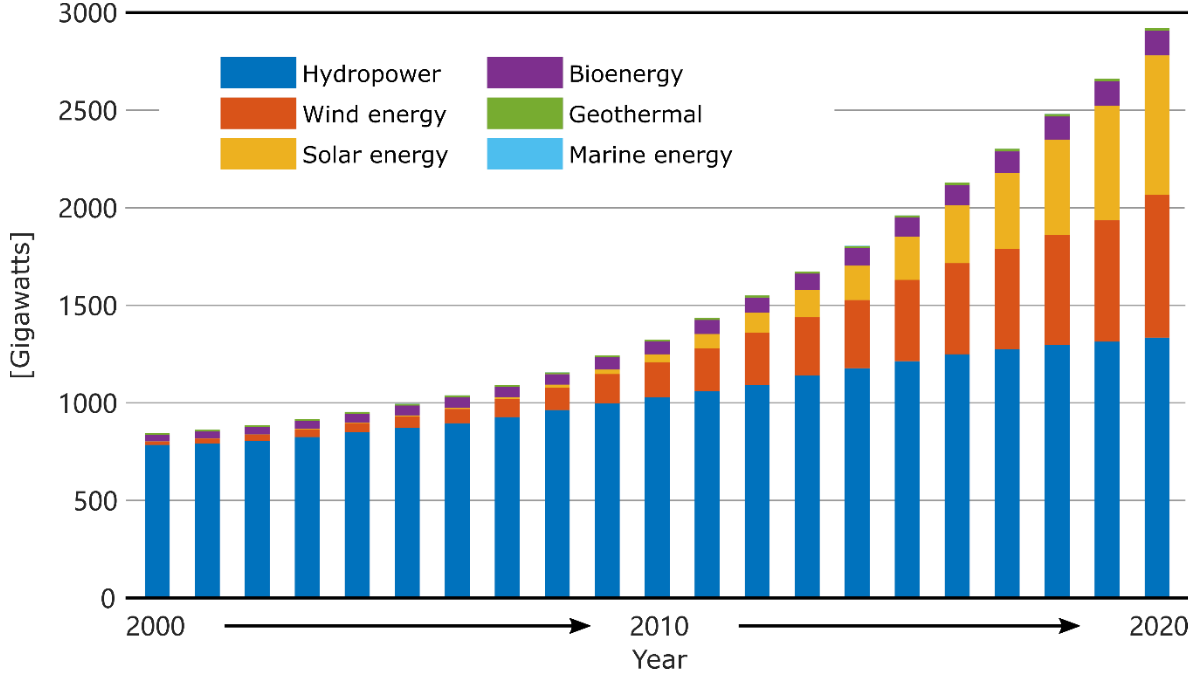
Outline

- **Overview of Renewable Energy Development**
  State-of-the-art; Mission profiles; Grid codes; Reliability and cost
- **Power Converters for Renewable Energy**
  PV application; Wind power application; Power semiconductor devices; Basic control
- **Future Challenges and Discussions**
  PV application; Wind power application; Other Generators

State of the Art – Renewable Evolution

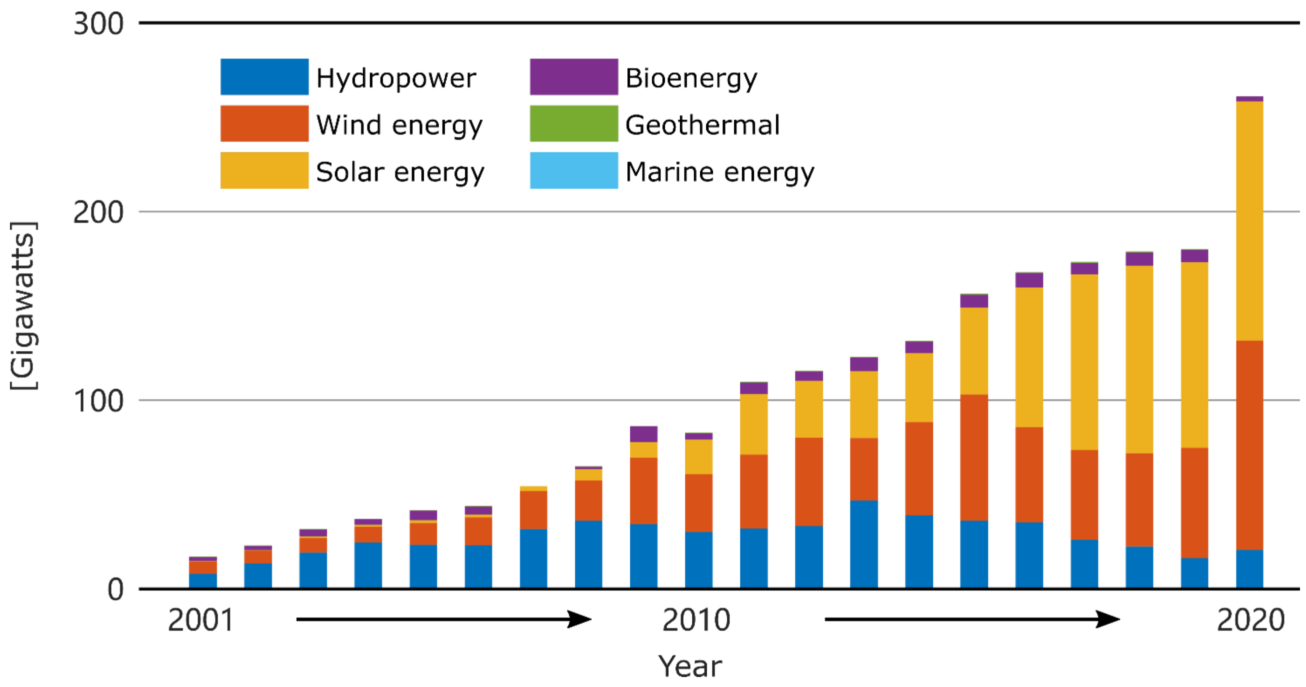


Worldwide Installed Renewable Energy Capacity (2000-2020)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy
3. Solar includes photovoltaics and solar thermal
4. Wind includes both onshore and offshore wind energy

(Source: IRENA, "Renewable energy capacity statistics 2019", http://www.irena.org/publications, March 2019)

Global RES Annual Changes

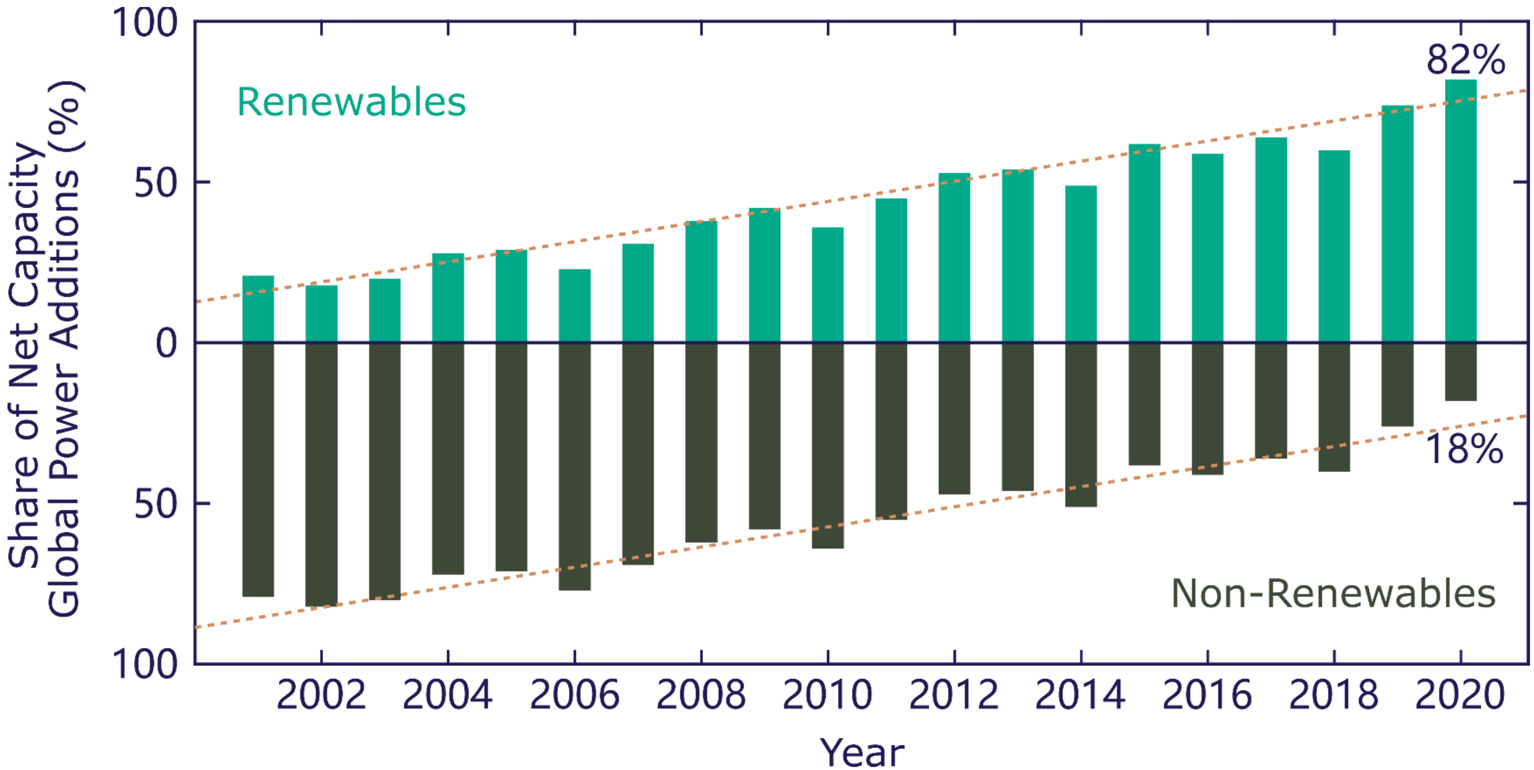


Global Renewable Energy Annual Changes in Gigawatt (2001-2020)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy
3. Solar includes photovoltaics and solar thermal
4. Wind includes both onshore and offshore wind energy

(Source: IRENA, "Renewable energy capacity statistics 2019", http://www.irena.org/publications, March 2019)

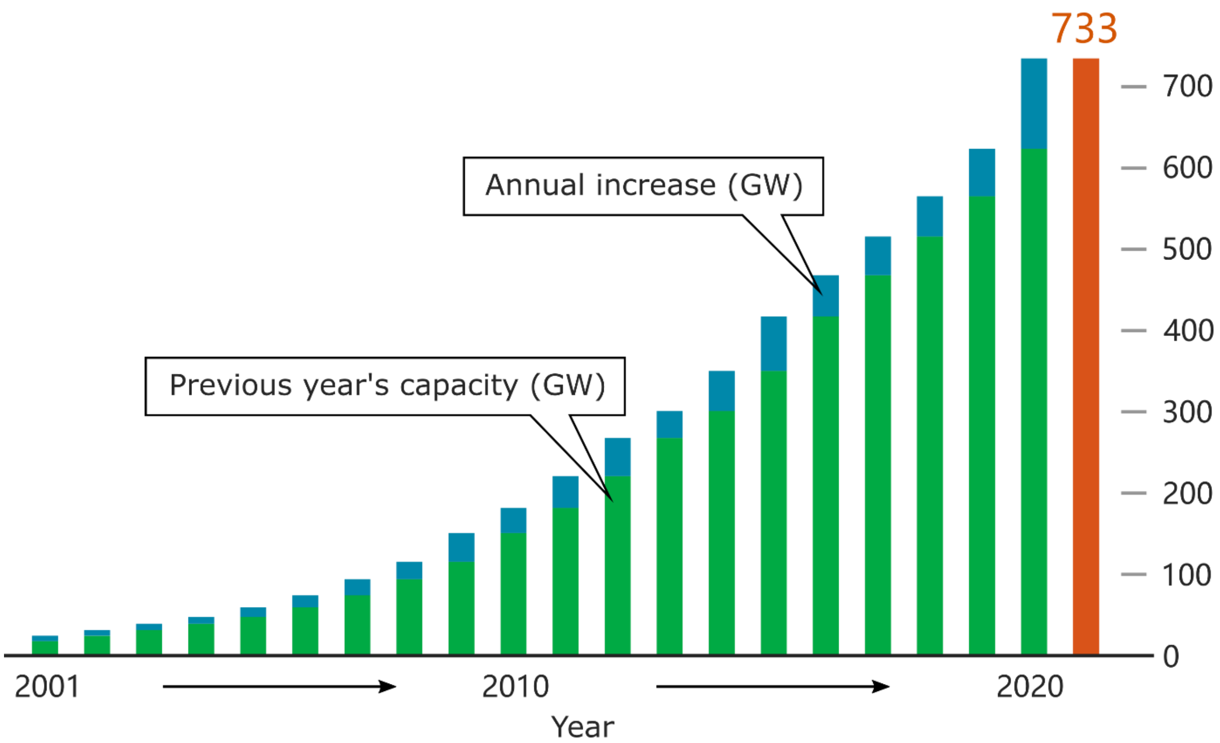
Share of the Net Total Annual Additions



RES and non-RES as a share of the net total annual additions

(Source: IRENA, “Renewable energy capacity statistics 2020”, http://www.irena.org/publications, March 2020)

State of the Art Development – Wind Power

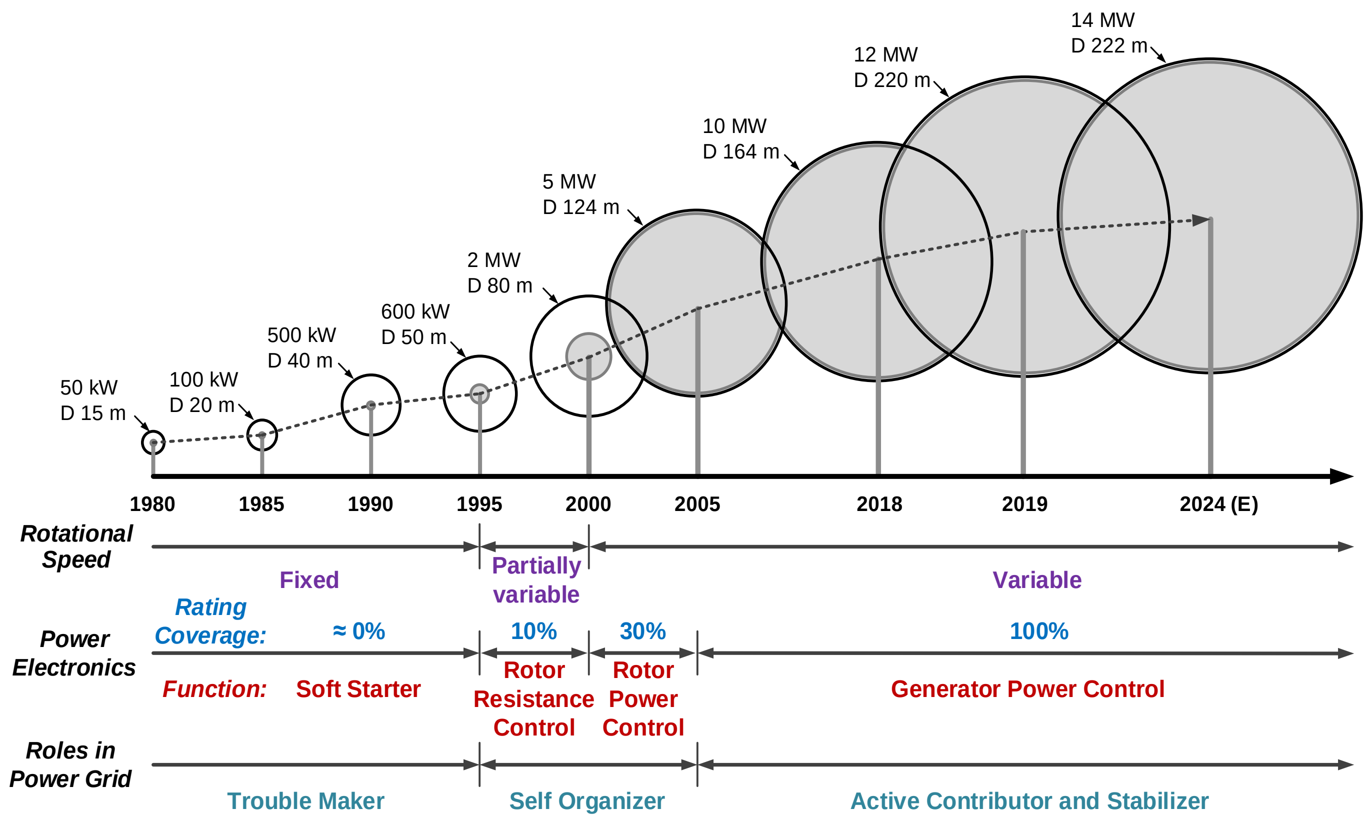


Global installed wind capacity (until 2020): 733 GW, 2020: 111 GW

- Higher total capacity (+50% non-hydro renewables).
- Larger individual size (average 1.8 MW, up to 6-8 MW, even 15 MW).
- More power electronics involved (up to 100 % rating coverage).

(Source: IRENA, "Renewable capacity statistics 2021", http://www.irena.org/publications, March 2021)

State of the Art Development – Wind Power

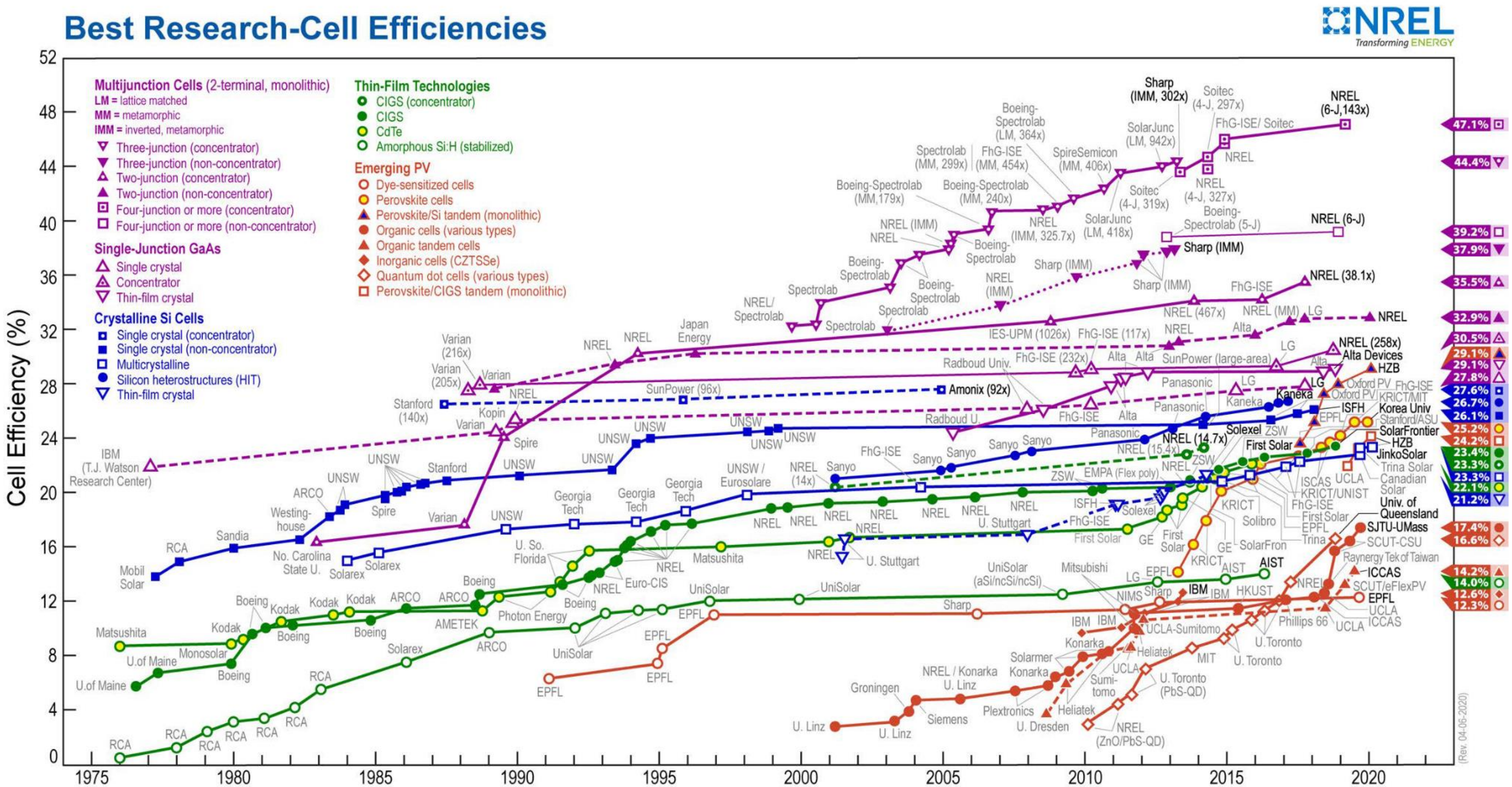


Global installed wind capacity (until 2020): 733 GW, 2020: 111 GW

- Higher total capacity (46% non-hydro renewables; ~1/4 total incl. hydro).
- Larger individual size (average 1.8 MW, up to 6-8 MW, even 15 MW).
- More power electronics involved (up to 100 % rating coverage).

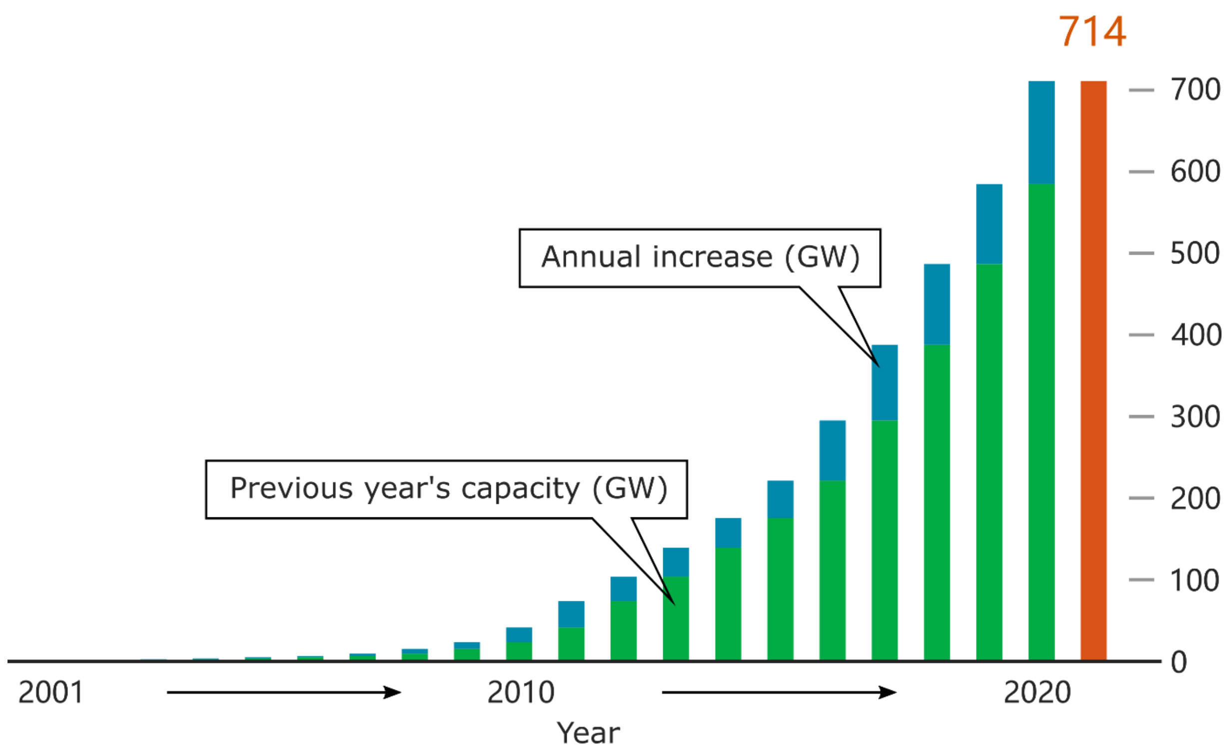
(Source: IRENA, "Renewable capacity statistics 2021", http://www.irena.org/publications, March 2021)

State of the Art – PV Cell Technologies



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

State of the Art Development – Photovoltaic Power

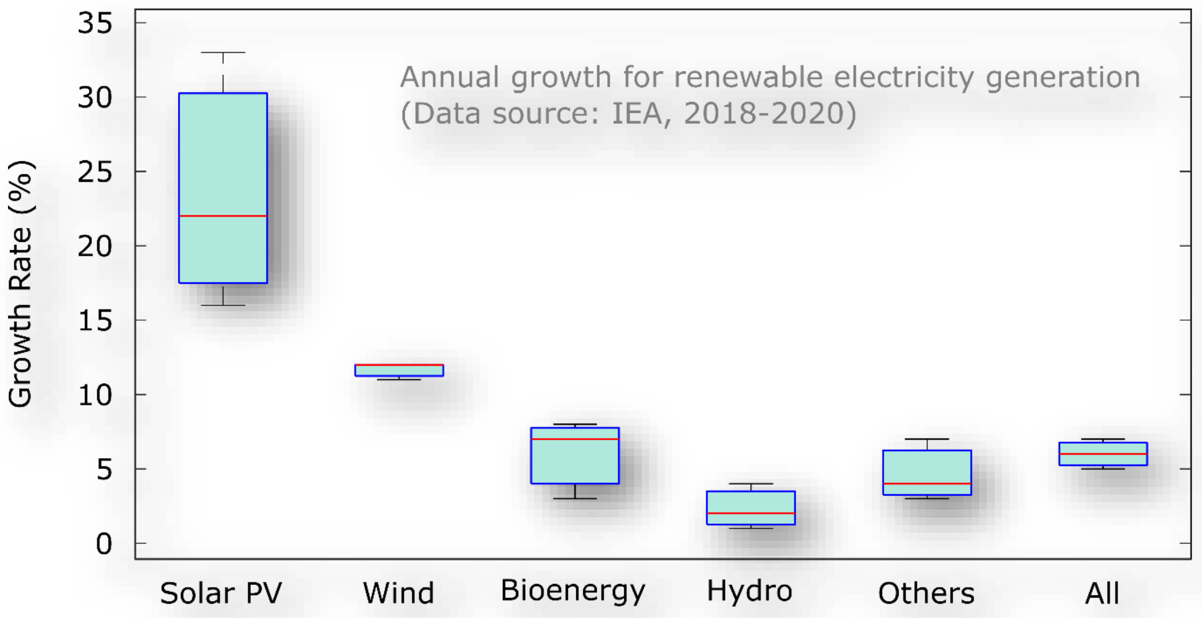


Global installed solar PV capacity (until 2020): 714 GW, 2020: 127 GW

- More significant total capacity (45% non-hydro renewables; ~1/4 total incl. hydro).
- Fastest growth rate (22% between 2018-2020, 33% in 2018).

(Source: IRENA, "Renewable capacity statistics 2021", http://www.irena.org/publications, March 2021)

State of the Art Development – Photovoltaic Power

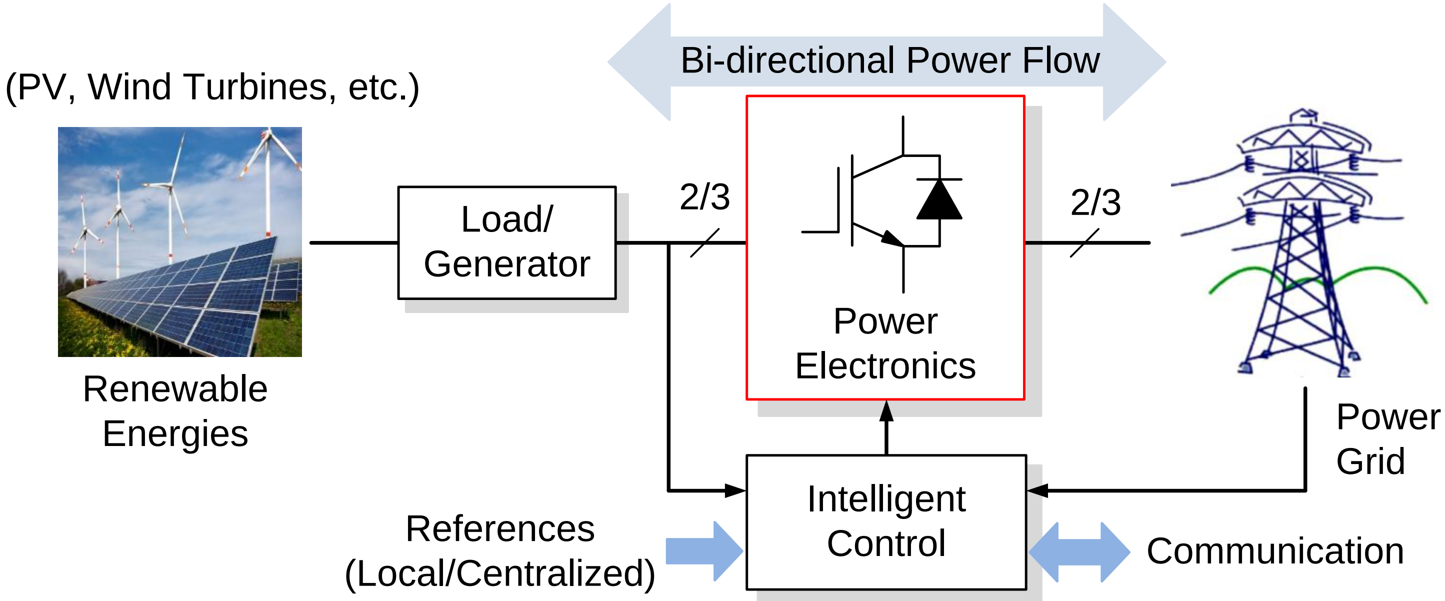


Global installed solar PV capacity (until 2020): 714 GW, 2019: 127 GW

- More significant total capacity (29% non-hydro renewables).
- Fastest growth rate (22% between 2018-2020, 33% in 2018).

(Source: Annual Growth for Renewable Electricity Generation by Source, 2018-2020, IEA
https://www.iea.org/data-and-statistics/charts/annual-growth-for-renewable-electricity-generation-by-source-2018-2020)

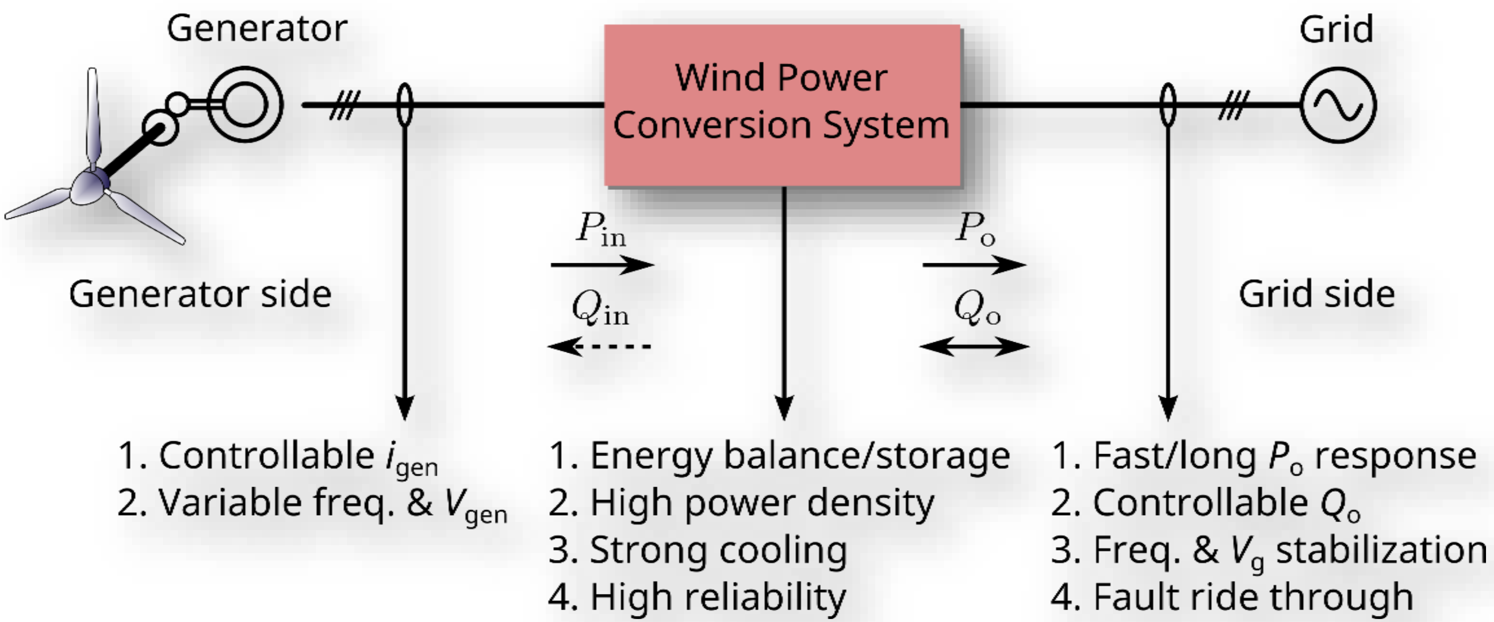
Power Electronics based Renewable Energy Systems



Important issues for converters in renewables:

- Reliability/security of supply
- Efficiency, cost, volume, protection
- Control active and reactive power
- Ride-through operation and monitoring
- Power electronics enabling technology
- …

Requirements for Wind Turbine Systems



General Requirements & Specific Requirements

Grid Codes for Wind Turbines

Conventional power plants provide active and reactive power, inertia response, synchronizing power, oscillation damping, short-circuit capability and voltage backup during faults.

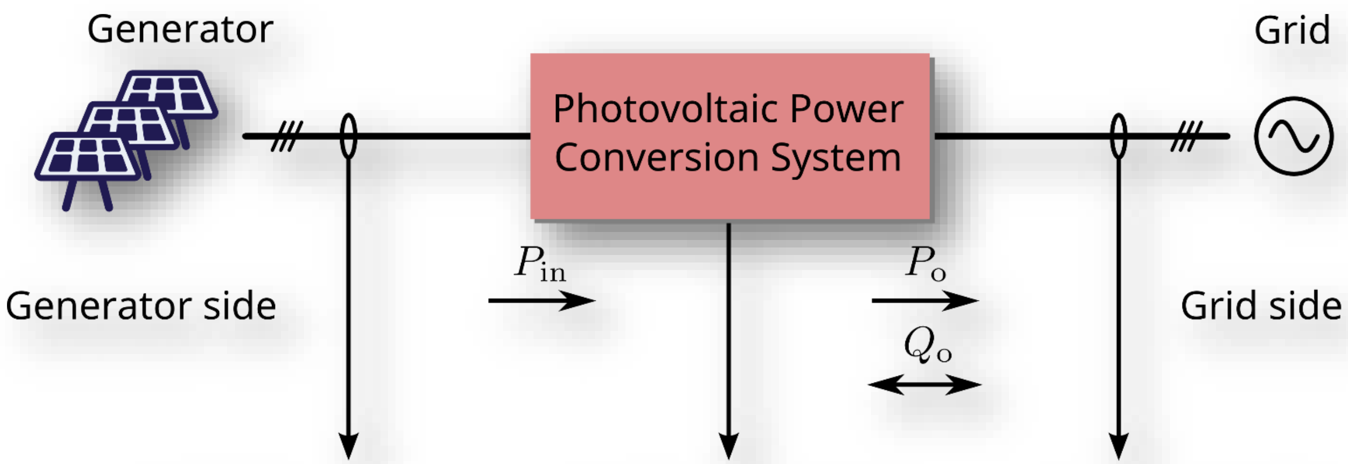
Wind turbine technology differs from conventional power plants regarding the converter-based grid interface and asynchronous operation

Grid code requirements today

- Active power control
- Reactive power control
- Frequency control
- Steady-state operating range
- Fault ride-through capability

Wind turbines are active power plants.

Requirements for Photovoltaic Systems



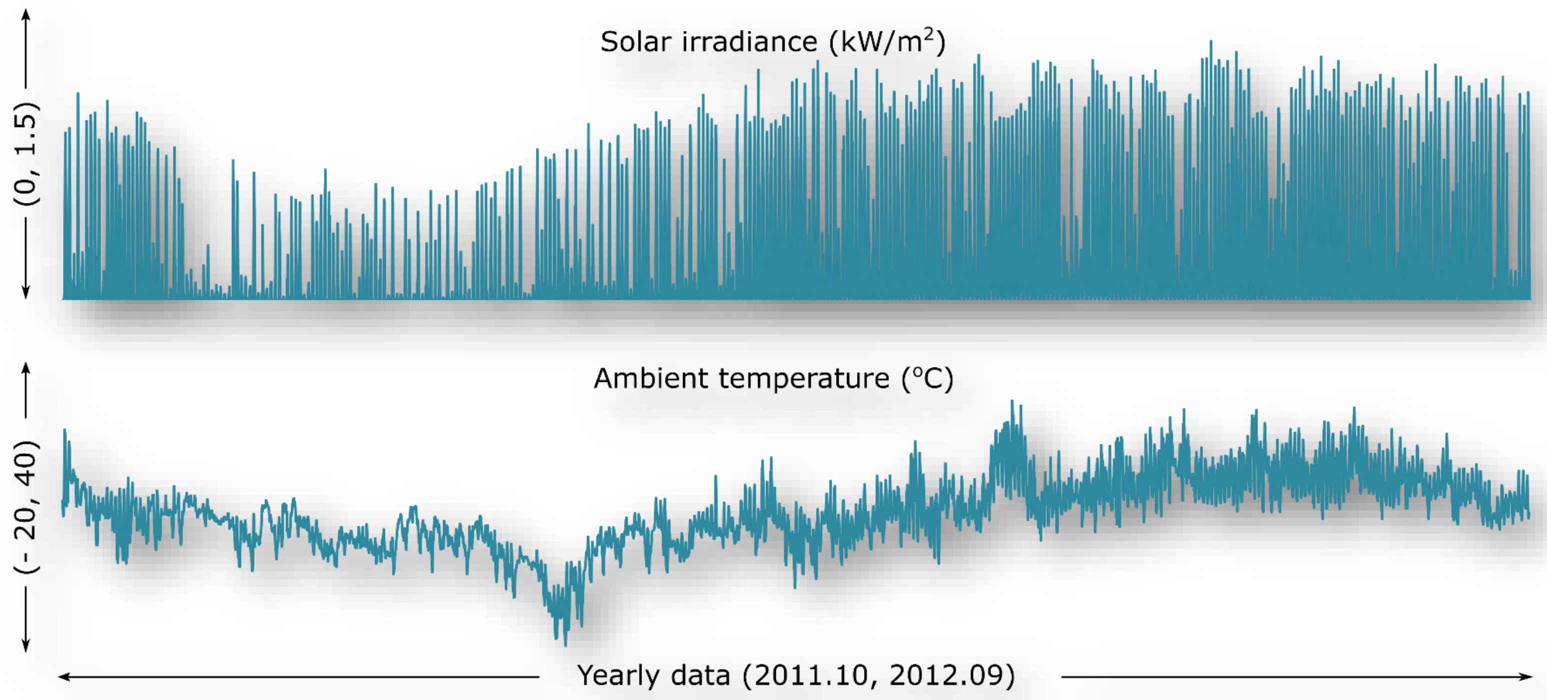
1. MPPT
2. DC voltage/current
3. Panel monitoring

1. High efficiency
2. Temp. management
3. High reliability
4. Islanding protection
5. Communication

1. Power quality
2. Voltage level
3. Frequency control
4. Fault ride-through

General Requirements & Specific Requirements

Input Mission Profiles for PV Systems



Mission Profile for PV Systems Measured at AAU (201110-201209)

- Highly variable solar irradiance
- Small power inertia to solar variation – quick response of PV panel.
- Small temperature inertia to ambient temp. variation – small case capacity.
- Temperature sensitive for the PV panel and power electronics.

Grid Codes for Photovoltaic Systems

Grid-connected PV systems ranging from several kWs to even a few MWs are being developed very fast and will soon take a major part of electricity generation in some areas. PV systems have to comply with much tougher requirements than ever before.

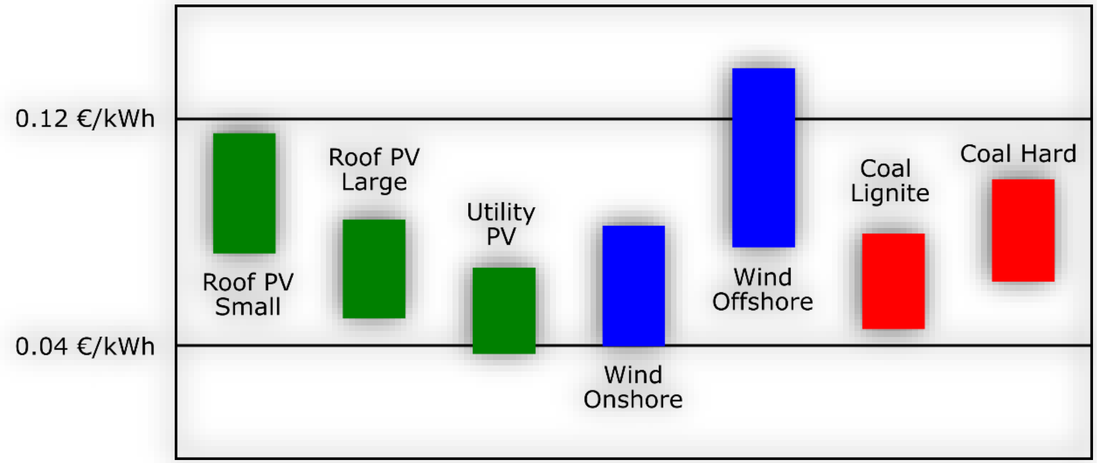
Requirements today

- Maximize active power capture (MPPT)
- Power quality issue
- Ancillary services for grid stability
- Communications
- High efficiency

In case of large-scale adoption of PV systems

- Reactive power control
- Frequency control
- Fault ride-through capability
- …

Cost of Energy (COE) – Today (2020)



Cost of Electricity (Energy) by Sources in Germany

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

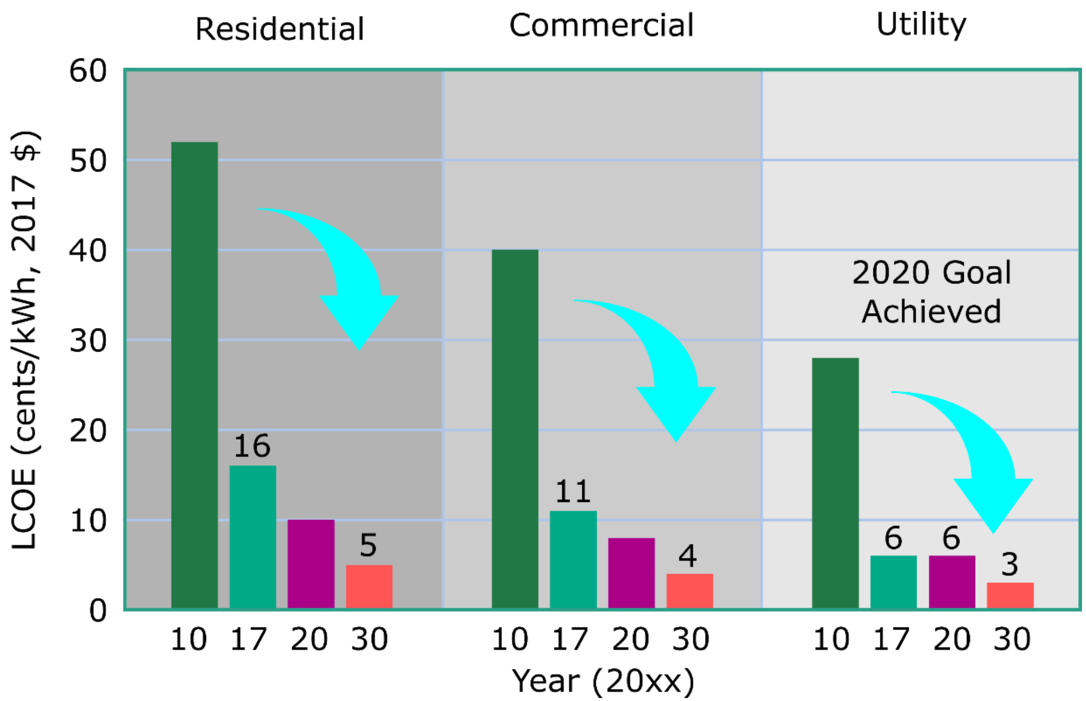
C_{Cap} – Capital cost
$C_{O\&M}$ – Operation and main. cost
E_{Annual} – Annual energy production

Determining factors for renewables
- Capacity growth
- Technology development

Wikipedia, "Cost of electricity by source", available: https://en.wikipedia.org/wiki/Cost_of_electricity_by_source

Continue Reducing the Cost

SunShot Goals by the U.S. Department of Energy



In 2017, DOE's Solar Energy Technologies Office (SETO) announced that the industry had achieved the 2020 cost goal for utility-scale solar of 6¢ per kilowatt hour (kWh).

*Levelized cost of electricity (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010–17.

U.S. DOE - https://www.energy.gov/sites/prod/files/2018/05/f51/SunShot%202030%20Fact%20Sheet.pdf

Approaches to Reduce Cost of Energy

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

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

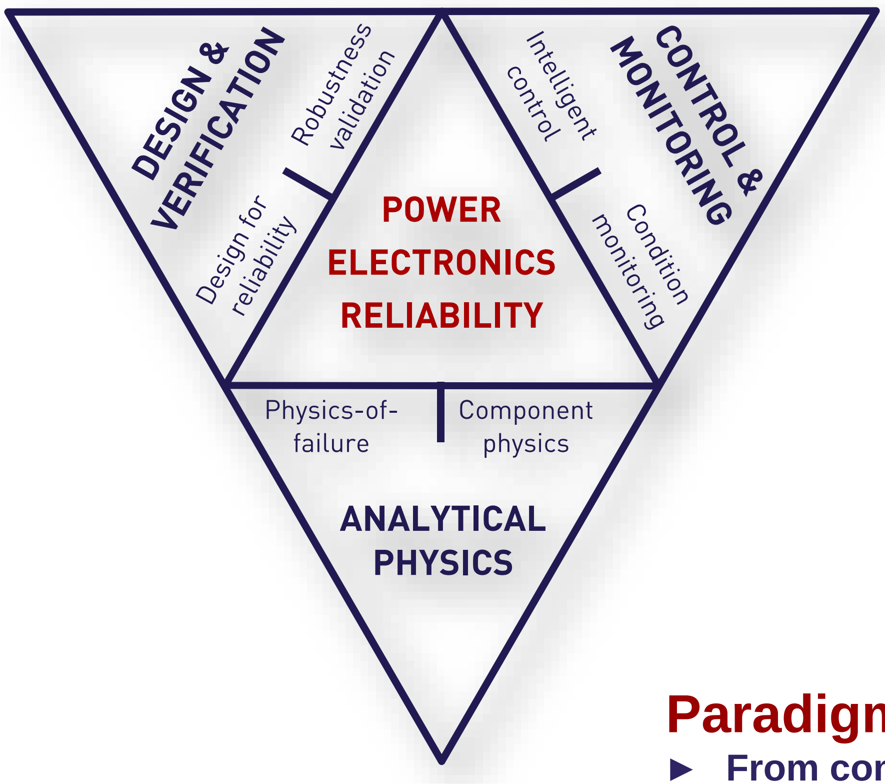
– **Lower $C_{O\&M}$ & Higher E_{Annual}**

Lifetime Targets in PE Intensive Applications

Applications	Typical design target of Lifetime
Aircraft	24 years (100,000 hours flight operation)
Automotive	15 years (10,000 operating hours, 300, 000 km)
Industry motor drives	5-20 years (60,000 hours in at full load)
Railway	20-30 years (73,000 hours to 110,000 hours)
Wind turbines	20 years (120,000 hours)
Photovoltaic plants	30 years (90,000 hours to 130,000 hours)

The Scope of Reliability of Power Electronics

A multi-disciplinary research area

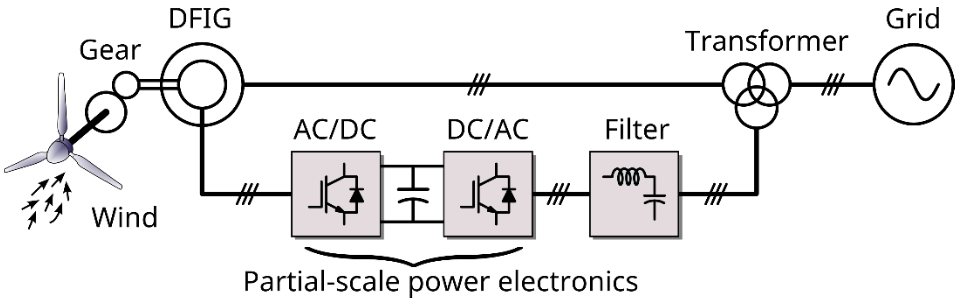


Paradigm Shift

- From components to **failure mechanisms**
- From constant failure rate to **failure level with time**
- From reliability prediction to also **robustness validation**
- From microelectronics to also **power electronics**

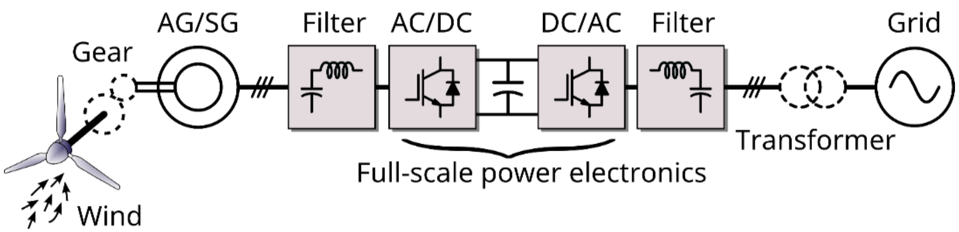
Power Converters for Renewables

Wind Turbine Concept and Configurations



Partial scale converter with DFIG

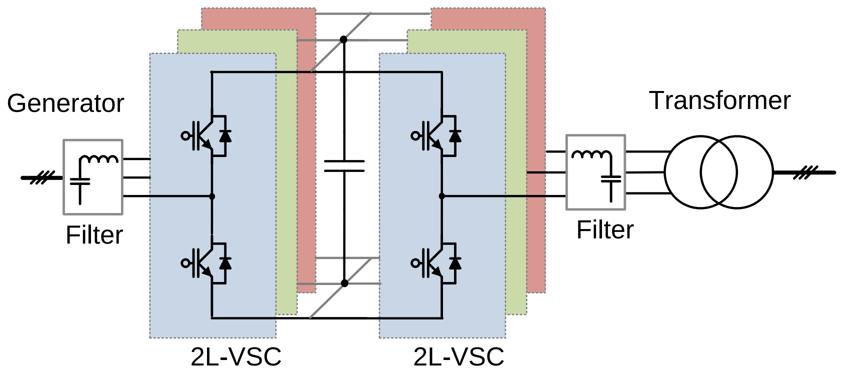
- Variable pitch – variable speed
- Doubly Fed Induction Generator
- Gear box and slip rings
- ±30% slip variation around synchronous speed
- Power converter (back to back/ direct AC/AC) in rotor circuit
- ✓ State-of-the-art solutions



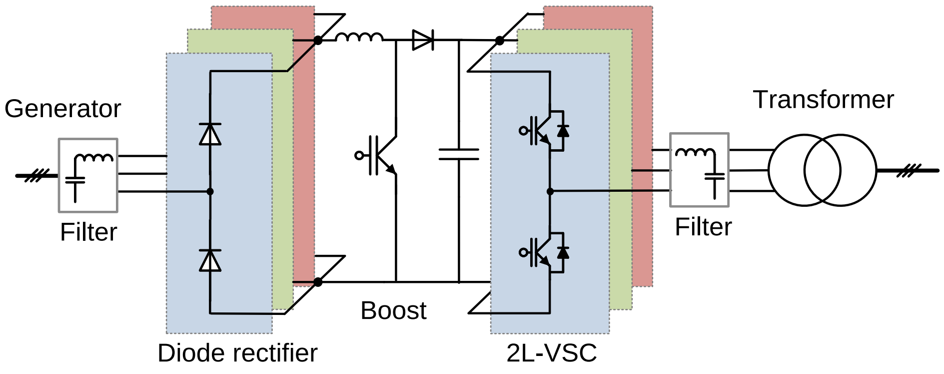
Full scale converter with SG/IG

- 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

Converter Topologies under Low Voltage (<690V)



Back-to-back two-level VSC



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

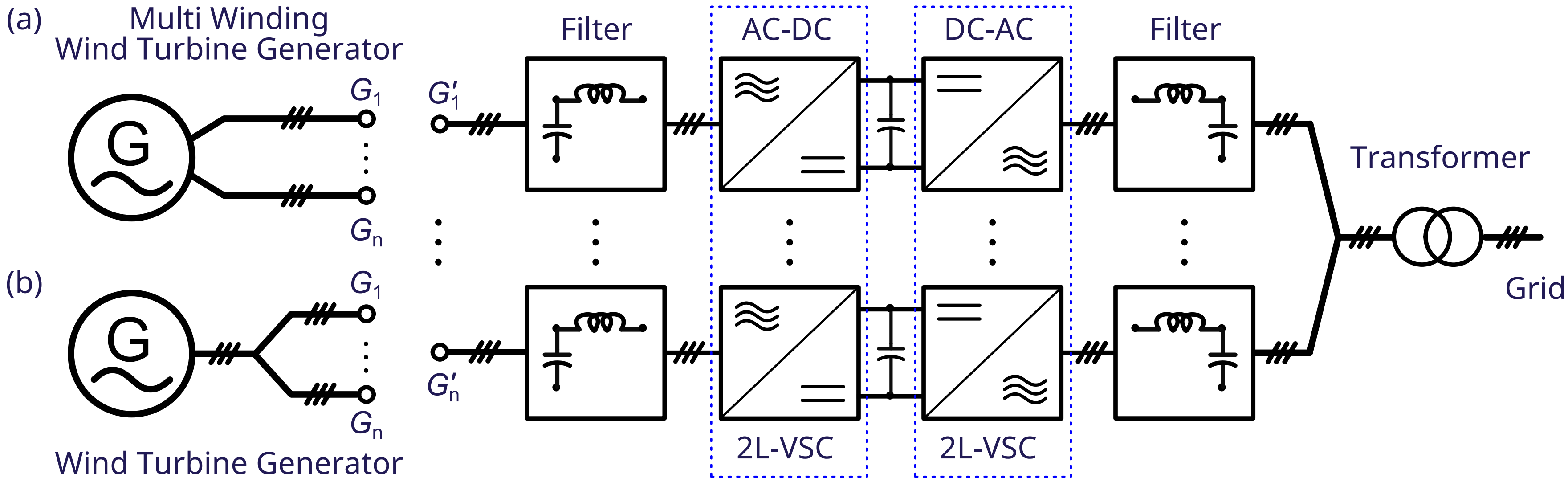
- Proven technology
- Standard power devices (integrated)
- Decoupling between grid and generator (compensation for non-symmetry and other power quality issues)

- 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

- 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



(a) with multi-winding generator.

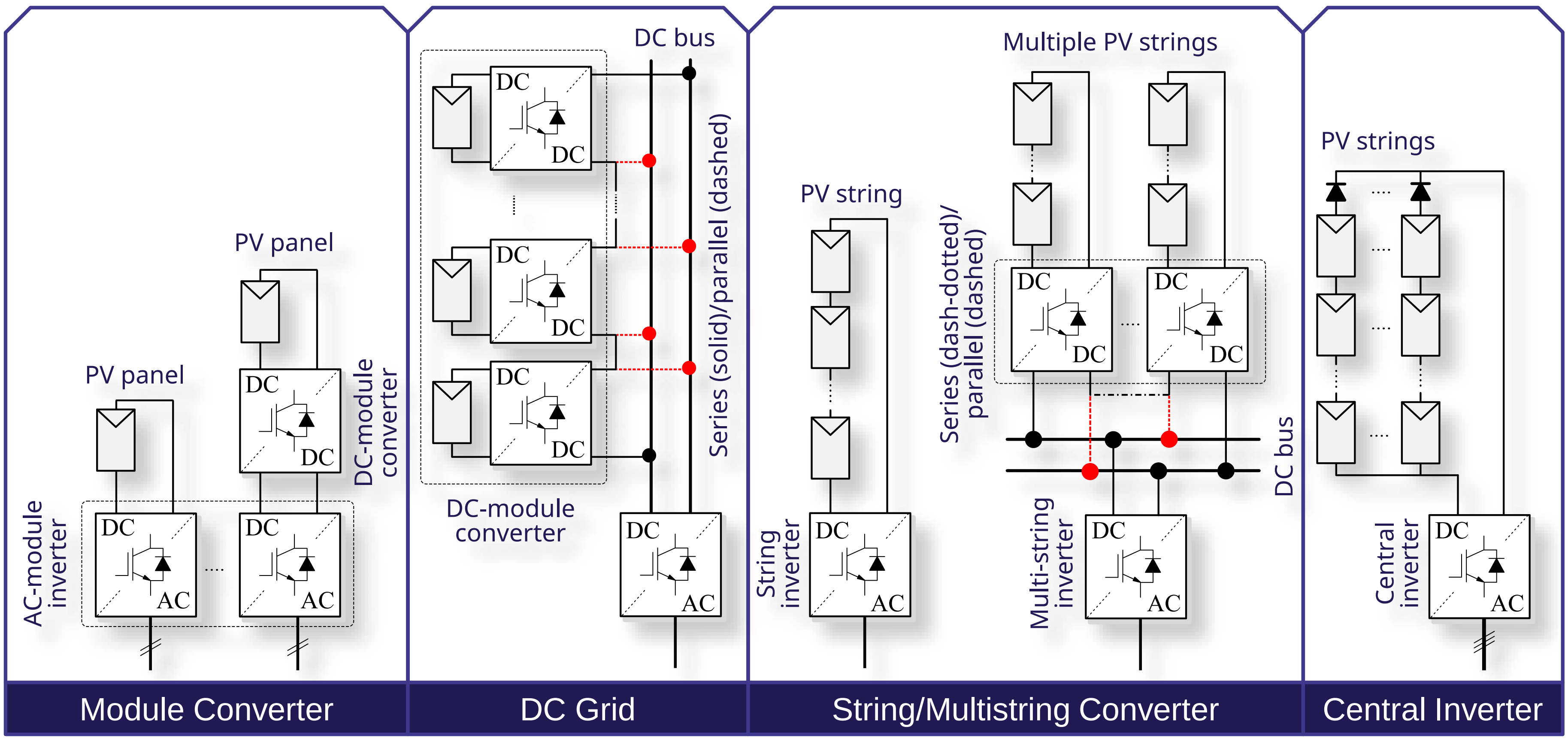
(b) with normal winding generator

Parallel converter to extend the power capacity

- State-of-the-art solution in industry (> 3 MW)
- Standard and proven converter cells (2L VSC)
- Redundant and modular characteristics.

- Circulating current under common DC link with extra filter or special PWM

PV Inverter System Configurations



- Single-phase
- Hundreds watts
- Small systems

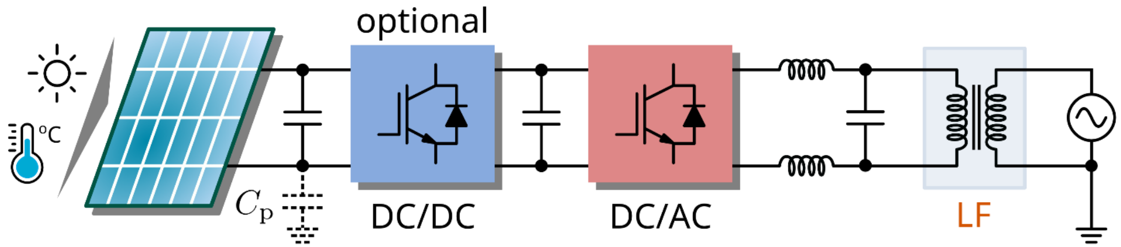
- DC grid → AC grid
- Single-/three-phase
- Several kilowatts
- Small systems / resisdential

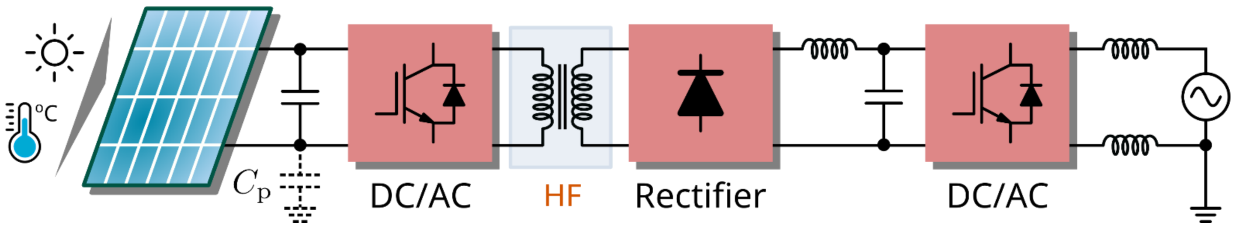
- Single-/three-phase
- 1~30 kW applications
- Residential/commercial

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

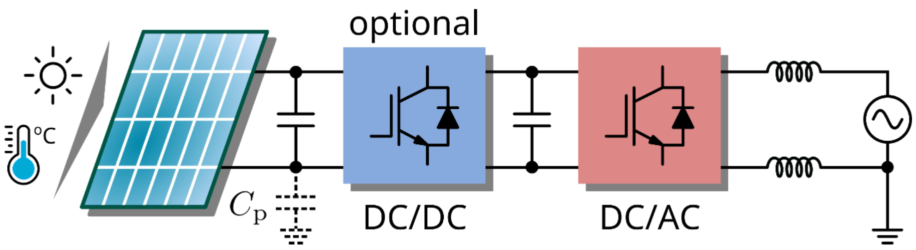
Grid-Connection Configurations

Transformer-based grid-connection





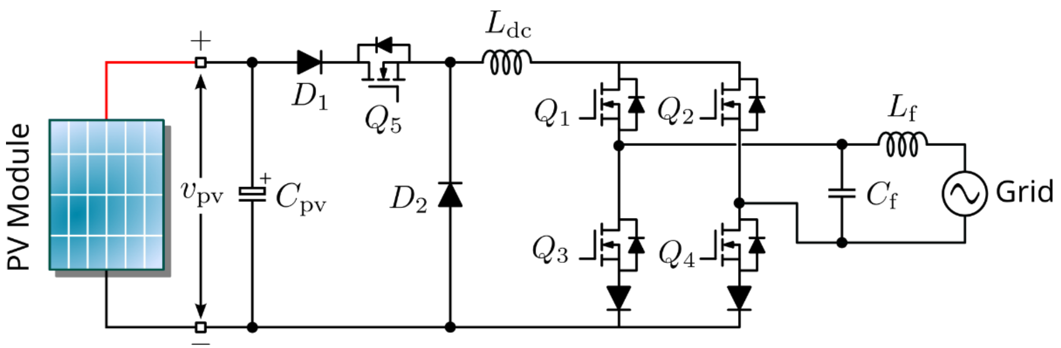
Transformerless grid-connection → Higher efficiency, Smaller volume



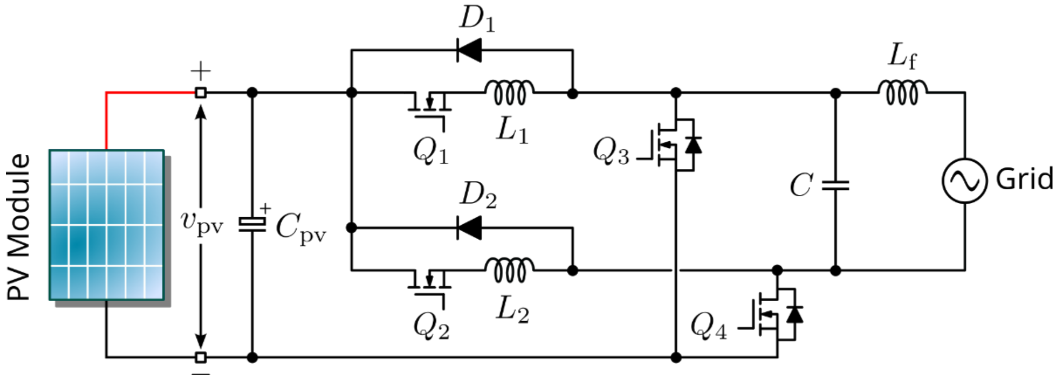
AC-Module PV Converters – Single-Stage

~ 300 W (several hundred watts)
High overall efficiency and High power desity.

Universal AC-module inverter



Buck-boost integrated full-bridge inverter

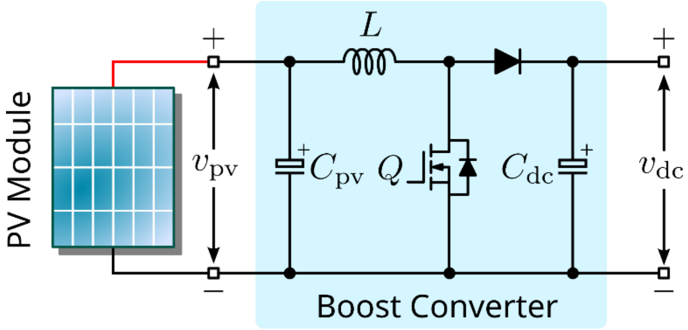


B.S. Prasad, S. Jain, and V. Agarwal, "Universal Single-Stage Grid-Connected Inverter," IEEE TEC, 2008.
C. Wang "A novel single-stage full-bridge buck-boost inverter", IEEE TPEL, 2004.

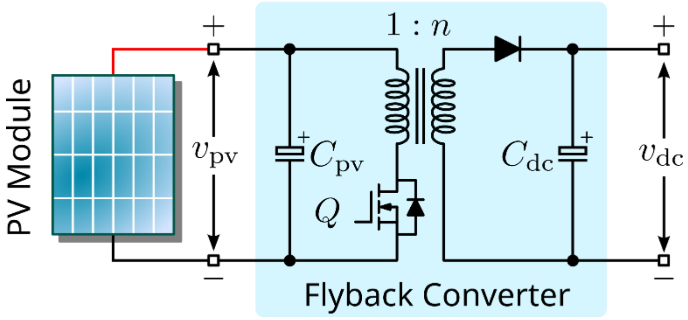
DC-Module PV Converters – Double-Stage

~ 300 W (several hundred watts)
High overall efficiency and High power desity.

Conventional DC-DC Converters



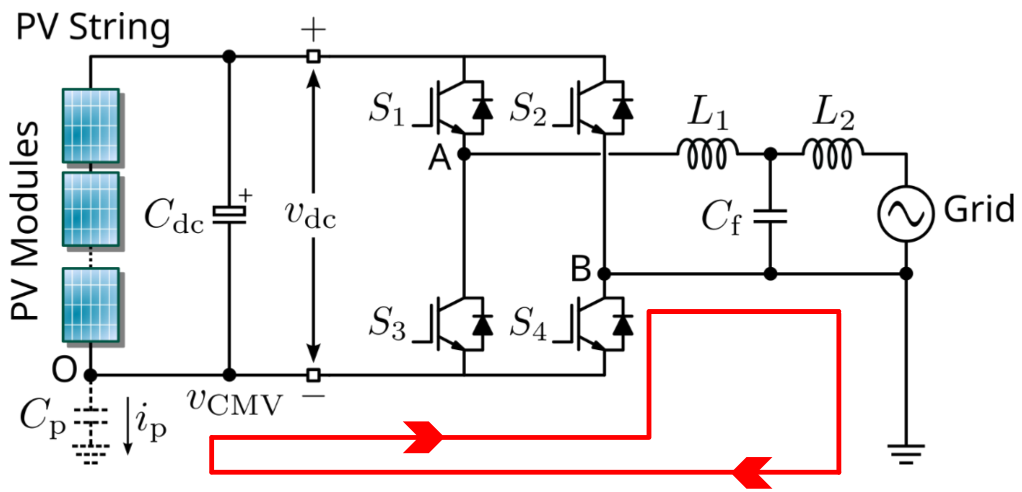
Flyback DC Optimizer



Y. Yang, K. A. Kim, F. Blaabjerg, and A: Sangwongwanich, Advances in Grid-Connected Photovoltaic Power Conversion Systems, Woodhead Publishing, 2018.

String/Multi-String PV Inverters

1 kW ~ 30 kW (tens kilowatts)
High efficiency and also Emerging for modular configuration in medium and high power PV systems.

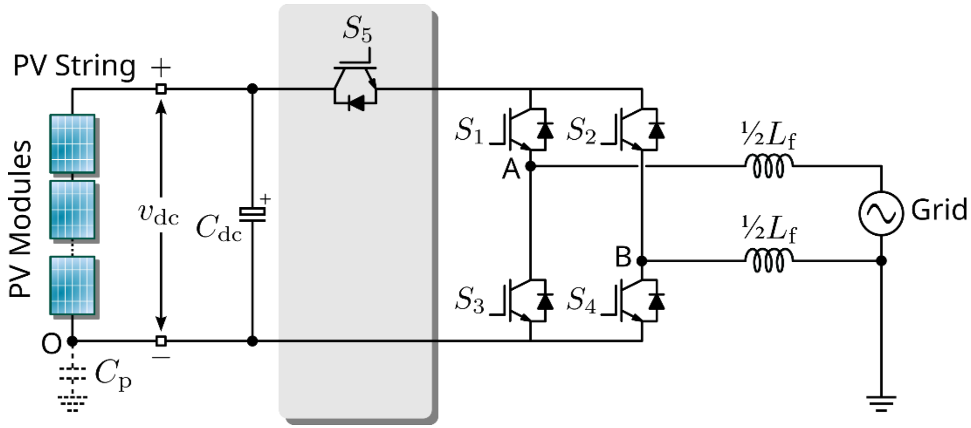


Bipolar Modulation is used:

- No common mode voltage → V_{PE} free for high frequency →low leakage current
- Max efficiency 96.5% due to reactive power exchange between the filter and C_{PV} during freewheeling and due to the fact that 2 switched are simultaneously switched every switching
- This topology is not special suited to transformerless PV inverter due to low efficiency!

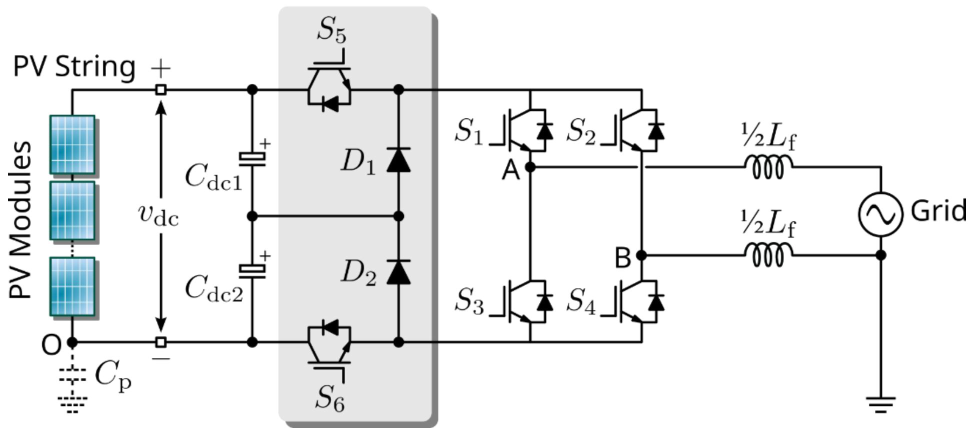
Transformerless String Inverters

H5 Transformerless Inverter (SMA)



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

H6 Transformerless Inverter (Ingeteam)

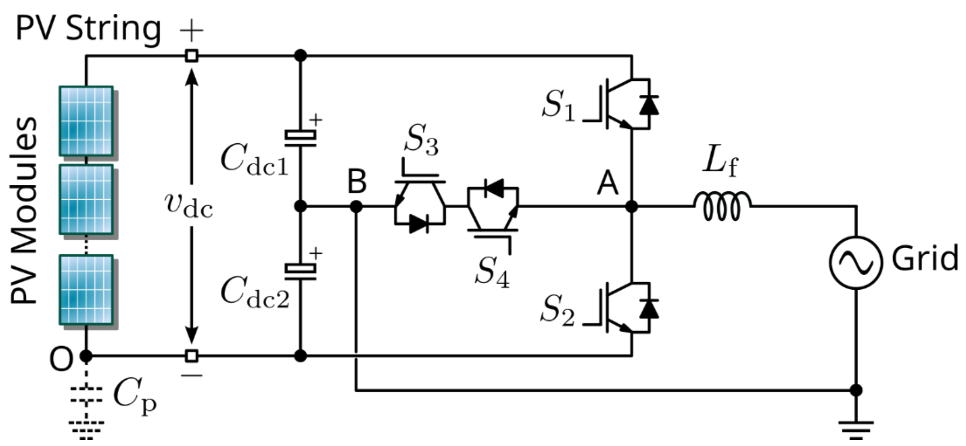


- High efficiency
- Low leakage current and EMI
- DC bypass switches rating: $V_{dc}/2$
- Unipolar voltage accross the filter

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.

NPC Transformerless String Inverters

Neutral Point Clamped (NPC) converter for PV applications

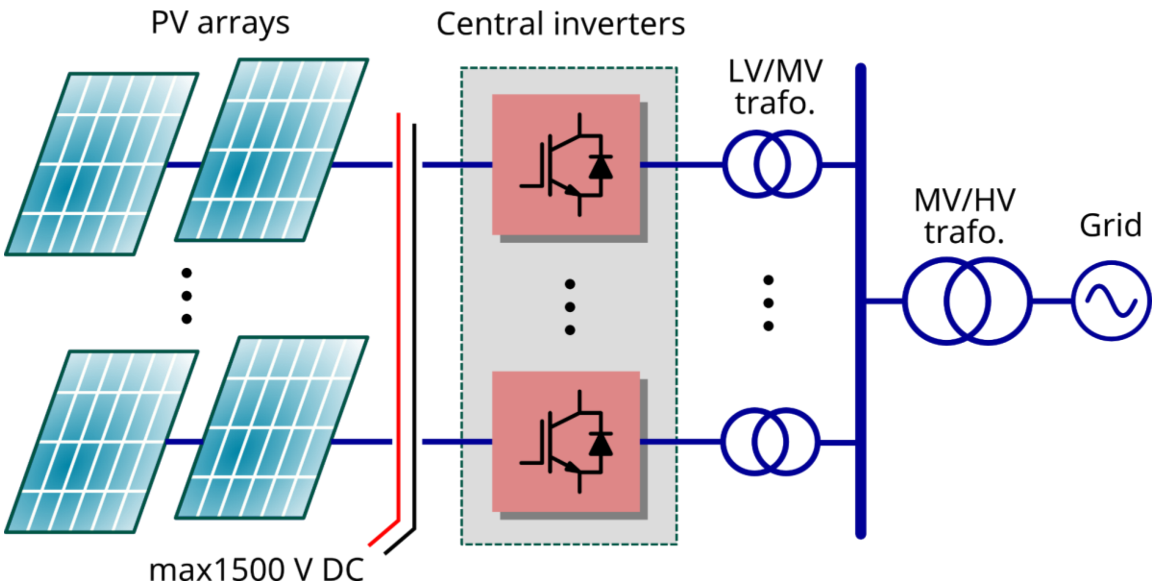


- Constant voltage-to-ground → Low leakage current, suitable for transformerless PV applications.
- High DC-link voltage (> twice of the grid peak voltage)

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

Central Inverters

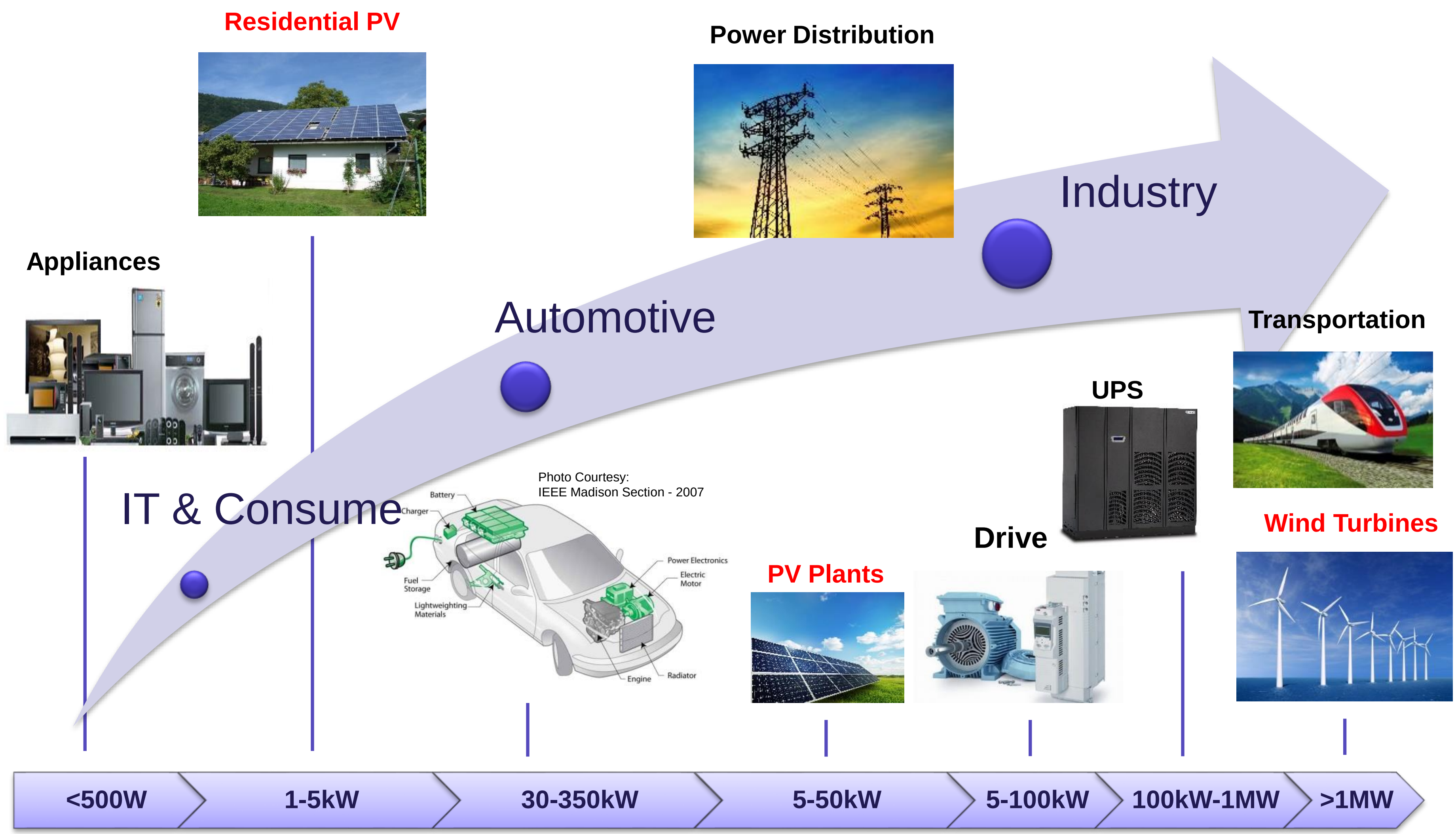
~ 30 kW (tens kilowatts to megawatts)
Very high power capacity.



- Large PV power plants (e.g. 750 kW by SMA), rated over tens and even hundreds of MW, adopt many central inverters with the power rating of up to 900 kW.
- DC-DC converters are also used before the central inverters.
- Similar to wind turbine applications → NPC topology might be a promising solution.

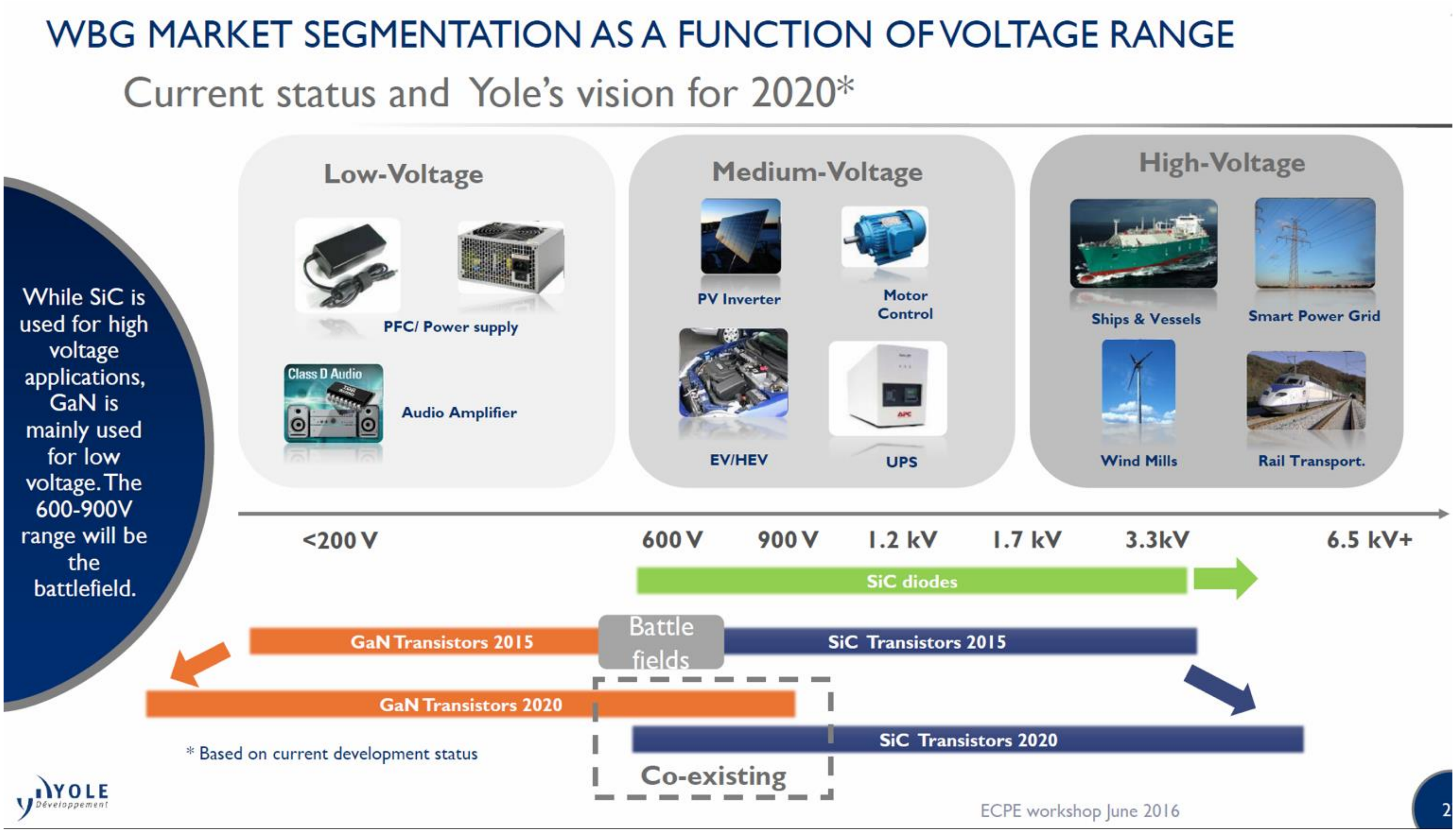
Y. Yang, K. A. Kim, F. Blaabjerg, and A: Sangwongwanich, Advances in Grid-Connected Photovoltaic Power Conversion Systems, Woodhead Publishing, 2018.

Power Level for Renewable Applications



Yole Developement. Status of the power electronics industry. 2012

Wide-bandgap Semiconductors: Application ranges



Sources

Yole Developpement, ECPE Workshop 2016

G. Meneghesso, “Parasitic and Reliability issues in GaN-Based Transistors”, CORPE Workshop 2018, Aalborg, Denmark

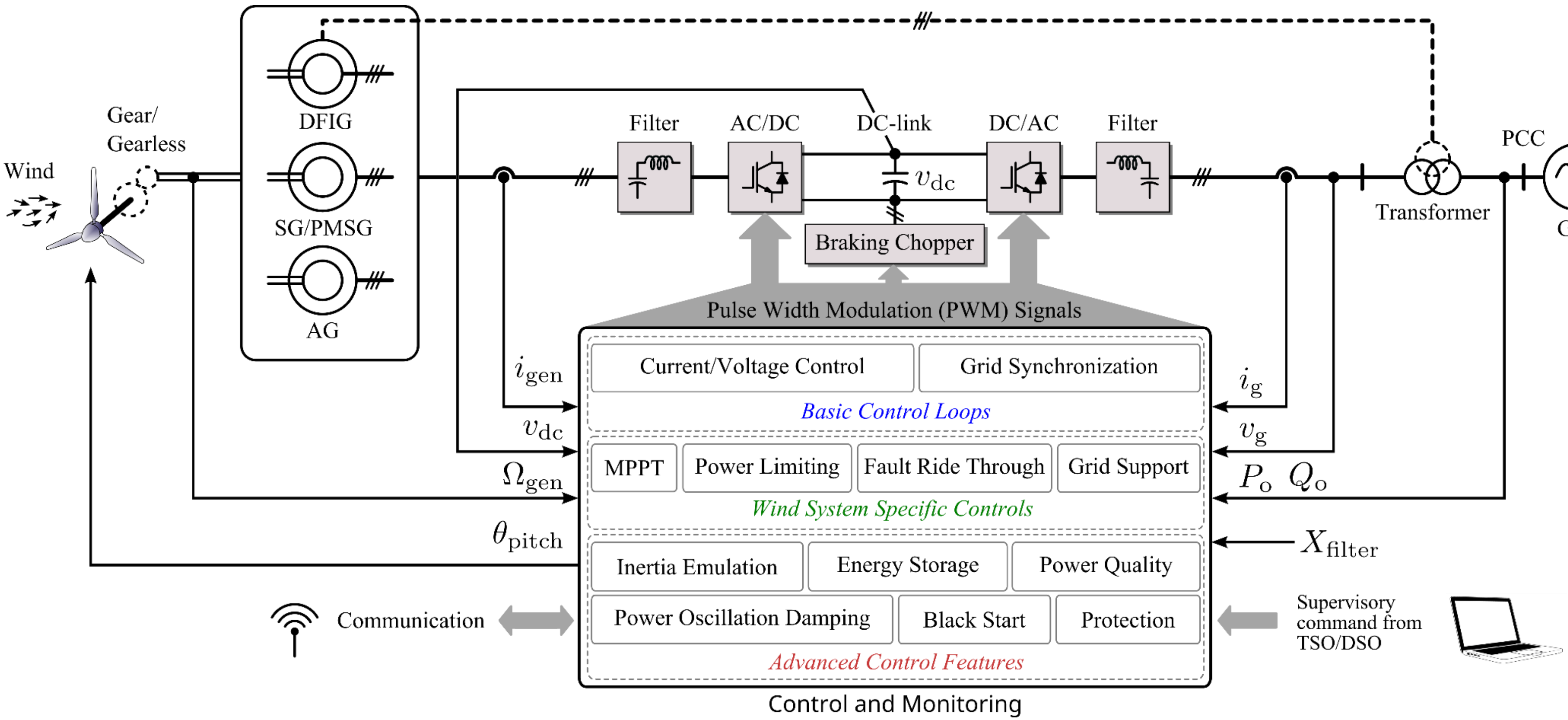
Potential power devices for lower voltage (Eg. PV)

Performances	GaN HEMT	Superjunction SI MOSFET	SiC MOSFET
Power Density	High	Moderate	High
Reliability	High	High	Unknown
Cost	High	Low	High
Failure mode	Short circuit	Both short- and open circuit	Both short- and open circuit
Insulation to heat sink	Yes	No	No
Switching loss	Low	Moderate	Low
Conduction loss	Low	Moderate	Low
Thermal resistance	Moderate	Moderate	Low
Cost factor	High	Low	High
Gate driver	Complex	Simple	Moderate
Major suppliers	EPC, Navitas, Transphorm, Panasonic, GanSystems, NXP, Texas Instruments, Infineon, Fujitsu	Infineon, Renesas, Panasonic, Mitsubishi Electric, Toshiba, Hitachi, STMicrorlectronics, Bosch, Sumitomo Electric, Raytheon, CRRC	Wolfspeed, Rohm, Mitsubishi, Infineon, Littelfuse, GE, Fuji, GeneSiC, Microsemi, OnSemi, USCi, GlobalPower
Voltage ratings in real power application	≤ 650 V	≤ 600 V	≤ 1700 V
Max. current ratings	90 A (100 V), 50 A (650 V)	20 A (600 V)	1200 A (1700 V)

Potential power devices for wind power

Performances	Si-IGBT module	Si-IGBT Press-pack	SiC MOSFET module
Power Density	Low	High	Low
Reliability	Moderate	High	Unknown
Cost	Moderate	High	High
Failure mode	Open circuit	Short circuit	Open circuit
Insulation to heat sink	Yes	No	Yes
Switching loss	Moderate	Large	Low
Conduction loss	Moderate	Moderate	Large
Thermal resistance	Large	Small	Moderate
Cost factor	Moderate	High	High
Gate driver	Moderate	Moderate	Small
Major suppliers	Infineon, Semikron, Mitsubishi, ABB	Westcode, ABB	Cree, Rohm, Mitsubishi
Voltage ratings in wind power application	1.7 / 2.5 / 3.3 / 4.5 / 6.5 kV	2.5 / 4.5 / 5.2 / 6.5 kV	1.2 / 1.7 / 10 kV
Max. current ratings	3.6 / 1.5/ 1.8 /1.5 / 1.0 kA	2.25 / 3 / 3 / 0.9 kA	0.8 / 1.2 / 0.02 kA

General Control for Wind Turbine System



Level I – Power converter

- ✓ Grid synchronization
- ✓ Converter current control
- ✓ DC voltage control

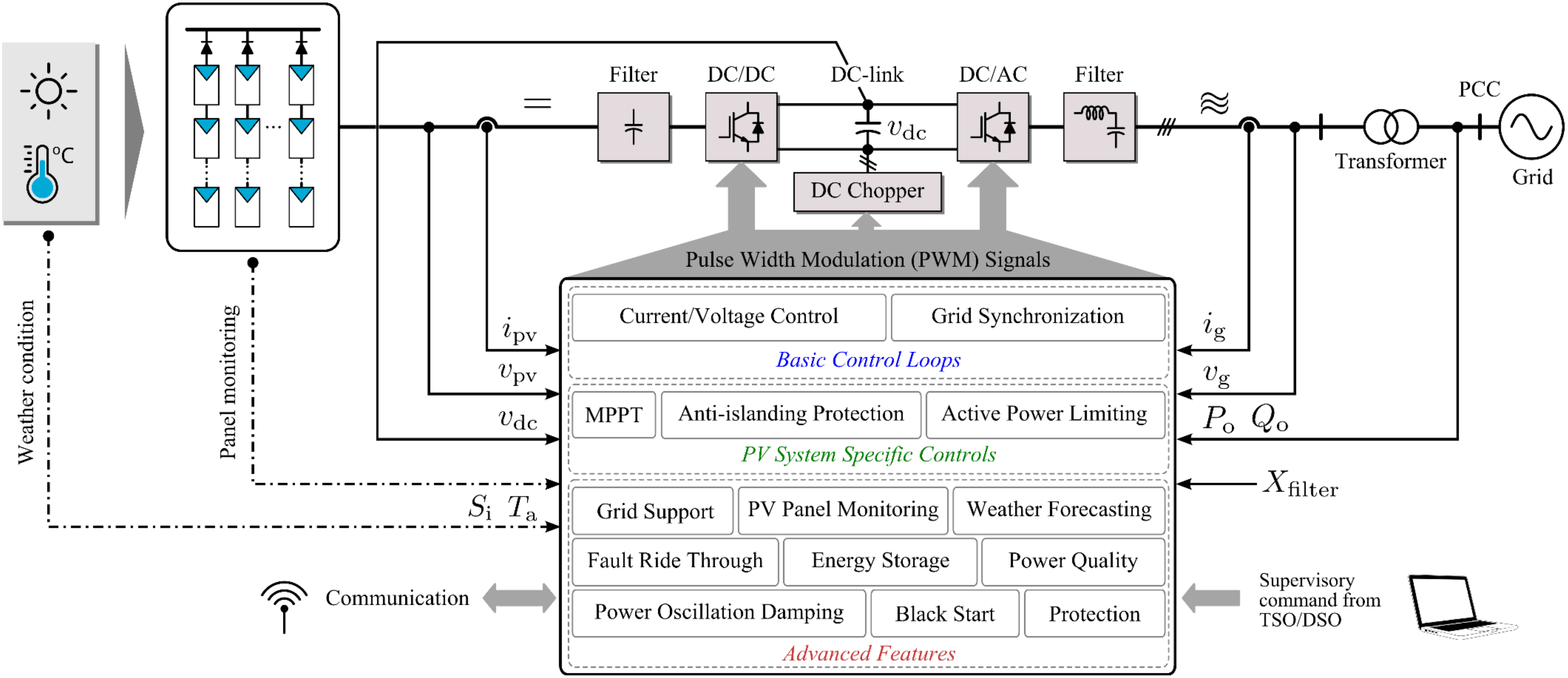
Level II – Wind turbine

- ✓ MPPT
- ✓ Turbine pitch control
- ✓ DC Chopper

Level III – Grid integration

- ✓ Voltage regulation
- ✓ Frequency regulation
- ✓ Power quality

General Control Structure for PV Systems



Control and Monitoring

Basic functions – all grid-tied inverters

- Grid current control
- DC voltage control
- Grid synchronization

PV specific functions – common for PV inverters

- Maximum power point tracking – MPPT
- Anti-Islanding (VDE0126, IEEE1574, etc.)
- Grid monitoring
- Plant monitoring
- Sun tracking (mechanical MPPT)

Ancillary support – in effectiveness

- Voltage control
- Fault ride-through
- Power quality
- …

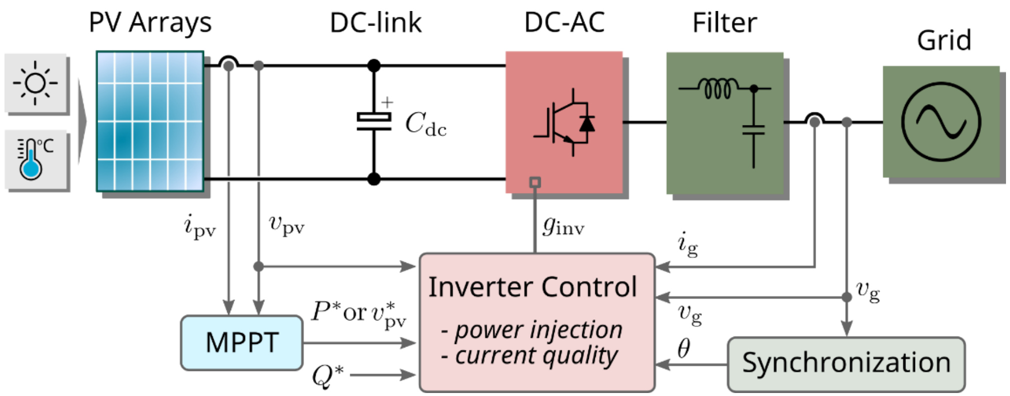
MPPT Algorithms

MPPT Methods	Advantages	Disadvantages
Perturb & Observe (P&O) / Incremental Conductance	• Simple • Low computation • Generic	• Tradeoff beteween speed and accuracy • Goes to the wrong way under fast changing conditions
Constant Voltage (CV)	• Much simple • No ripple due to perturbation	• Energy is wasted during Voc measurement • Inaccuracy
Short-Current Pulse (SCP, i.e., constant current)	• Simple • No ripple due to perturbation	• Extra swith needed for short-circuiting • Inaccuracy
Ripple Correlation Control	• Ripple amplitude provides the MPP information • Noneed for perturbation	• Tradeoff between efficiency loss due to MPPT or to the ripple

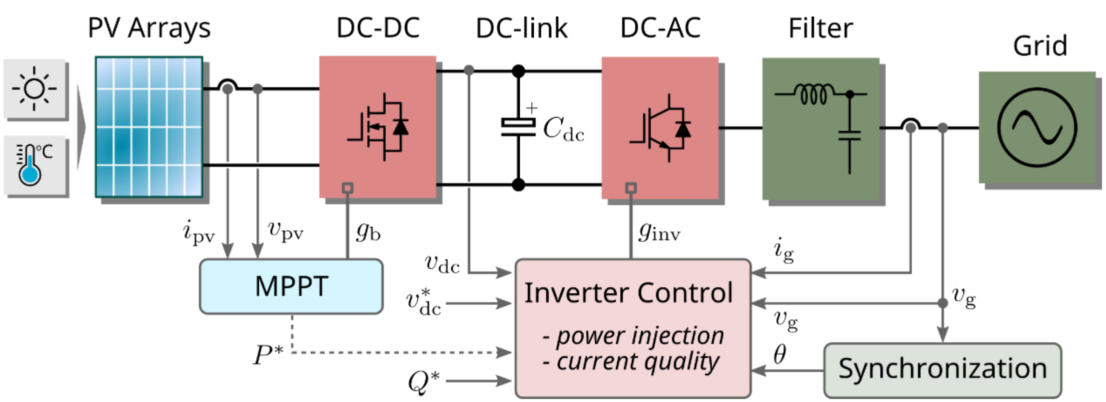
P&O – the most commonly used MPPT algorithm!

Implementation of MPPT Control

- Single-Stage System



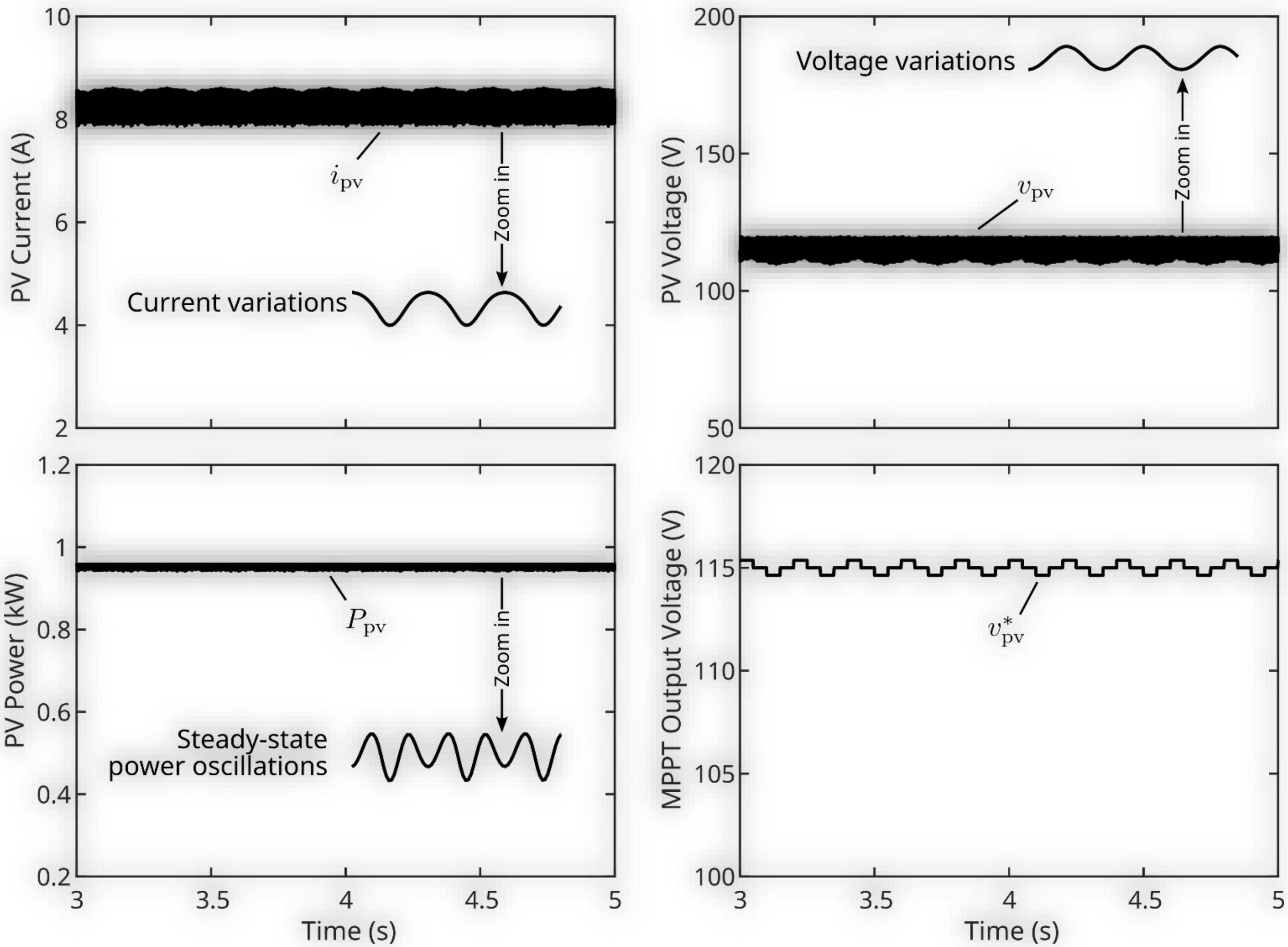
- Double-Stage System (in the DC-DC converter)



Y. Yang, K. A. Kim, F. Blaabjerg, and A: Sangwongwanich, Advances in Grid-Connected Photovoltaic Power Conversion Systems, Woodhead Publishing, 2018.

Example of MPPT Control

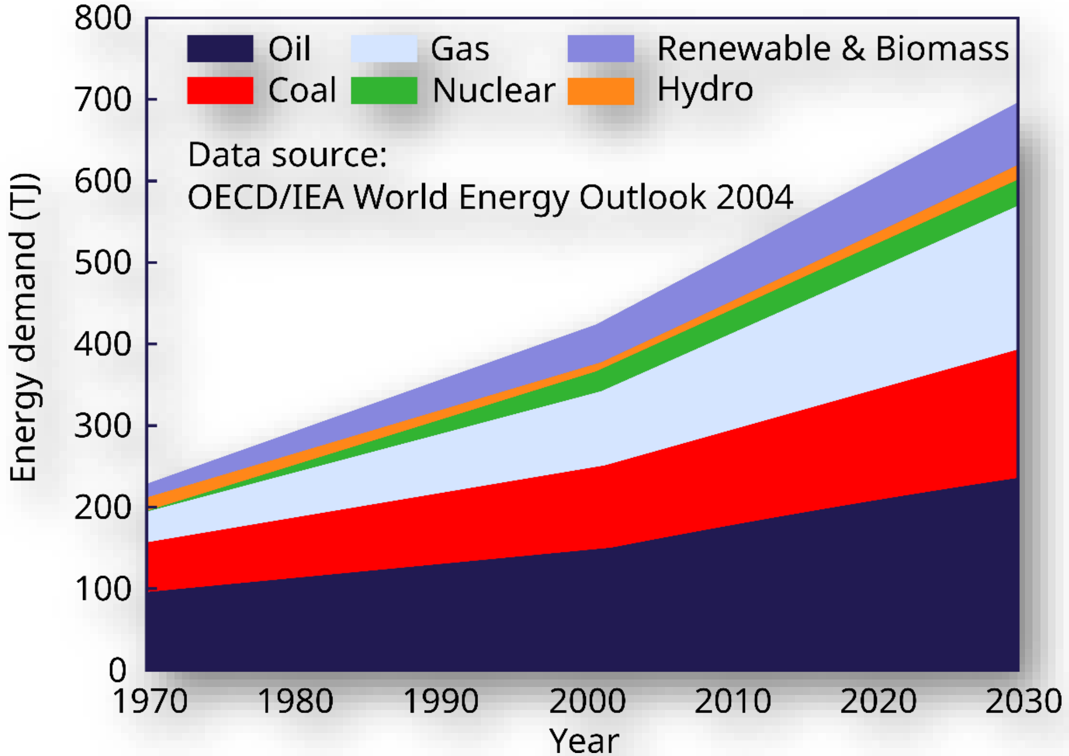
For a boost optimizer:



Y. Yang, K. A. Kim, F. Blaabjerg, and A: Sangwongwanich, Advances in Grid-Connected Photovoltaic Power Conversion Systems, Woodhead Publishing, 2018.

Future Challenges and Discussions

Increasing Energy Demand

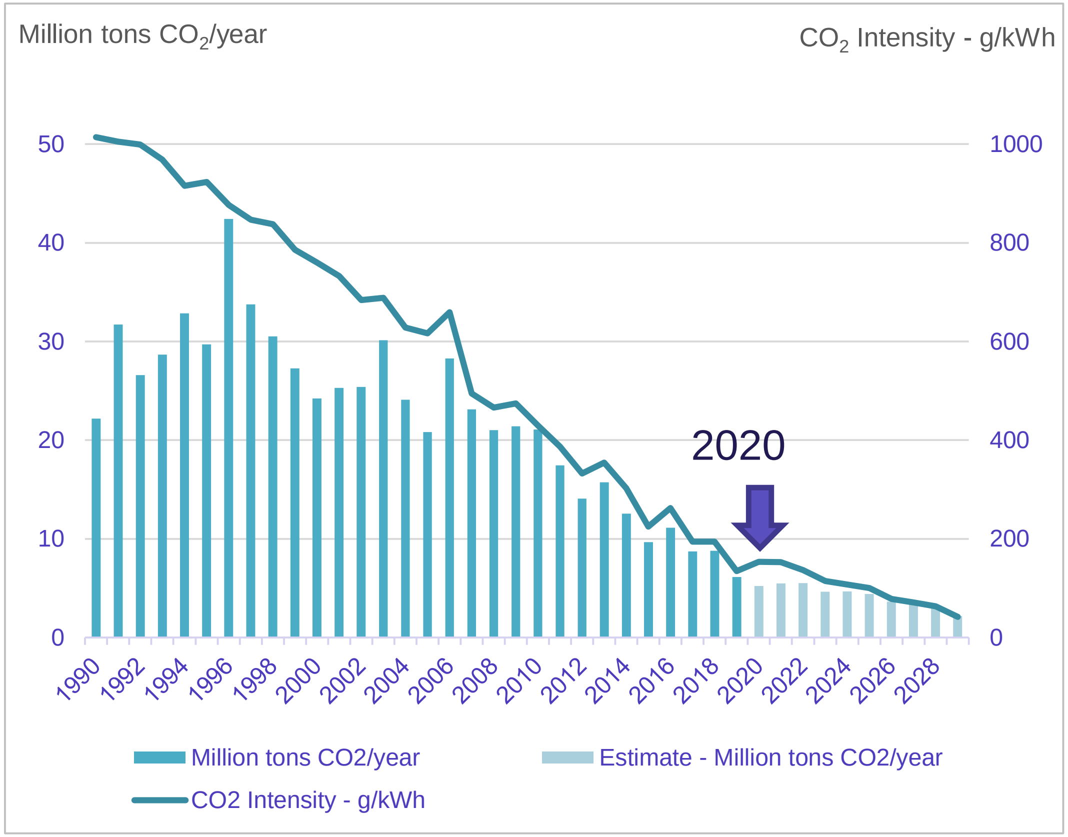


Worldwide Energy Demand Since 1970 and The Estimation till 2030

(Source: International Energy Agency (IEA), World energy outlook 2004 http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2004.pdf.)

The Danish Plan to Reduce CO2

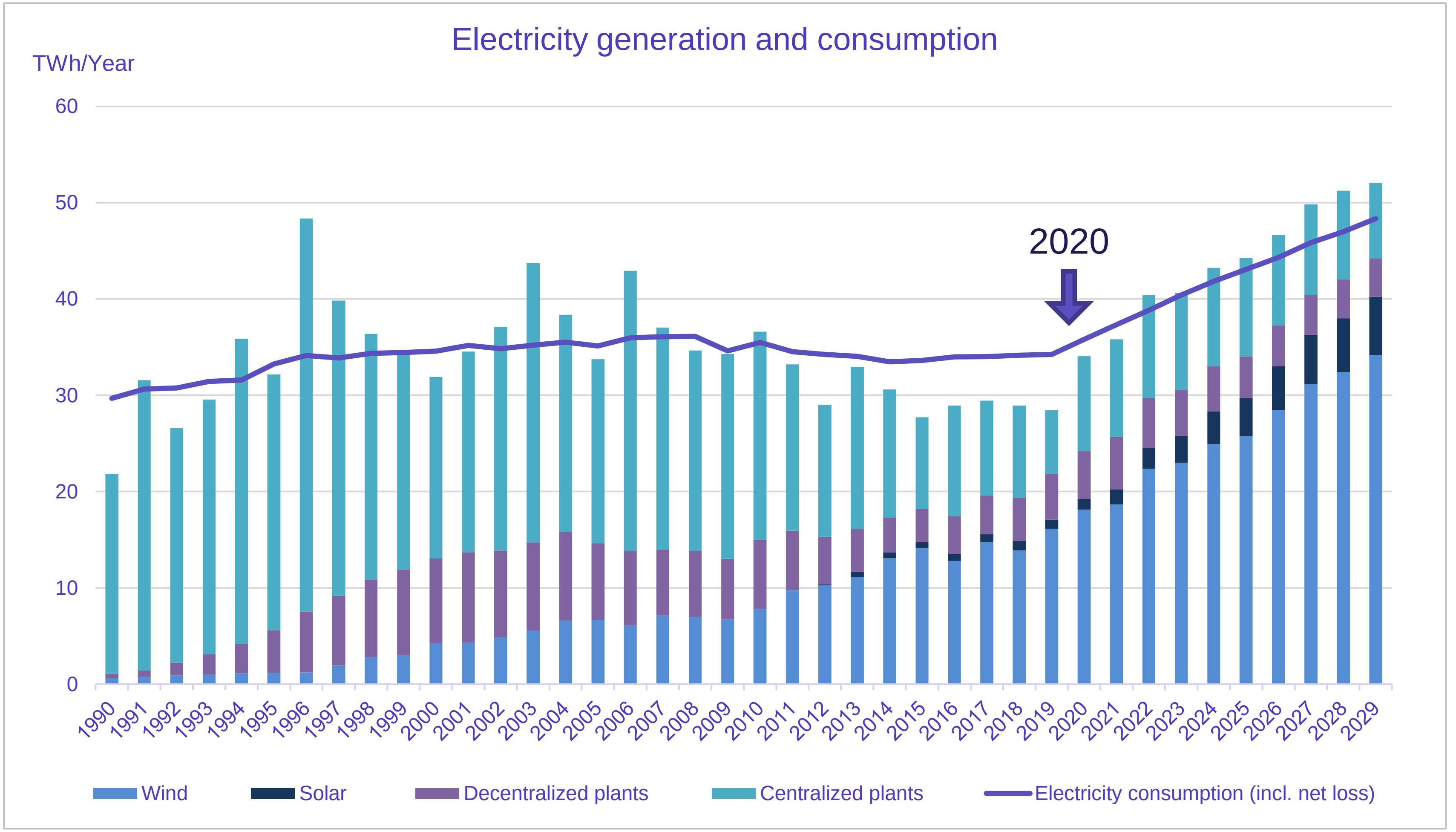
Danish prime minister Mette Frederiksen (Photo: News Oresund/Commons)



Under the agreement, the new government pledged to introduce binding decarbonization goals and strengthen its 2030 target to reduce emissions by **70%** below the 1990 level – the current target is 40%.

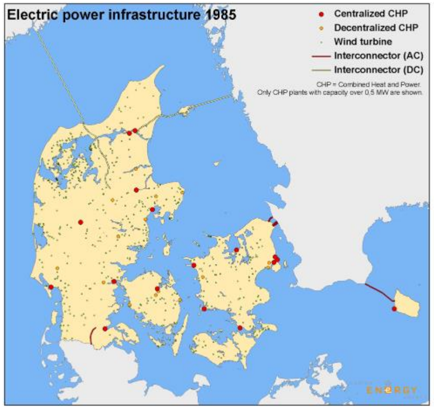
Energinet.dk, Miljørapport 2020 (in Danish) - https://energinet.dk/Om-publikationer/Publikationer/Miljoerapport-2020

Electricity Generation and Consumption in DK



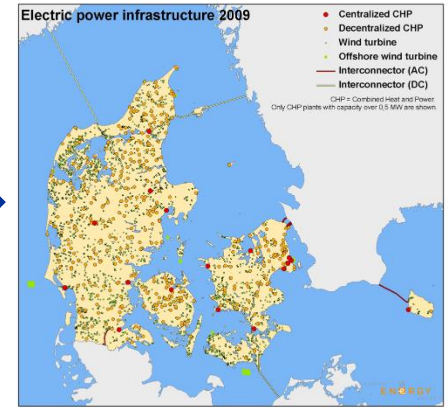
Energinet.dk, Miljørapport 2020 (in Danish) - https://energinet.dk/Om-publikationer/Publikationer/Miljoerapport-2020

Transition of Energy System



(Source: Danish Energy Agency)

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

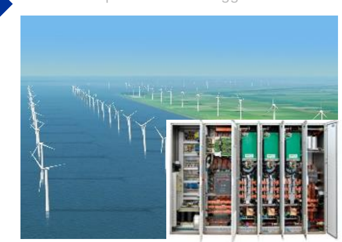


(Source: Danish Energy Agency)

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

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

Source: http://media.treehugger.com

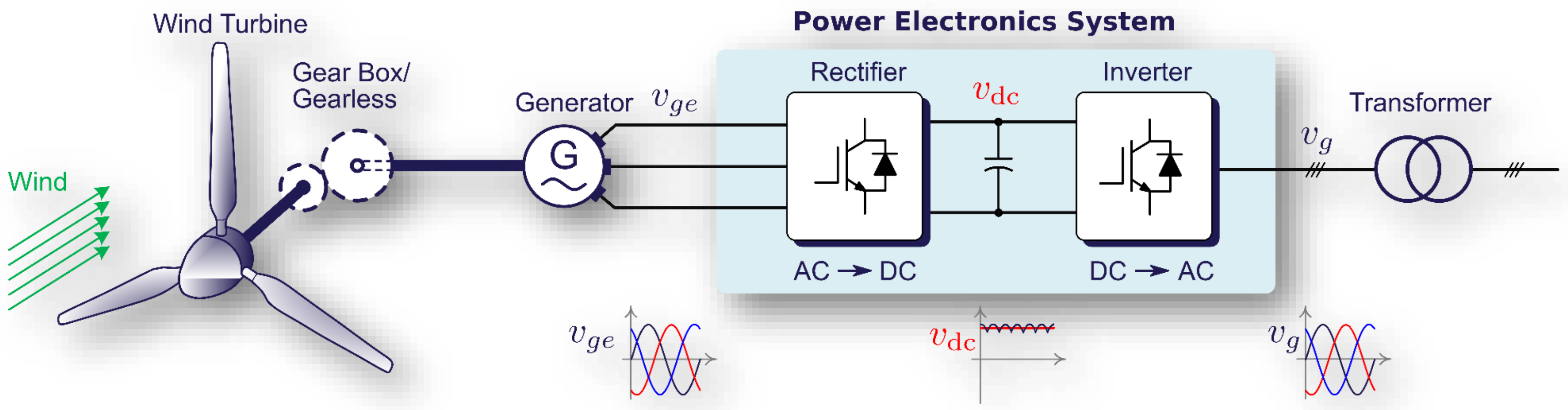


Source: www.offshorewind.biz

Towards 100% Power Electronics Interfaced

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

Wind Turbine Technologies

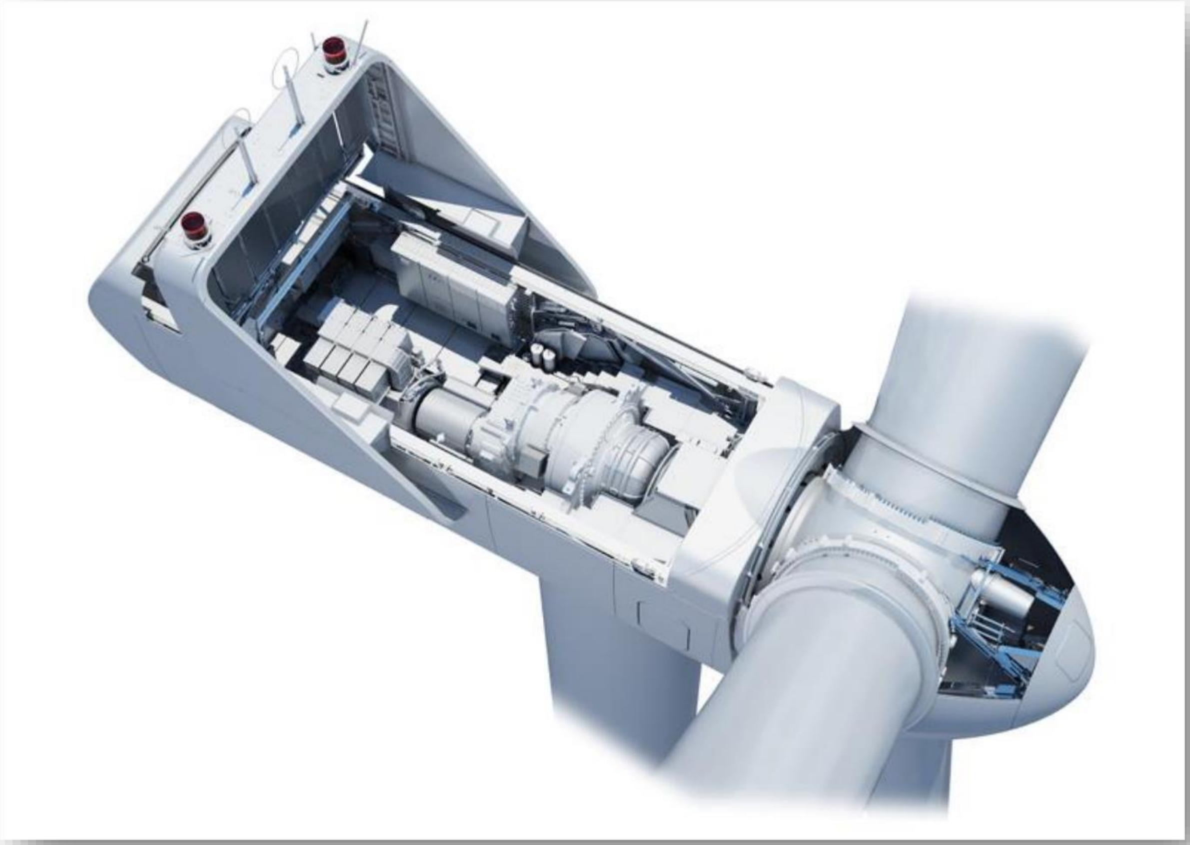


In the **1980s**, a wind turbine of 50 kW was considered large, while today's typical wind turbines are rated at 2–3 MW and design is now approaching **10 MW**. Much of the development for larger units was driven by the need for **lower cost of energy**, while some of the electric technology changes were imposed by performance improvements, especially in terms of grid connection.

A 400 MW off-shore Wind Power System in Denmark

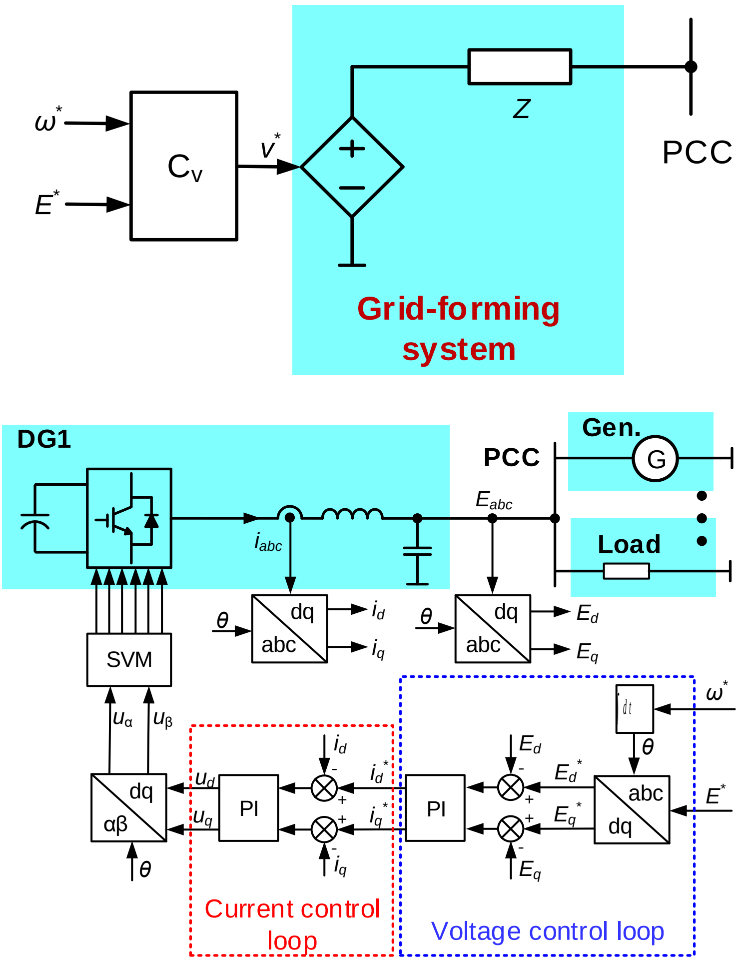
Anholt-DK (2016) – Ørsted

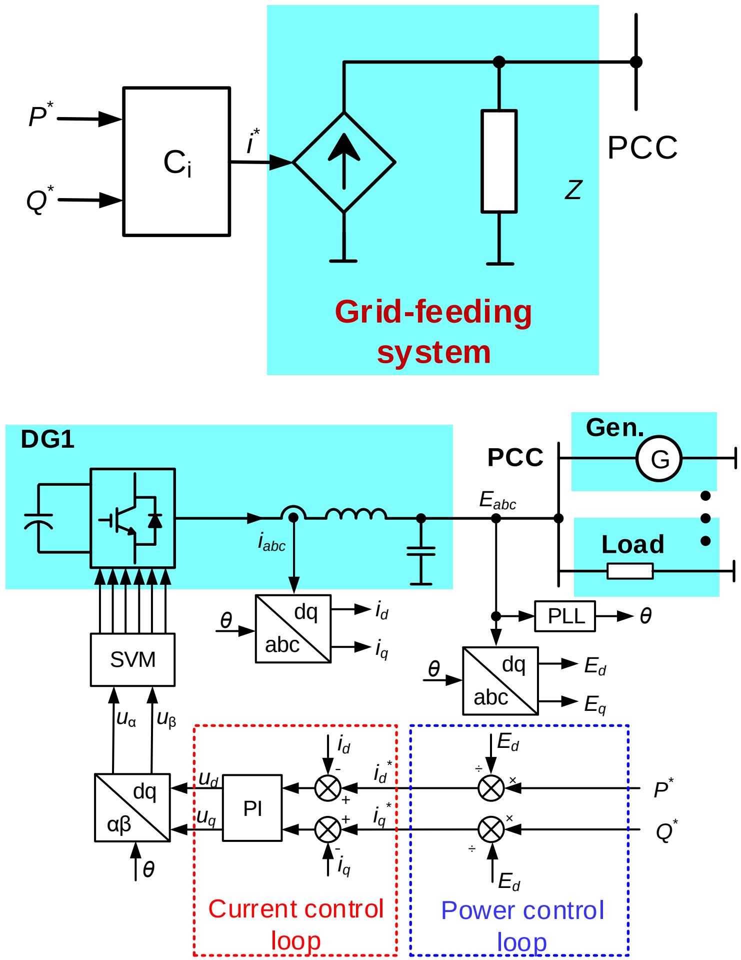
Wind Turbine Technologies



Bird's-eye view of the nacelle of a state of the multi-MW wind turbine, including electric generator and power electronics converters. (Courtesy of Vestas Wind Systems A/S.)

Grid-forming & Grid-feeding Systems (examples)

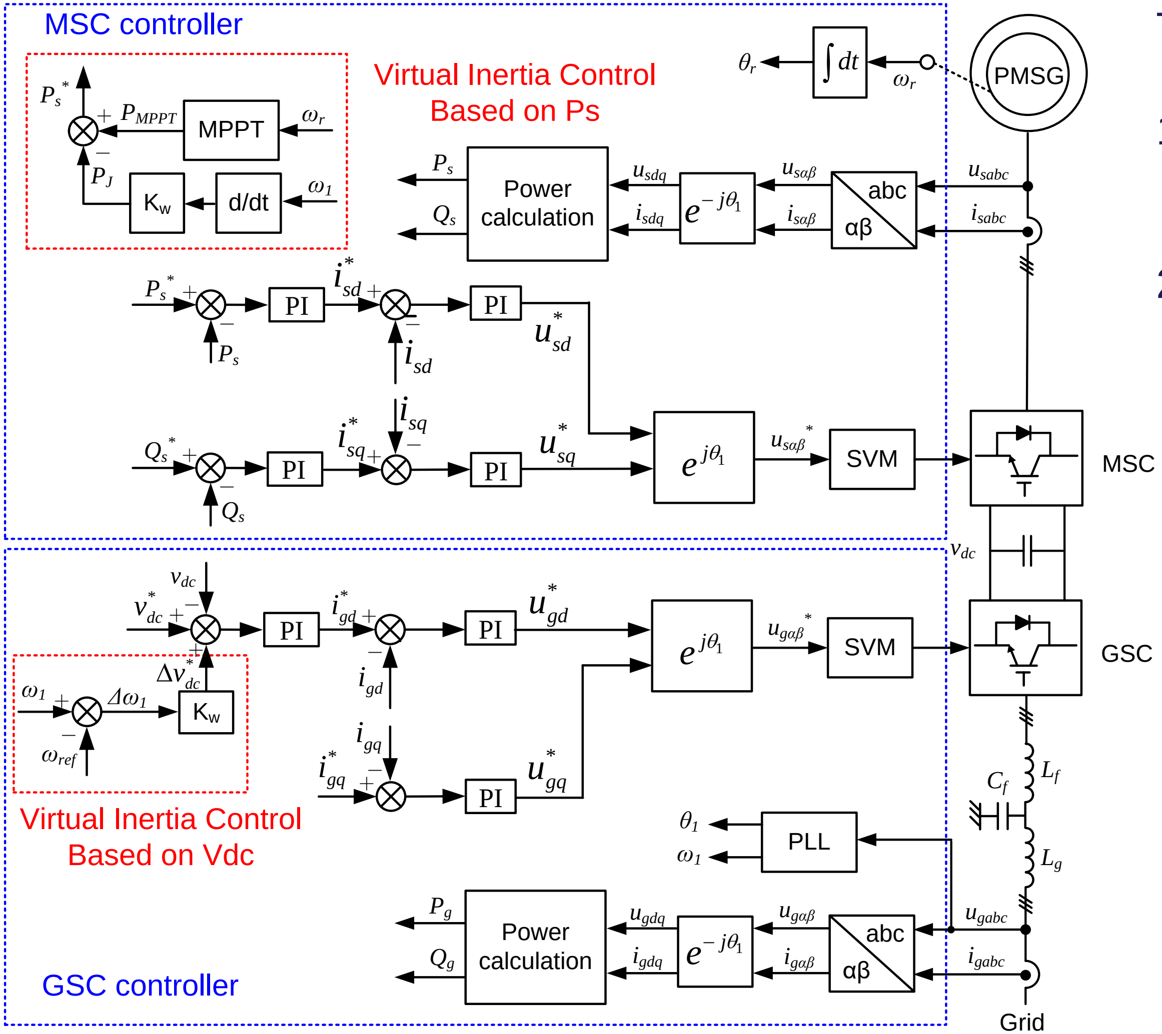




- Voltage-source based inverter
- Control reference: voltage amp. & freq.

- Current-source based inverter
- Control reference: active & reactive power

Virtual Inertia Emulation in PMSG based Wind System



Two virtual inertia solutions:

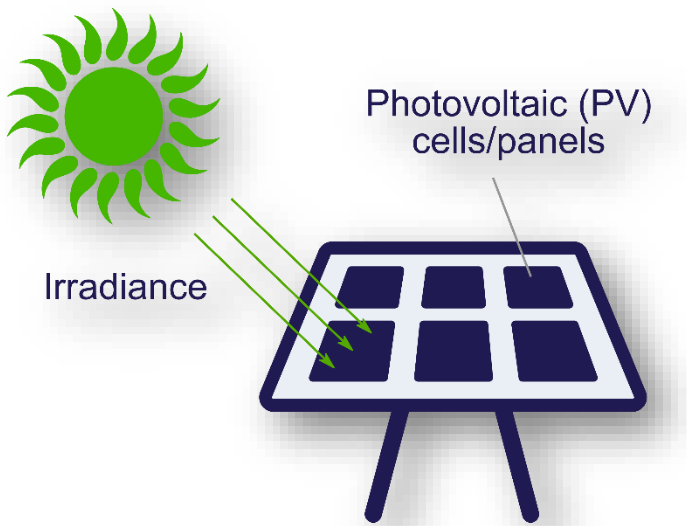
1) Virtual inertia control based on Ps in MSC controller;

2) Virtual inertia control based on Vdc in GSC controller;

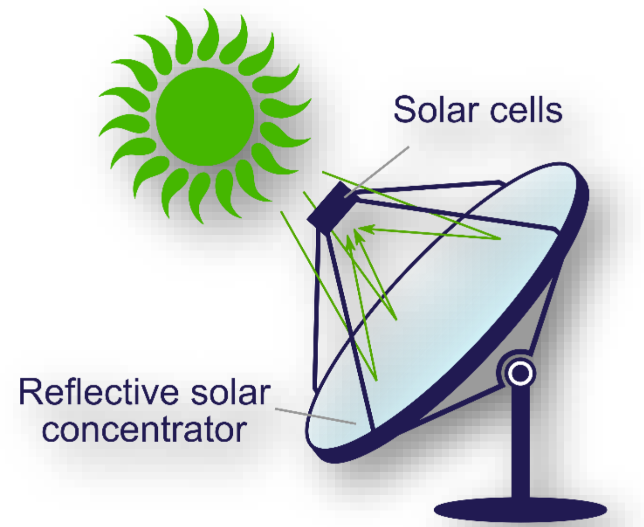
Solar Energy

Can be captured via two ways:

- Solar photovoltaic
- Concentrated solar power (CSP)

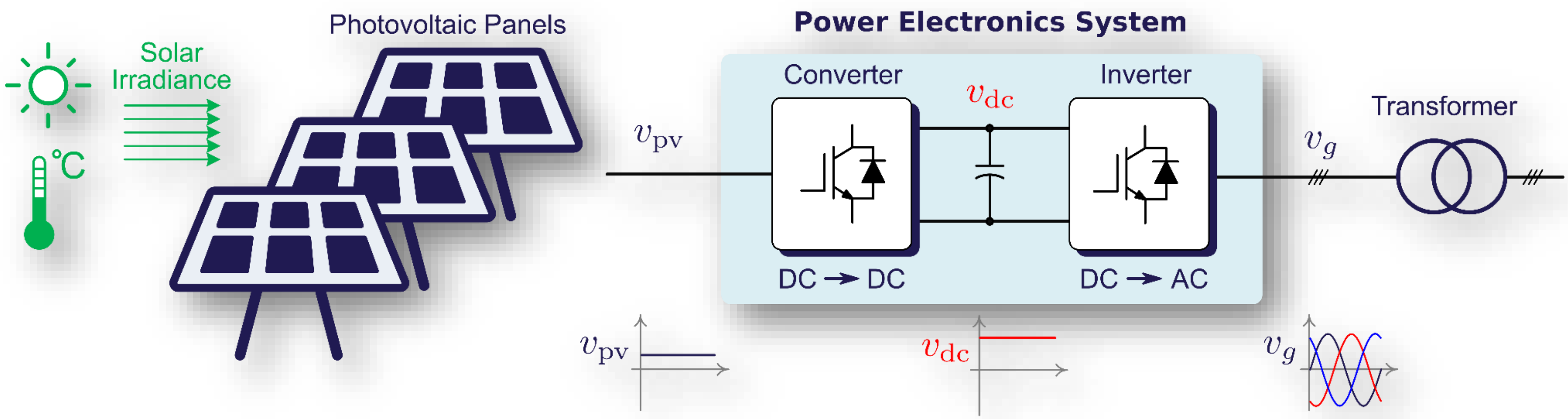


Solar Photovoltaic (PV)



Concentrated Solar PV (CPV)

Solar Photovoltaic Technologies



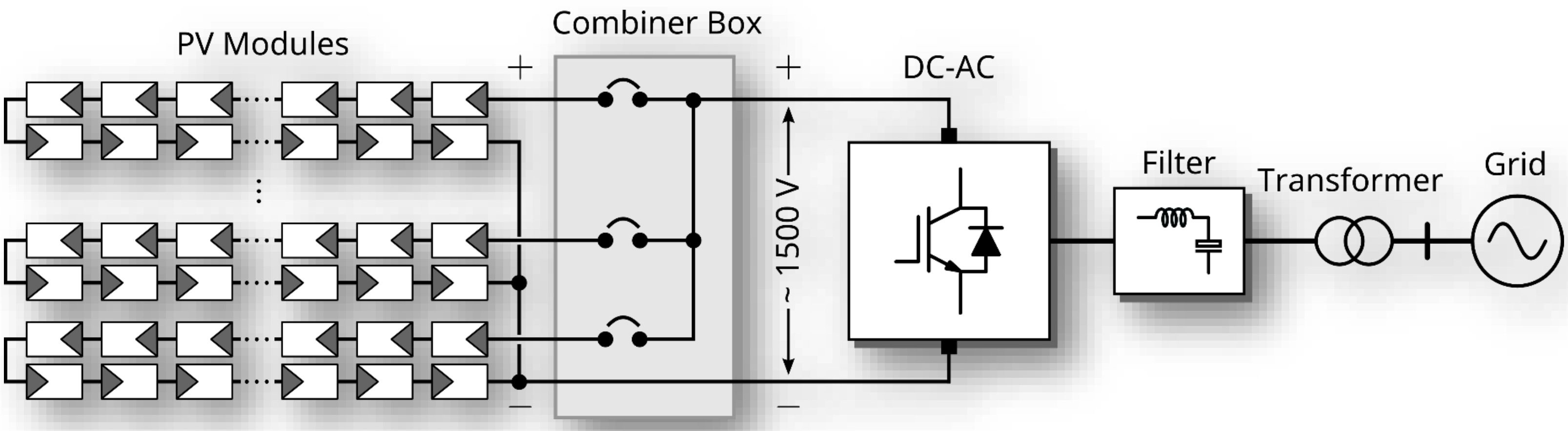
Grid-connected PV systems comprise a power electronics DC/DC converter, which ensures a maximum solar energy harvesting through a maximum power point tracking (MPPT) control, and a DC/AC converter for interconnection to the grid. PV systems have gained large popularity not only for multi-MW **utility-scale** power plants/farms but also as **rooftop installations** on commercial and residential buildings with ratings as small as hundreds of Watts, but typically in the kW range.

Solar Photovoltaic Technologies

Rooftop-installed PV systems: (a) PV arrays with a total rating of 60 kW installed on the roof of Aalborghus High School in Denmark and (b) power electronic converters with the schematic are installed within the building and are connected to the AC grid.

1500-V DC PV System

Becoming the 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

1500-V DC PV System

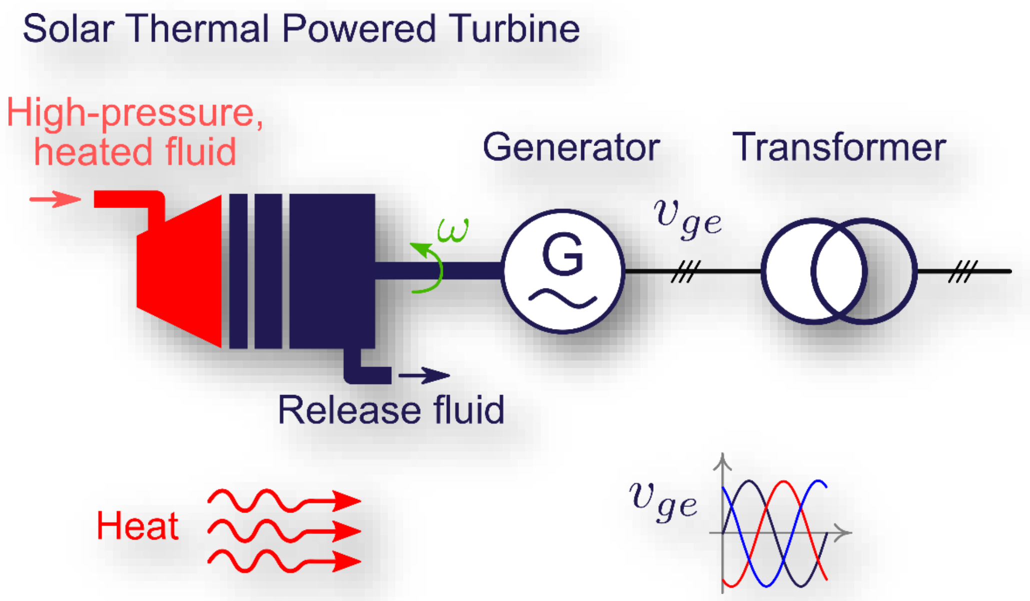
Becoming the mainstream solution!

ABB MW Solution

Sungrow five-level topology

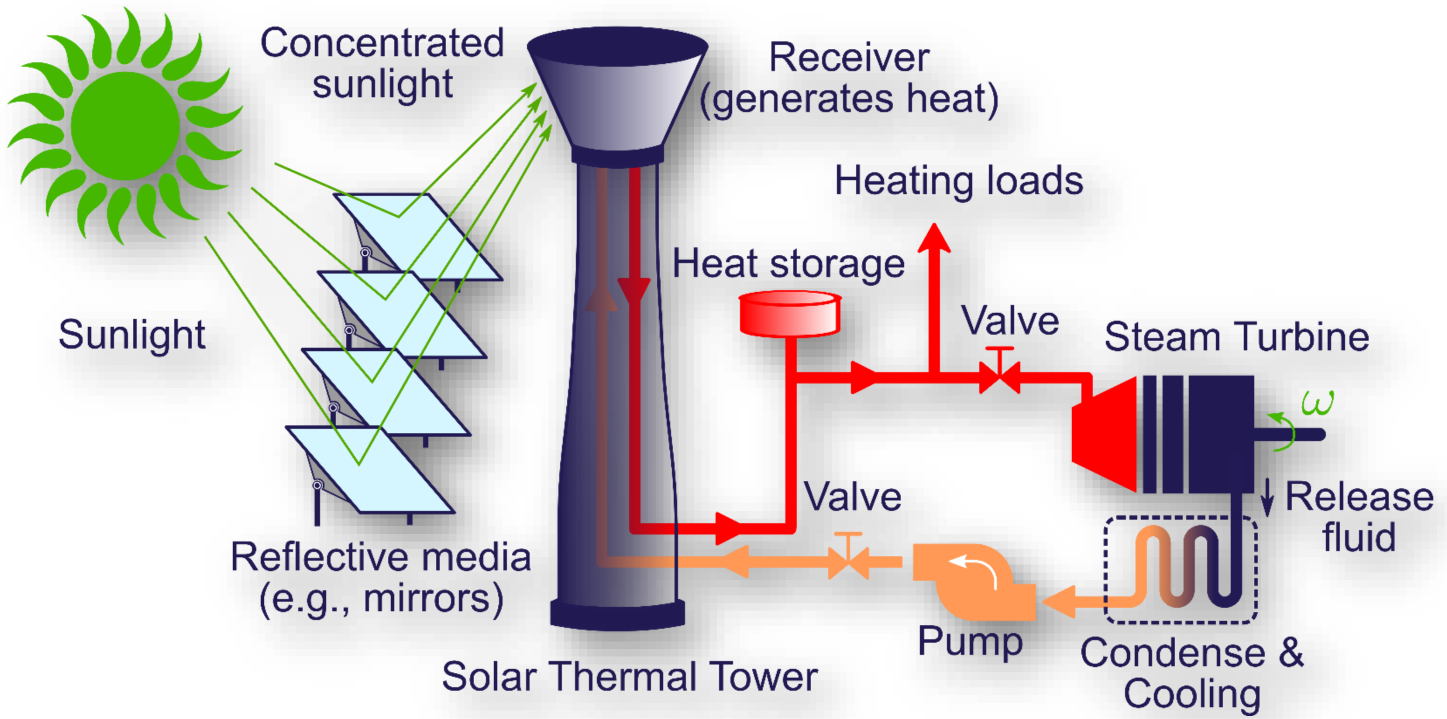
https://www.pv-tech.org/products/abb-launches-high-power-1500-vdc-central-inverter-for-harsh-conditions
https://www.pv-tech.org/products/sungrows-1500vdc-sg125hv-string-inverter-enables-5mw-pv-power-block-designs

CSP Technologies



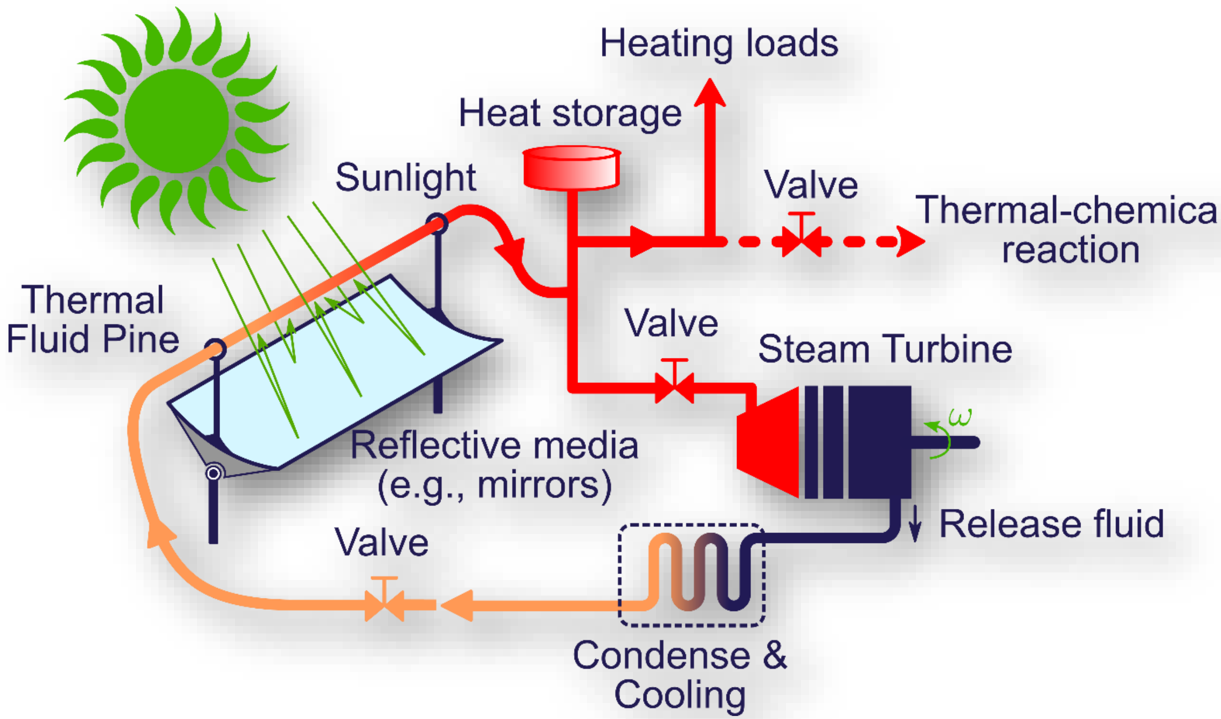
Solar energy can be captured by **concentrating sunlight** using **reflective components** to receivers, which can carry or transfer the generated heat. . Then, the heat can **drive an engine** that is further connected to an electrical generator to produce electricity; or the heat can be used to **power thermal–chemical reactions**.

CSP Technologies



Central solar tower as a receiver for heat generating

CSP Technologies



Sunlight concentrated by a parabolic trough line structure

CSP Example 1

On the left, phase 1 of the Noor CSP plant is generating energy. On the right, phase 2 will be completed in 2017 and phase 3 in 2018.

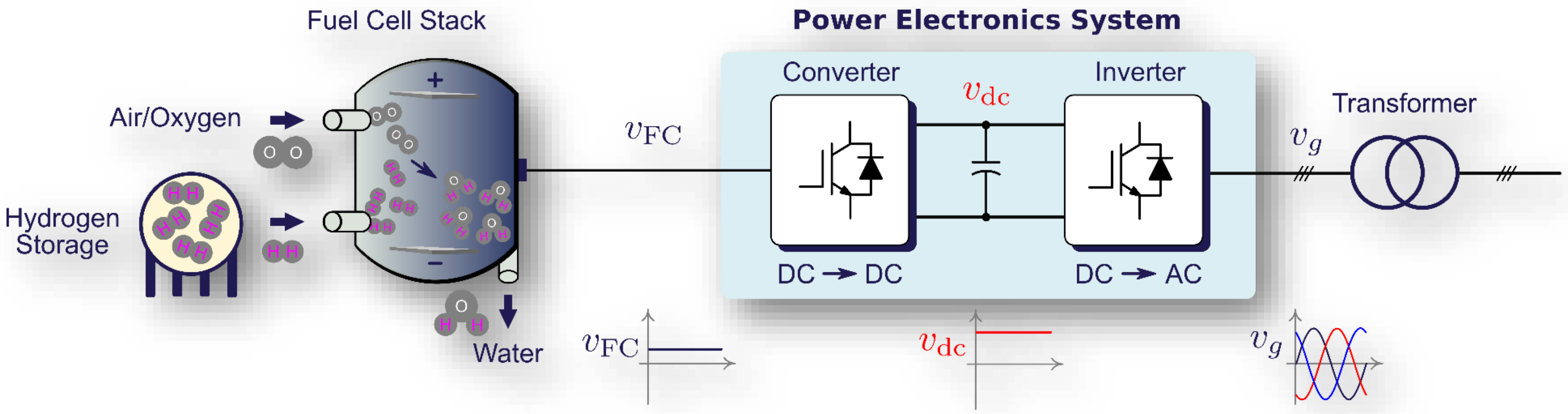
https://www.cio.com/article/3031898/worlds-largest-solar-plant-goes-live-will-provide-power-for-11m-people.html

CSP Example 2

Close up view of parabolic trough and heat collector

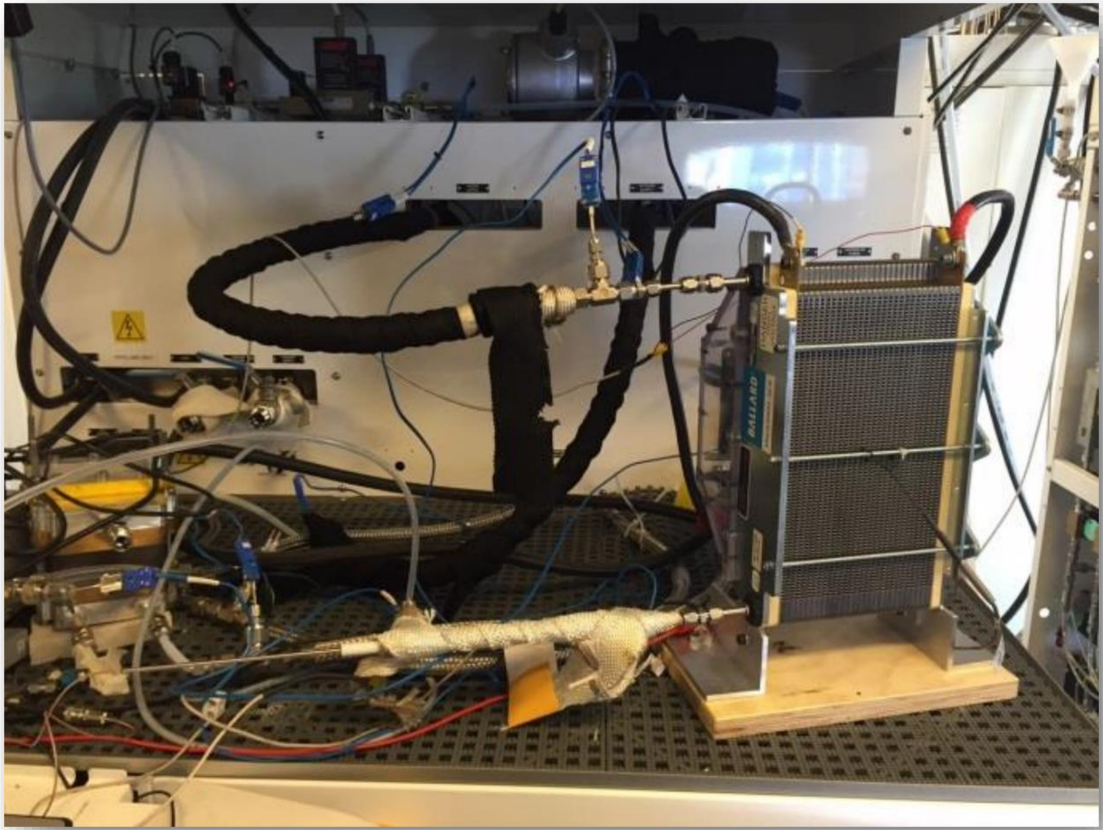
http://theoildrum.com/node/2583

Fuel Cell Systems



Fuel cell systems have been **expected for many years** to increase their presence in applications over a wide range of power ratings. The typically low-temperature **proton exchange membrane (PEM)** technology and the higher-temperature **solid oxide fuel cells (SOFC)** type can be applied for large power supplies, with some demonstrators being completed for uninterruptible power supply (UPS) systems.

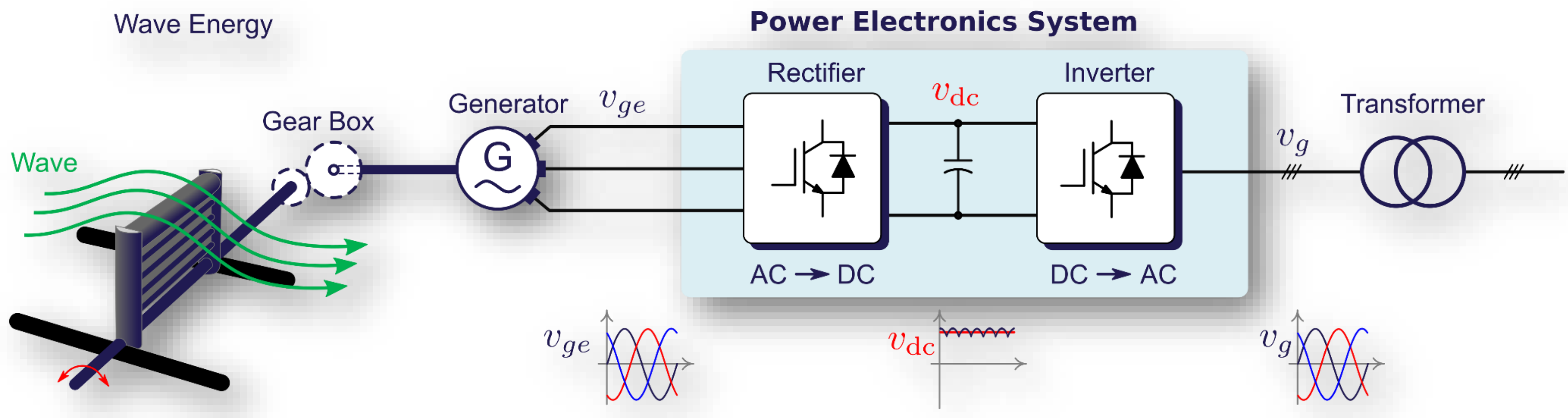
Fuel Cell Systems



Low-temperature PEM fuel cell setup at Aalborg University with approximate 1.2 kW electrical capacity (28 cells each of 43 W) and hydrogen as fuel.

BREAKING NEW GROUND
AALBORG UNIVERSITY

Wave Energy



More than **70%** of the earth surface is covered by water, making oceans and seas **a potentially huge energy resource**, which is yet largely untapped. In the example solution, the movement of waves engages a mechanical transmission that is coupled to an electric generator.

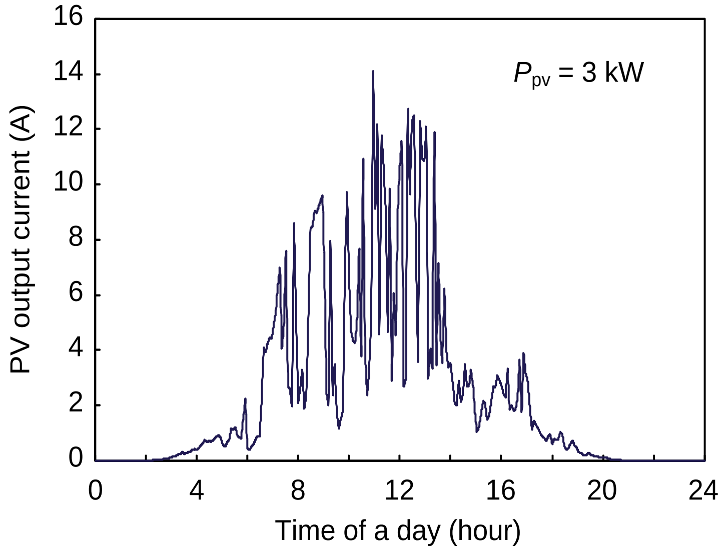
- Very low speeds and large power variations require special solutions and may result in relatively reduced conversion efficiencies.
- Long-term reliability under very harsh environmental conditions and survivability during storms are major challenges that drive up the investment, operation and maintenance efforts, and ultimately the final cost of energy for such system.

Wave Energy

Wave Star wave energy generator located at the Hanstholm test site in Denmark. (Courtesy of Wave Star Company.)

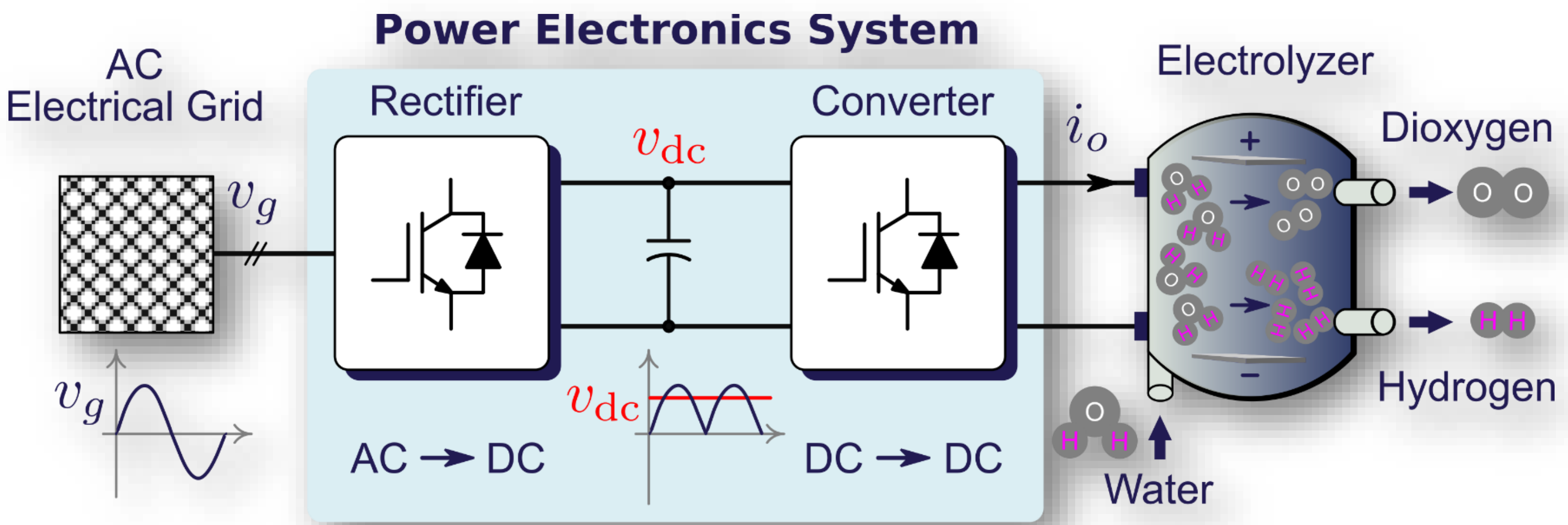
Energy Storage Technologies

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.



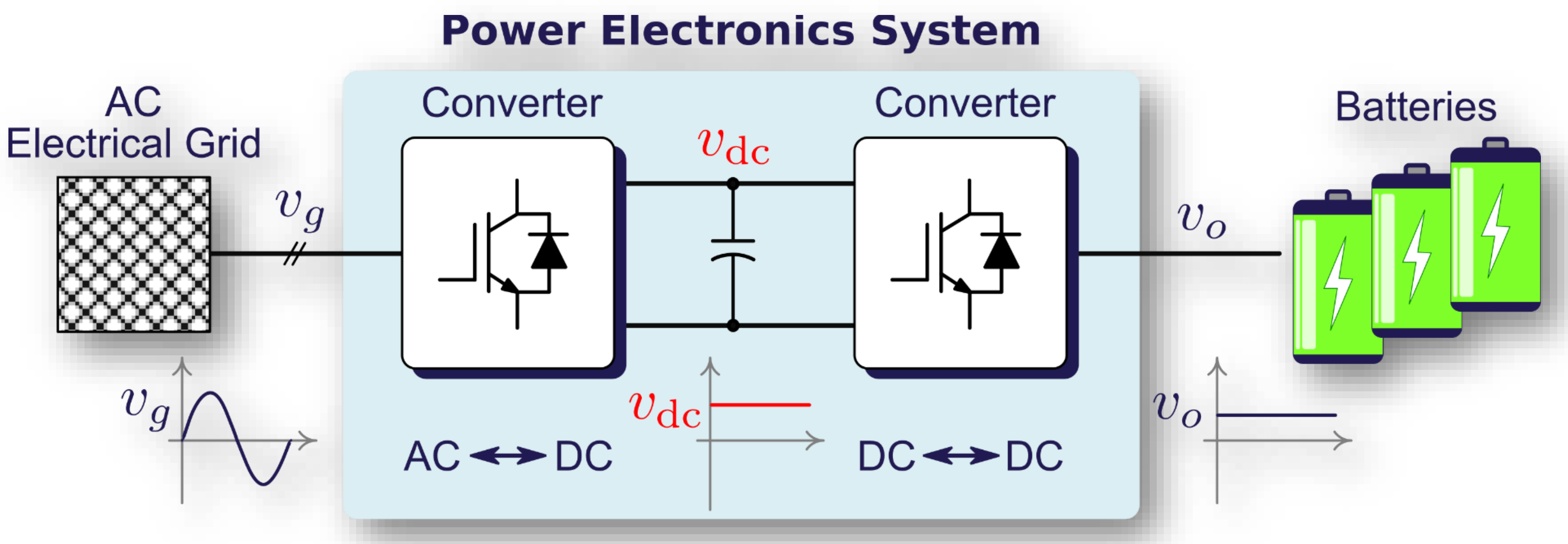
PV power weather-dependency

Energy Storage – Electrolyzer



System for producing hydrogen using an electrolyzer supplied with electricity from the AC electrical grid or renewable energy sources. The hydrogen can be stored under pressure and/or used with fuel cells.

Energy Storage – Batteries



System using batteries for storing electric energy from the AC electrical grid or renewable energy sources. Power electronics control ensures bidirectional energy flow.

Energy Storage Examples

Li-on Batteries for PV Applications

Redox Flow Batteries for PV Applications

Renewable energy systems – Summary

- Solar power fully competitive with fossil today
- Large pressure on reducing CoE for wind
- WBG might reduce converter technology size and cost !?
- All types of PV inverters will evolve – but not major cost in PV..
- Grid codes will constantly change – improve technology
- More intelligence into the control of renewables
- Grid-feeding/Grid forming – how to do in large scale systems ?
- Storage is coming into system solutions
- Black start of systems (Inrush currents – how to do it)
- Protection coordination in future grid ?
- Stability of PE-Dominated grid
- Other energy carriers will be a part of large scale system balance
- Renewables 100 % competitive in 10 Years………. Power electronics is enabling

Acknowledgment

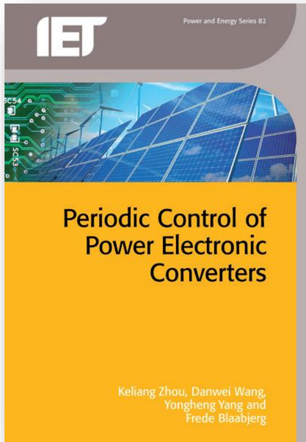
Prof. Frede Blaabjerg, Dr. Xiongfei Wang, Dr. Dao Zhou, Dr. Tomislav Dragicevic, Dr. Huai Wang

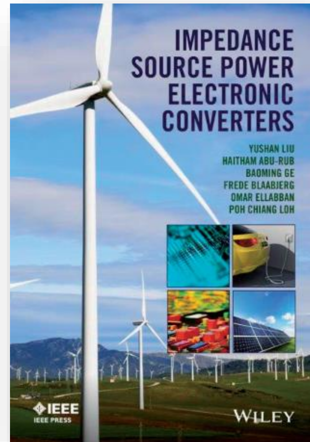
from Department of Energy Technology
Aalborg University

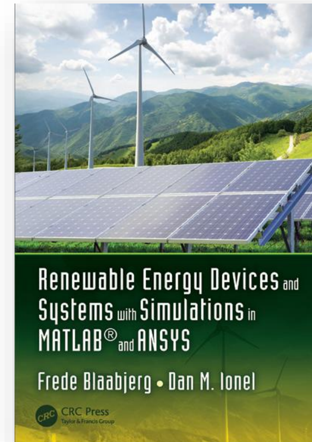
Look at

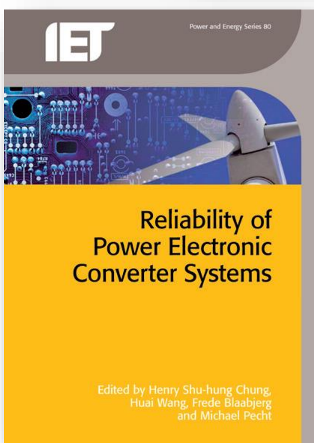
www.et.aau.dk
www.corpe.et.aau.dk
www.harmony.et.aau.dk
www.repeps.et.aau.dk

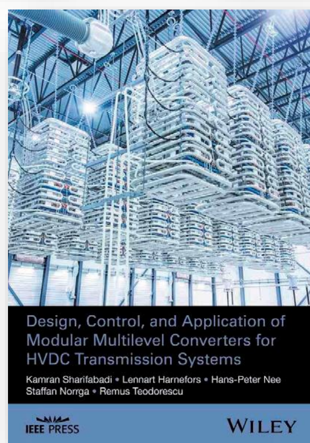
Books available

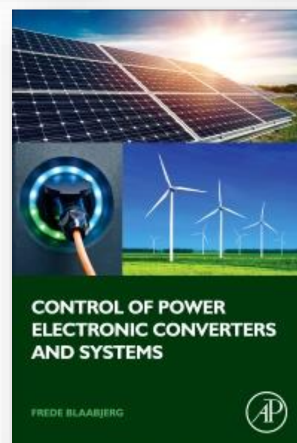


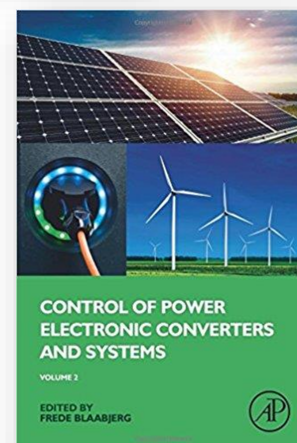




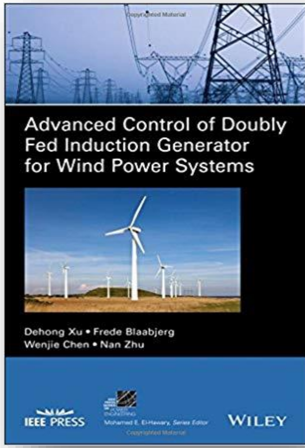


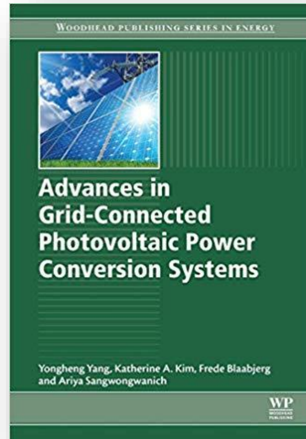


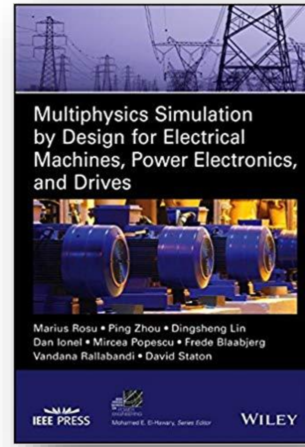


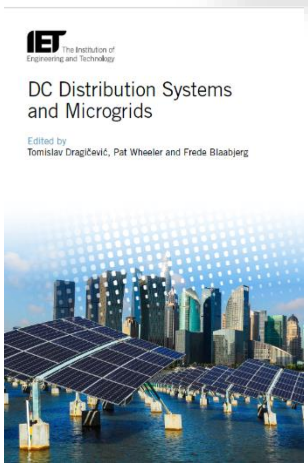


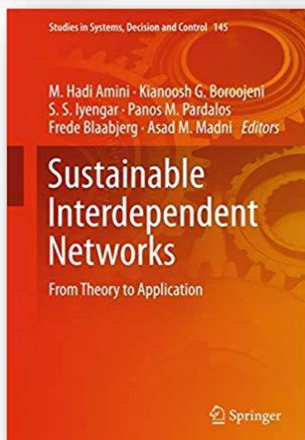
Books available

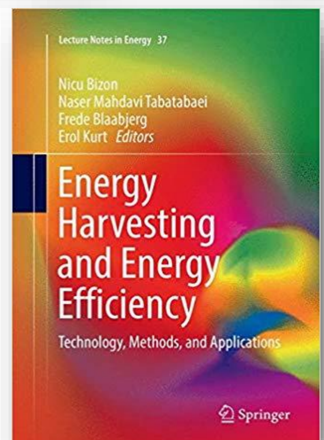












Thank you!

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