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Flexible Elektrische Netze

DC Distribution Grids and Interoperability with Emobility Power Electronics - a Key Enabling Technology

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Forschungscampus
Flexible Electrical Networks

July 4, 2018

Overview

- Decentralized power generation and renewables
  - Background – market and policies
  - Impact on energy supply system (decentralized and renewables, storage requirements)
  - Challenges with e-mobility sector
  - Consequences – requirements for energy supply system
- CO_2 neutral grid structure
- Intelligent, interconnected MVDC substations
- Integration of buildings and e-mobility
- Summary

Background
Energy market mechanisms that enabled more decentralized power production

Market changes that were introduced stepwise (EU):

1. **Market liberalization** allowed decentralized power generation, creating prosumers, typically small scale power generation (CHP) and REN sources (mostly volatile sources, such as PV and wind)

2. CO_2 certificates

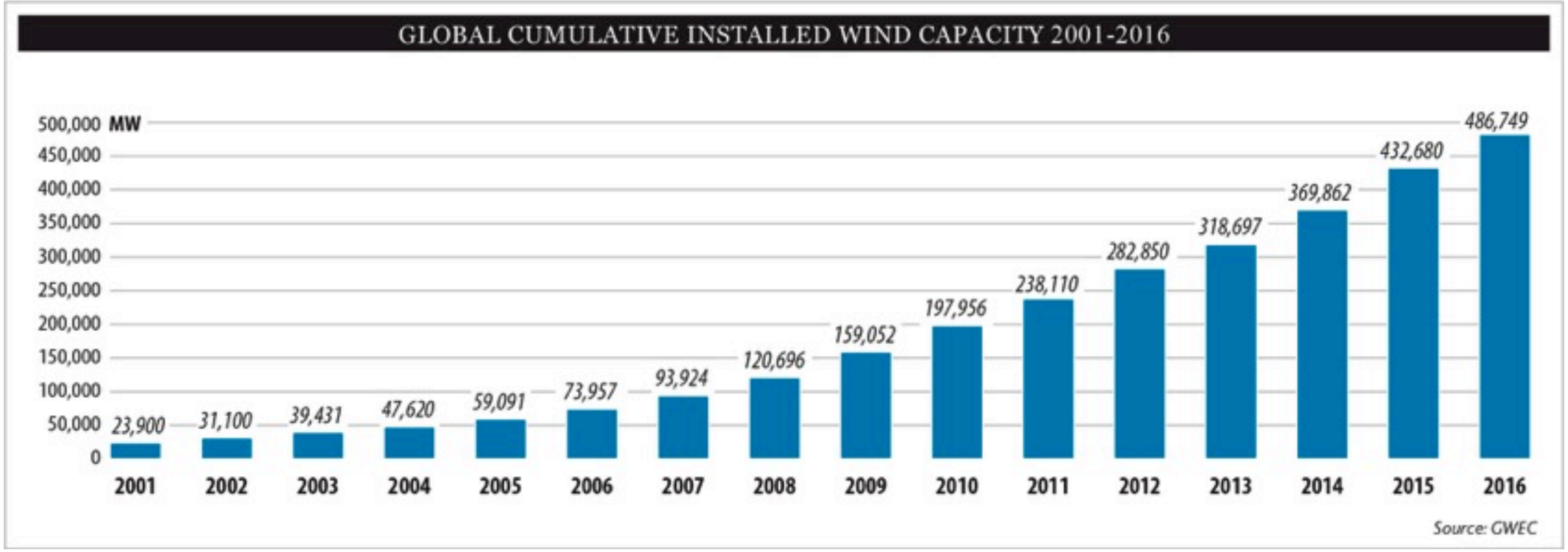
3. **Unbundling** of power generation and grid operation

4. **Unbundling** of TSO and DSO

Engineering challenges:

Need to find technical solutions that are socially and economically viable within these new markets and regulations

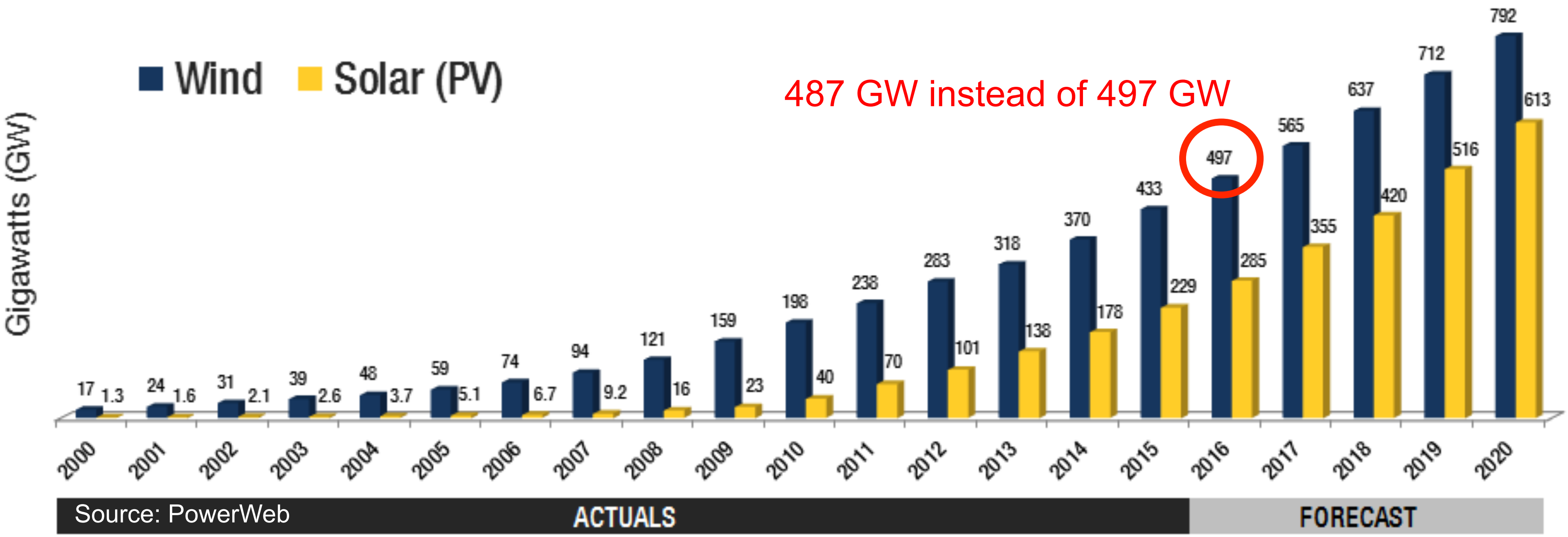
Global installed capacity of wind



487 GW_{peak} installed capacity by the end of 2016 – assuming 50% DFG, this translates in approximately **750 GVA** of power electronic converters

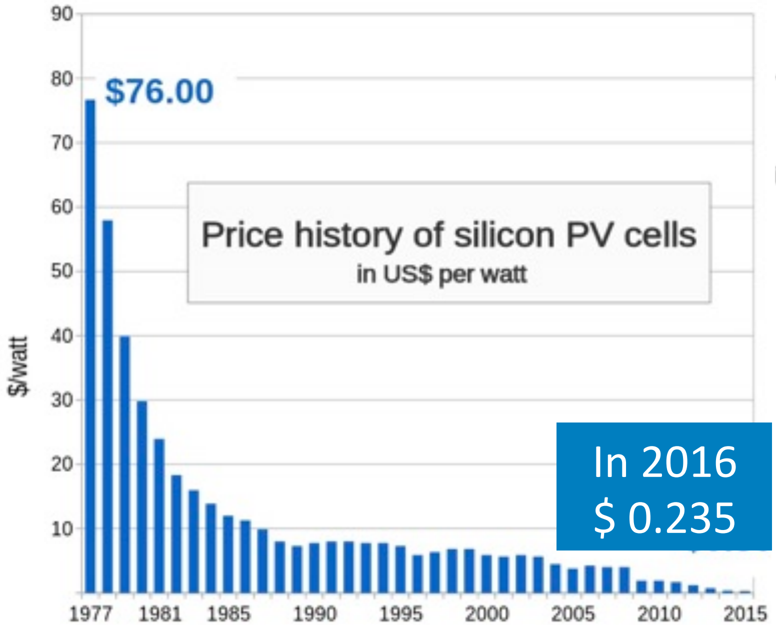
Multi-megawatt power electronic converters are becoming a mass product. During the past 25 years a major cost reduction of voltage source inverters took place; from 500 €/kVA down to 25 €/kVA

Global installed capacity of PV is accelerating

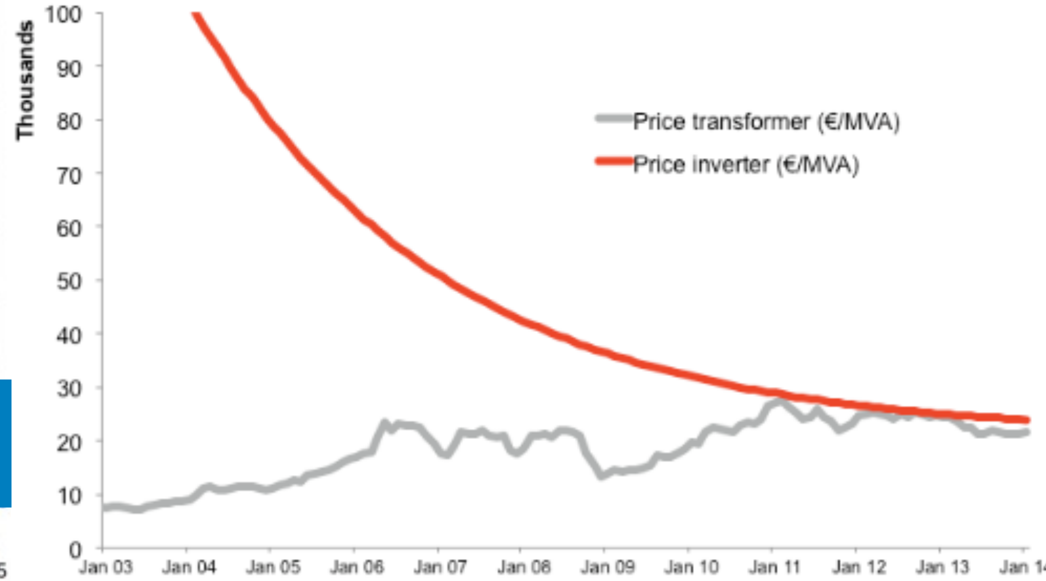


- 285 GW_{peak} of PV installed by 2016
- About 315 GVA of PV (string and central) inverters are installed by 2016
- LCE of PV in some countries is lower than that of wind or coal power plants

Price of silicon cells and power electronics inter-twined?



Source: Bloomberg New Energy Finance & pv.energytrend.com



Silicon is made of SiO_2 (i.e. sand, an abundant material) and **energy**
Energy is produced by **PV**
PV energy is controlled and converted by **power electronics** made of **silicon**

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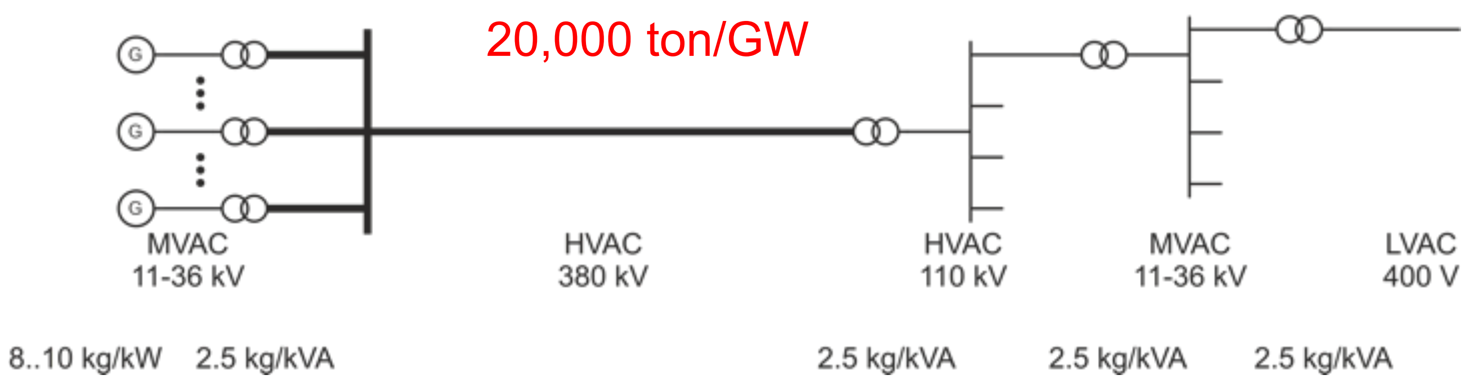
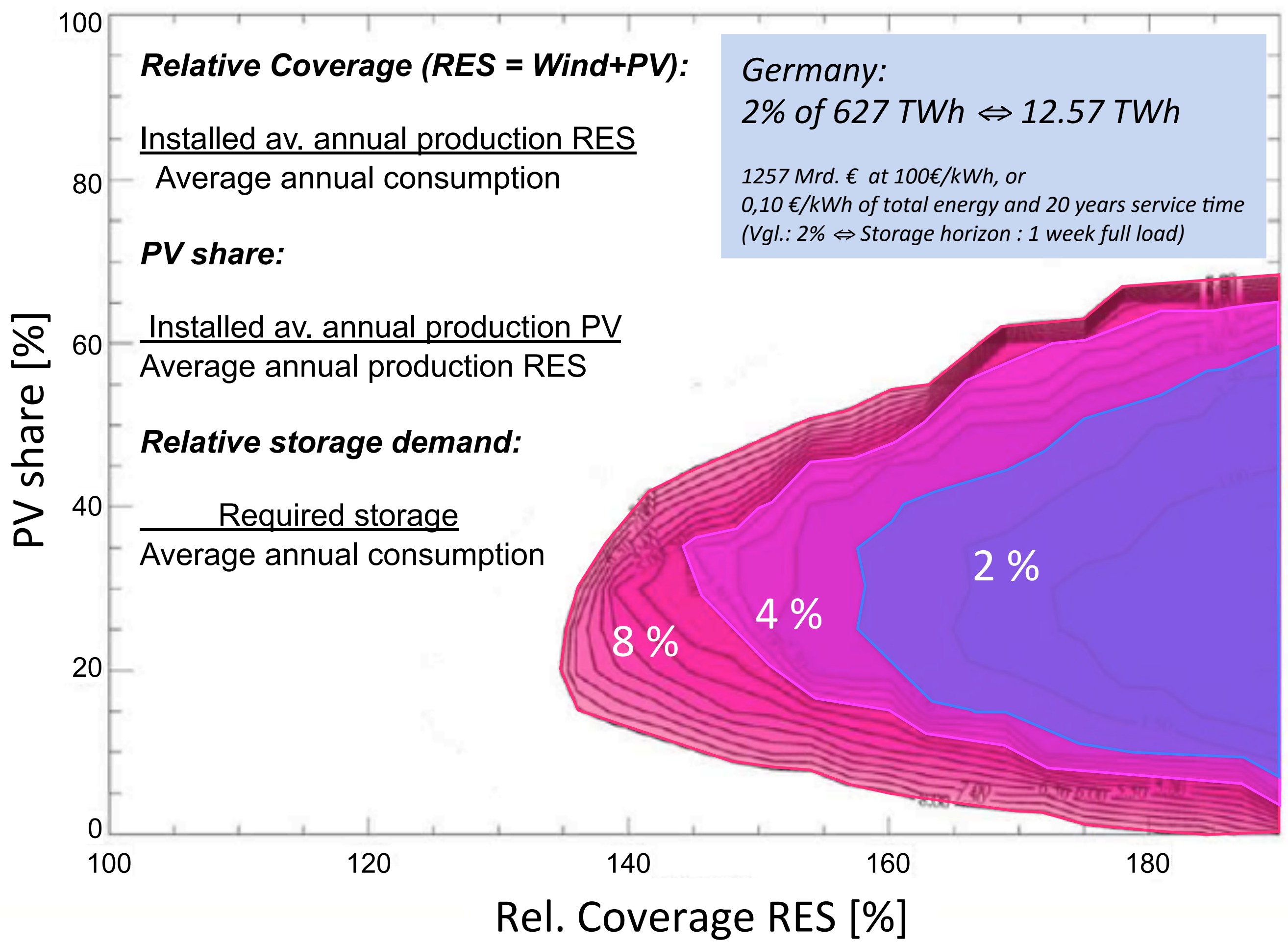
Standard AC Transmission and Distribution
Inconvenient truth – cost is increasing

- AC grids are based on transformer technology
  - Designed for top down energy transmission
  - Constant voltage and constant frequency
  - Flexible AC grids (FACTS) will require major investments in infrastructure and power electronic energy conversion and storage systems
  - In 2000, EU29 had 685GW installed capacity, i.e. 13,7 Mton on Cu and Si-Steel in generators and transformers, i.e. 109,6 B€ (at price of 8 €/kg)



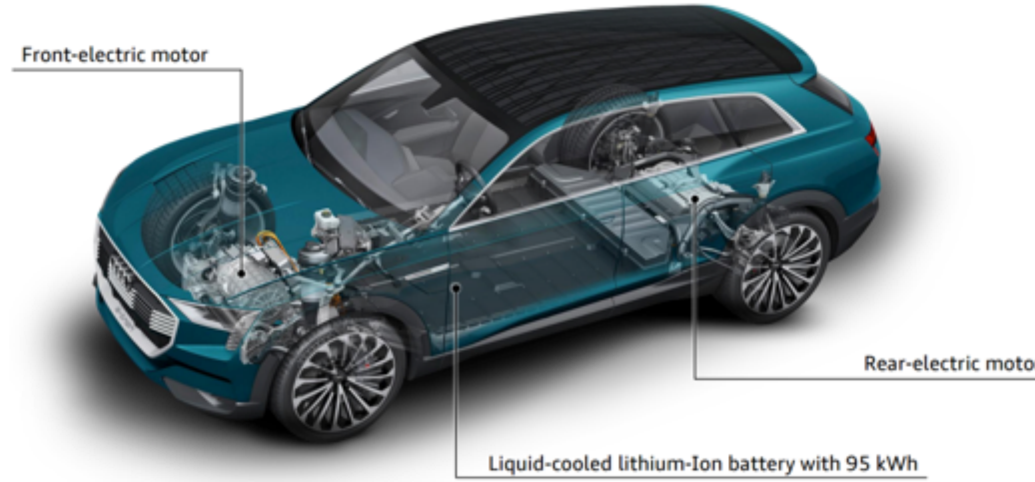
Storage Requirements in pan-European Electricity System (C. Hoffmann, IRES 2008)



E-Mobility is coming

Demand for Ultra Fast Charging is coming with it, regardless if it is realistic!

e performance developed at RWTH/ISEA - predecessor of the Audi Q6 , production at AUDI Plant Brussels



e performance

- Demonstrator
  - 280 kW
  - 2x 115 kW ASM
  - 1x 50 kW PMSM
  - 2 LiIon batteries
  - 144 V and 216 V
  - 38,4 kWh

- Audi Q6 e-tron quattro
  - 370 kW (three motors)
  - Max. speed 210 km/h
  - 95 kWh LiIon, 500 km driving range
  - **DC charging with 150 kW**
  - **400 km in 30 min, 100 km in 8 min**

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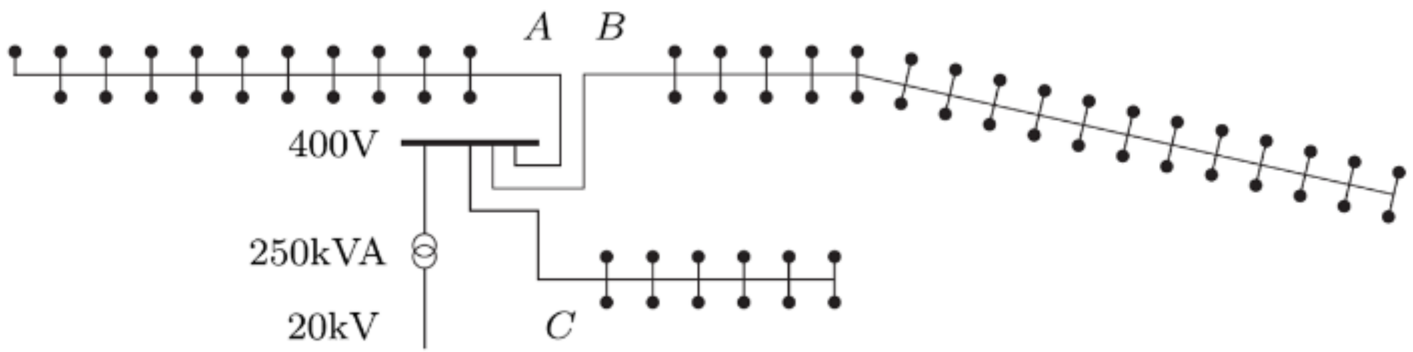
Distribution Grid - Challenges
Typical Urban Grid Structure



Branch A
- 21 households, max. total power: 98 kW
- Length: 461 m

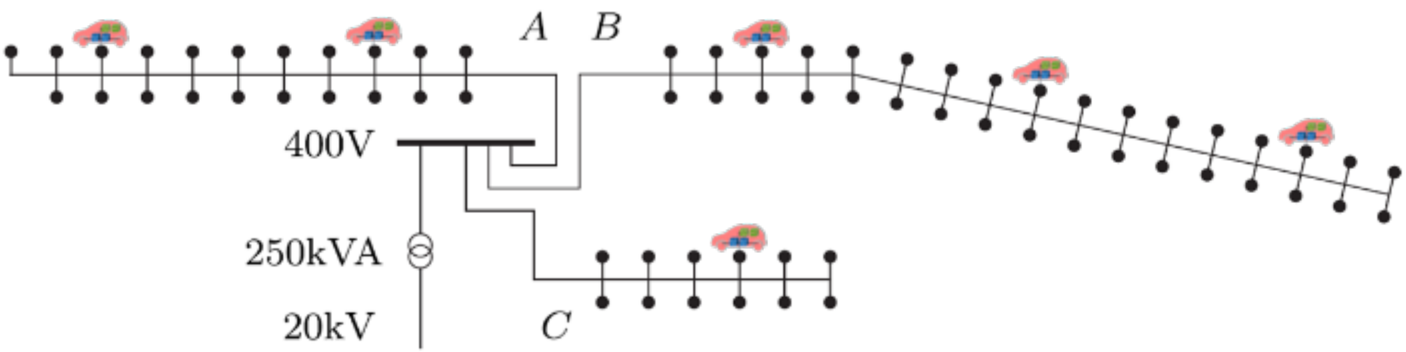
Branch B
- 34 households, max. total power : 129 kW
- Length : 715 m

Branch C
- 10 households, max. total power : 68 kW
- Length : 185 m

Connection to transmission grid
- Max. total power : 250 kVA

M. Stieneker and R. W. De Doncker, "Medium-voltage DC distribution grids in urban areas," 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Vancouver, 2016

Distribution Grid - Challenges
Typical Urban Grid Structure with e-Mobility (150 kW charger)



Branch A

- 21 households, max. total power: 98 kW → 398 kW (2 veh.)
- Length: 461 m

Branch B

- 34 households, max. total power : 129 kW → 479 KW (3 veh.)
- Length : 715 m

Branch C

- 10 households, max. total power : 68 kW → 218 kW (1 veh.)
- Length : 185 m

Connection to transmission grid

- Max. total power : 250 kVA → 1.1 MVA

M. Stieneker and R. W. De Doncker, "Medium-voltage DC distribution grids in urban areas," 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Vancouver, 2016

Requirements of CO_2 Neutral Energy Supply System

Volatile power sources and high peak loads require new grid infrastructure

- CO_2 market should work properly, without subsidies (from 7 €/ton to > 40 €/ton)
- Energy efficiency improvements by electrification
  - Building sector (all electric home) takes 40% of primary energy. New built requires more cooling power than heating. Heat pumps fed by PV are becoming the norm.
  - Transportation (railway, EVs)
- Develop and search for low cost storage systems
  - Sector coupling (heat, cold and gas) as low cost energy storages
  - Dual use batteries of electric vehicles
  - DSM: full automated (IoT) alignment of demand and generation
- Flexible electrical grids
  - Prevention of bottlenecks in the transmission grid (AC to DC conversion)
  - Interconnect distribution grids (MVDC underlay)

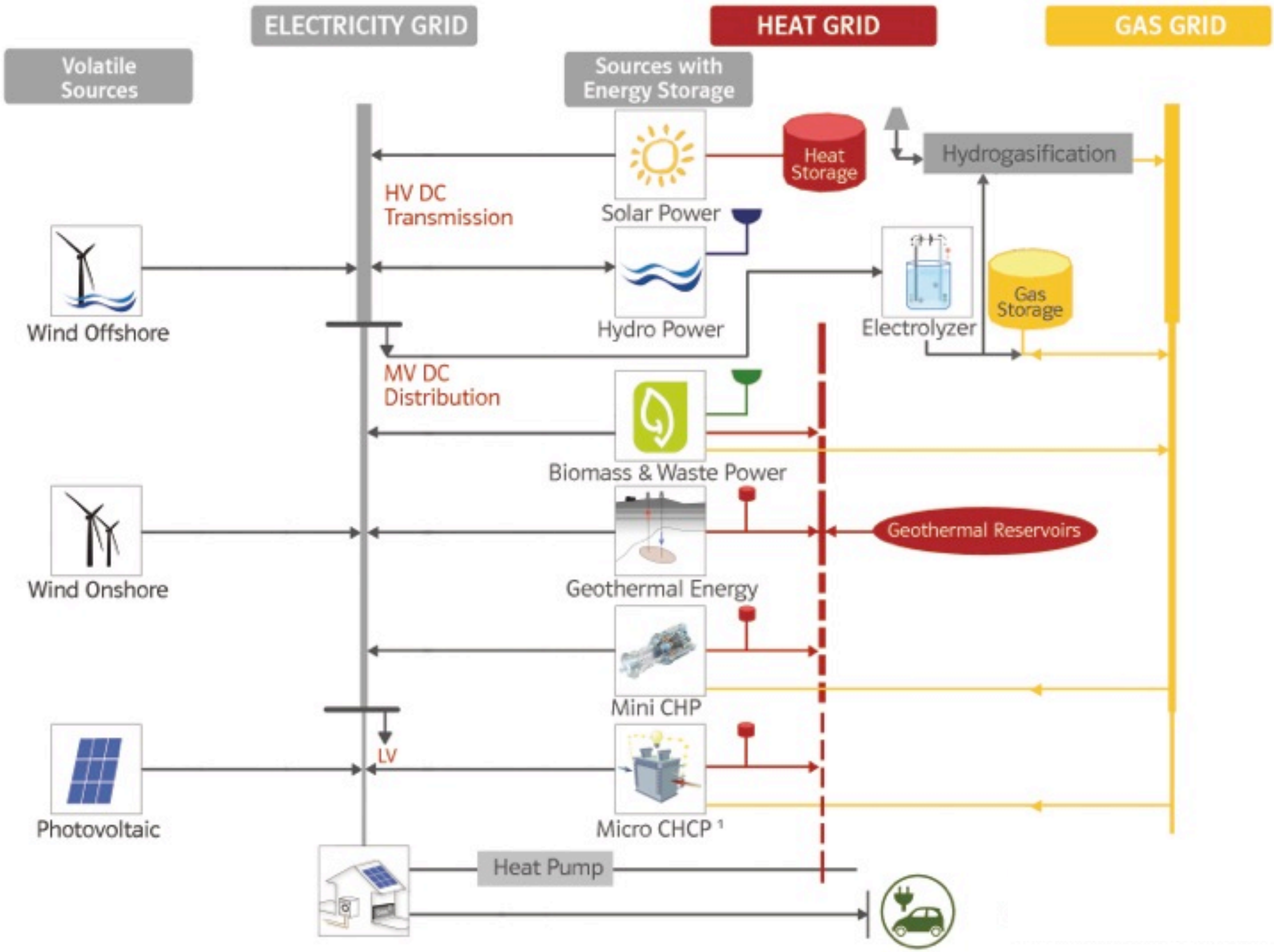
CO_2 neutral grid structure

Electrical grid has to cope with volatile REN and high peak loads for e-mobility

Low-cost storage capacity by sector coupling

Flexibility by direct current – no frequency nor phase

Electrical Grids for a CO_2 Neutral Electrical Energy Supply System
Sector coupling to provide massive energy storage



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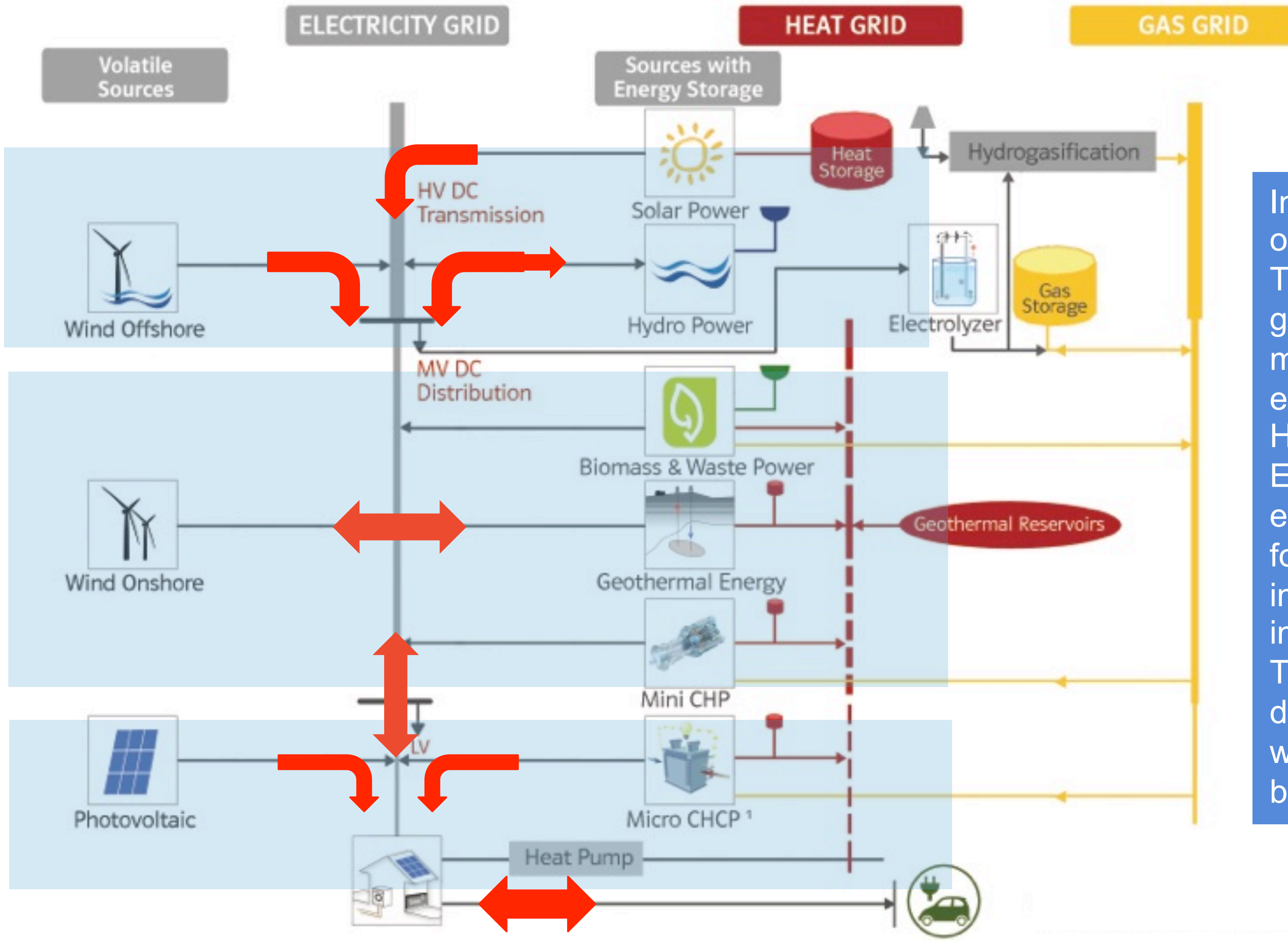
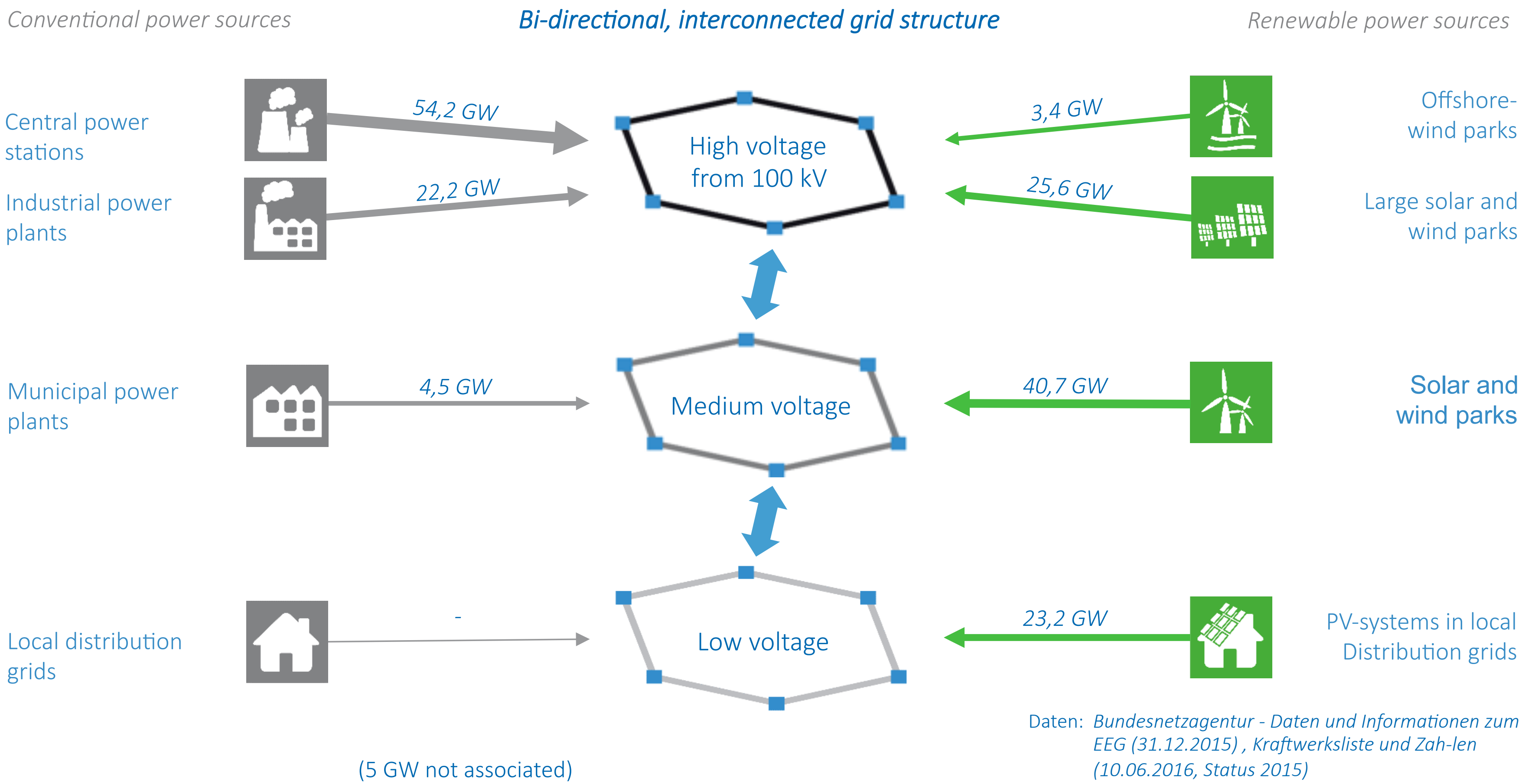
Electrical Grids for a CO2 Neutral Electrical Energy Supply System
About 1/3 in HV, 1/3 in MV, 1/3 in Low-Voltage Distribution Grid



Interesting observation:
The transmission grid requires just minimal extension with HVDC.
ETG Task Force expects less cost for DC integration in infrastructure.
The MV distribution grid will become bottleneck.

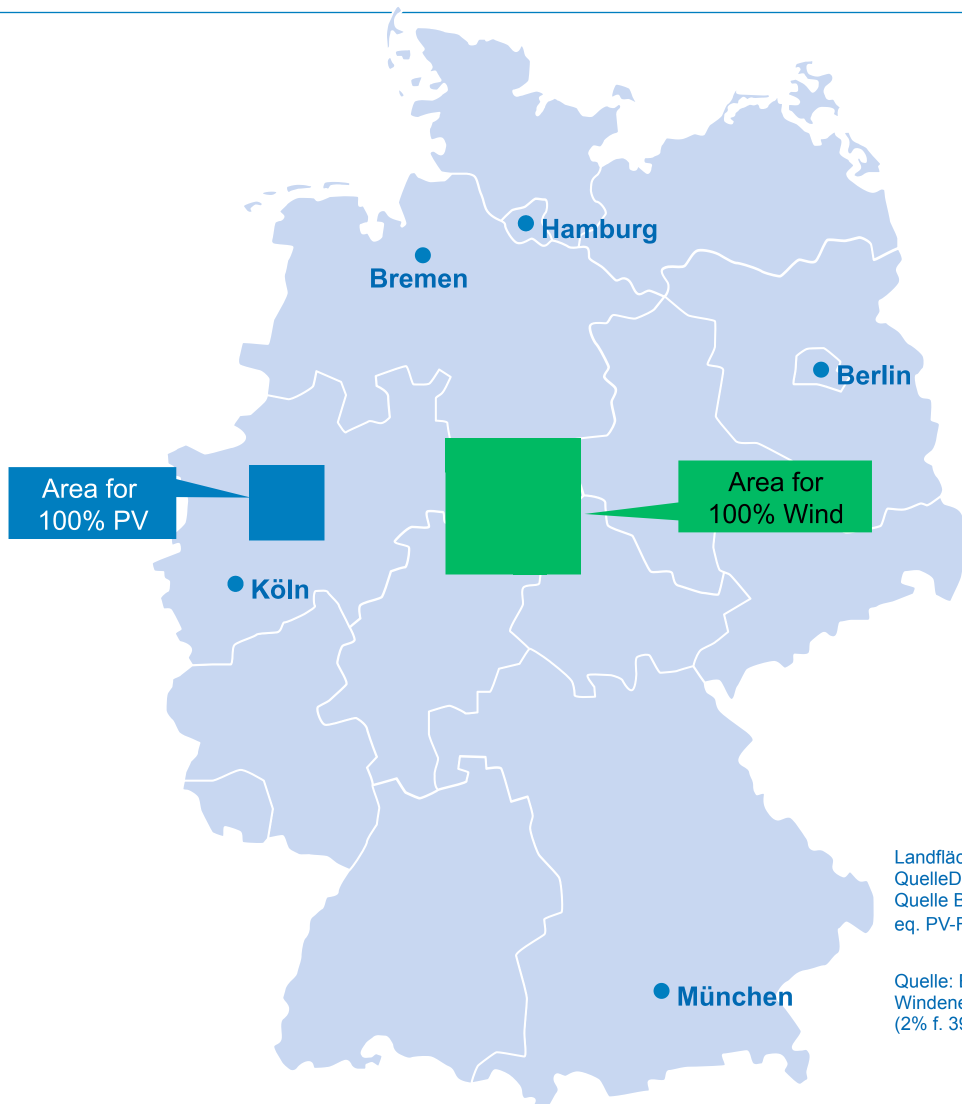
The "1/3 rule" already applies to the German installed capacities



Daten: *Bundesnetzagentur - Daten und Informationen zum EEG (31.12.2015) , Kraftwerksliste und Zah-len (10.06.2016, Status 2015)*

Future grids cannot ignore the energy feed-in in medium- and low-voltage distribution grids and must become interconnected

Renewable Energy Supplies can Cover all Electricity Needs
(example Germany)

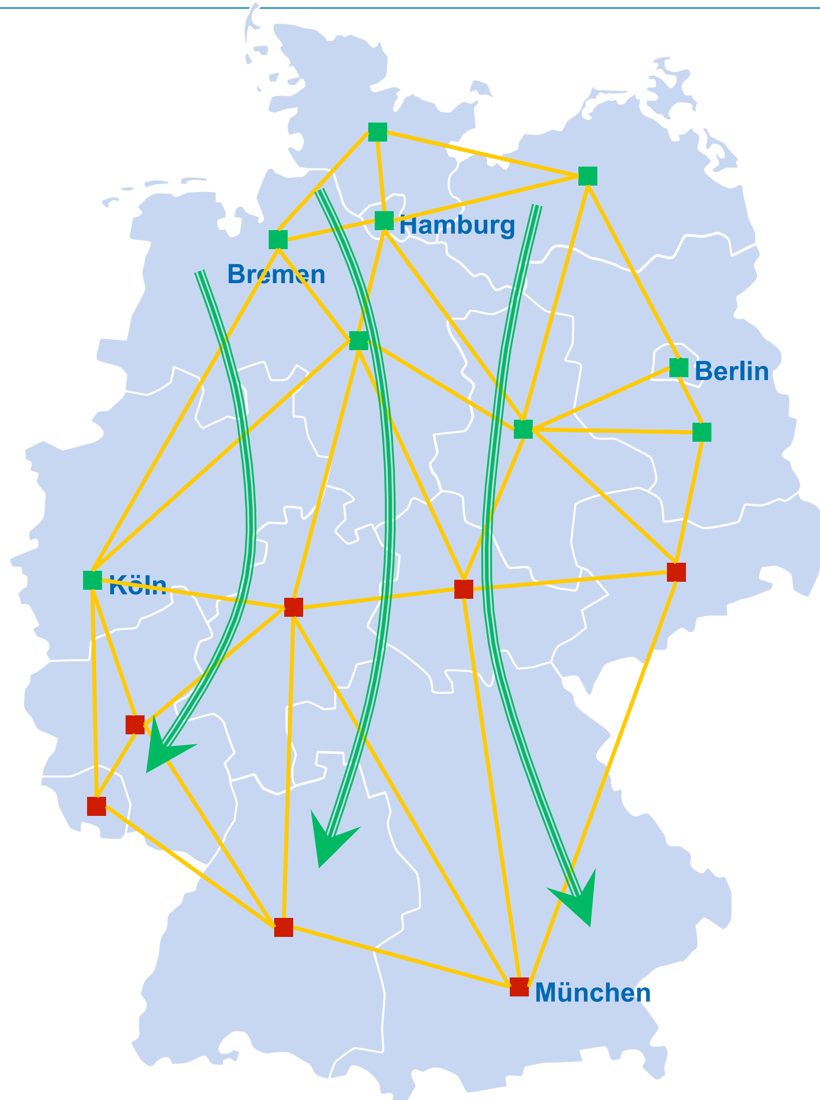


Landfläche BRD: 357.186 km^2
QuelleDWD: 1050 $kWh/m^2 \cdot a$ → 15% Wirkungsgrad →157 $GWh/km^2 \cdot a$
Quelle BMWi: Bruttostromerzeugung 2015: 627,8 TWh,
eq. PV-Fläche 3993 km^2 (1,1%, ca, 63 km x 63 km)

Quelle: BWE Studie Potenzial
Windenergienutzung an Land (Kurzfassung)
(2% f. 390 TWh)

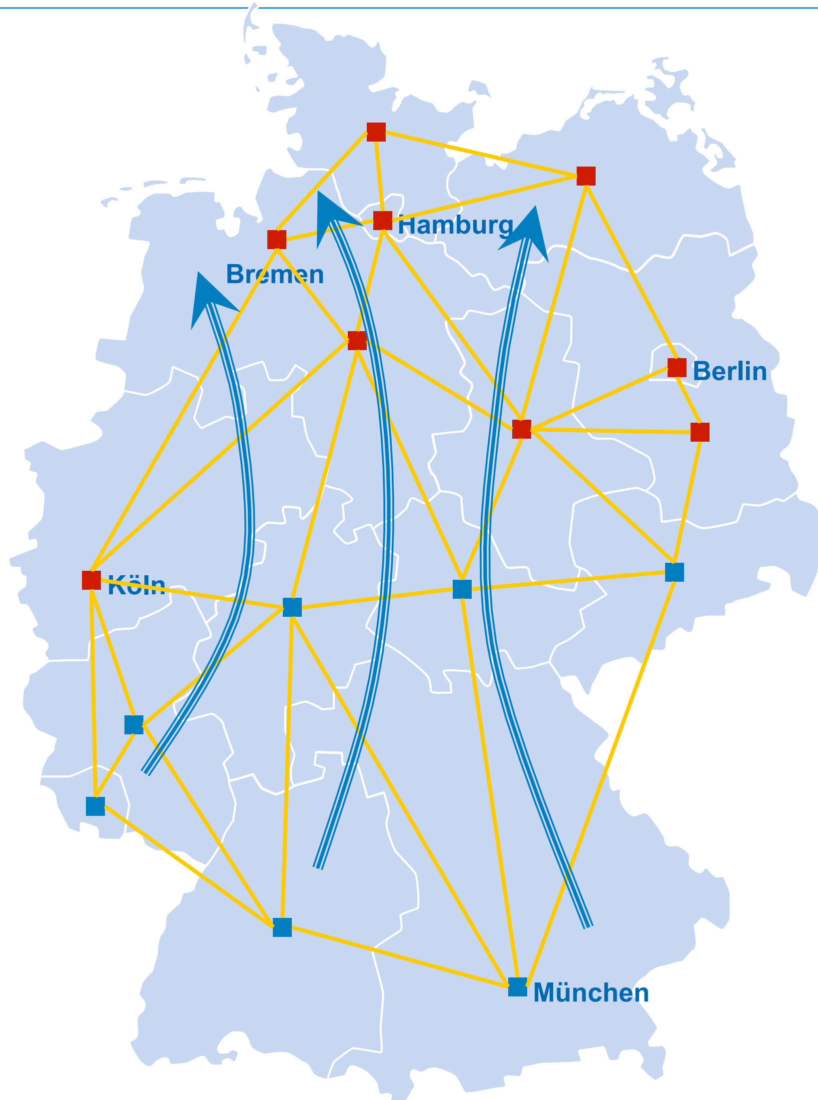
Fall and Winter – mostly Wind Energy

Massive Power transfer needed from South to North – Overlay HVDC



Spring and Summer – mostly PV

Massive Power transfer needed from South to North – Overlay HVDC



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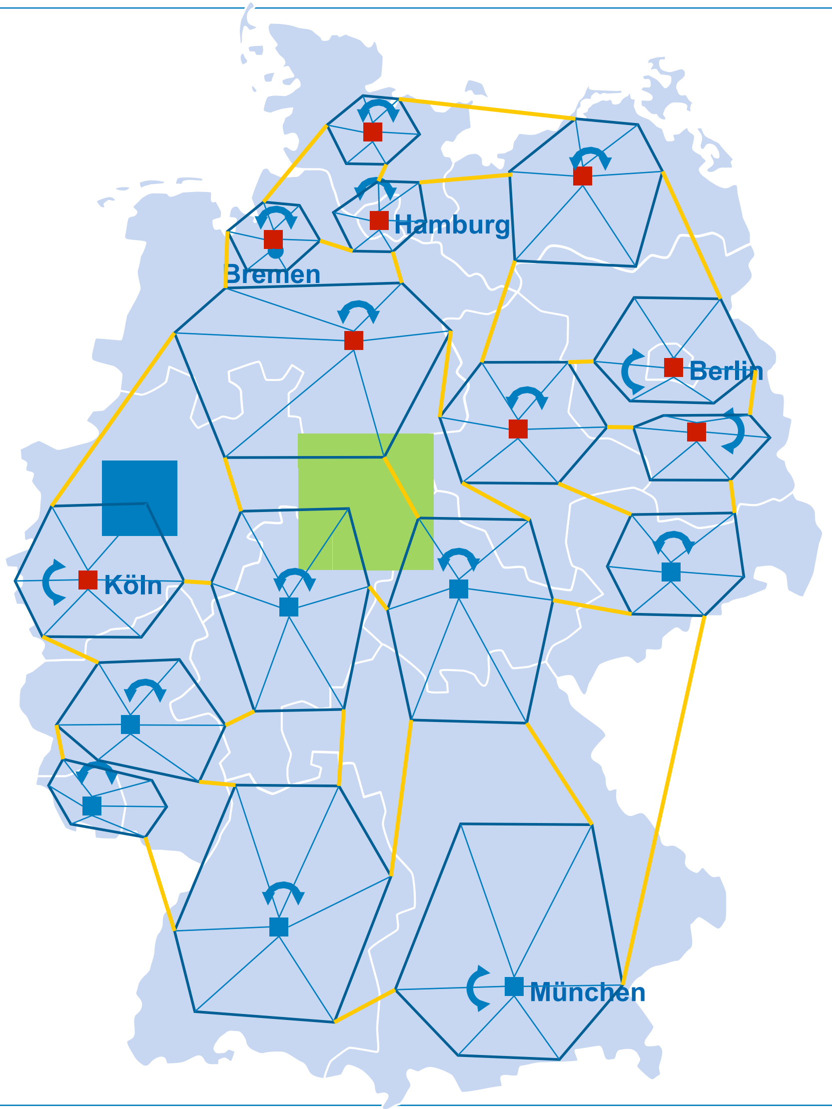
Distributed Installation of REN - Underlay Grid

Exchange of energy via cellular, interconnected medium-voltage distribution grid

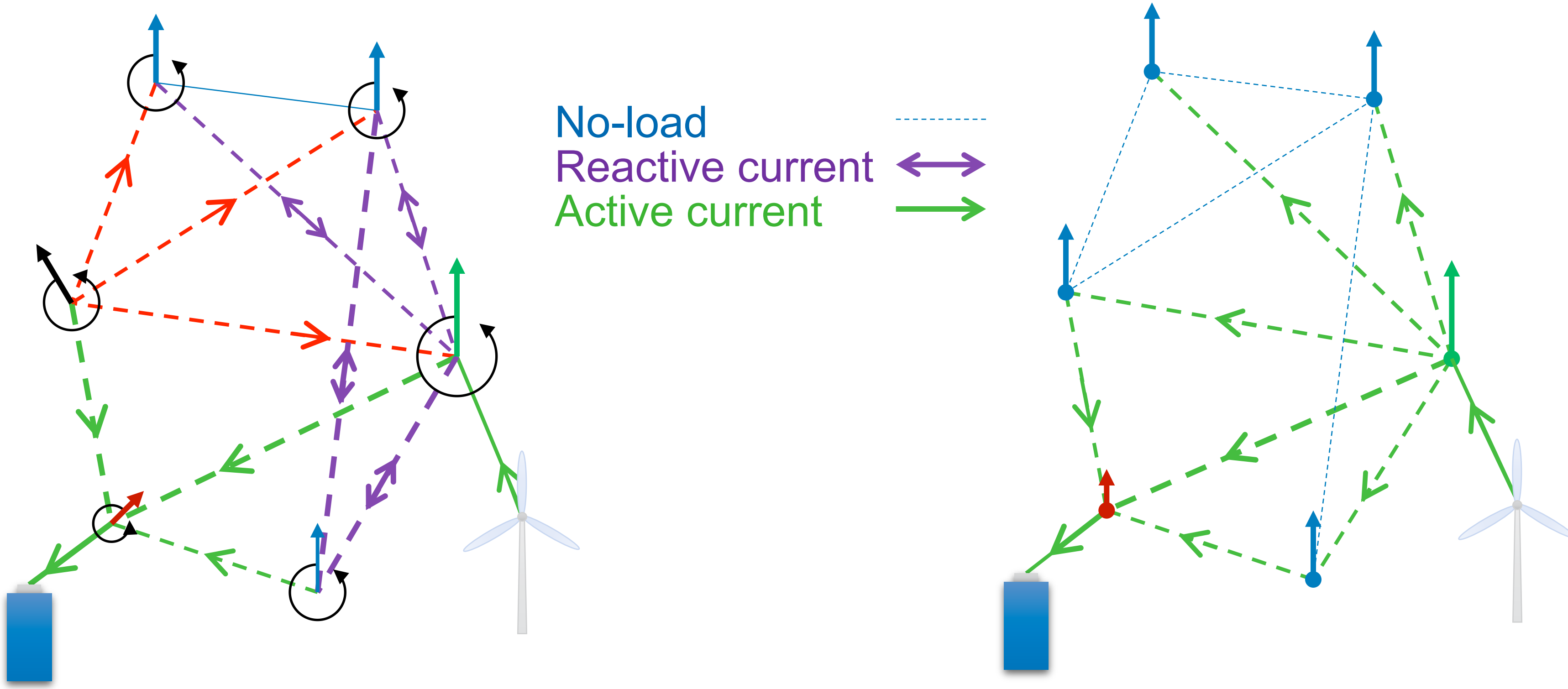
Underlay distribution grid is an interesting business proposition from DSO perspective



DC-Grids are less prone to instabilities and are more flexible to control via intelligent sub-stations than AC grids

Power flow in AC grids is controlled by voltage and phase

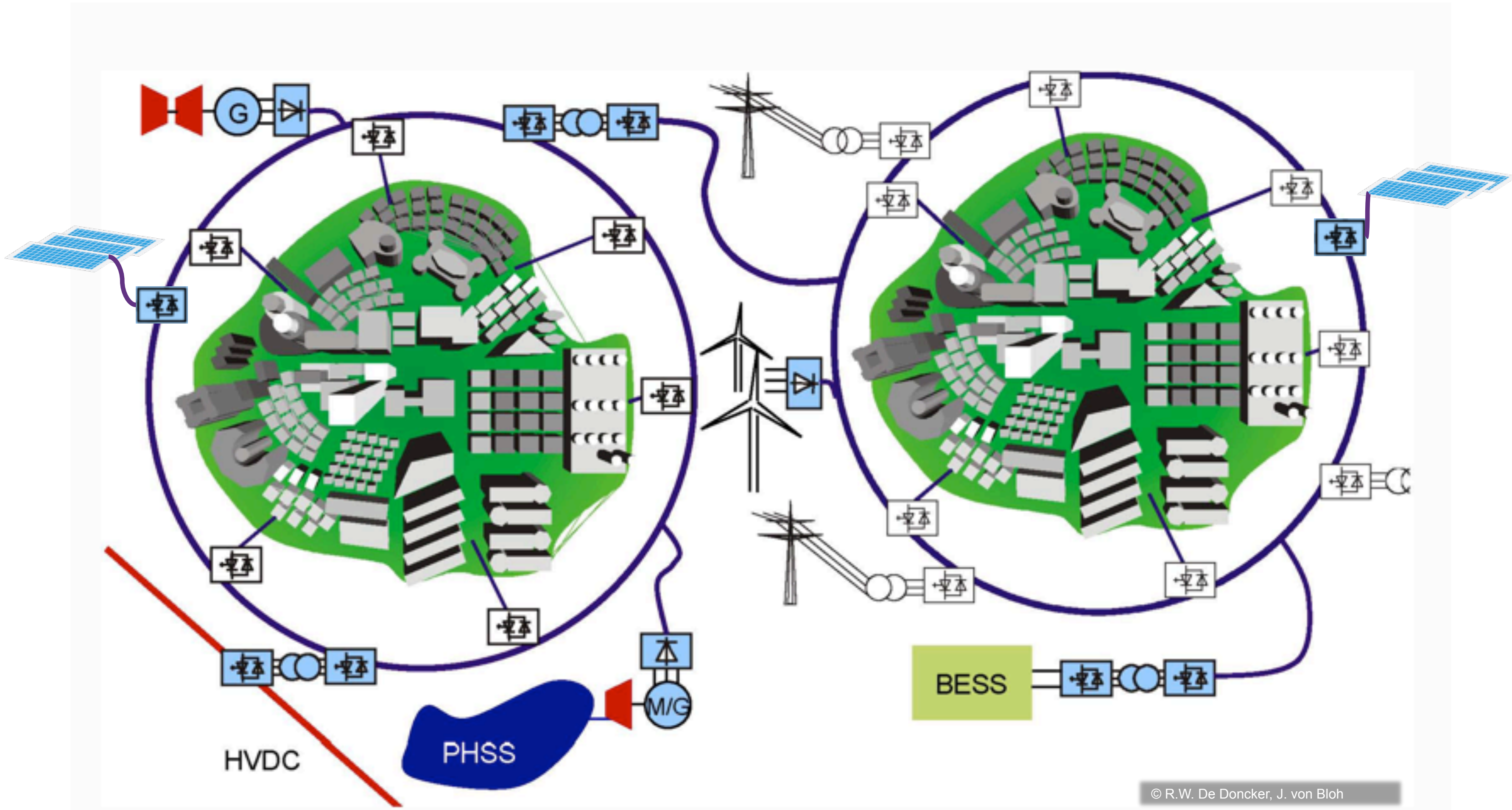
Power flow in DC grids depend only on voltage



Unwanted Power Flow
Reactive Currents

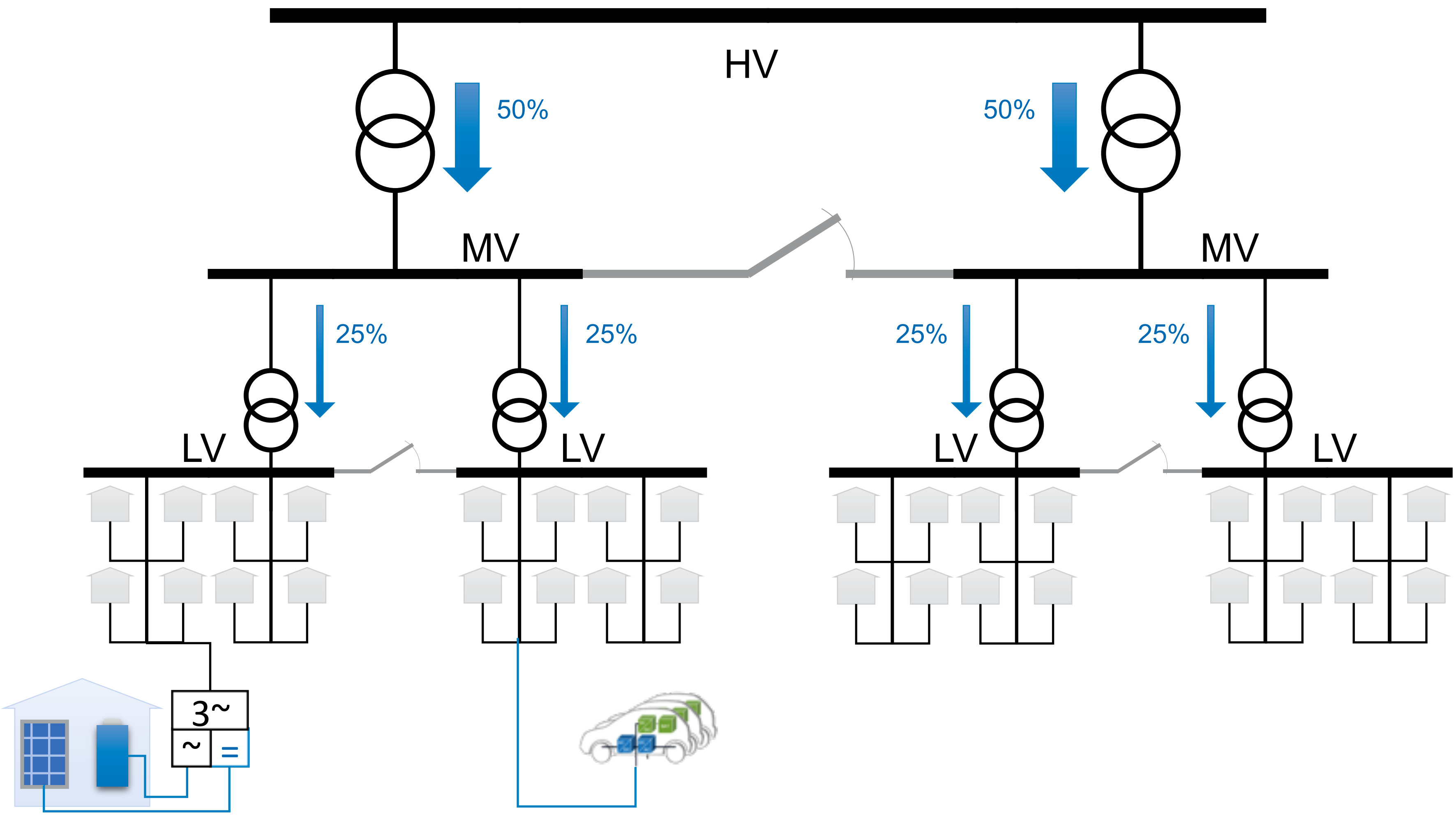
DC current follows voltage and path of lowest resistance

Urban Regional, Flexible MVDC Distribution Grid



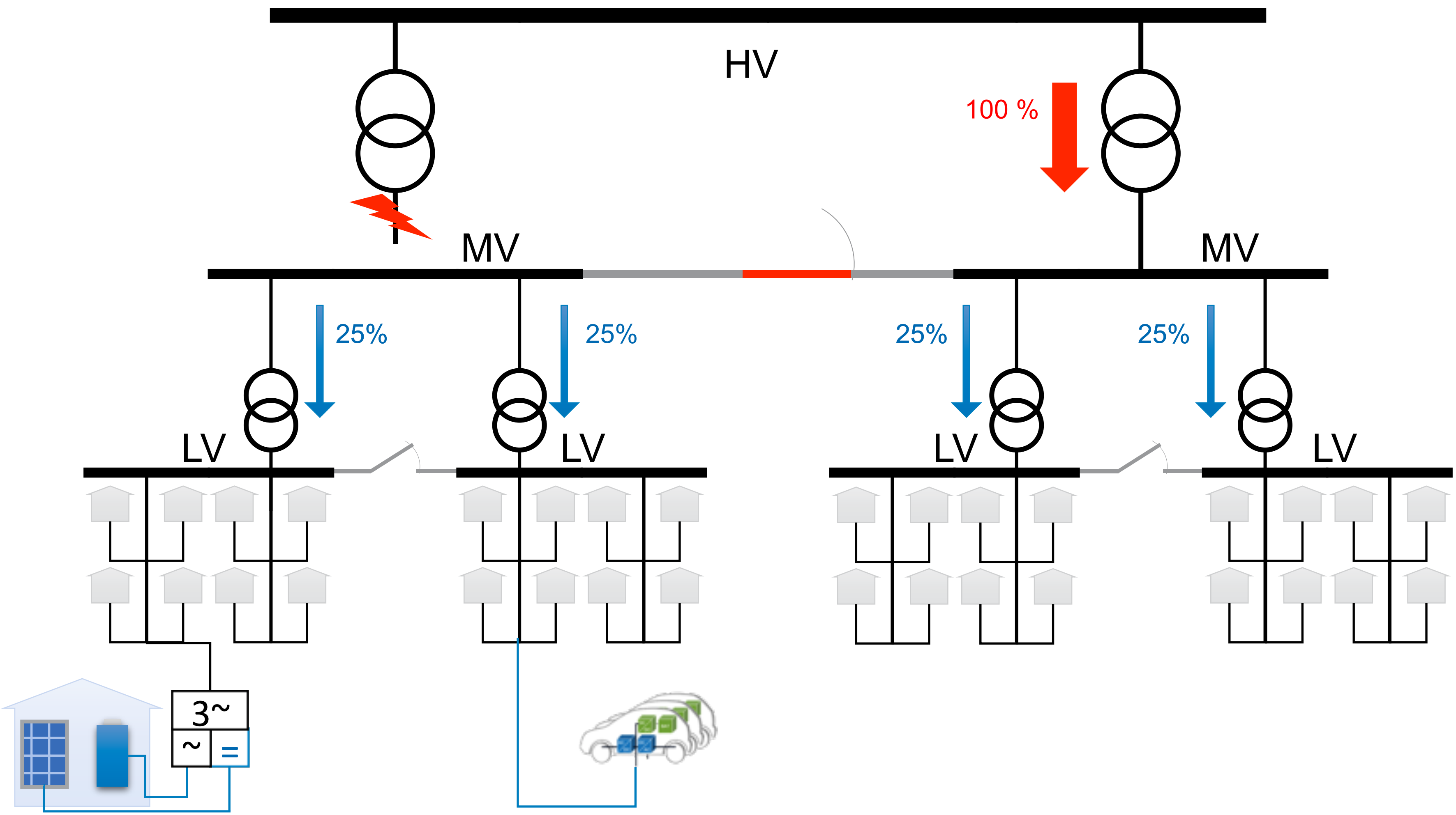
Classical Distribution Grids are radial

Integration of decentralized supplies. renewables, storage and e-Mobility is difficult

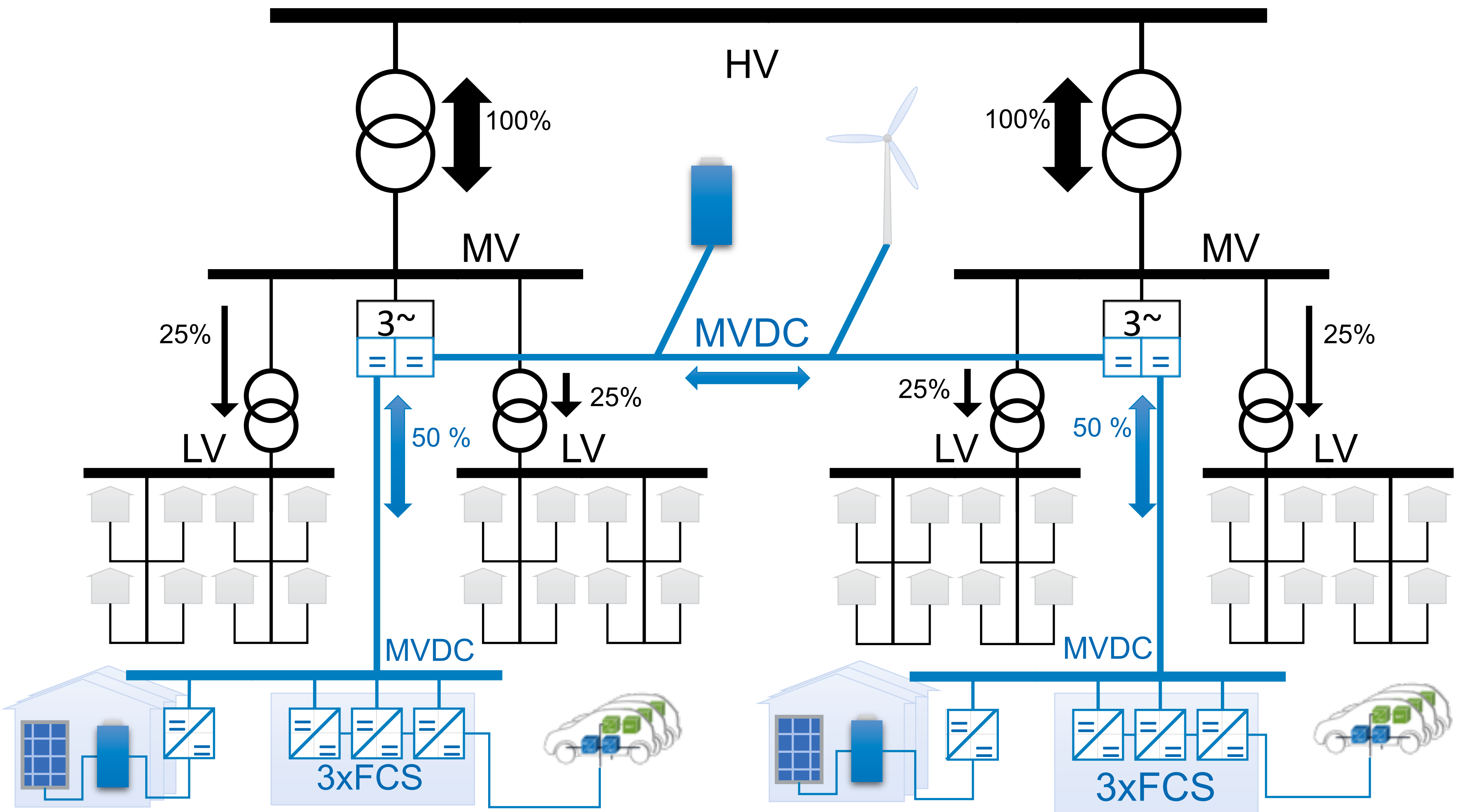


Classical Distribution Grids are radial and massively oversized

Integration of decentralized supplies. renewables, storage and e-Mobility is difficult



Hybrid Approach to Maximize Capacity of Distribution Grids
Integration of e-Mobility, PV, Wind, Storage … by MVDC-Backbone



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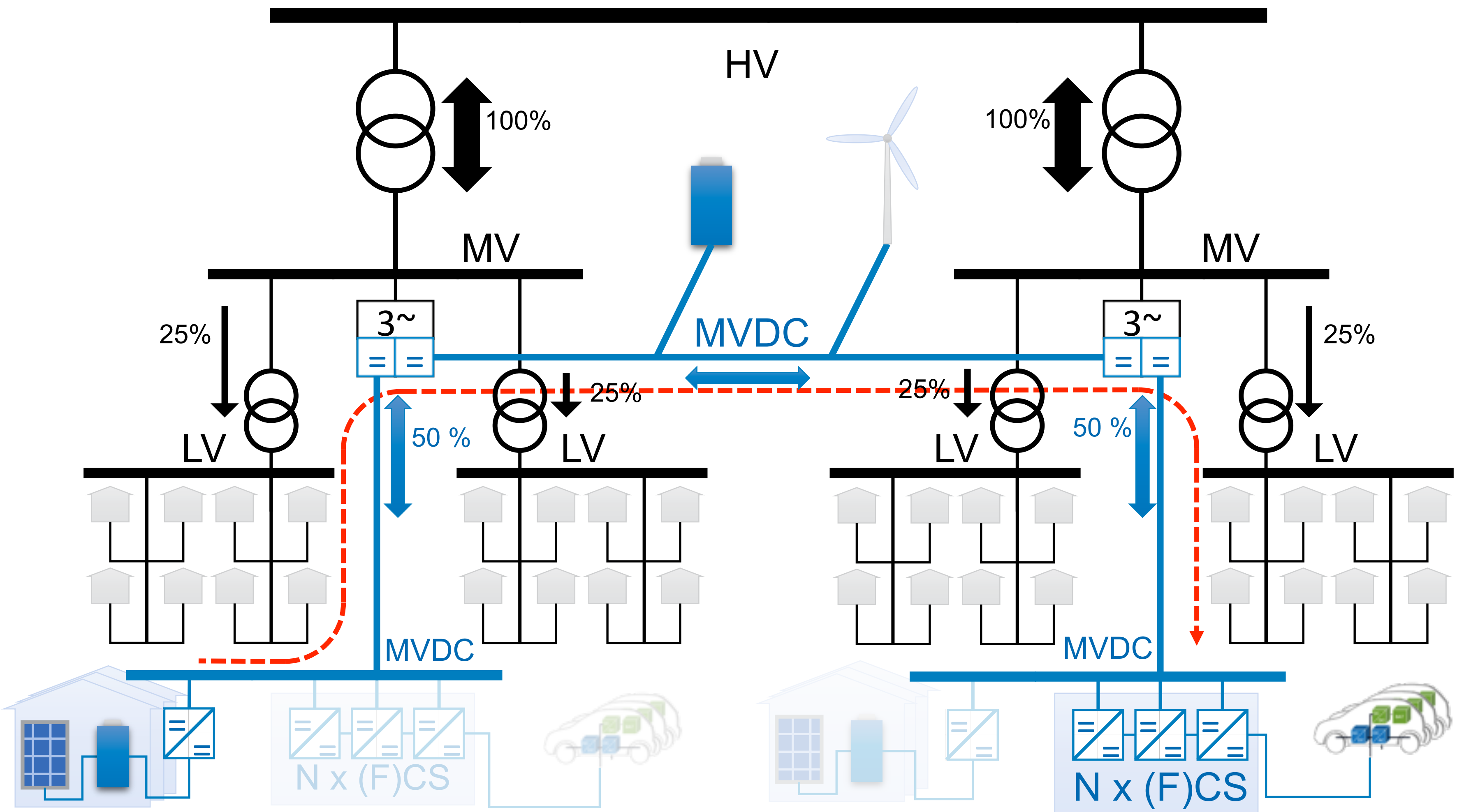

Integration of e-Mobility and all-electric buildings

Opportunity for fast charging service with DC
Opportunities for cost and energy savings and efficiency
Improvements in building and industry sector

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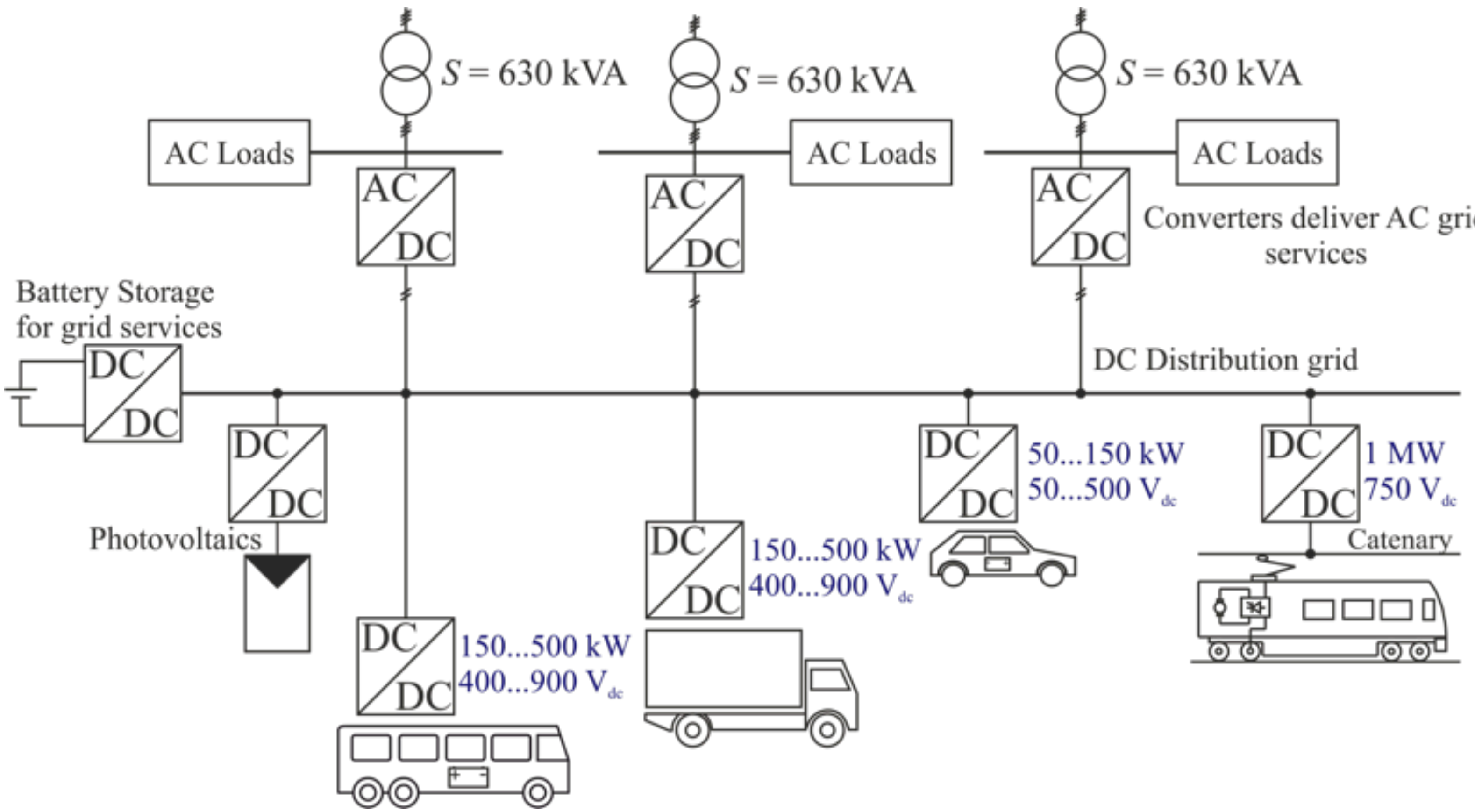
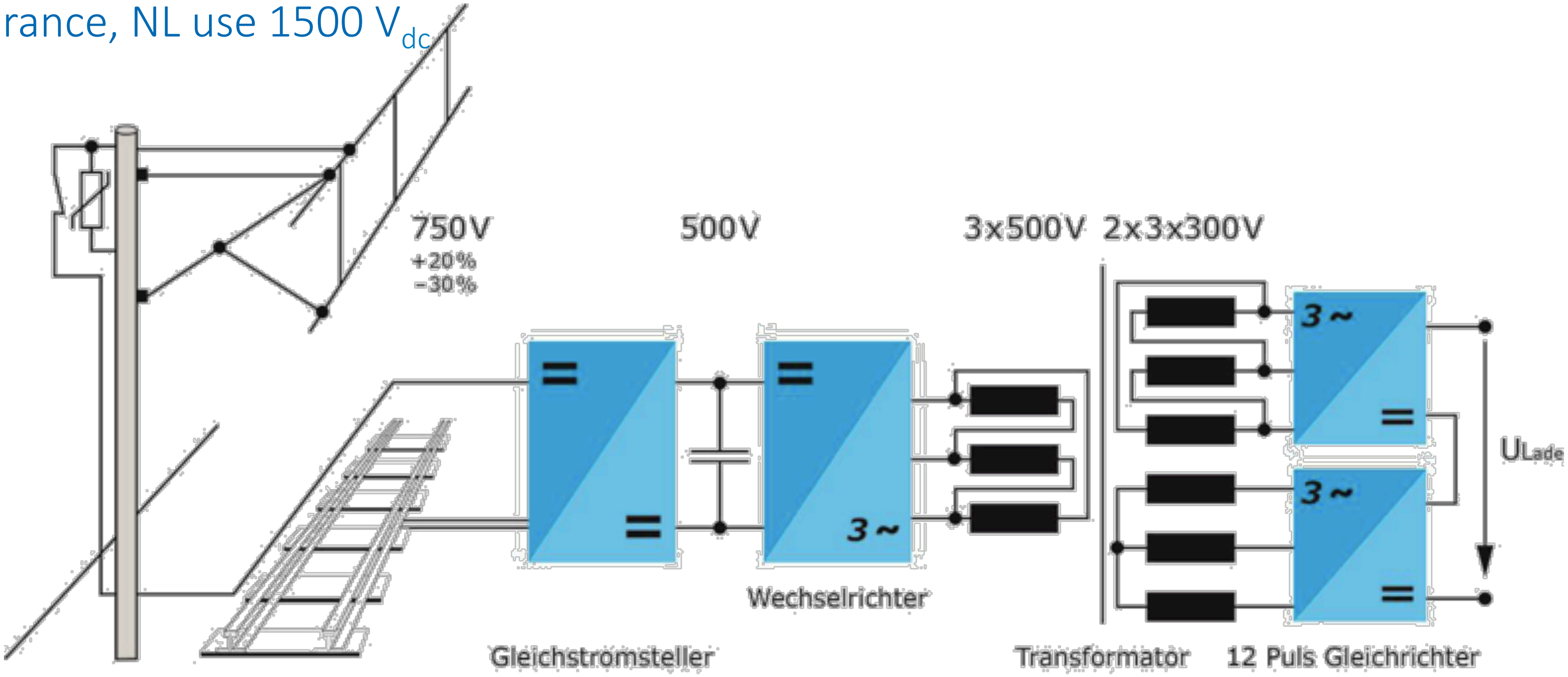
Concept of urban distribution grids for fast-charging

- Converters boost utilization of substation transformers (voltage regulation)
- Interconnecting medium- and low-voltage substations to bundle high-peak power



Fast-Charging Infrastructure
Double Use of Railway and Light Rail Infrastructure

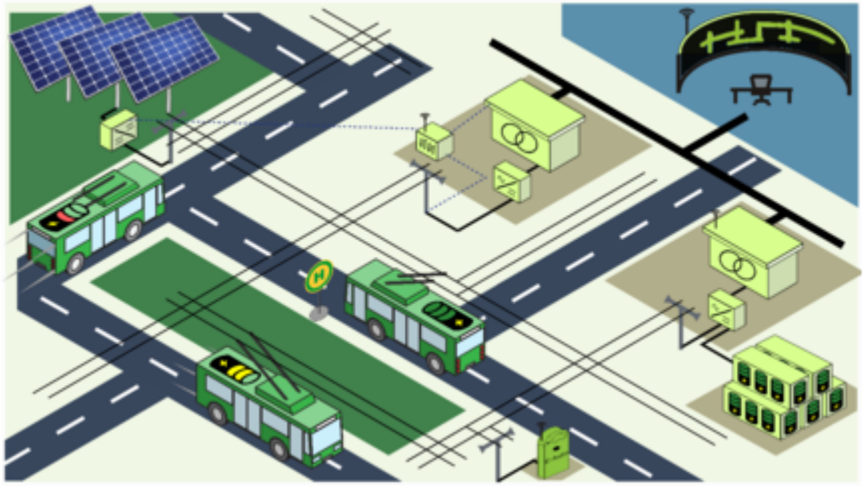
- Low utilization of large capacity railway infrastructure (12%)
- Existing capacities can be used for fast charging
- Railway and light-rail grids are available in cities
  - Light rail typically 750 V_{dc}
  - Belgium, Spain, Italy, Russia use 3000 V_{dc}
  - France, NL use 1500 V_{dc}



Source: Müller-Hellmann

Fast-Charging Infrastructure
Double Use of Railway and Light Rail Infrastructure

- Research project „BOB“ (Solingen)
  - Double use of Trolley bus infrastructure
  - Catenary power used for charging of on-board batteries during operation
  - Possible electrification of lines without catenary
  - Integration of renewable energies
  - Services for feeding ac grid



Source: Uni Wuppertal

- 4 GW (750 V_{dc}) installed capacity in German cities alone (VDV)
  - Average use is 12%
  - Each day about 85 GWh is available to charge EV
    - 1.4 million EVs with 60 kWh battery
    - 420 million km range (@20 kWh/100 km)

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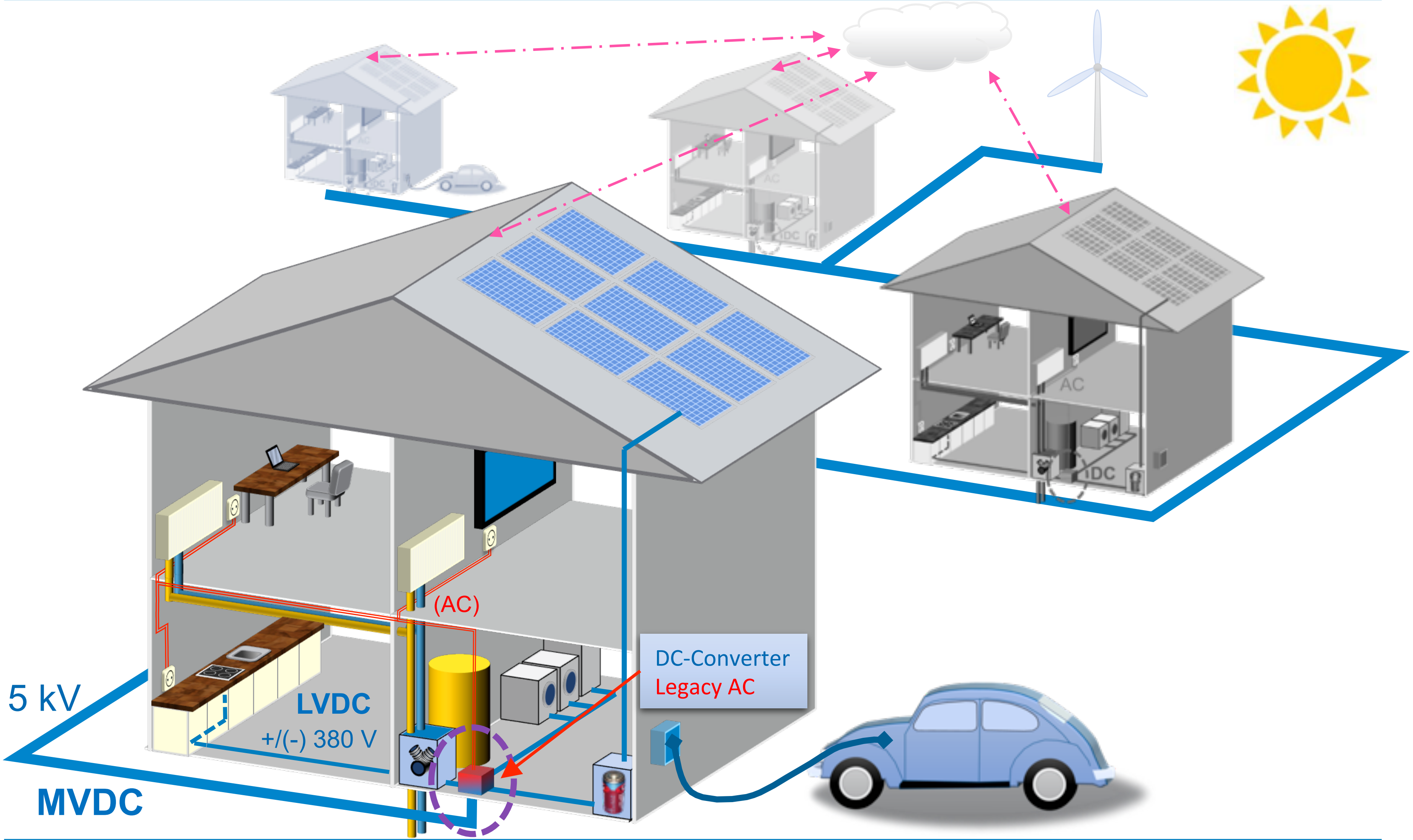
DC grid and energy management in a DC quarter
Lower infrastructure cost, higher efficiency, and bidirectional



Intelligent MVDC interconnected substations

Dual-Active Bridge as modular PEBB
Multiport converter as power router

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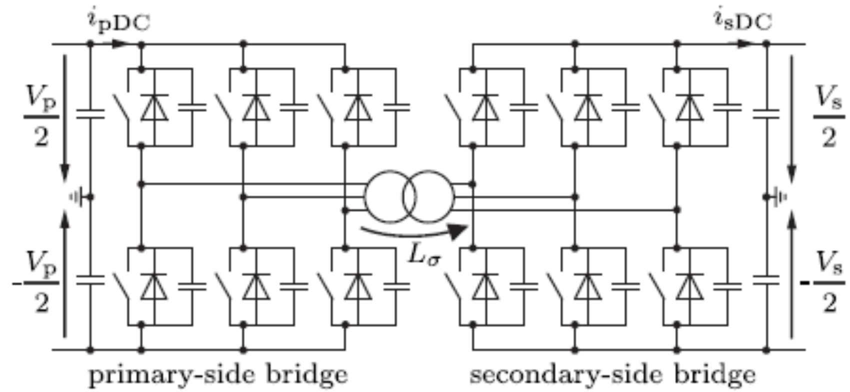
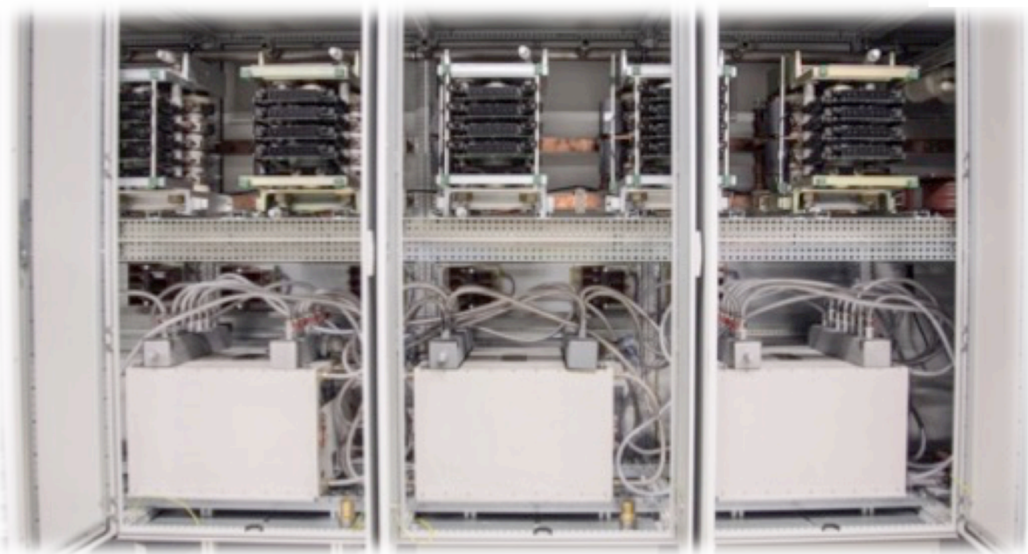
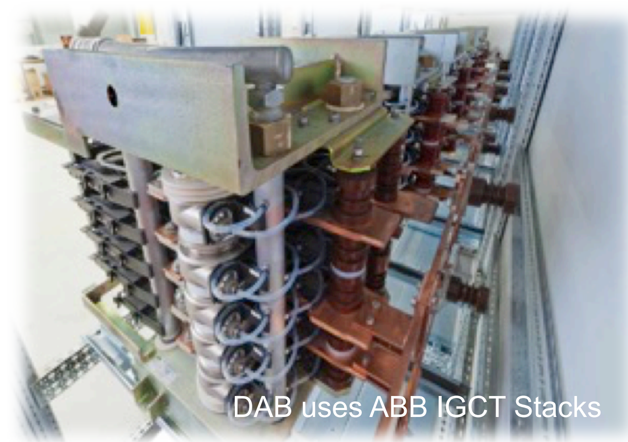
Dual Active Bridge DC-DC Converter
Medium-Voltage High-Power DC-DC Converter

- P = 7 MW, VDC = 5 kV ±10 %
- Si-Steel 180 µm lamination
- Efficiency up to 99.2 % @1 kHz
- Ultimately air-cooled devices are an option
- DC substation at 1/3 weight of 50 Hz transformer







R. Lenke, „A Contribution to the Design of Isolated DC-DC Converters for Utility Applications", Diss. RWTH Aachen University, E.ON ERC, 2012

N. Soltau, „High-power medium-voltage DC-DC converters : design, control and demonstration", Diss., RWTH Aachen University, E.ON ERC, 2017

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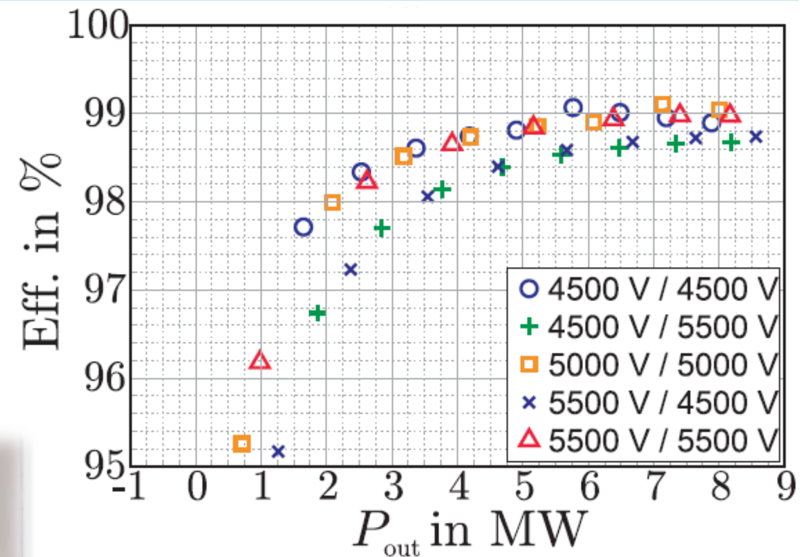

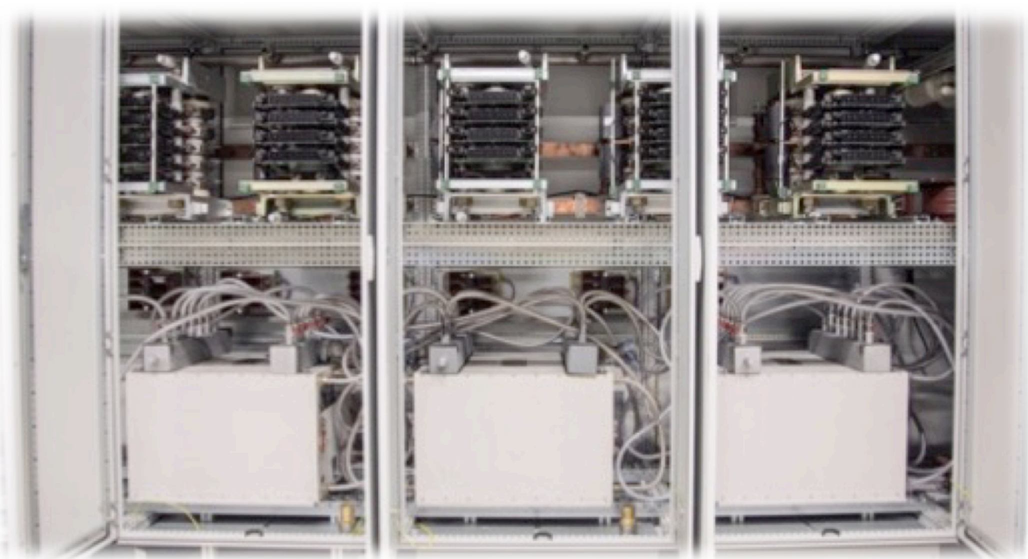

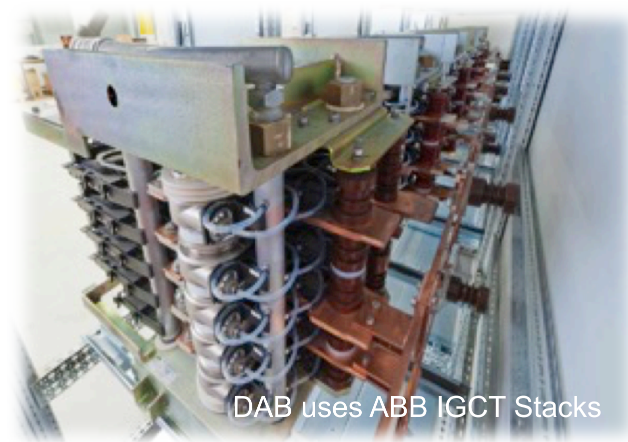

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Material usage in power transformers
Frequency matters!

Weight distribution of copper and Si-steel in machines and transformers:
Copper: 25 – 30 %
Iron lamination: 70 – 75 %
Specific weight Fe: 8 g/cm³
Specific weight Cu: 9 g/cm³

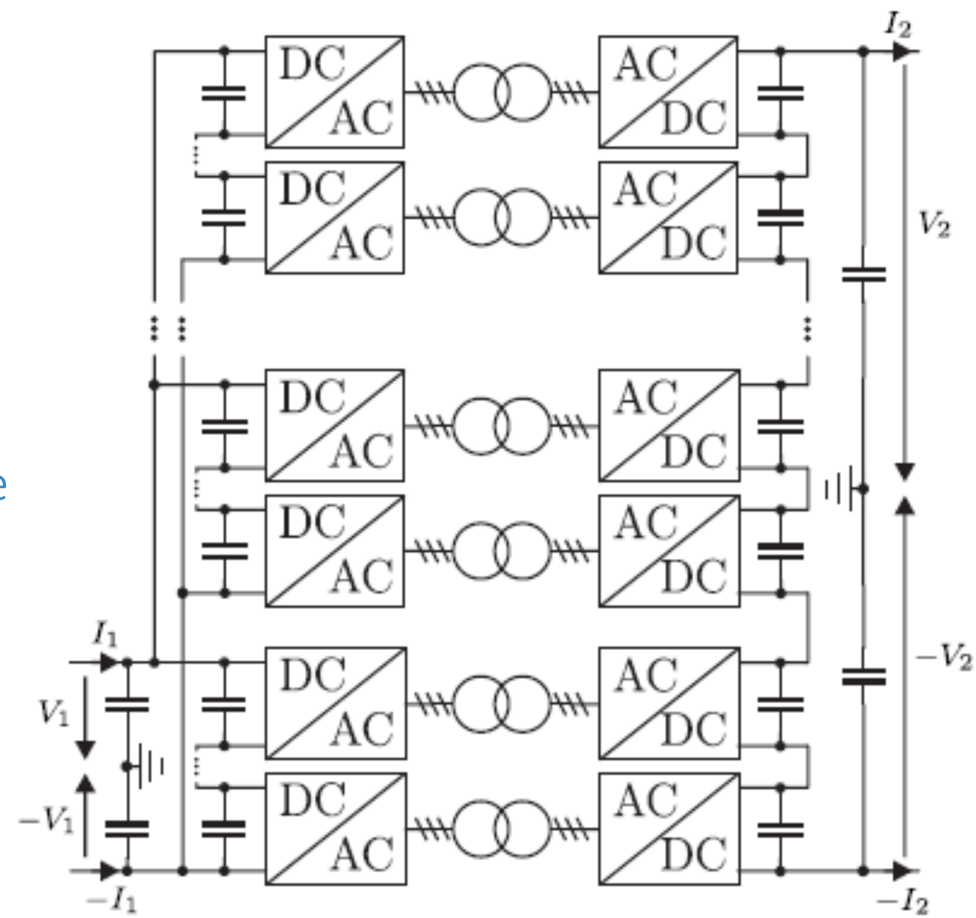
50 Hz Transformer. 2.5 kg/kVA

1,000 Hz Transformer: 0.25 kg/kVA

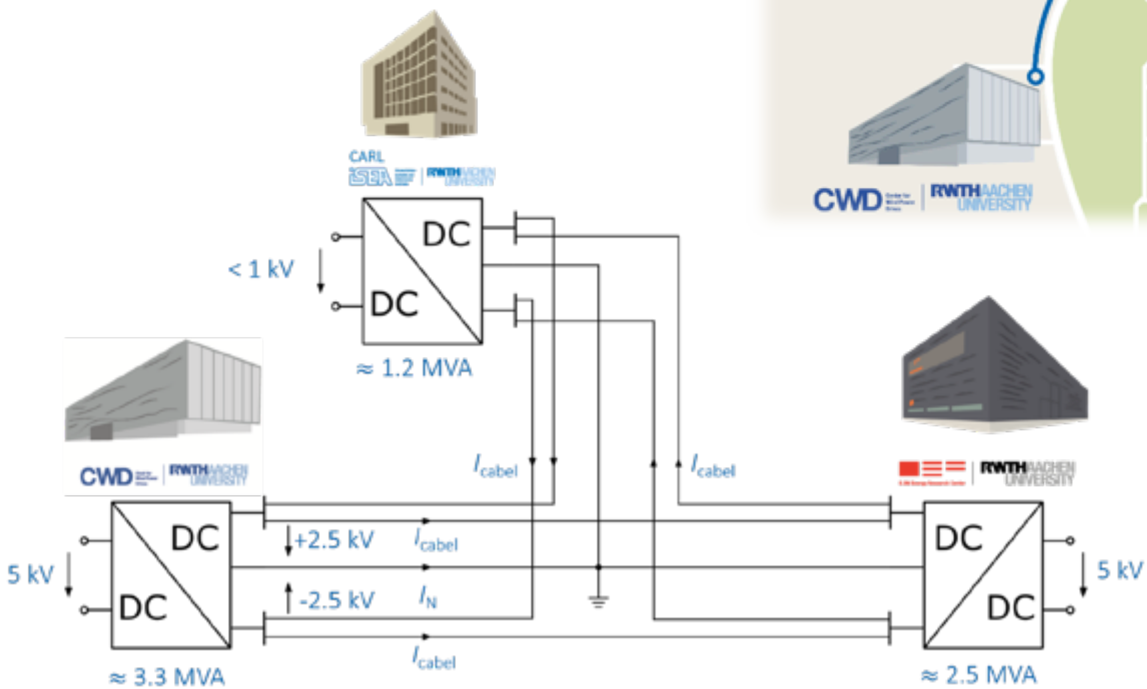
Medium-Voltage High-Power DC-DC Converter

Dual-Active Bridge as a universal PEBB

- Three-Phase Dual-Active Bridge (DAB)
  - High efficiency (99%)
  - Medium-frequency ac-link
  - Modular approach- PEBB
  - Scalable in power and voltage
  - Buck-Boost operation
  - Short circuit proof
  - Primary and secondary side can be connected in series or parallel
  - Can be built with redundancy



FEN Leuchtturmprojekt
P4 Medium-voltage (5 kV) CAMPUS grid



Multiport DC-DC Converters as Power Router

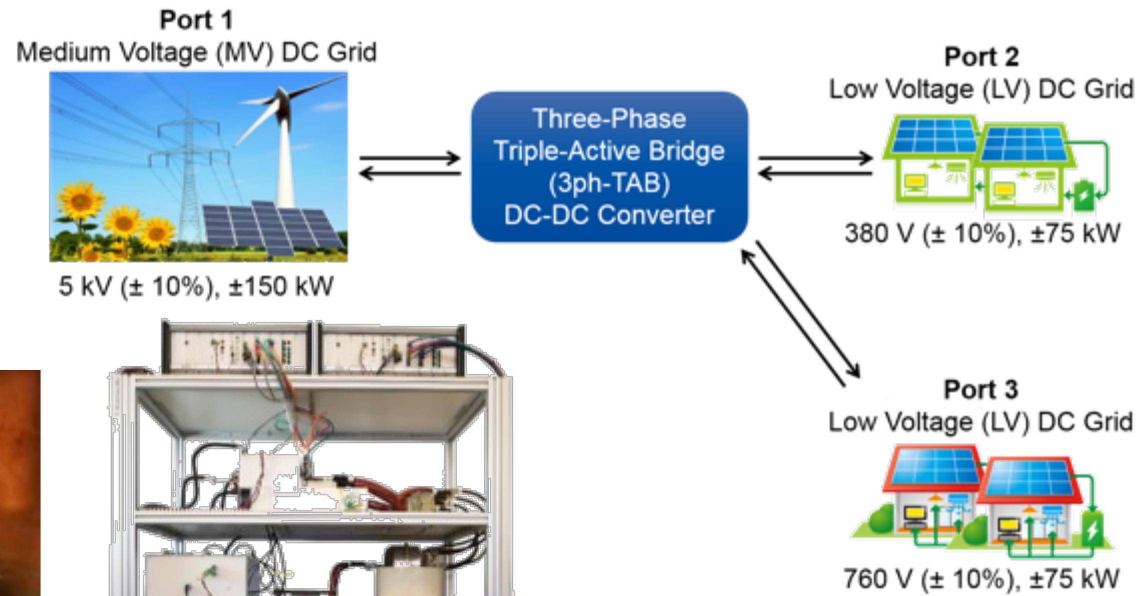
- Fully bidirectional power flow between different loads/grids, i.e., no intermediate (high voltage) stage is required to exchange power between loads/grids of different or equal voltage levels
- Low component count (each load/grid requires only one power electronic port)
- High utilization of components
- Arbitrary number of loads/grids can be operated in island mode

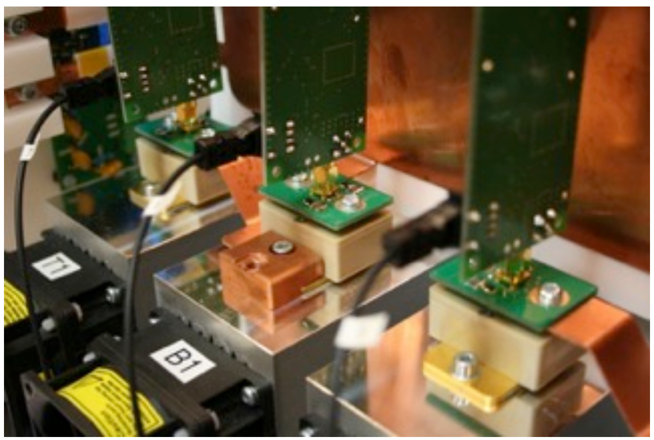
→ Highly efficient and flexible way for interconnecting dc grids/loads

Using multi-port dc-dc converter

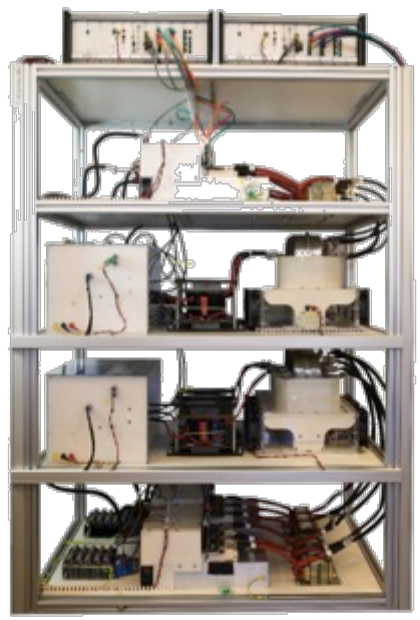
Using separate dc-dc converters

Three-Phase Triple-Active Bridge DC-DC Converter





10 kV SiC MOSFETs and gate drivers
of medium-voltage port

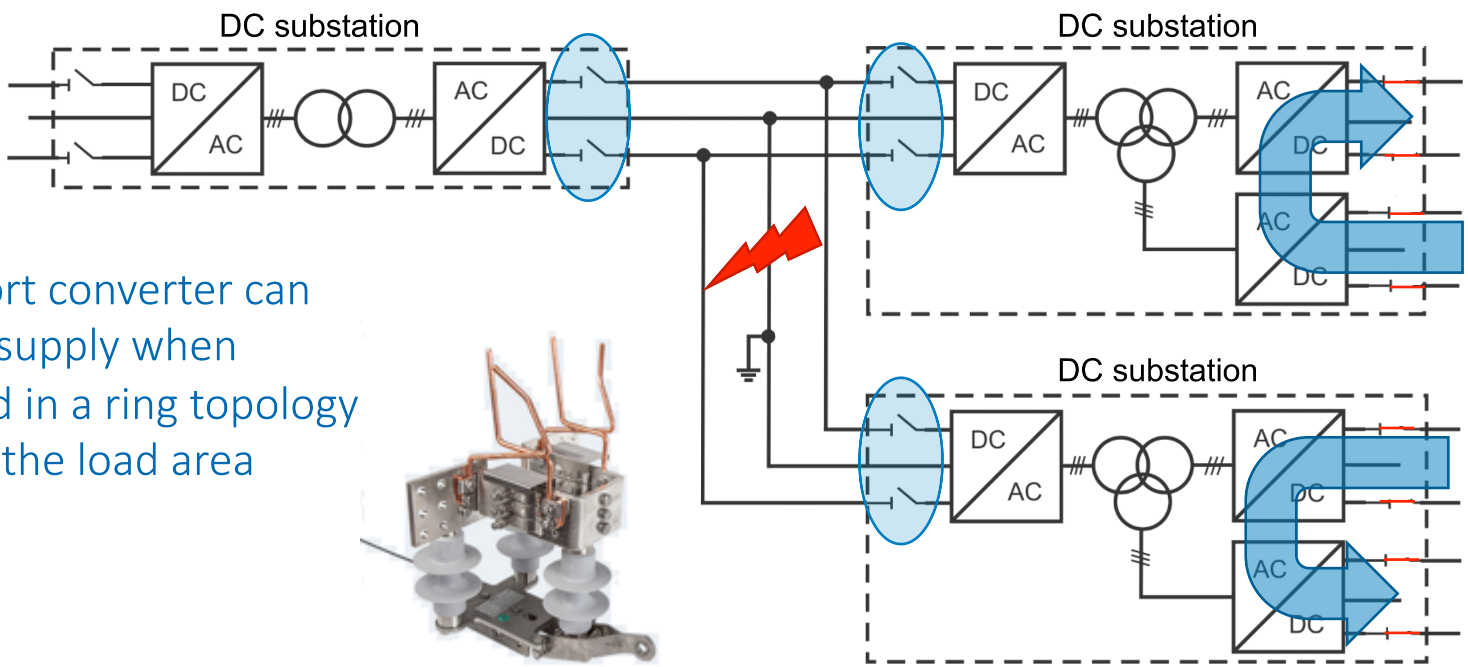


- 150 kW, 20 kHz
- 5 kV, 760 V and 380 V
- 10 kV SiC MOSFETs

M. Neubert, A. Gorodnichev, J. Gottschlich and R. W. De Doncker, "Performance analysis of a triple-active bridge converter for interconnection of future dc-grids," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp. 1-8., doi: 10.1109/ECCE.2016.7855337

Fault in Meshed DC Grid
Fault Isolation with DC Disconnects

- Fault occurs
  - Fault extinction via DC-DC converters (short interruption in power supply)
  - Isolation of fault with disconnectors (eliminates need for circuit breakers)
  - Non affected zones of three-port converter can continue operation

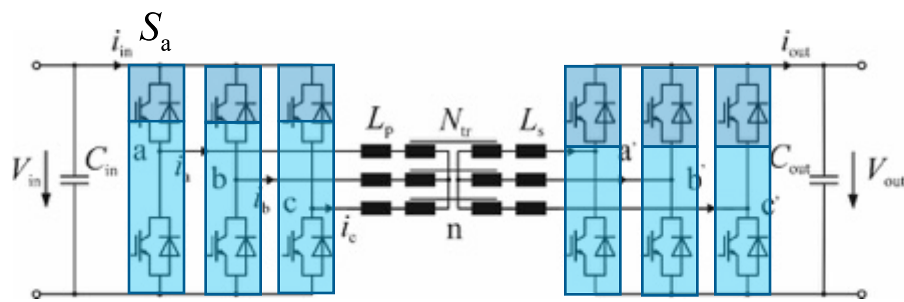


Multiport converter can ensure supply when installed in a ring topology around the load area

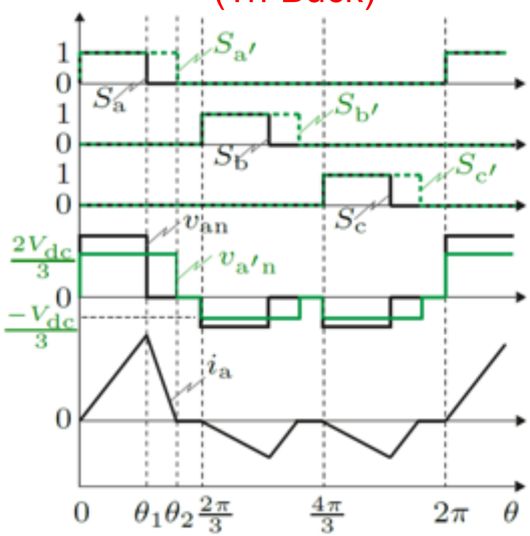
Picture: Siemens, Sicat 8WL6134 DC disconnector, 3 kV

DC Fault Analysis of Asymmetrical Duty-Cycle Control

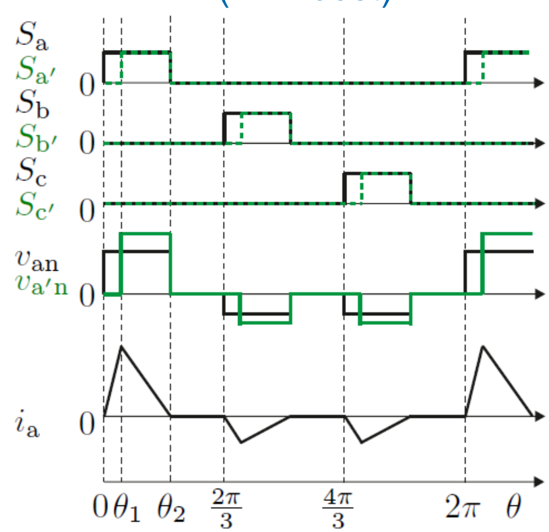
- Inject common mode voltages (000) to the neutral point of transformer
- Existing 3 operation modes for soft-switching operation with wide voltages under part load conditions



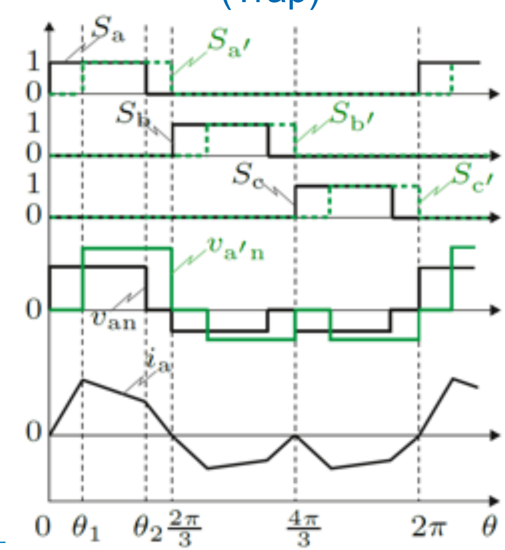
3-phase triangular buck (Tri-Buck)



3-phase triangular boost (Tri-Boost)



3-phase trapezoidal (Trap)

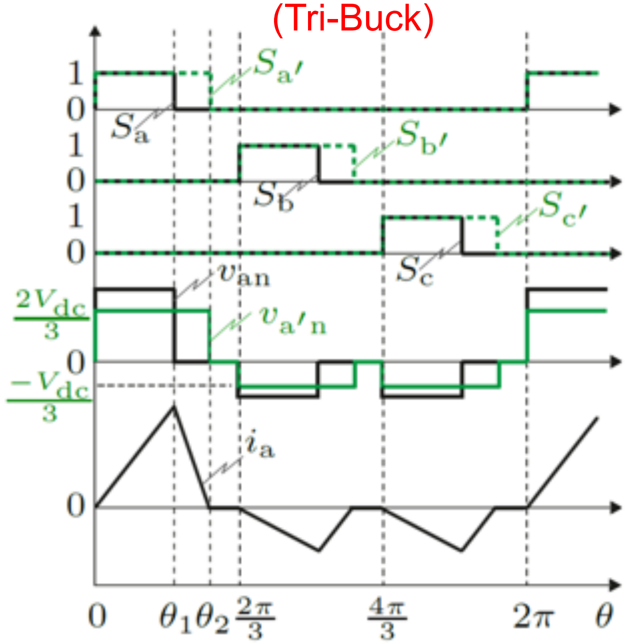


Tri-Buck Space Vector Asymmetric Duty Cycle Control

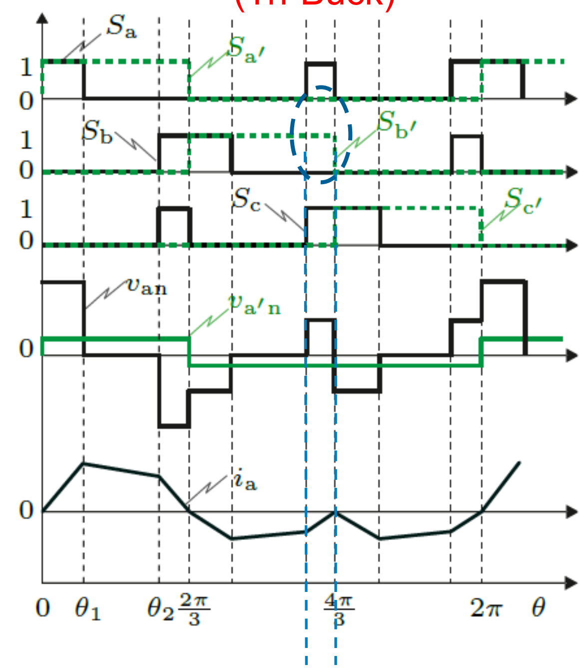
Soft-switching operation during fault ride-through

- Devices at fault-free side (input) switch twice per period (double effective switching frequency)
- Soft-switching is realized
- Low thermal stress during fault ride-through

3-phase triangular buck (Tri-Buck)



3-phase SV-ADCC (Tri-Buck)



	1st turn-on	1st turn-off	2nd turn-on	2nd turn-off
Unfaulty-side top switch	ZCS	ZVS*	ZVS	ZCS
Unfaulty-side bottom switch	ZVS	ZVS*	ZCS	ZVS*
Faulty-side top/bottom switch	ZCS	ZCS	NA	NA

* No diode reverse recovery

Operation Range of SV-ADCC

Operation range of the FRT-Buck mode

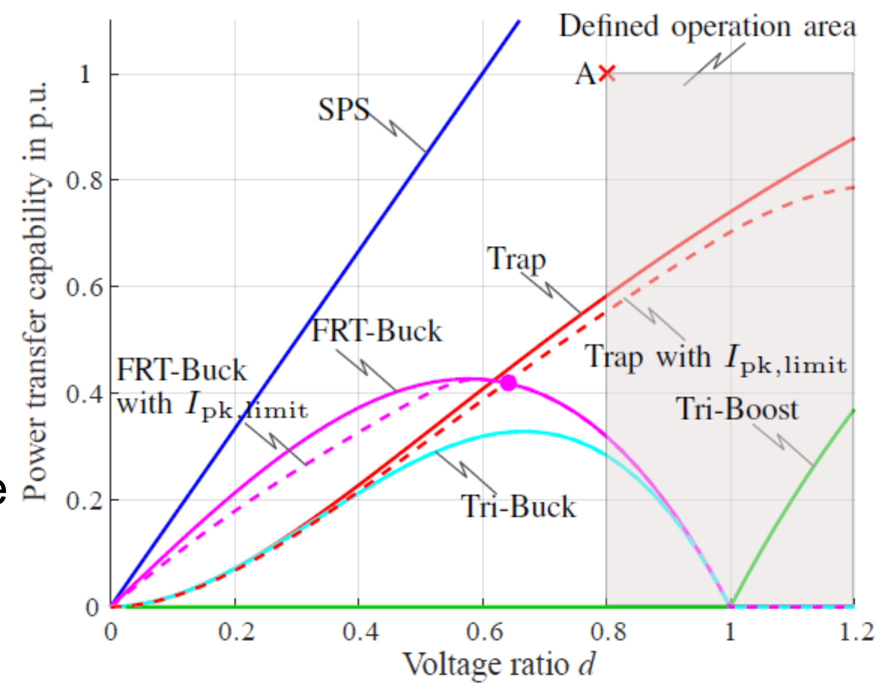
- Power transfer capability of FRT-Buck

$$P_{\mathrm{FRT-Buck}} = \frac{2dV_{\mathrm{in}}^2}{fL_\sigma}\left(-\left(\frac{\theta_1}{2\pi} - \frac{1+d}{6}\right)^2 + \frac{1-d^2}{36}\right)$$

- Peak current limit condition

$$\theta_1 \leq \frac{3\omega L_\sigma I_{\mathrm{pk,limit}}}{2(V_{\mathrm{in}} - N_{\mathrm{tr}}V_{\mathrm{out}})}$$

- FRT-Buck can recover the dc-link voltage following the trajectory of the maximum allowable dc output current



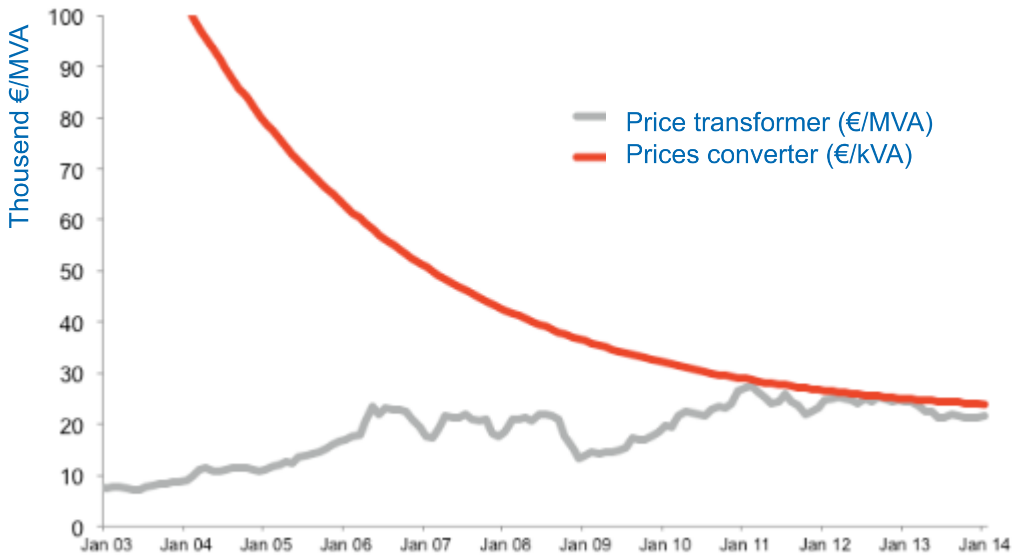
Jingxin Hu, Shenghui Cui, Rik W. De Doncker "**DC Fault Ride-Through of a Three-Phase Dual-Active Bridge Converter for DC Grids**, IEEE IPEC ECCE, May 2018, Niigata, Japan

Roadmap development of DC Converters

Cost development
Impact of New Materials – Increased power density

Price development for transformer can change the AC-paradigm

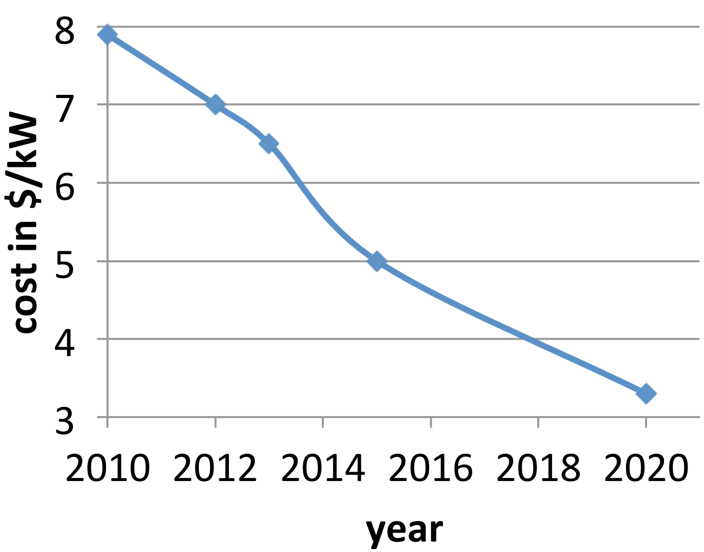
- Metal prices (Cu, Al , Si-Fe) for transformers at LMEx are increasing on long term
- Prices of power electronic systems are continuously dropping
  - Increasing production quantities, new semiconductor generations and materials
  - Higher operating frequency and voltage levels
- During last 25 years a reduction of specific cost for frequency inverters from 500 €/kVA to 25 €/kVA, 5 €/kVA expected in 2020

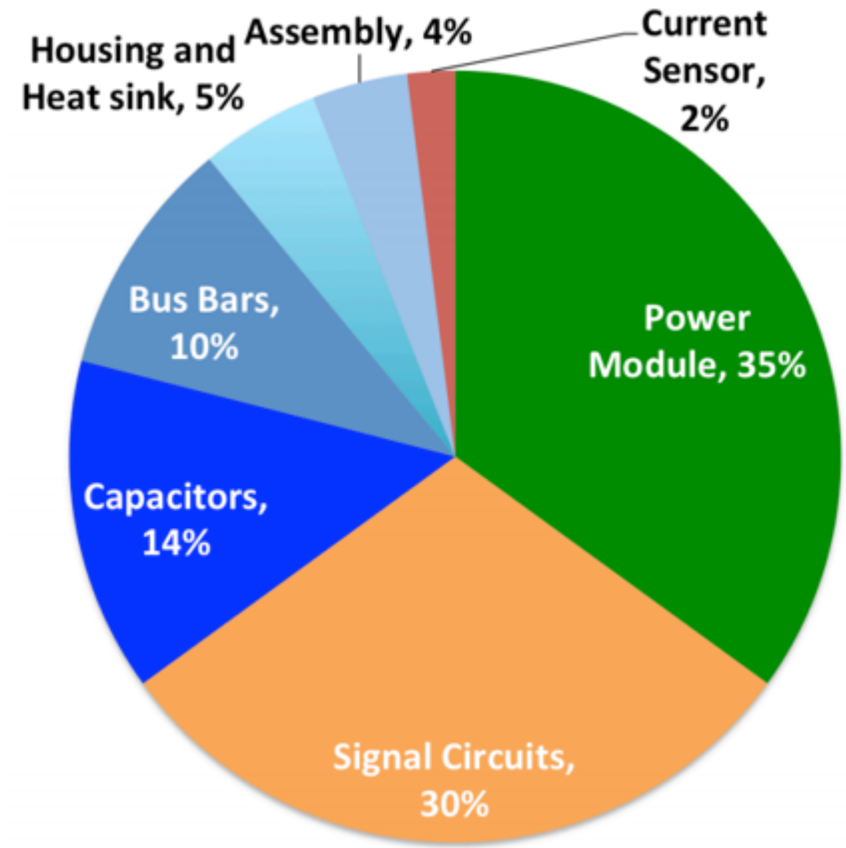


Milestone: In 2013 a frequency inverter was no longer more expensive (20 k€/MVA) than a 50 Hz transformer

Technology Drivers
Price Development of Power Electronics

- Specific cost for EV inverters
  - 1995: $50/kVA[1]
  - 2015: $5/kVA[2]
  - 2020 R&D target: $3.3/kVA





[1] Source: Data provided by R. De Doncker
[2] Source: U.S. Department of Energy, Vehicle Technologies Office

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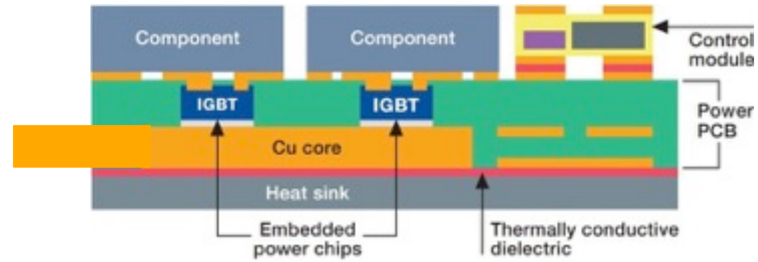
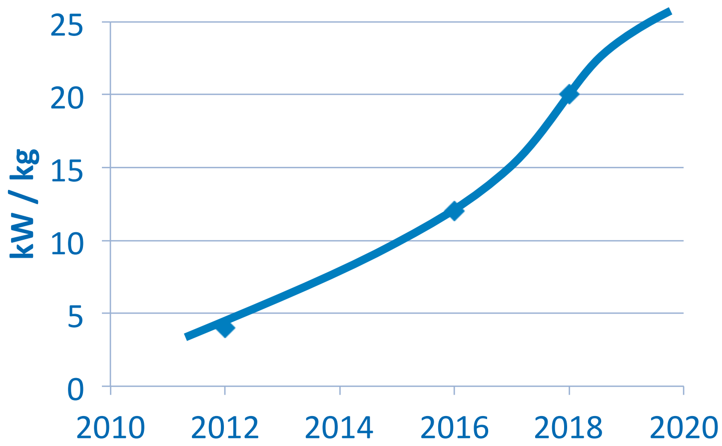
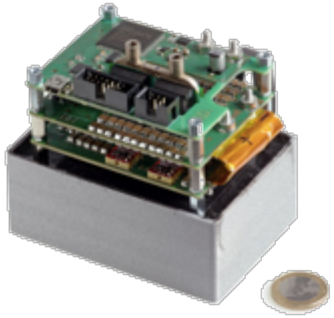


- DC-DC converter cost
  - Comprises two inverters and HF transformer
  - 2020 R&D target: $7.7/kW
  - Cost reduction using soft-switching and Wide Bandgap Devices

[1] **Source: Data provided by R. De Doncker**
[2] **Source: U.S. Department of Energy, Vehicle Technologies Office**

Power Density Development of DC-DC Converters



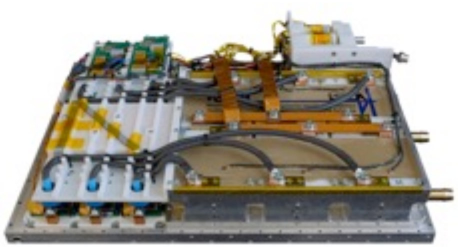


2018

- f_{sw} = 400 kHz
- discrete SiC devices
- 3D-printed cooler and inductor bobbin

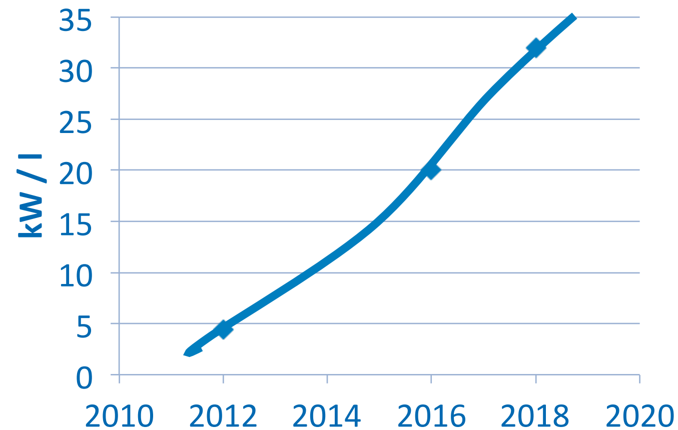
2016

- f_{sw} = 150 kHz
- SiC-Module
- classic cooler and inductances



2012

- *f_{sw} = 16 kHz*
- *Si-Module*
- *classic cooler and inductances*

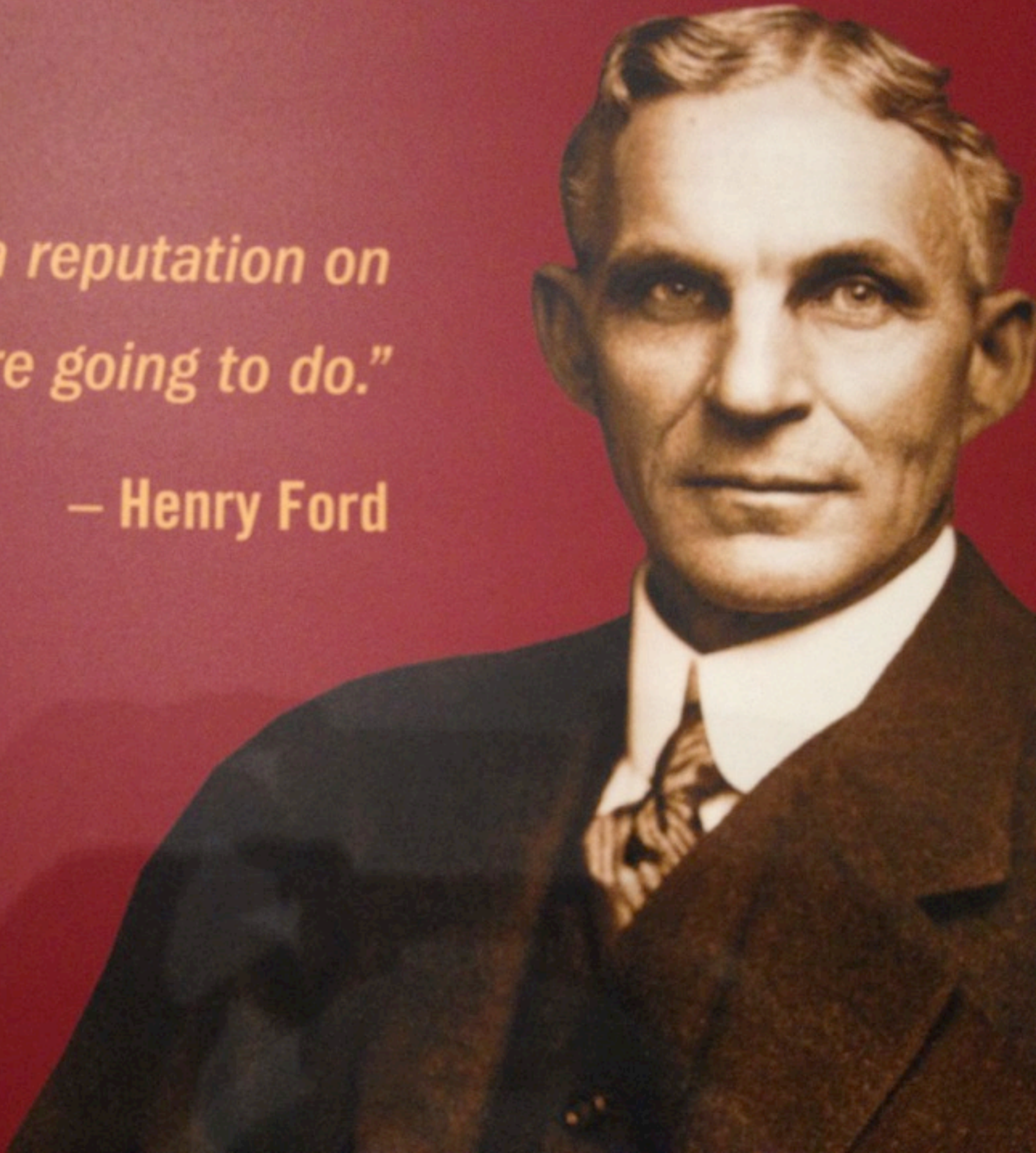


Summary

- Renewable energy has the full potential as a foundation for the future sustainable energy supply of industrial societies
- Underlay DC grids are more flexible and cost advantageous in distributing volatile renewable energy
- Interconnected DC grids offer efficient and low cost interoperability solutions for prosumers and fast charging services
- Power electronics is a key enabling technology for the energy transition towards a CO_2 neutral society

"You can't build a reputation on
what you're going to do."

– Henry Ford



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E.ON Energy Research Center | IAEW Institute of Power Systems and Power Economics | IAW Institute of Industrial Engineering and Ergonomics | IEM Institute of Electrical Machines | IFHT Institute for High Voltage Technology | ISEA Power Electronics and Electrical Drives | RWTH AACHEN UNIVERSITY

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* Member of CIGRE C6.31 MVDC Feasibility Study and DKE LVDC Std. Committee

Status: January 2017

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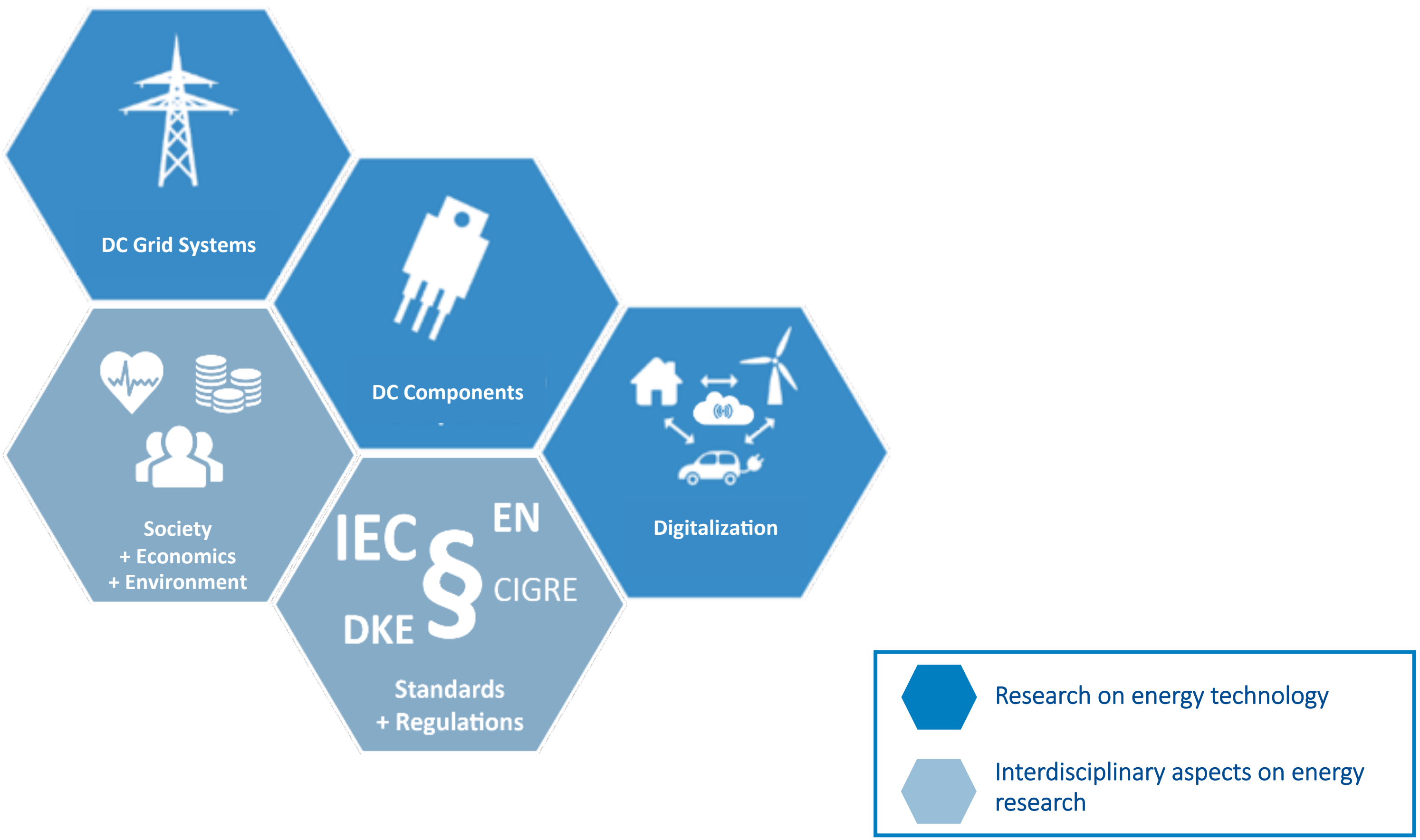

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