Power Electronics
Key Enabling Technology for a Sustainable Energy Supply

Vision now and beyond 2040



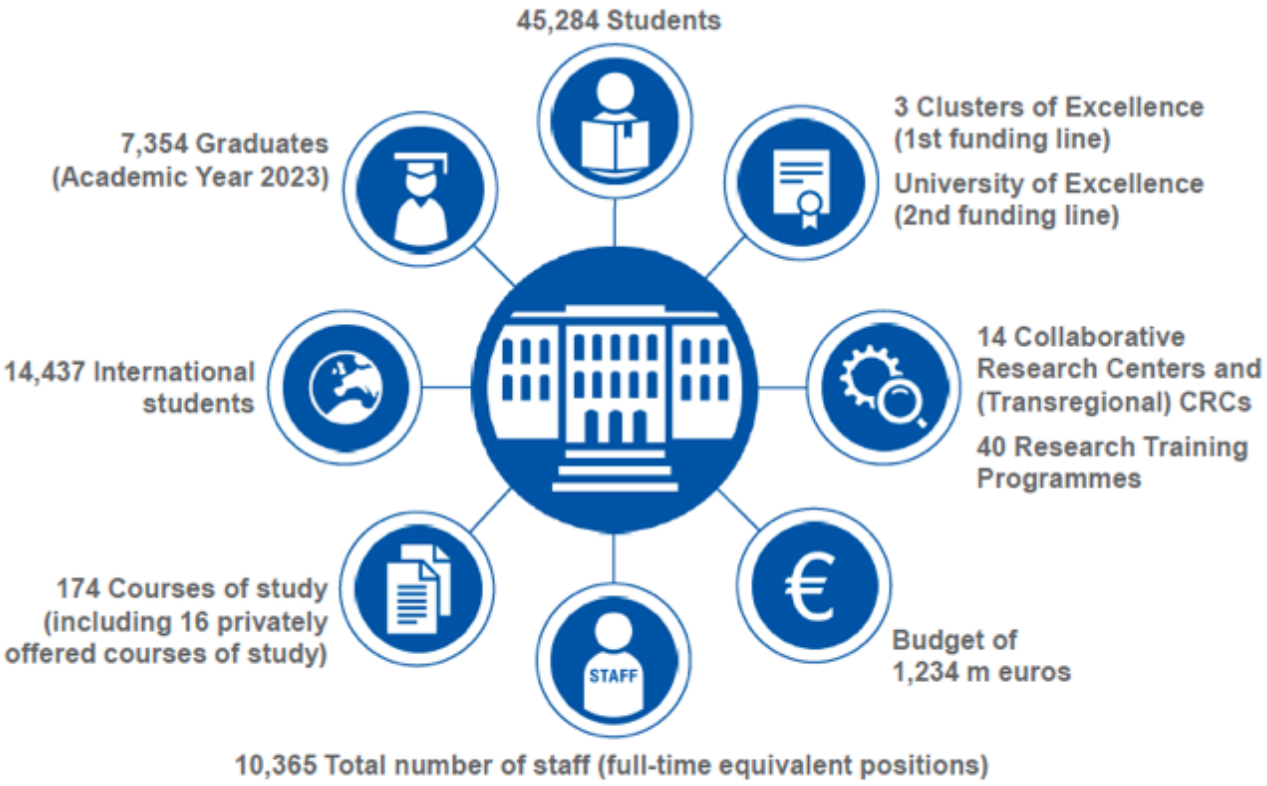




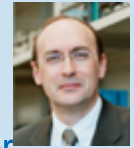
Rik W. De Doncker
Director E.ON Energy Research Center, ISEA & Research Campus FEN
RWTH Aachen University

CPE 2024
Newcastle, July 9, 2024

RWTH Aachen University
Figures at a glance 2023



Two chairs – two institutes ISEA and PGS at RWTH Aachen University

	ISEA – Institut für Stromrichtertechnik und Elektrische Antriebe – RWTH AACHEN	E.ON Energy Research Center – PGS | Institute for Power Generation and Storage Systems
Chair for Power Electronics and Electrical Drives – LEA/PED  Prof. De Doncker	Power electronics and drives systems with a voltage < 1000 V	Power electronics and drives systems with a voltage > 1000 V
Chair for Electrochemical Energy Conversio and Storage Syst – ESS  Prof. Sauer	Mobile energy storage systems	Stationary energy storage systems

Research areas and staff at ISEA and PGS

Univ.-Prof. Dr. ir. Dr. h. c. Rik De Doncker
Power Electronics
Electrical Drives
Electronic Devices, Switched Mode Power Supplies

Univ.-Prof. Dr. rer. nat. Dirk Uwe Sauer
Electrochemical Energy Conversion and Storage Systems

Univ.-Prof. Dr. rer. nat. Egbert Figgemeier
Ageing Processes and Lifetime Prediction of Batteries (Helmholtz - FZJ)

- 14 Chief Engineers
- 1 Adjunct Professor, 2 Lecturers
- 102 Research Associates
- ca. 90 Student Co-Workers
- ca. 150 Graduate Students per Year
- 30 Permanent Staff
- 9 Apprentices

E.ON Energy Research Center in Aachen

Successful Collaboration since 2006

4 Institutes

- Automation of Complex Power Systems
  Prof. Monti – Prof. Ponci
- Energy Efficient Buildings and Indoor Climate
  Prof. Müller
- Future Energy Consumer Needs and Behavior
  Prof. Madlener – Prof. Praktiknjo
- Power Generation and Storage Systems
  Prof. De Doncker – Prof. Sauer

7 Professorships

14 Mio. Euro Project Volume p.a.

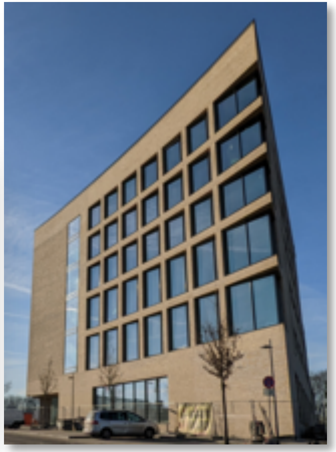
- Portfolio of Different Projects per year in all Innovation Areas
- 2 Mio€ Projects with E.ON Business Areas

Introduction of New Research Center - CARL

Center for Ageing, Reliability and Lifetime Prediction of Electrochemical and Power Electronic Systems

- Center focused on **Ageing, Reliability** and **Lifetime estimation** of batteries and power electronic systems
  - Interdisciplinary research of over 20 RWTH institutes

- The Center has three main laboratory areas
  - Load and environmental simulations
    - Investigation of electrical, mechanical, chemical or climatic influences
    - Accelerated aging tests
    - Analysis of aging processes and effects
  - Construction of prototypes
    - State-of-the-art equipment for the manufacturing of future components and systems
  - Physical-electrochemical analysis
    - Analysis of structures and properties of materials down to molecular level



Flexible Electrical Networks (FEN) Research Campus
Academia and Industry work together under one roof to accelerate innovation for distribution grids

Status: April 2023

Flexible Electrical Networks (FEN) Research Campus

Commercial Partners

ABB · AixControl · aq · e·on · EATON Powering Business Worldwide · Flexible Elektrische Netze GmbH · hager · HITACHI Inspire the Next · HYOSUNG · infineon · KIEPE ELECTRIC · LEADRIVE Technology Germany GmbH · MR · OPAL-RT TECHNOLOGIES · Regionetz · STAWAG · EWV · SUNGROW Clean power for all · thyssenkrupp

Scientific Partners

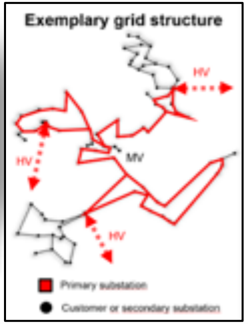
RWTH AACHEN UNIVERSITY · ACS · FCN · PGS · EBC · GGE · E.ON Energy Research Center · IAEW · IAW Institute of Industrial Engineering and Ergonomics · ISEA Power Electronics and Electrical Drives · städtebau · Institute of Landscape Architecture · Textlinguistics & Technical Communication · HCIC - Human-Computer Interaction Center · humtec

FORSCHUNGS CAMPUS
öffentlich-private Partnerschaft für Innovationen

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FEN Landmark Projects 1st Phase
Medium-voltage DC CAMPUS Grid, Design Tools & Real Time Emulators

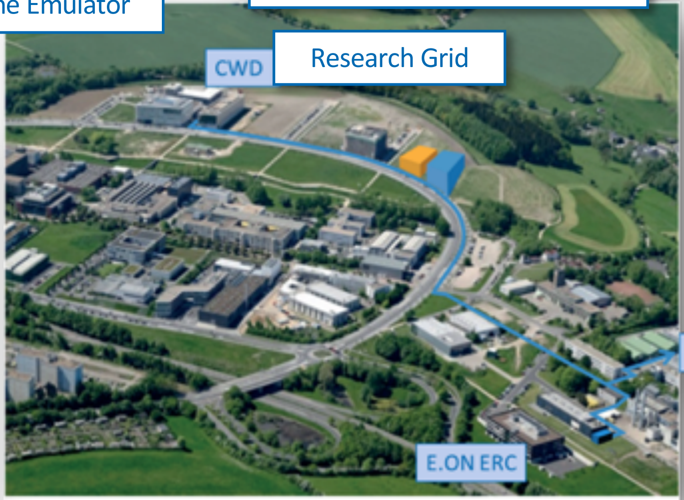
Landscape Architecture



DC Grid Planning Tool

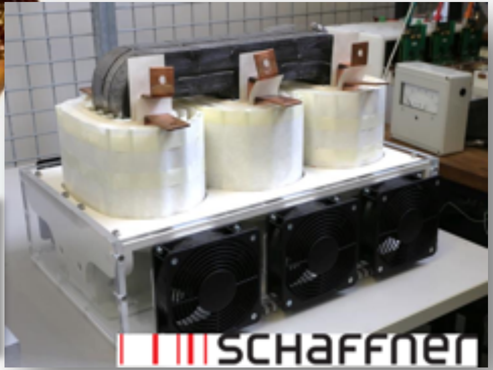
AixControl XRS7070
Real Time Emulator

7 MW / 1 kHZ DC-DC Converter

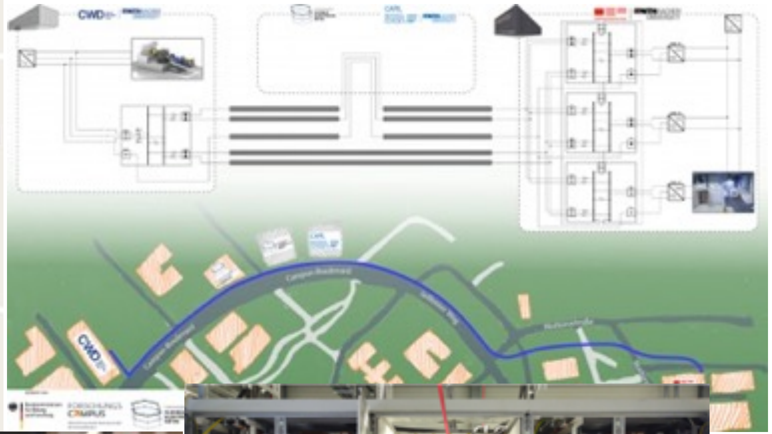


Research Grid

DAB & Tri-port DC converters
Medium Frequency Transformers



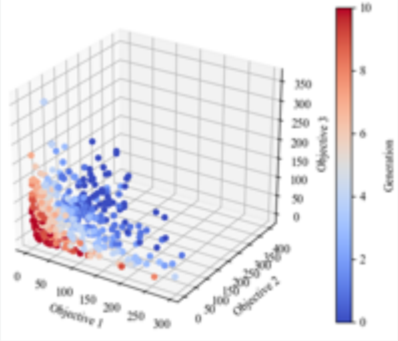
FEN Major Achievement 1st phase : MVDC - Grid at RWTH Campus (connecting 2 AC substations)
Official start of operation 5 kV MVDC-Grid 19.11.2019



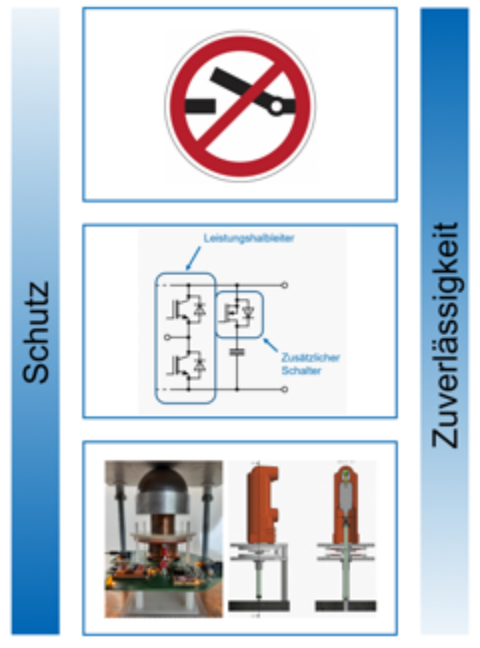
R&D highlights of on-going projects

Power Electronics
Quadport for mashed DC grids

Rapid Product Development

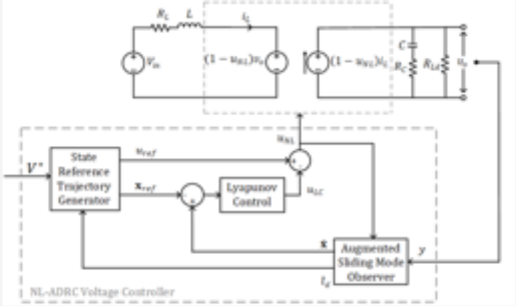


MVDC Protection
Components and Strategies



Hardware-in-the-Loop
Realtime Models

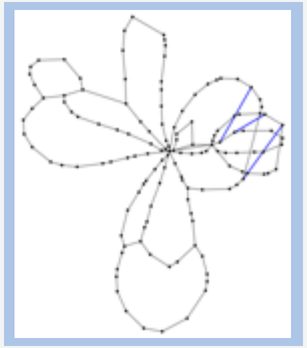
Model based control
of DC-DC converters



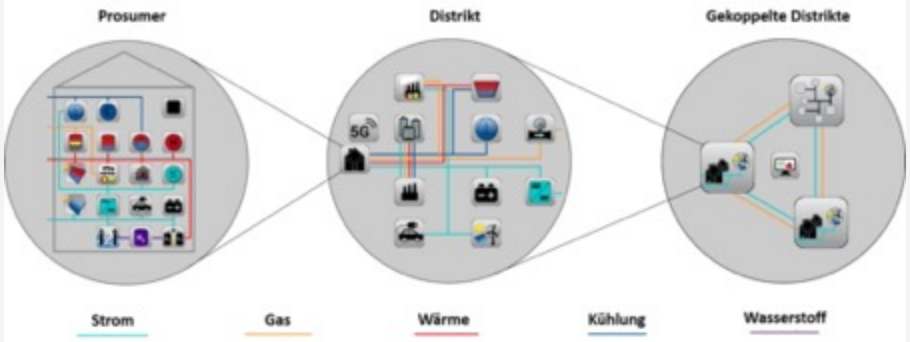
R&D highlights of on-going projects

Simulation and Planning Tools
for AC and DC Grids

Greenfield- und Brownfield-Ansatz



FOCUS-Framework

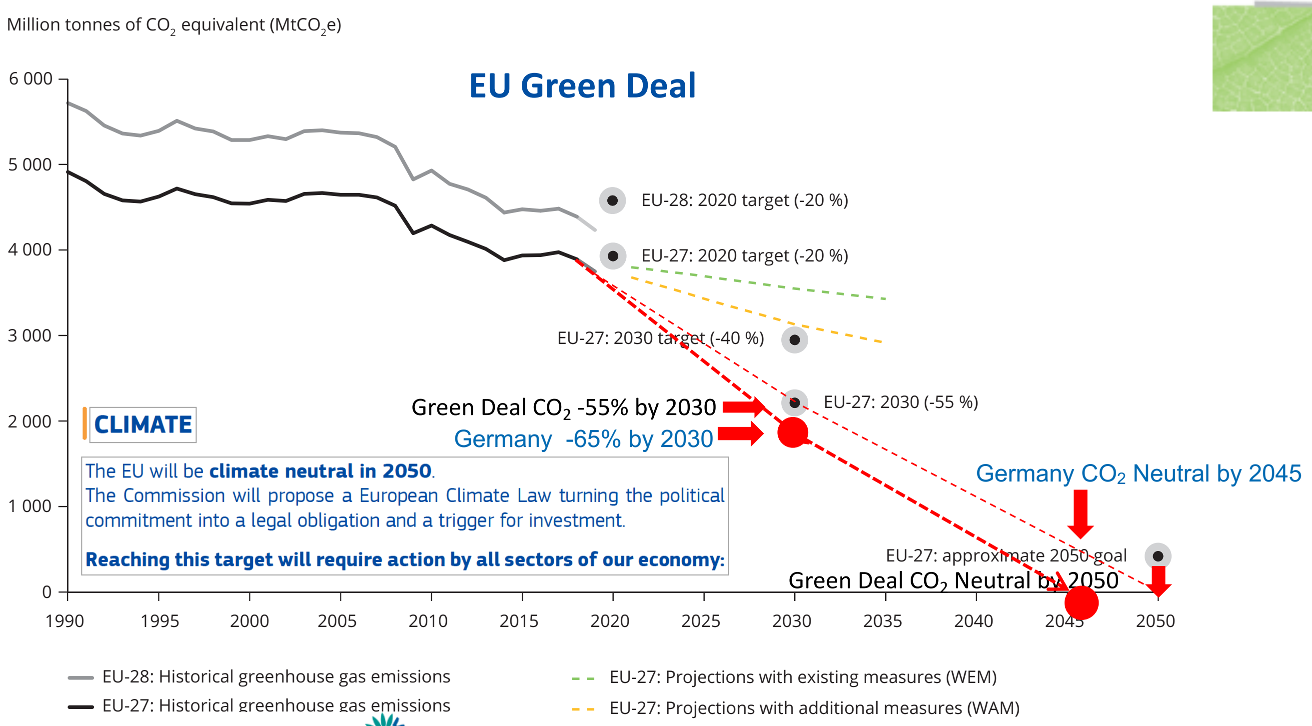


Niche Readiness Level Model

Overview

- Introduction
  - RWTH, CARL & BMBF Research Campus Flexible Electrical Networks
- Motivation
  - EU Green Deal
  - Pillars of sustainable solutions (technical, economical, ecological)
  - Peak Copper - the real thread to realizing the energy transition
  - DAB based substations to electrify the entire world
- Concept of a CO_2 neutral energy supply system
  - Cellular MVDC distribution grid
  - DC transformers a key power electronic building block
  - Innovations for the electrification of sectors
- Conclusions

Background
EU GREEN DEAL



Source Graph: European Environment Agency

What will we do?

ENERGY

Decarbonise the energy sector

The production and use of energy account for more than **75%** of the EU's greenhouse gas emissions

BUILDINGS

Renovate buildings, to help people cut their energy bills and energy use

40% of our energy consumption is by buildings

INDUSTRY

Support industry to innovate and to become global leaders in the green economy

European industry only uses **12%** recycled materials

MOBILITY

Roll out cleaner, cheaper and healthier forms of private and public transport

Transport represents **25%** of our emissions

European Commission

All sectors need to decarbonize. This is a challenge, but also an opportunity as sector coupling provides storage capacity.

IEEE Spectrum Oct. 2022

Cost:

275 trillion$
or
9 trillion$/year

= 10 % World economic product

but

when we stick to business as usual the cost will be much higher!

Engl.: trillion = Deutsch Billion = 1.000.000.000.000

OPINION, INSIGHT, AND ANALYSIS

BY VACLAV SMIL

Numbers Don't Lie

Decarbonization Is Our Costliest Challenge

It has no clear beginning or end, and it affects every aspect of life

In his 1949 book *The Concept of Mind*, Gilbert Ryle, an English philosopher, introduced the term "category mistake." He gave the example of a visitor to the University of Oxford who sees colleges and a splendid library and then asks, "But where is the university?" The category mistake is obvious: A university is an institution, not a collection of buildings.

Today, no category mistake is perhaps more consequential than the all-too-common view of the global energy transition. The error is to think of the transition as the discrete, well-bounded task of replacing carbon fuels by noncarbon alternatives. The apparent urgency of the transition leads to calls for confronting the challenge just as the United States dealt with two earlier ones: winning the nuclear-arms race against Nazi Germany and the space race against the Soviet Union. The Manhattan Project produced an atomic bomb in three years, and Project Apollo put two U.S. citizens on the moon in July 1969, eight years after President Kennedy had announced the goal.

But as difficult and costly as those two endeavors were, they affected only small parts of the economy, their costs were relatively modest, and the lives of average citizens were hardly affected. It is just the opposite for the decarbonization of the energy supply.

Ours is an overwhelmingly fossil-fueled civilization, and the size and complexity of our extensive supersystem of fuel extraction, processing, distribution, storage, and conversion means that a complete displacement of it will directly affect every person and every industry, not least the growing of food and the long-distance transport of goods and people. The costs will be stupendous.

Affluent nations would have to devote on the order of 15 to 20 percent of their annual economic product to the task of decarbonizing the economy.

Each red cube = US $1 billion

MANHATTAN PROJECT: US $33 billion in 2022 dollars

PROJECT APOLLO: US $207 billion in 2022 dollars

GLOBAL ENERGY TRANSITION: US $275 trillion

Sources: CTBTO Preparatory Commission; ScienceDirect; McKinsey Global Institute

By the time the Manhattan Project ended in 1946, it had cost the country nearly US $2 billion, about $33 billion in today's money, the total equal to only about 0.3 percent of the 1943–45 gross domestic product. When Project Apollo ended in 1972, it had cost about $26 billion, or $207 billion in today's money; over 12 years it worked out annually to about 0.2 percent of the country's 1961–72 GDP.

Of course, nobody can provide a reliable account of the eventual cost of global energy transition because we do not know the ultimate composition of the new primary energy supply. Nor do we know what shares will come from converting natural renewable flows, whether we will use them to produce hydrogen or synthetic fuels, and the extent to which we will rely on nuclear fission (and, as some hope, on fusion) or on other, still unknown options.

But a recent attempt to estimate such costs confirms the magnitude of the category mistake. The McKinsey Global Institute, in a highly conservative estimate, puts the cost at $275 trillion between 2021 and 2050. That is roughly $9.2 trillion a year, compared with the 2021 global economic product of $94 trillion. Such numbers imply an annual expenditure of about 10 percent of today's world economic product. And because the world's low-income countries could not carry such burdens, affluent nations would have to devote on the order of 15 to 20 percent of their annual economic product to the task. Such shares are comparable only to the spending that was required to win World War II. ■

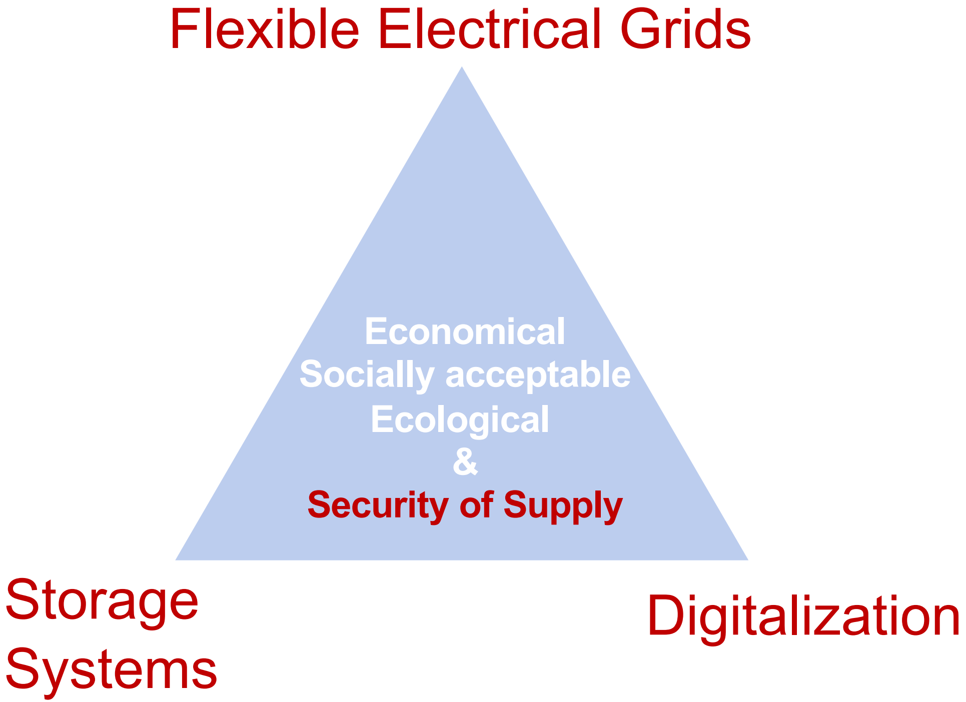
Illustration by Chris Philpot

PORTRAIT: SERGIO ALBIAC

22 SPECTRUM.IEEE.ORG OCTOBER 2022

OCTOBER 2022 SPECTRUM.IEEE.ORG 23

A techno-economical optimum has to be found for the electrical grid that is socially acceptable, ecologically sound and sustainable



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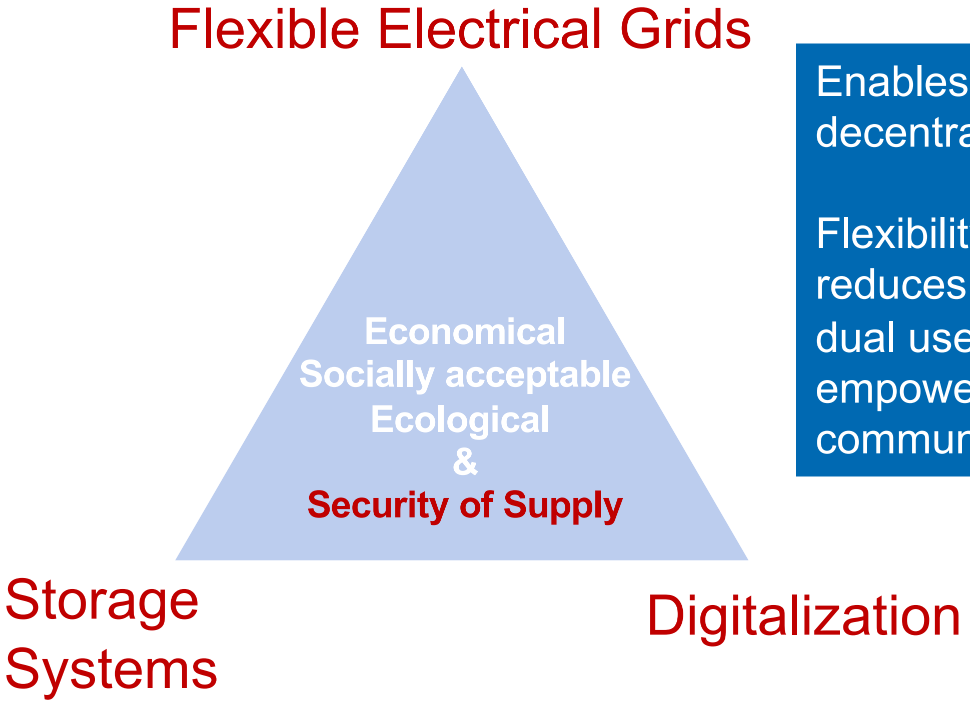


Enables massive feed-in of decentralized REN sources

Flexibility in distribution grids reduces storage needs, enables dual use of EV batteries, and empowers prosumers & energy communities

A techno-economical optimum has to be found for the electrical grid that is socially acceptable, ecologically sound and sustainable

Flexible Electrical Grids

Heat & cold storages and local distribution grids based on heat pumps are least expensive

Strategic storages across seasons with H_2

Storage Systems

Digitalization

A techno-economical optimum has to be found for the electrical grid that is socially acceptable, ecologically sound and sustainable

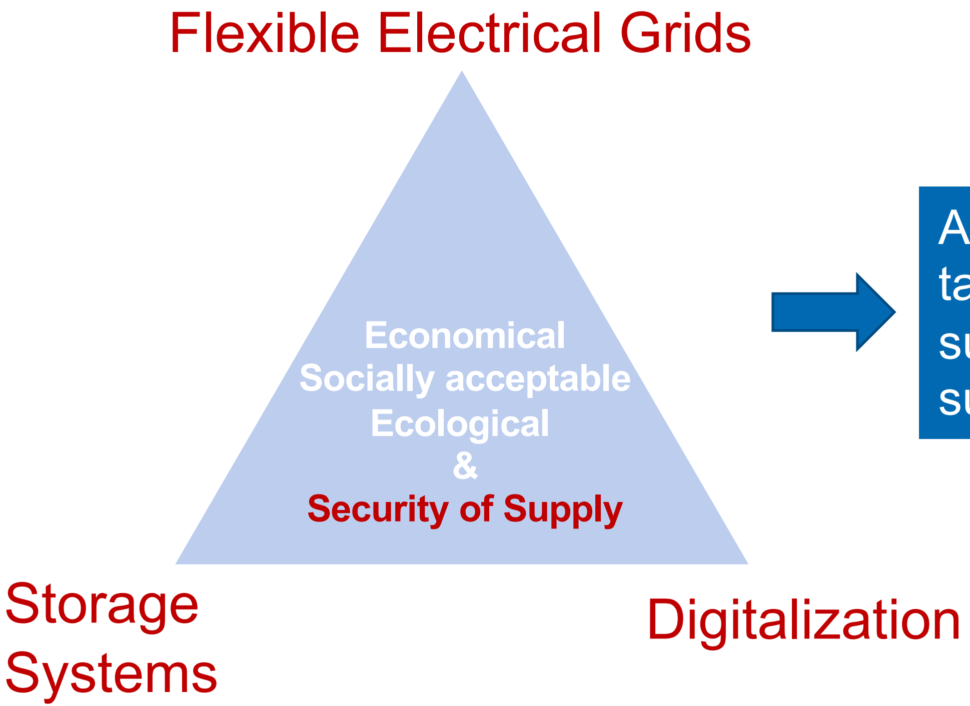
Flexible Electrical Grids

Control and automation to manage complexity of energy dispatching, guarantee stability and demand side management

Storage Systems

Digitalization

A techno-economical optimum has to be found for the electrical grid that is socially acceptable, ecologically sound and sustainable

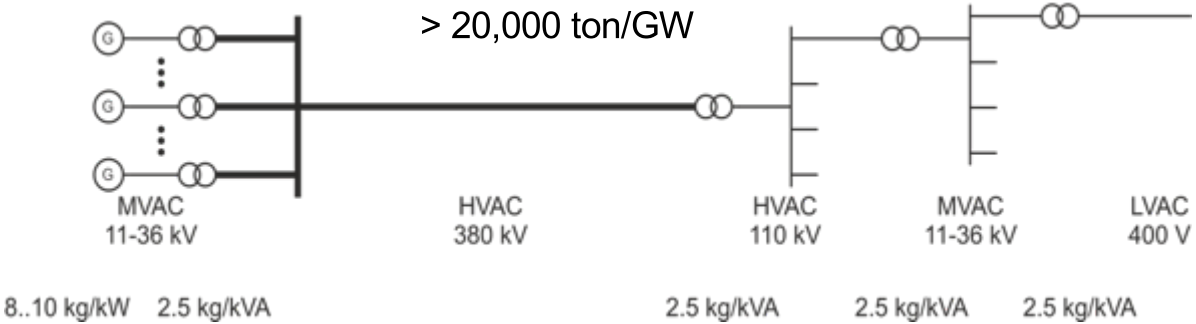


Achieving Green Deal targets requires a sustainable & secure supply of materials

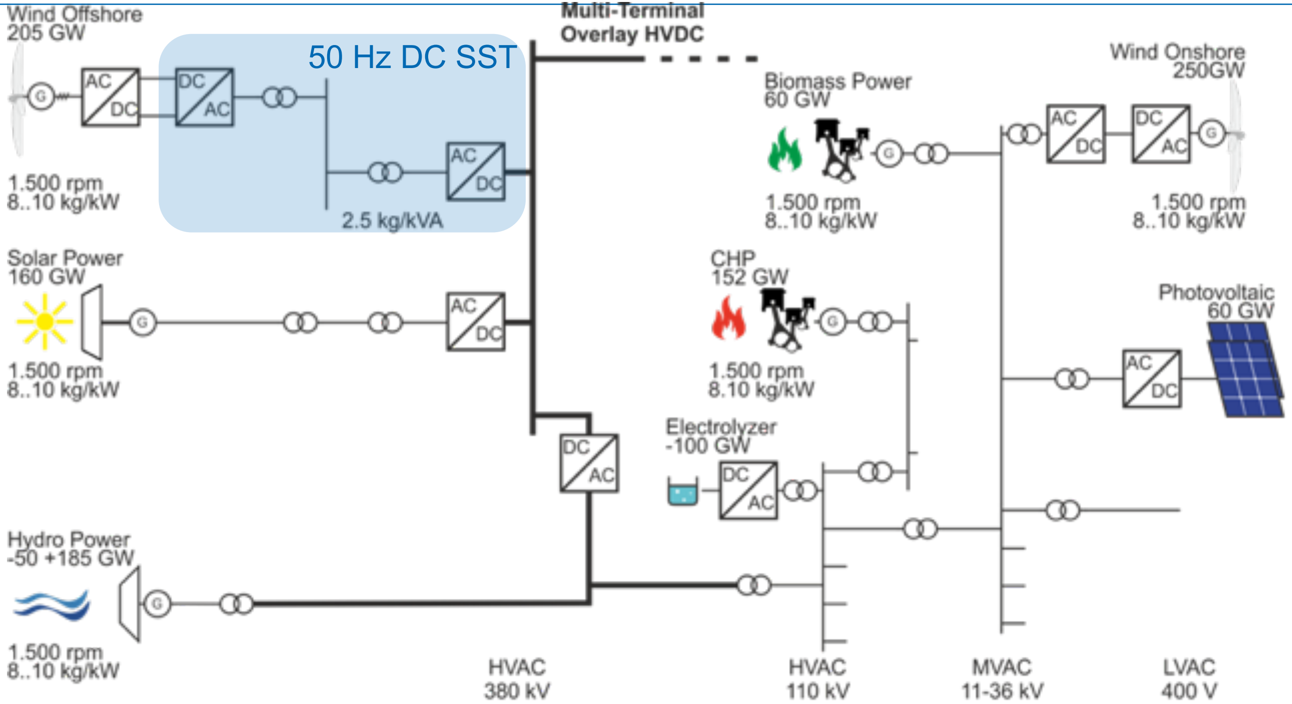
Classical AC Grid Configuration for Transmission and Distribution – high ecological footprint
AC grids are based on transformer technology

- Designed for top down energy transmission and distribution
- 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)

* Not including reactive power ratings and redundancy in distribution grid



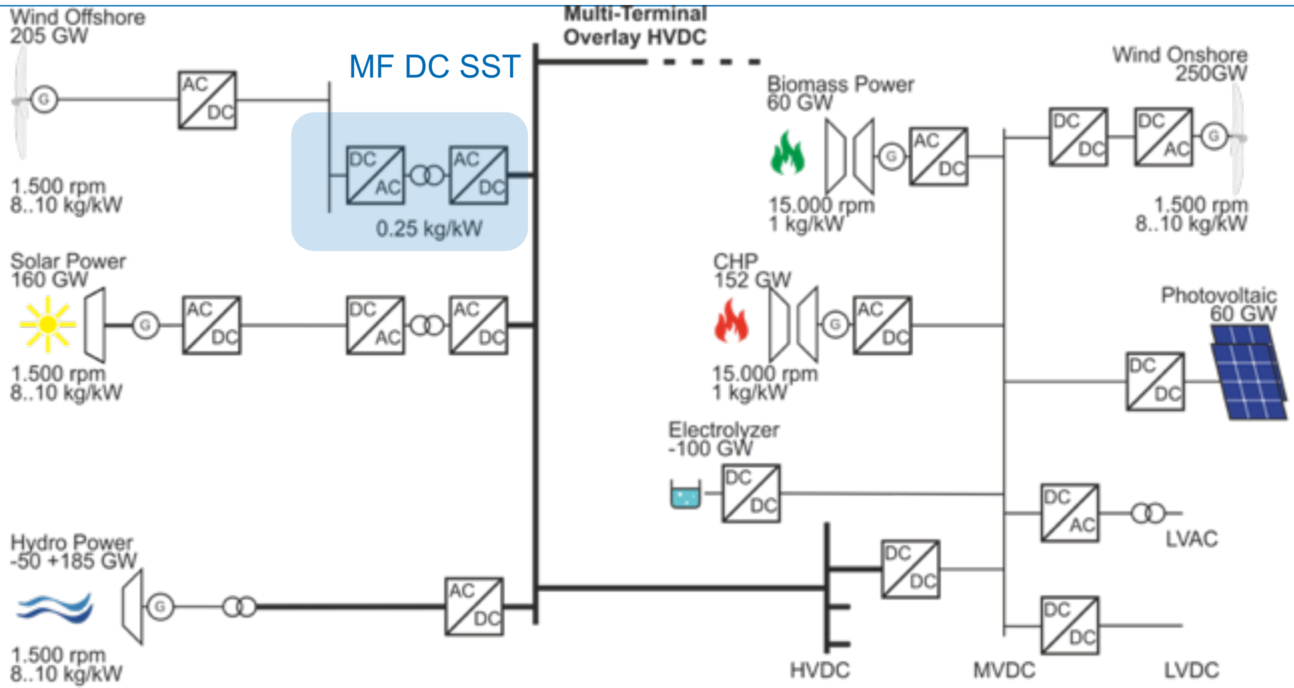
Multi-Terminal HVDC (Overlay Grid) with Standard AC Collector Fields and AC Distribution Grid leads to higher transformer cost



Renewables will require 17,8 Mton Cu & Fe at cost of 142 B€

R. W. De Doncker, "Power electronic technologies for flexible DC distribution grids," IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima, 2014, pp. 736-743, doi: 10.1109/IPEC.2014.6869670

Multi-Terminal HVDC with Medium-Voltage DC Collector Field and DC Distribution Grids leads to lower transformer cost, higher reliability and lower CO_2 footprint



Renewables will require 9,1 Mton Cu & Fe at cost of 73 B€

R. W. De Doncker, "Power electronic technologies for flexible DC distribution grids," IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima, 2014, pp. 736-743, doi: 10.1109/IPEC.2014.6869670

In Conclusion

DC CO_2 Neutral Energy Supply System based on DC Technology has Lower Cost

	AC classic	AC CO_2 neutral	DC CO_2 neutral
Efficiency of converters	94%	89%	95%
Weight Transformers Cu/Si-Fe (Mton)	13,7	17,8	9,1
Cost Transformers (B€ @ 8€/kg)	110	142	73
Cost PEL Converters (B€ @ 20 €/kVA) (B€ @ 5 €/kVA)	-	36 9	60 15
Sum (B€) Sum (B€)	110	178 151	133 88
Grid transmission capacity	100 %	100 %	> 200%

All numbers are estimates anno 2014, hybrid AC/DC solutions were not considered
R. De Doncker, IEEE IPEC ECCE 2014, Hiroshima, Japan

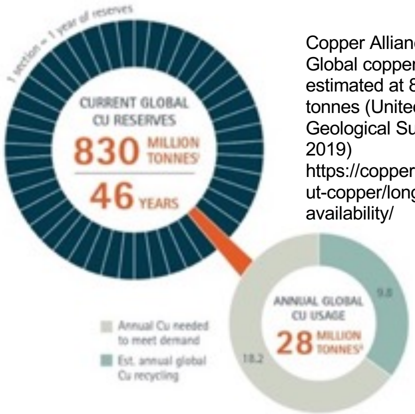
Urgency to innovate in all sectors to meet EU Green targets
More Silicon, less Copper and Steel!

- US Geological Survey report 2019 predicted **Peak Copper** prior to 2065

However

- Standard of living (and emissions) is correlated to electricity use
- About 1 Billion people have limited or no access to electricity

- Electrification of all sectors will increase massively copper use



Copper Alliance,based on Global copper reserves are estimated at 830 million tonnes (United States Geological Survey [USGS], 2019) https://copperalliance.org/about-copper/long-term-availability/

Time out 2065 (predicted in 2019)
Consumption in 2021: 21 MioTonnes
Time out: 2058

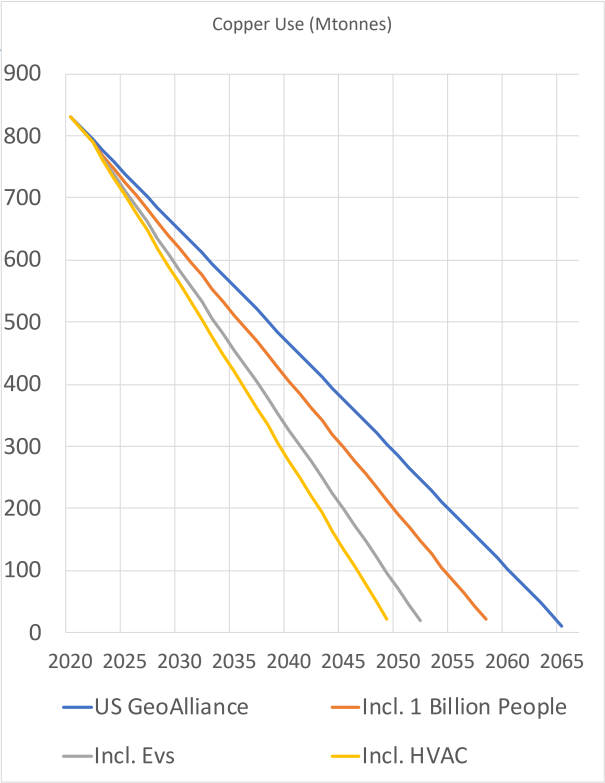
Urgency to innovate in all sectors to meet EU Green targets

More Silicon, less Copper and Steel!

- US Geological Survey report 2019 predicted **Peak Copper** prior to 2065

However

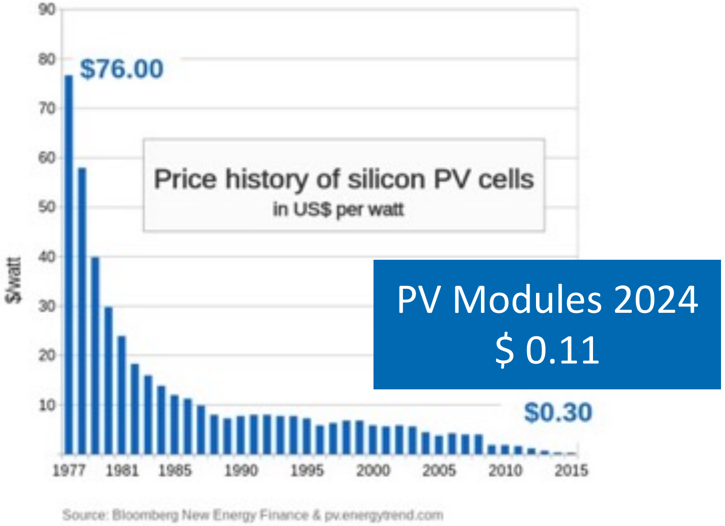
- Standard of living (and emissions) is correlated to electricity use
- About 1 Billion people have limited or no access to electricity
  - Requires 12,5 MioTons Cu extra when using 50 Hz grids (Time out 2057)
- Electrification of all sectors will increase massively copper use
  - Electrification of 1.4B vehicles will use > 130 MioTons Cu (Time out 2051)
  - Electrification of HVAC will use > 80 MioTons Cu (Time out 2047)



➡ Electrification of developing countries needed for geopolitical stability

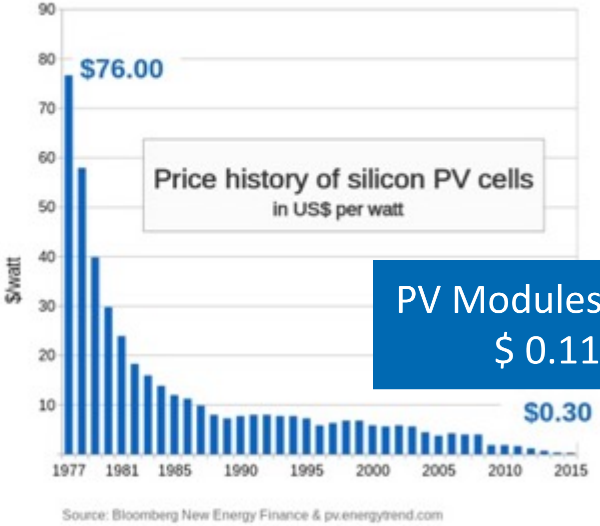
➡ Electrification of all sectors must be accelerated with innovative solutions to meet IPCC global warming targets

Security of supply – saving materials is essential
Price of copper has already doubled over past five years (LMEx)

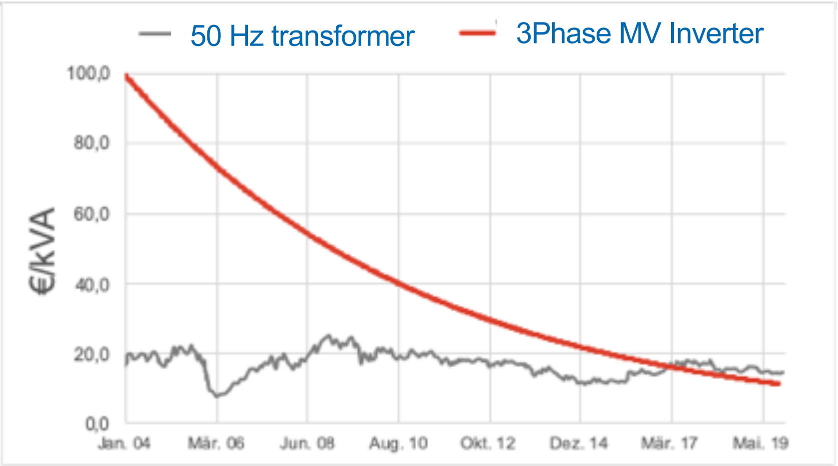


- **It is expected that price of silico**n will keep going down while price of metals, in particular copper price will be increasing. (best investment according to The Economist).
- 75 % of copper refining is in China ➡ Copper is a strategic material

Security of supply – saving materials is essential
Price of converters has dropped by 25x over past 25 years

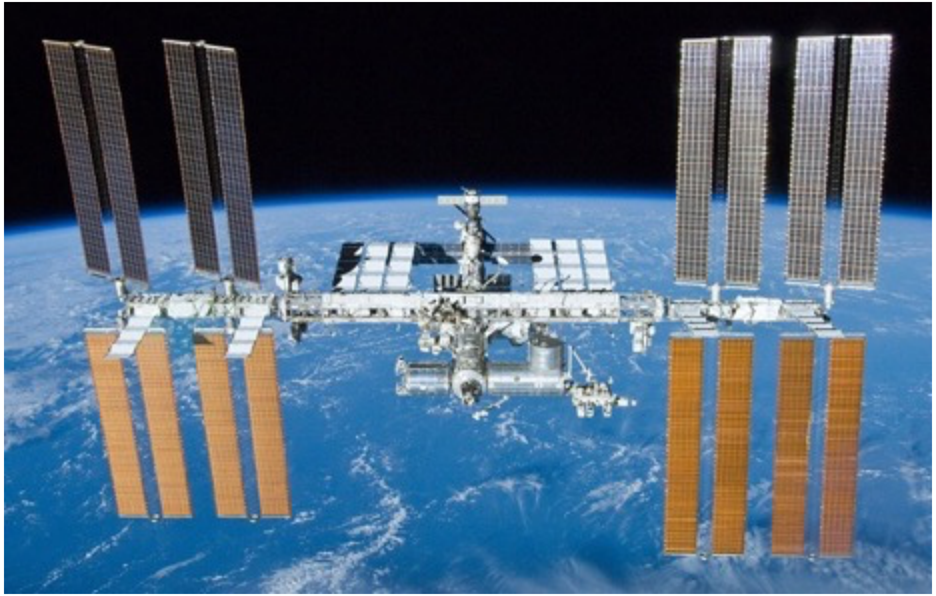


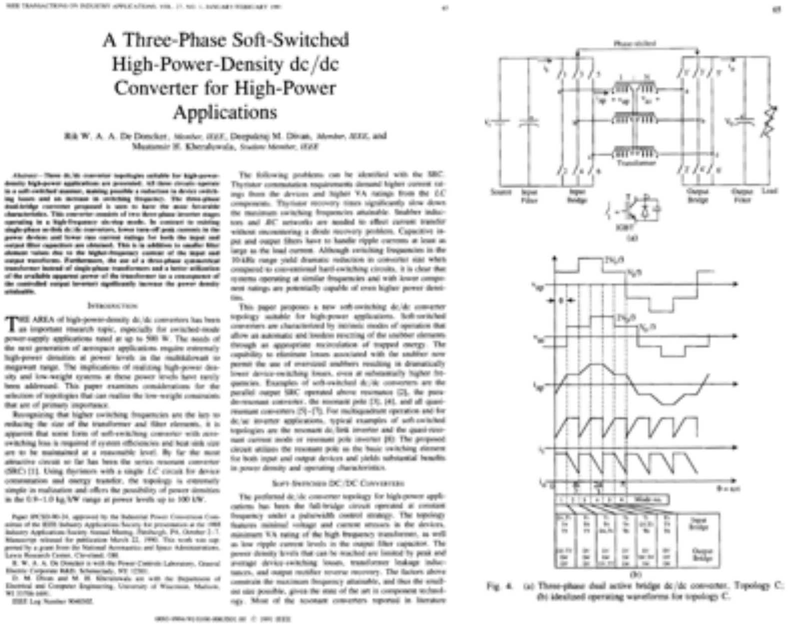
PV Modules 2024
$ 0.11



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**

Power Electronics offers a solution – solid state DC substations
DAB invented in 1988 at UW Madison for the power supply of ISS in NASA project*



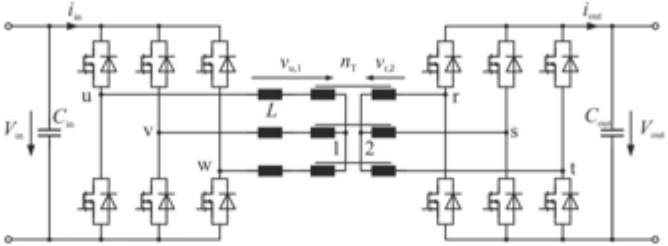


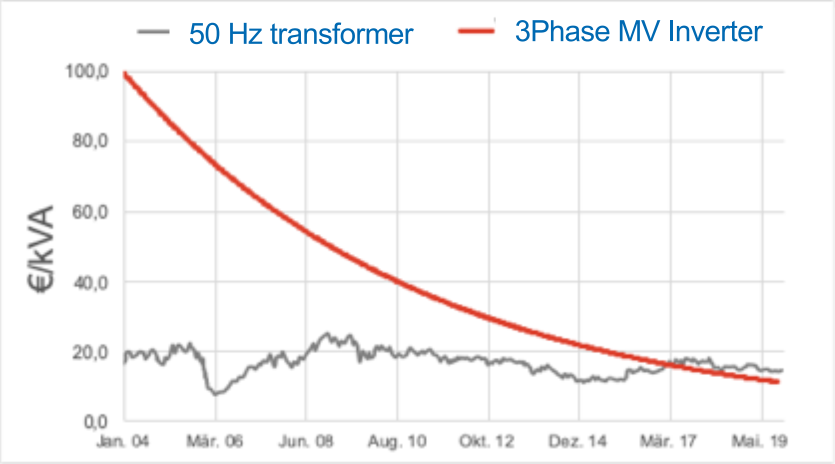
A Three-Phase Soft-Switched High-Power-Density dc/dc Converter for High-Power Applications

Fig. 4. (a) Three-phase dual active bridge dc/dc converter. Topology C. (b) Idealized operating waveforms for topology C.

*see US patent US5027264A and IEEE Xplore IAS Annual Meeting 1988 and Transaction paper 1991 (https://ieeexplore.ieee.org/abstract/document/67533)

Power electronic inverters are progressively having lower costs than 50 Hz transformers
Medium-frequency 3ph-DAB provides a low-cost PEBB for MVDC distribution grids





Estimated cost for 2021

Automotive inverter 3 €/kVA

DC solid-state DC transformer (3phase DAB) 9 €/kW

DC Transition with DC Solid State Transformers

Higher Efficiency, Saving Materials, Digital, Flexible, but also more Ecological to produce!

4,5 MVA, 50 Hz Transformer
11.500 kg (2,5 kg/kVA)

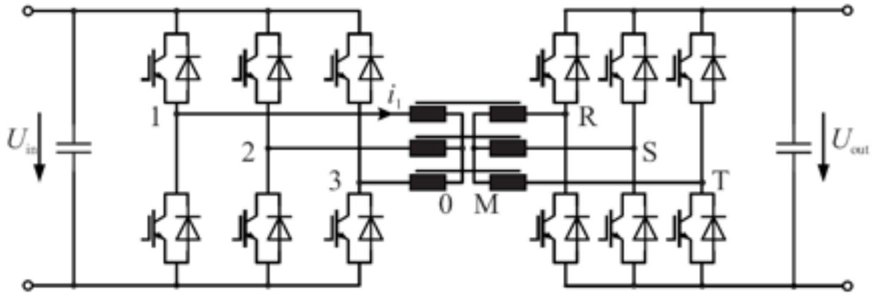
5,0 MVA, 1.000 Hz Transformer
675 kg (0,14 kg/kVA)

➡ Solid State DC transformers reduce significantly CO_2-foot print of electrical grids

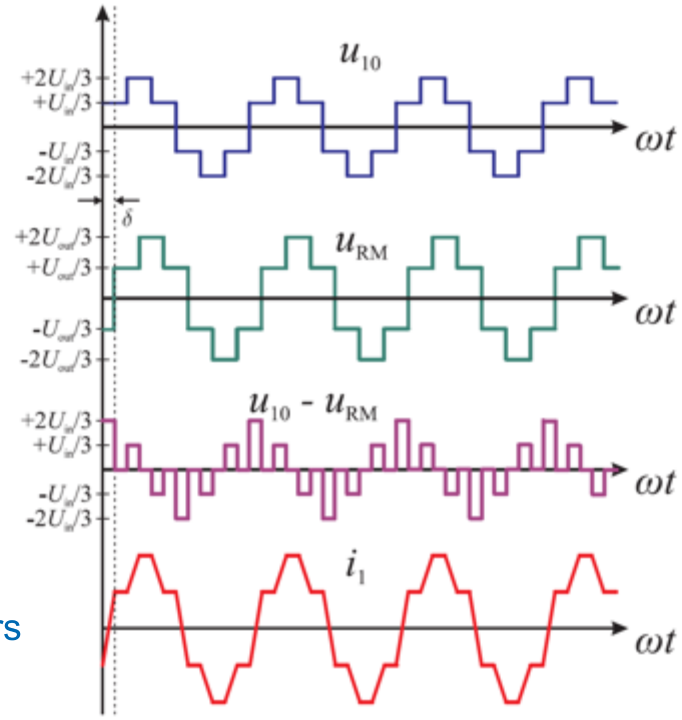
Estimated Transformer use; AC@50 Hz >25,000 ton/GVA, DC@1 kHz Grid < 1,500 ton/GW

Dual Active Bridge – galvanically isolated bi-directional DC converter
Three-Phase Converters operate in six-step block-mode (50 % duty cycle)

$$u = L \cdot \frac{\mathrm{d}i}{\mathrm{d}t} \Leftrightarrow i = \frac{1}{L}\int u\mathrm{d}t \quad \text{mit } L = L_{\mathrm{p}\sigma} + L'_{\mathrm{s}\sigma}$$



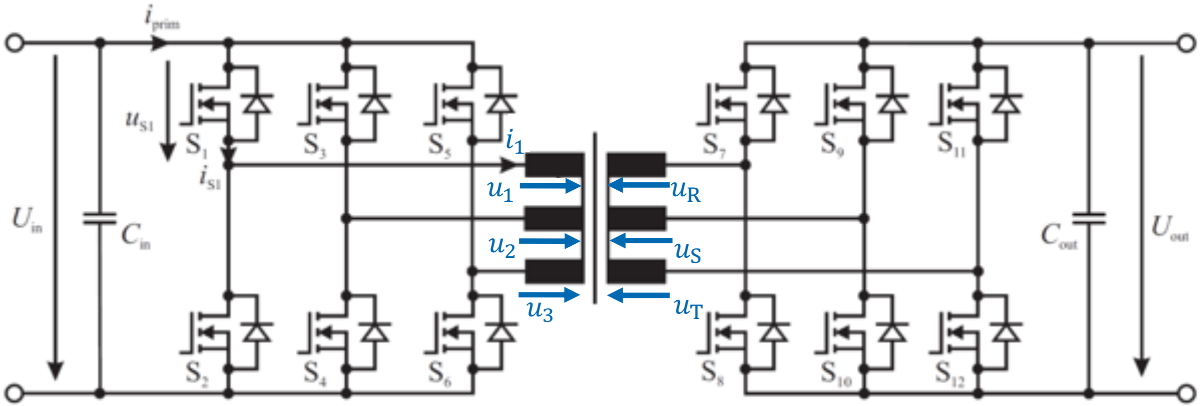
- Zero voltage softswitching operation of all devices
- Very low EMI and DC ripple current leads to small capacitors

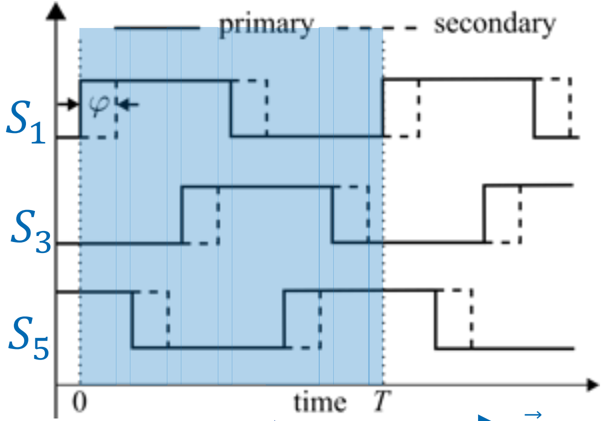


Waveforms of Dual Active Bridge

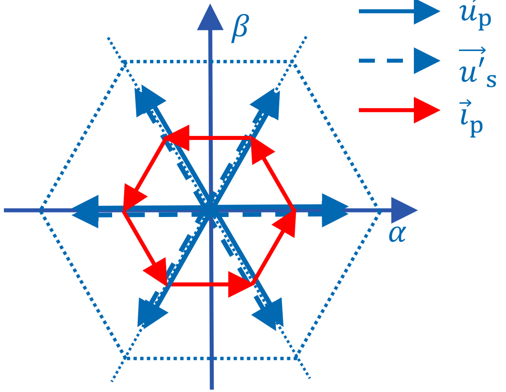
Dual Active Bridge – galvanically isolated bi-directional DC converter

Transient control and FRT modulation can be synthesized using well-known space vector transformation





$$\vec{u}_p = u_{p\alpha} + j u_{p\beta}$$
$$\vec{u}'_s = u_{s\alpha} + j u_{s\beta}$$
$$\vec{i}_p = i_{p\alpha} + j i_{p\beta}$$

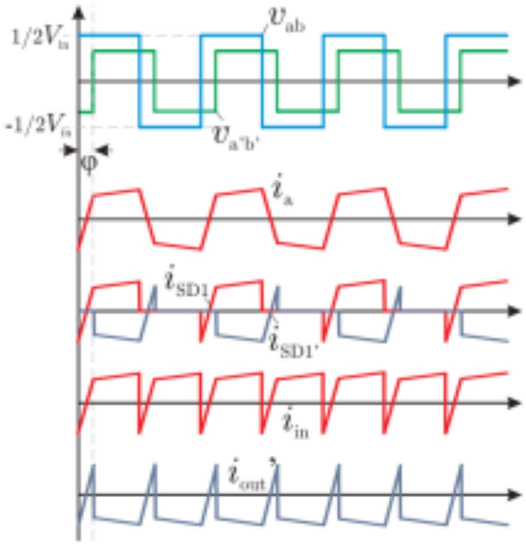


Comparison of Three-Phase DAB and Single-Phase DAB Converters

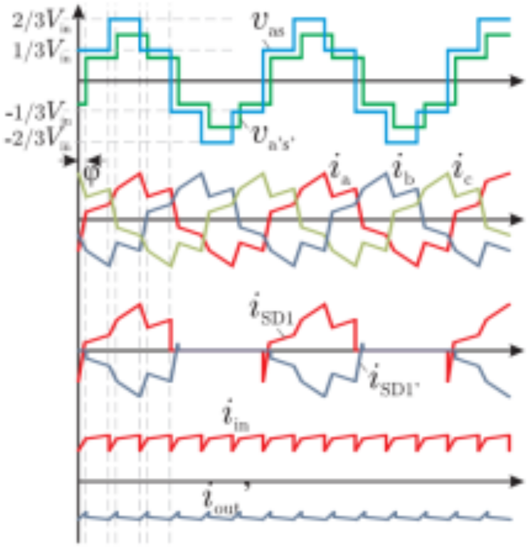
- Single-phase DAB converter
  - Transferred power
    - $P = \frac{U_1 U_2'}{X_{ser}} \varphi \left(1 - \frac{\varphi}{\pi}\right)$
  - Switching at the peak AC current
  - Large DC ripple current
  - Large transformer

- Three-phase DAB converter
  - Transferred power
    - $P = \frac{U_1 U_2'}{X_{ser}} \left(\frac{2\varphi}{3} - \frac{\varphi^2}{2\pi}\right)$
  - Switching at 2/3 of the peak AC current
  - Small DC ripple current
  - Minimal transformer size

Single-phase DAB

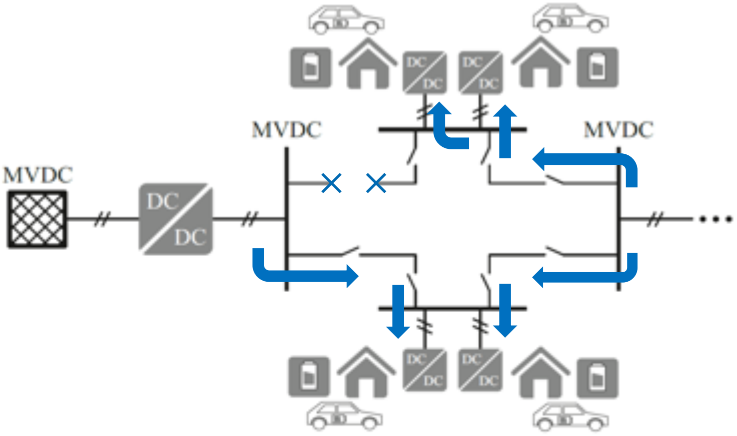


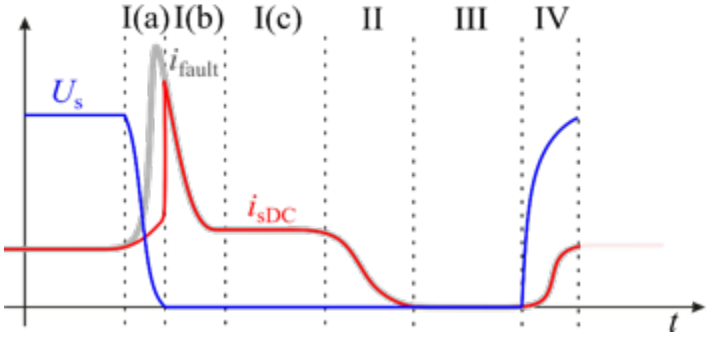
Three-phase DAB



Breakerless Protection Scheme for MVDC Grids

- Stage I:
  - DC fault current limited by dc-dc converter
  - Fault detection and localization
- Stage II:
  - De-energize dc grid by dc-dc converter (reduce current to zero)
- Stage III:
  - Isolate faulty line with high-speed mechanical disconnectors
- Stage IV:
  - Re-energize dc grid by dc-dc converter and reconnect loads

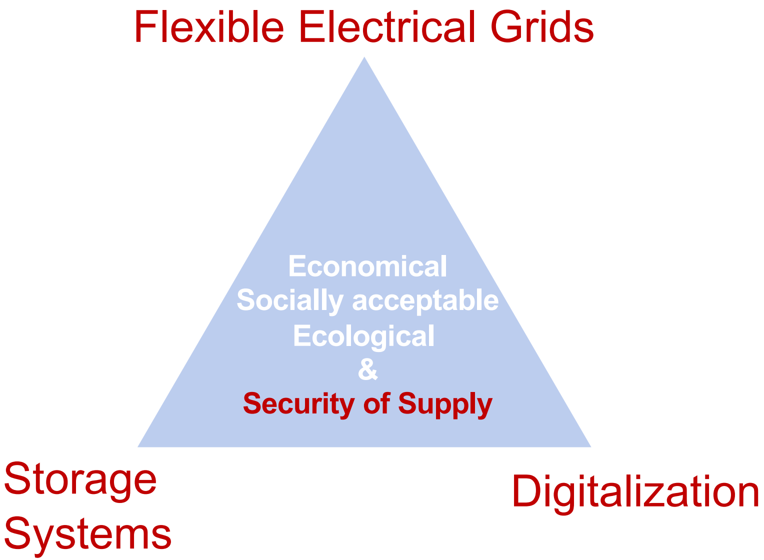




Jingxin Hu, "Modulation and dynamic control of intelligent dual-active-bridge converter based substations for flexible dc grids", PhD Dissertation, E.ON Energy Research Center, RWTH Aachen University, 2019

- 3phase DABs based on existing converter technologies fulfill all grid requirements
  - Compensation of asymmetries of three-phase transformers
  - Predictive IFCC control under transient condition to avoid oscillations and saturation
  - ZVS over the entire operating range (ARCP, Star-Delta, NPC)
    - → higher part load efficiency and reduced EMI
  - Active saturation avoidance of three-phase transformer
  - Asymmetric duty cycle control for fault ride through (FRT) capability, while keeping ZVS
    - → FRT enables electronic protection w/o circuit breakers
  - High-voltage (HVDC) to MVDC DC converter → uses existing converter solutions and reduces cost
  - Control of IPOS, ISOP → realizes a true DC PEBB for multiple voltage and power levels

Urgency to innovate to electrify all sectors to meet EU Green targets
More Silicon, less Copper and Steel!



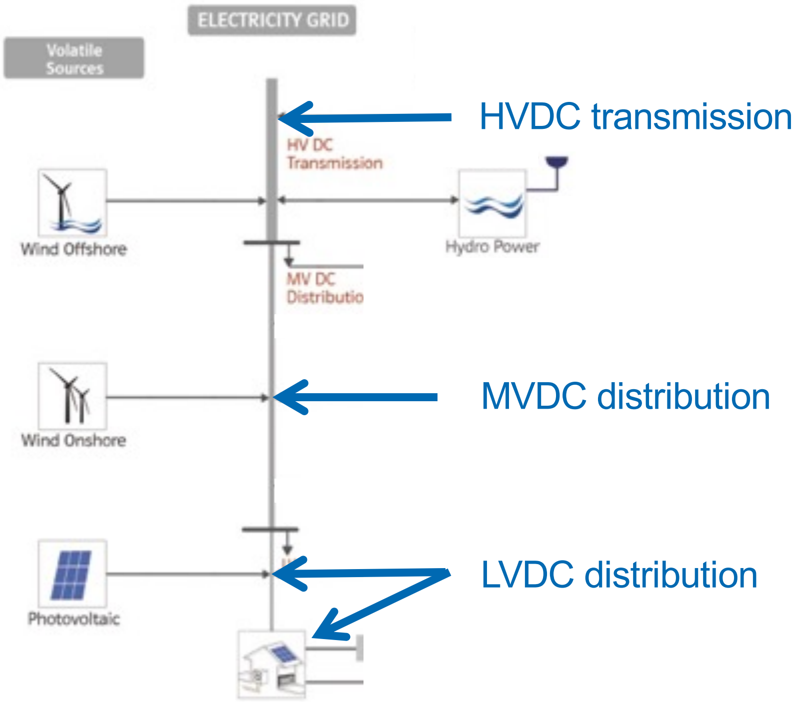
Power electronics is only way to avoid peak copper and meet climate goals

- New semiconductor materials to increase power density further saves materials
- Recycling of PEL components reduces CO_2 emissions
- Primarily distribution grids and automotive sector need to save materials (copper)

Overview

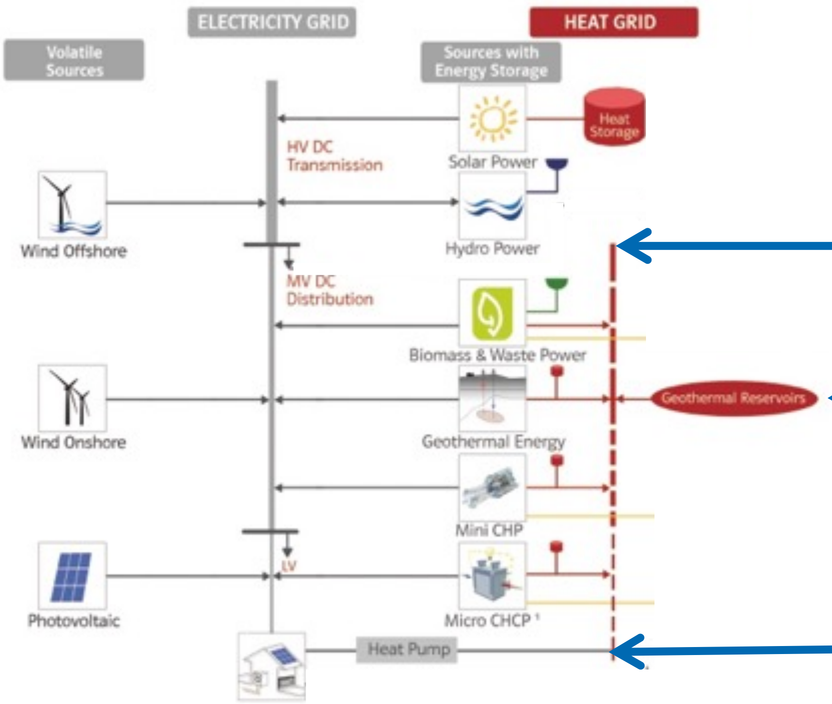
- Introduction
  - RWTH, CARL, BMBF Research Campus Flexible Electrical Networks
- Motivation
  - EU Green Deal
  - Pillars of sustainable solutions (technical, economical, ecological)
  - Peak Copper - the real thread to realizing the energy transition
  - DAB based substations to electrify the entire world
- Concept of a CO_2 neutral energy supply system
  - Cellular MVDC distribution grid
  - DC transformers a key power electronic building block
  - Innovations for the electrification of sectors
- Conclusions

Concepts for a CO_2-neutral Energy Supply System
Electrification linking Sectors to make the transition economically viable



Large scale use of renewables, i.e. hydro, wind and PV as primary energy sources. Sources are far distance (off shore), as well as dispersed locally in buildings, city quarters.

Concepts for a CO_2-neutral Energy Supply System
Electrification linking Sectors to make the transition economically viable

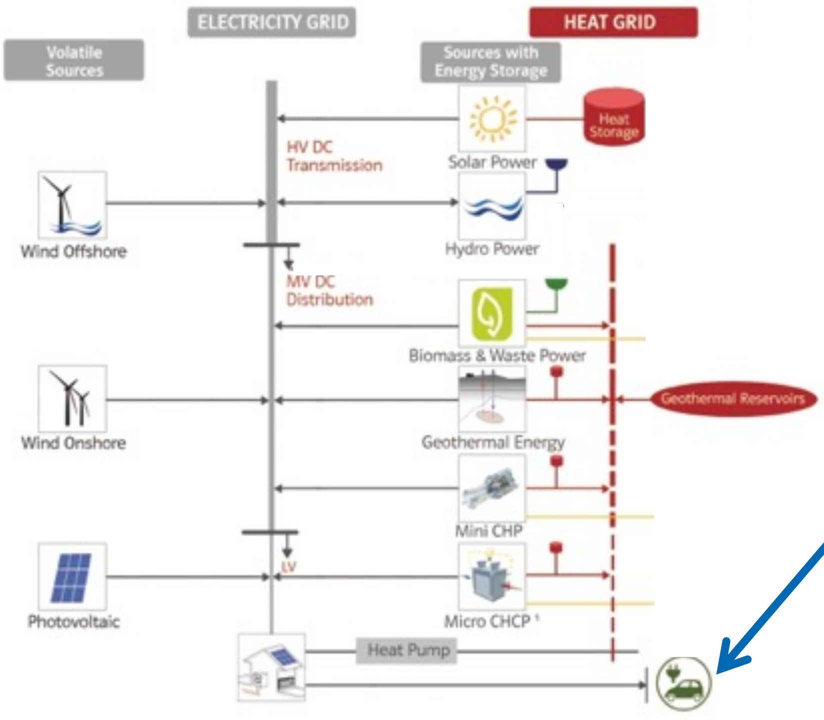


Linking e-grid to heat sector for short term and seasonal energy storage.

Small scale CHP power back-up sources.

Heat pumps for full electrification of HVAC of buildings.

Concepts for a CO_2-neutral Energy Supply System
Electrification linking Sectors to make the transition economically viable

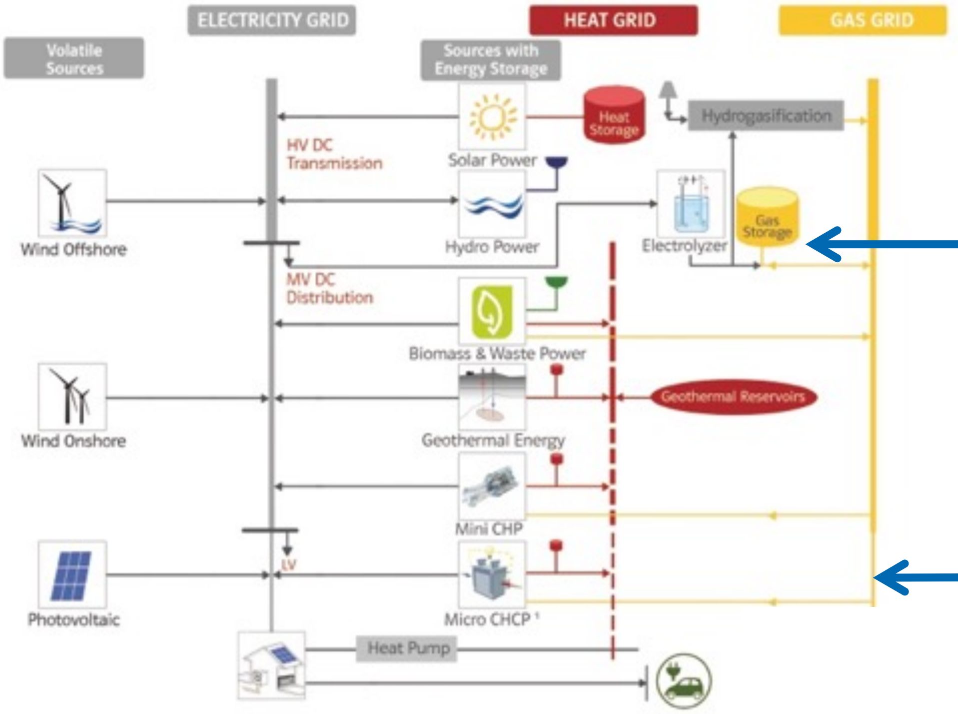


Linking e-grid to e-Mobility sector.

Providing DMS and short term grid stability.

Full electrification of mobility in the urban environment

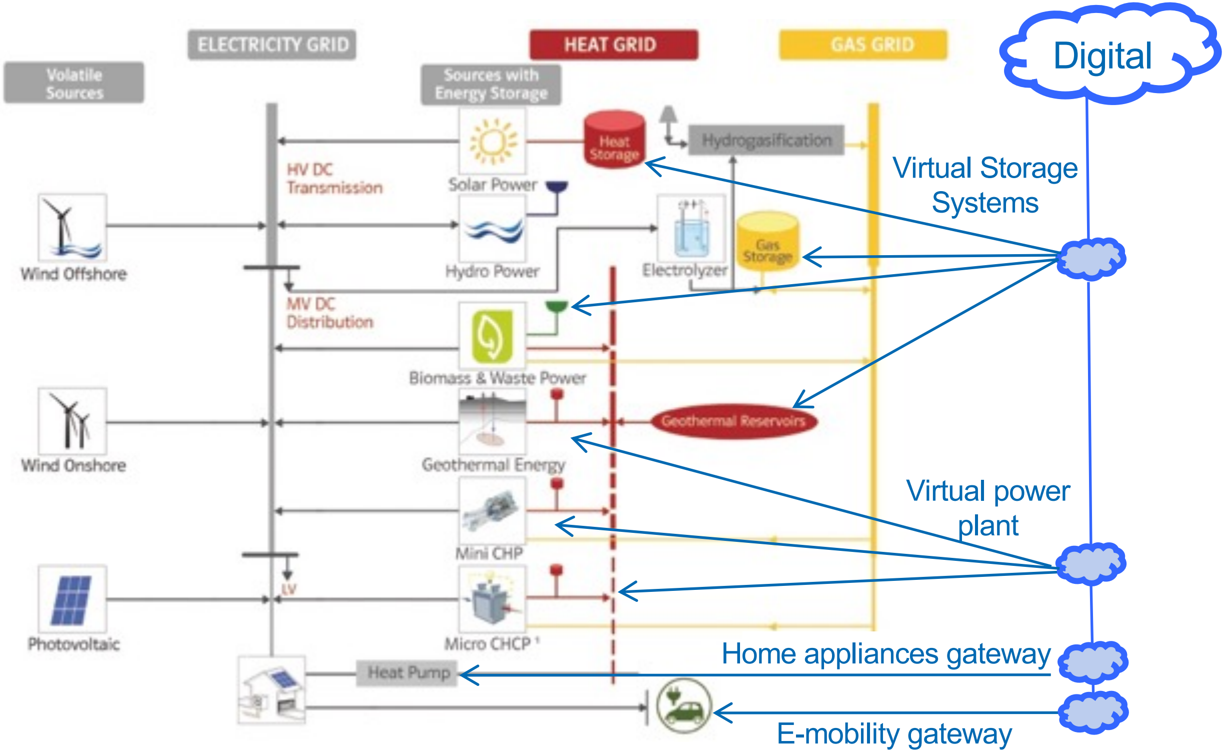
Concepts for a CO_2-neutral Energy Supply System
Electrification linking Sectors to make the transition economically viable



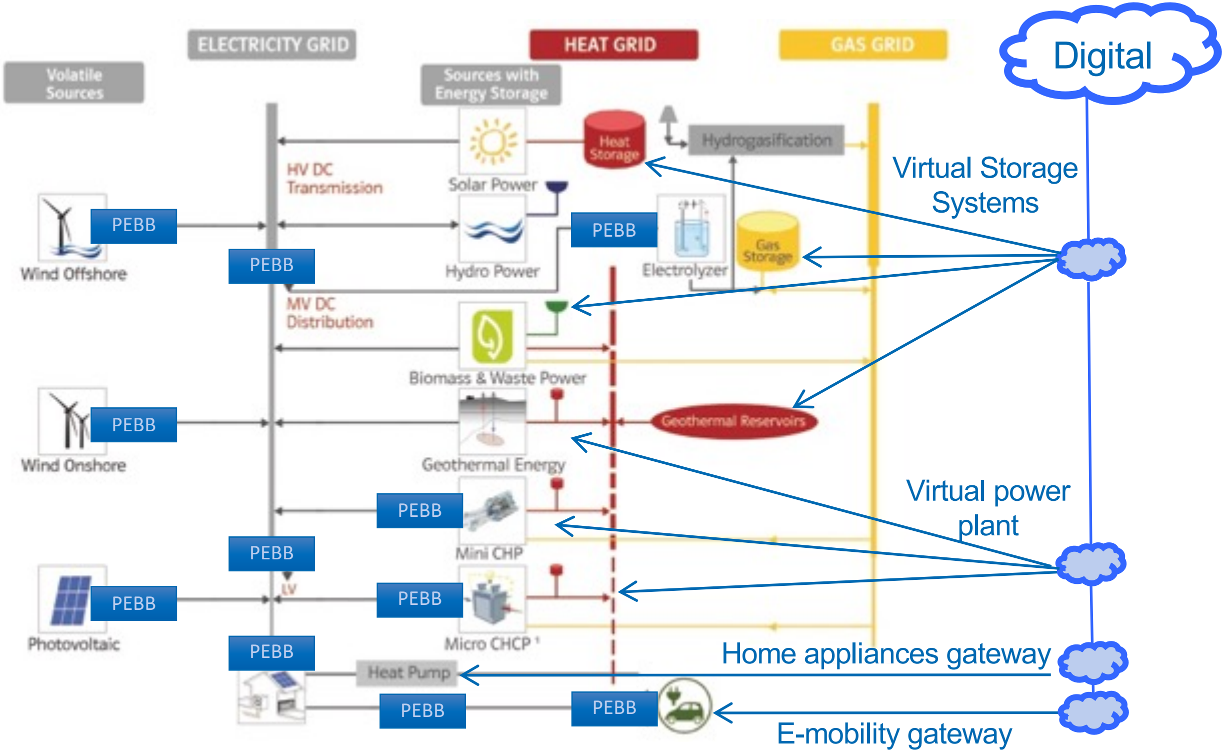
Linking e-grid and heat grid with electrolyzers to gas and synthetic fuels sector for long term strategic energy storage.

Reuse of existing infrastructure

Concepts for a CO_2-neutral Energy Supply System
Digitalization to master complexity and provide fast response

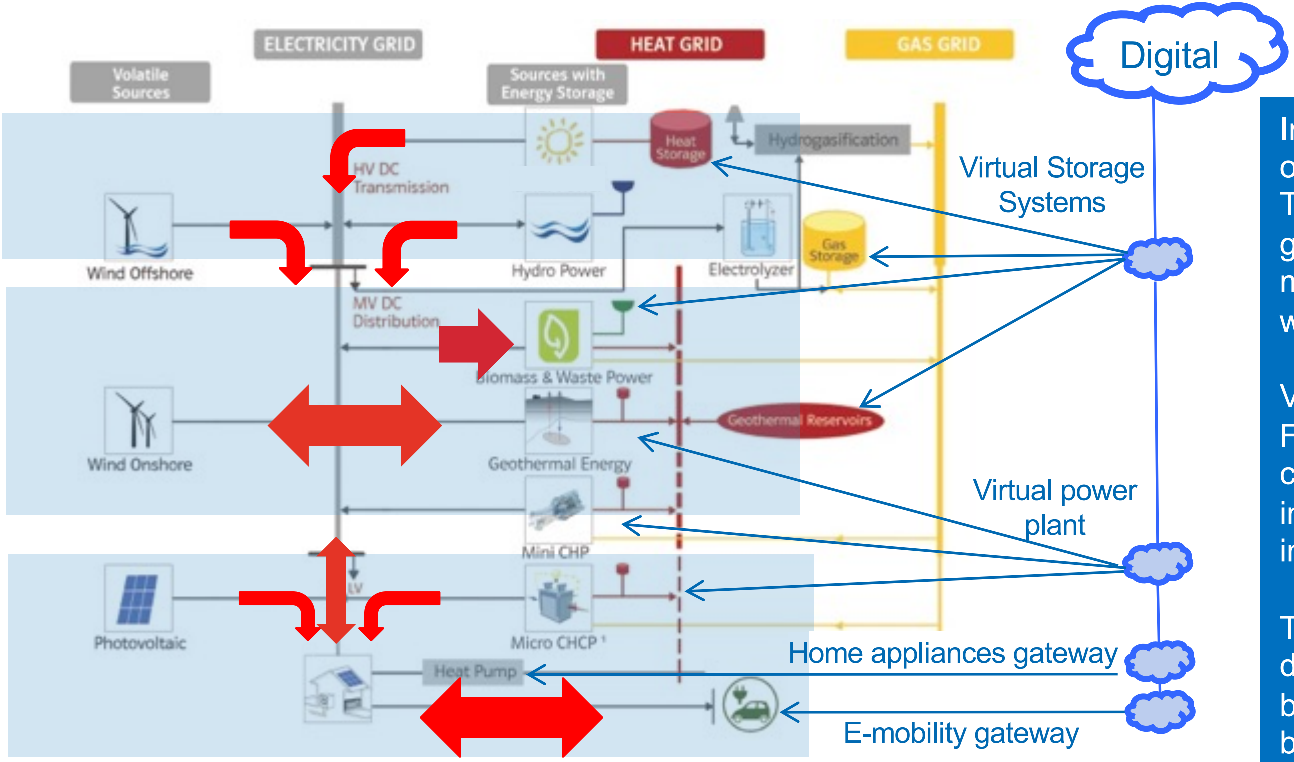


Electrical Grids for a CO_2 Neutral Electrical Energy Supply System
Energy flow dynamically controlled by power electronic energy converters (electronic grid)



PEBB Power Electronic building Block

Electrical Grids for a CO_2 Neutral Electrical Energy Supply System
Energy flow - about 1/3 in HV, 1/3 in MV, 1/3 in Low-Voltage Distribution Grid

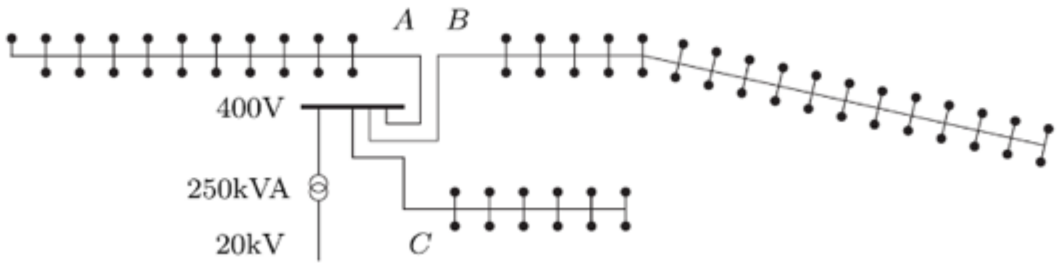


Interesting observation:
The transmission grid requires just minimal extension with HVDC.

VDE ETG Task Force expects less cost for DC integration in infrastructure.

The MV distribution grid will become bottleneck.

Distribution Grid – Challenge with 5 kW EV Chargers
Typical Urban Grid Structure designed for 3,6 kW peak power consumption per end-user



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

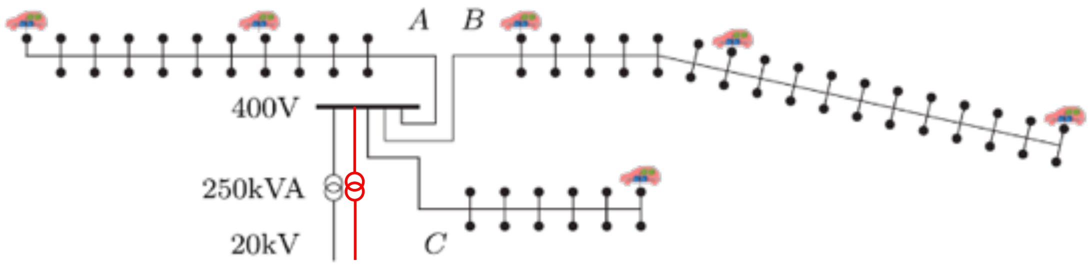
Branch B
- 34 households, max. total power : 129 kW
- Length : 715 m

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 – Challenge with 5 kW EV Chargers
Typical Urban Grid Structure with e-Mobility slow charging, 6 EVs



Branch A
- 21 households, max. total power: 98 kW → 108 kW (2 veh.)
- Length: 461 m

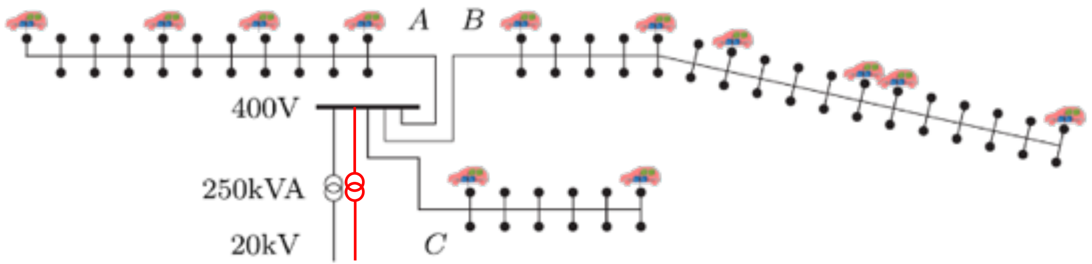
Branch B
- 34 households, max. total power : 129 kW → 144 kW (3 veh.)
- Length : 715 m

Branch C
- 10 households, max. total power : 68 kW → 73 kW (1 veh.)
- Length : 185 m

Connection to transmission grid
- Max. total power : 250 kVA → 325 kW (worst case)

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 – Challenge with 5 kW EV Chargers
Typical Urban Grid Structure with e-Mobility slow charging, 12 EVs



Branch A

- 21 households, max. total power: 98 kW → 118 kW (4 veh.)
- Length: 461 m

Branch B

- 34 households, max. total power : 129 kW → 159 kW (6 veh.)
- Length : 715 m

Branch C

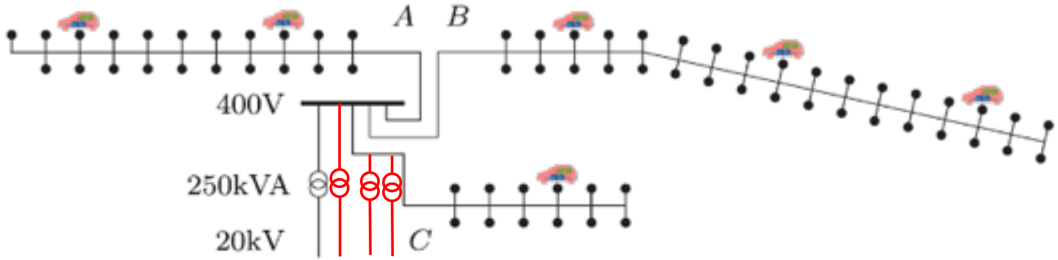
- 10 households, max. total power : 68 kW → 78 kW (2 veh.)
- Length : 185 m

Connection to transmission grid

- Max. total power : 250 kVA → 355 kW (worst case)

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 – Major Problem with 150 kW EV Charging
Typical Urban Grid Structure with e-Mobility fast charging, 6 EVs is not sustainable



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

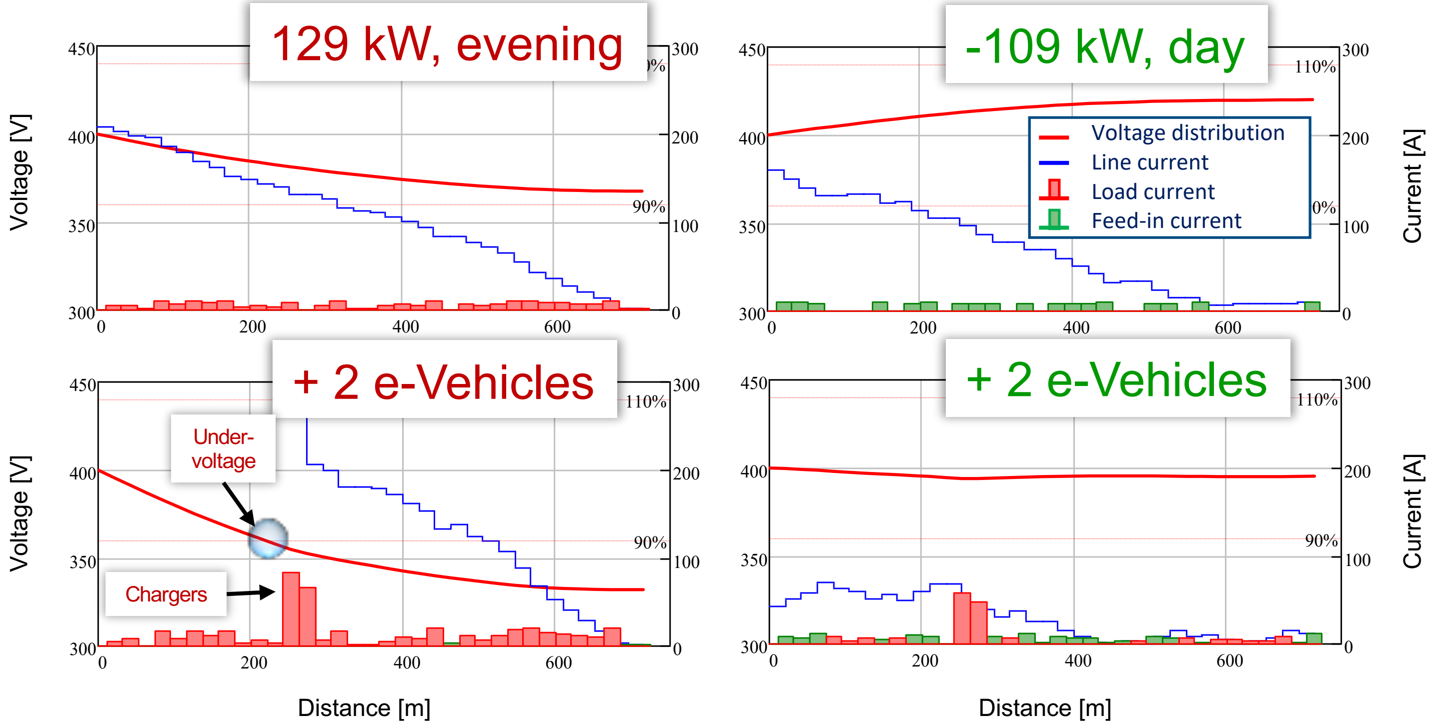
Branch B
- 34 households, max. total power : 129 kW → 479 kW (3 veh.)
- Length : 715 m

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

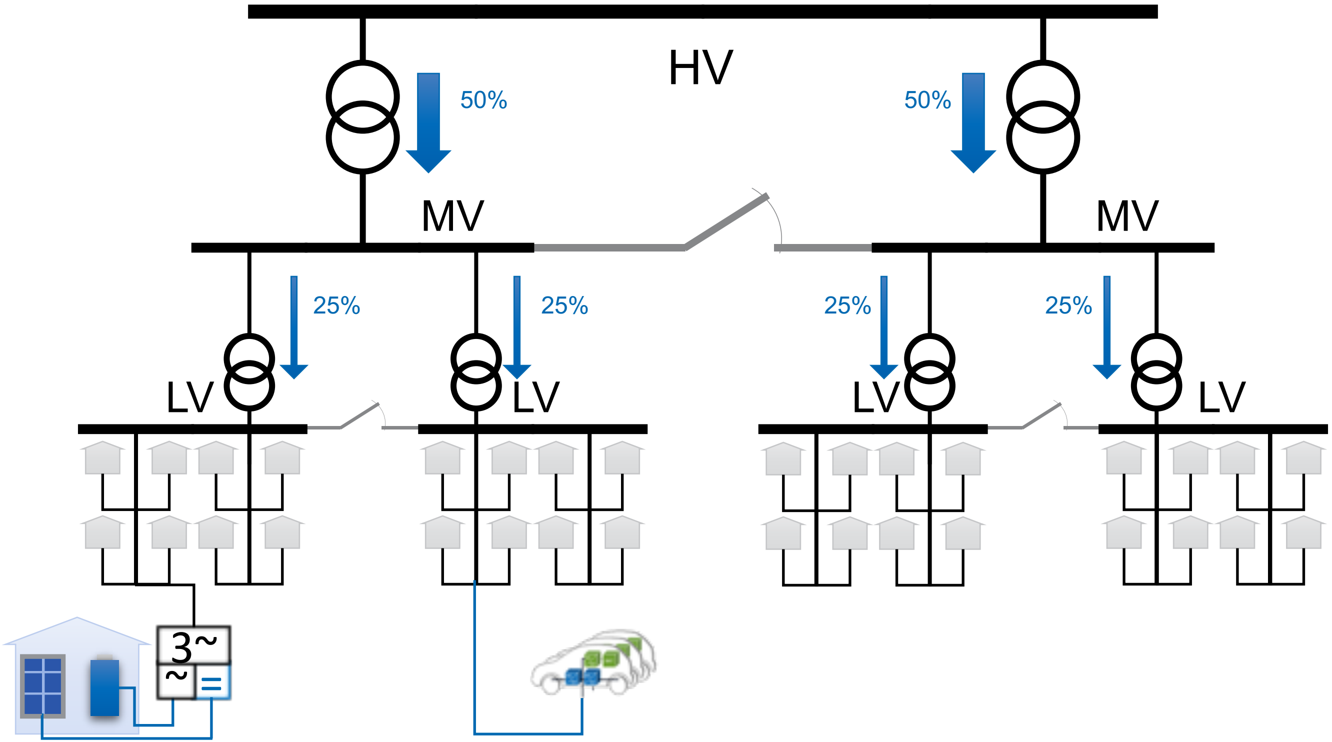
Connection to transmission grid
- Max. total power : 250 kVA → 1.1 MW (worst case)

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

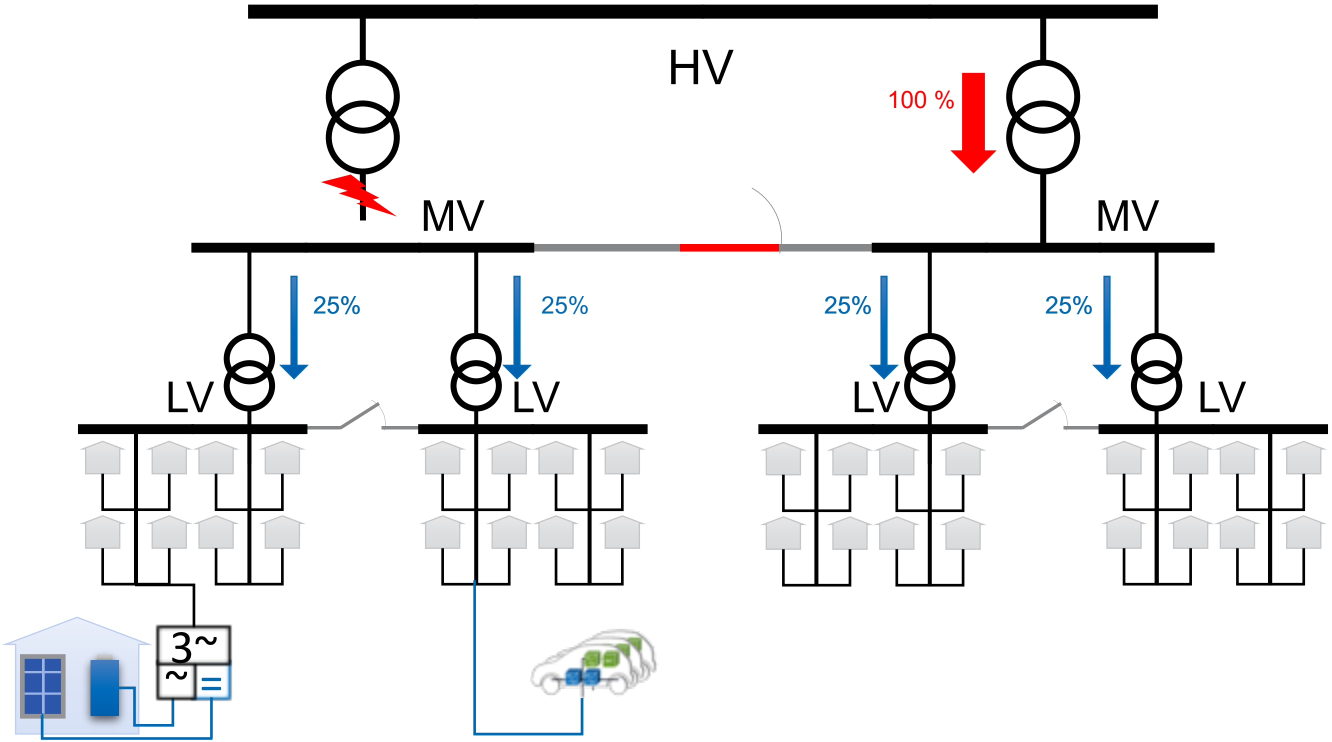
Low voltage distribution grid cannot reliably support e-Vehicles at higher power
Power quality issues arise, e.g. 40 kW, Segment "B"



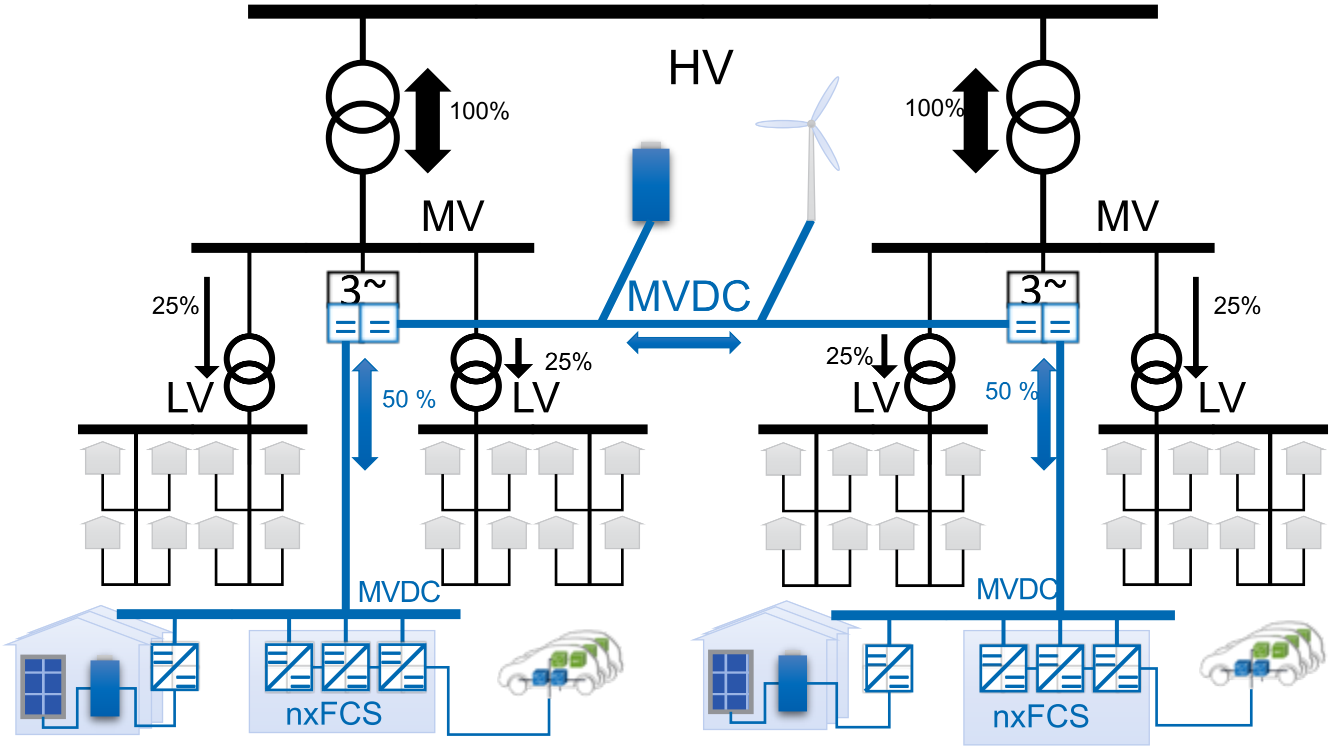
Classical Distribution Grids are radial
Integration of decentralized supplies. renewables, storage and e-Mobility is difficult



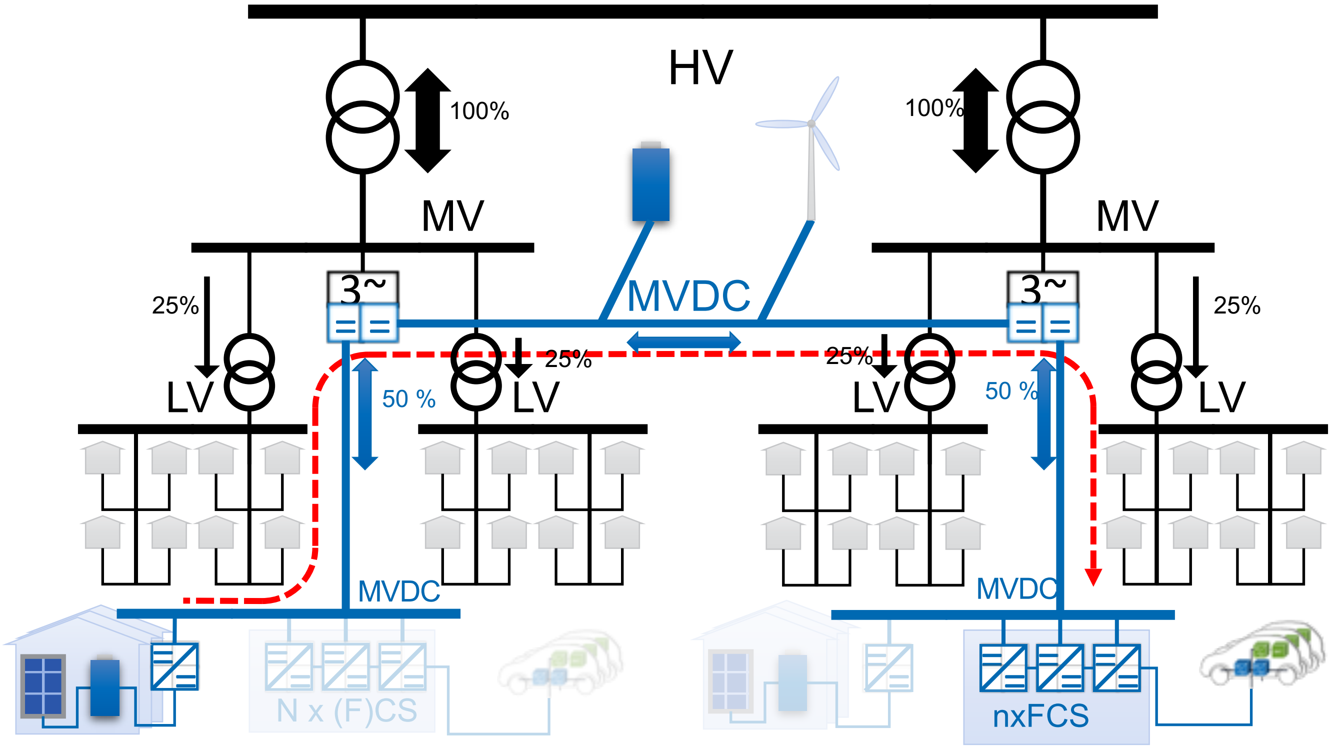
Classical Distribution Grids are radial and massively oversized
Integration of decentralized supplies. renewables, storage and e-Mobility is difficult



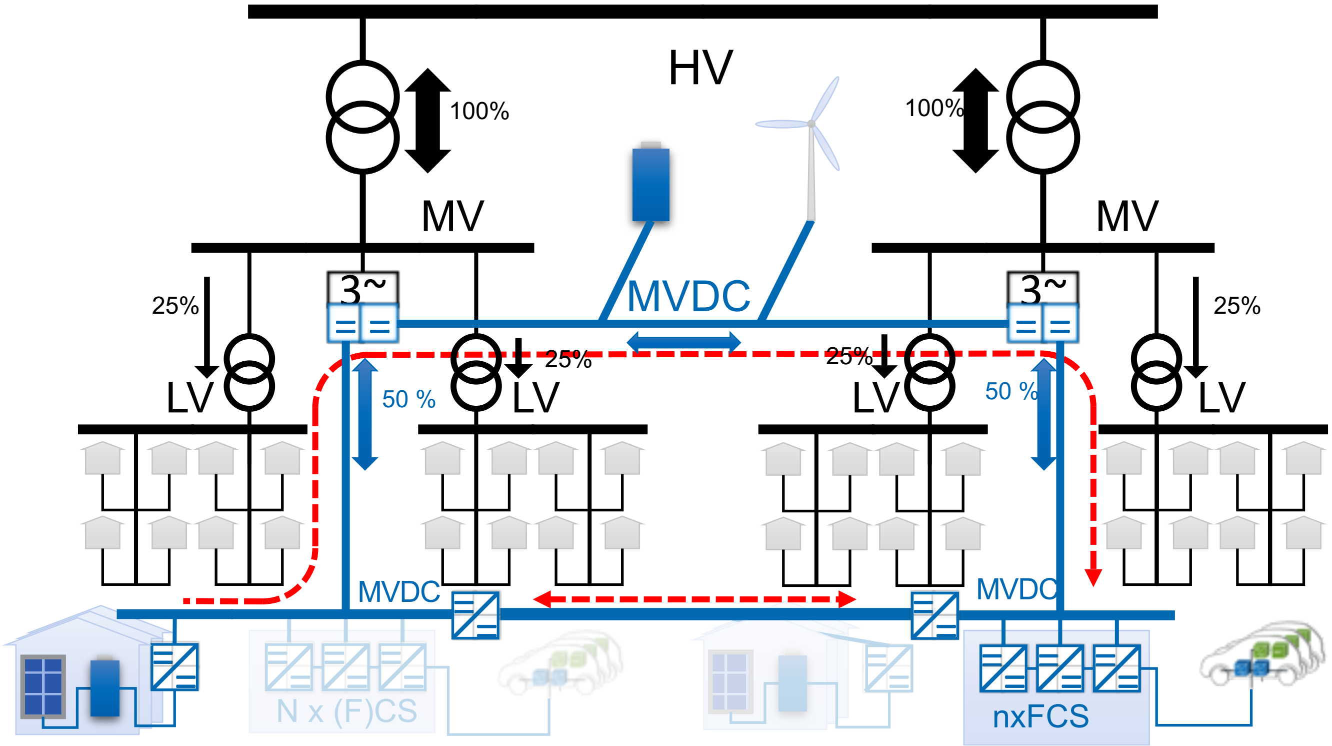
Hybrid Approach to Maximize Capacity of Distribution Grids
Integration of e-Mobility, PV, Wind, Storage … by MVDC-Backbone



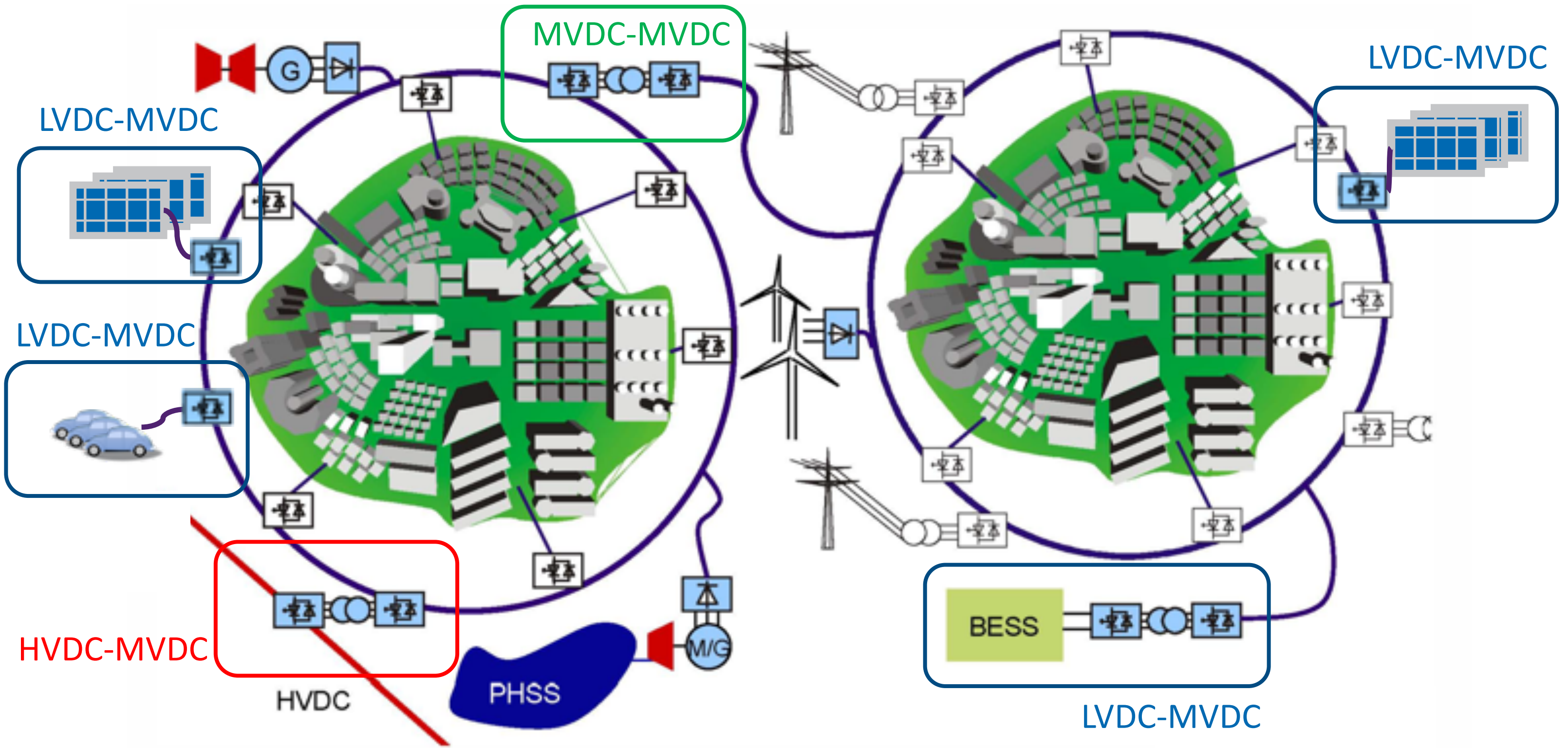
Hybrid Approach to Maximize Capacity of Distribution Grids
Integration of e-Mobility, PV, Wind, Storage … by MVDC-Backbone



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

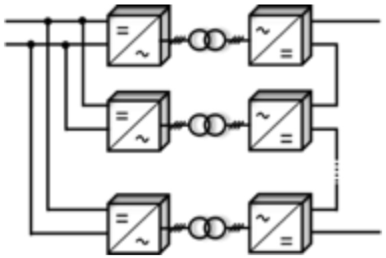


Flexible DC Distribution Grids for Massive Decentralized Power Generation
Cellular Grid Topologies, Sector Coupling and DC Intelligent Substations

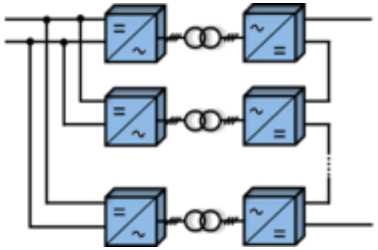


DC Intelligent Substations
Status Quo – Commercial products exist today

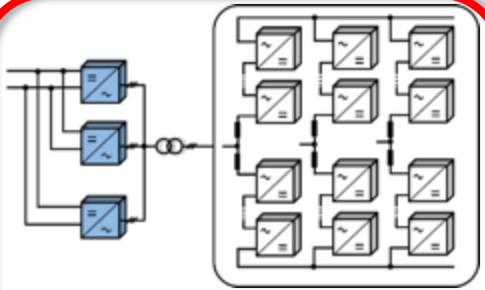
LVDC-MVDC	MVDC-MVDC	MVDC-HVDC



- IPOS DAB converter
- Modular, scalable
- IGBT, SiC MOSFET



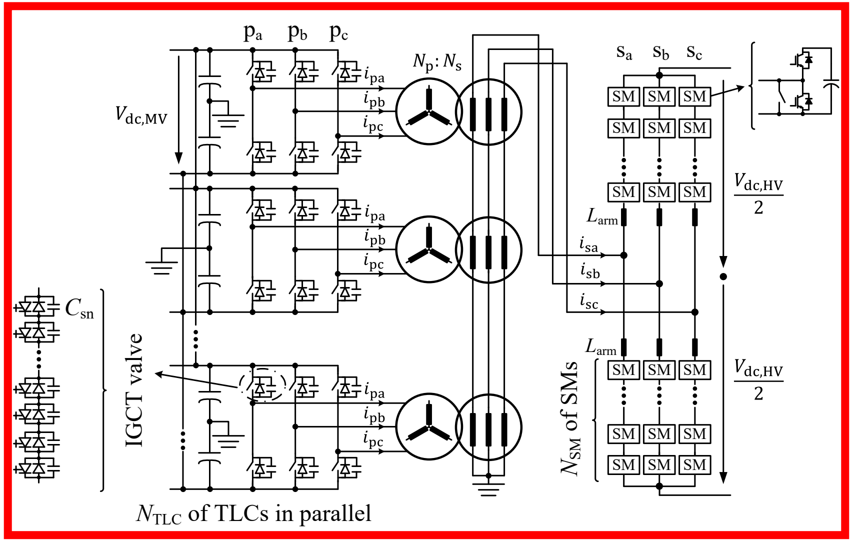
- IPOS DAB converter
- Multi-level topology or device series connection
- IGBT, IGCT



- MMC + DAB
- Insulation requirement for IPOS transformer is too high
- Multi-level topology or device series connection on MV side
- IGBT, IGCT

HVDC to MVDC Converters
Configuration of TLC-MMC Converter based on existing technology

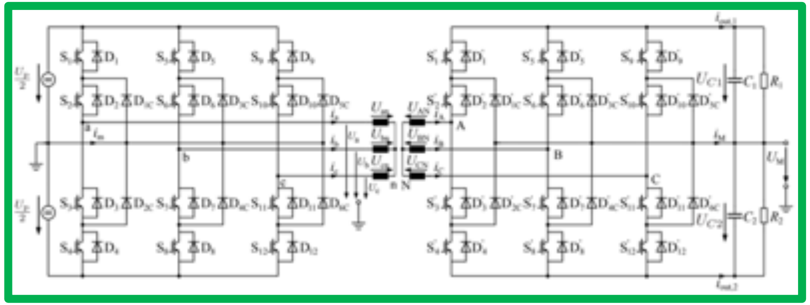
- HV side – MMC
  - Simple voltage scaling, 16 x smaller capacitors @400 Hz
- MV side – Multi-level Converters (TLCs) in parallel
  - Less amount of devices, smaller dc capacitors
  - Series connection of IGCTs
    - Directly reach MV-side dc-link voltage
    - Lowest conduction losses
    - Snubber capacitors in parallel
- Transformer 200-400 Hz, HV BIL-rating
  - Secondary sides are connected in series
    - Circulating current among TLCs is inherently prevented
    - Proven technology in first generation STATCOMs
- Based on proven hardware components

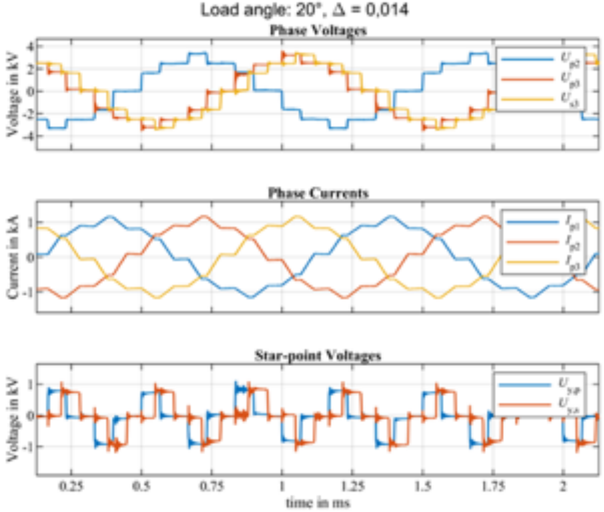


Shenghui Cui, "Modular multilevel DC-DC converters interconnecting high-voltage and medium-voltage DC grids", PhD Dissertation, E.ON Energy Research Center, RWTH Aachen, 2019. http://publications.rwth-aachen.de/record/762795

Medium-Voltage High-Power DC-DC-Converters
Commercially available 3-Level converters linked to medium frequency 3phase transformer

- Modular three-phase dual active bridge
  - $P = 5\text{ MW}, V_{DC} = 5\text{ kV} \pm 10\%$
  - Off-the shelf three-level neutral-point-clamped converter and newly-developed 1 kHz transformer with 16x power density compared 50 Hz state-of-the-art



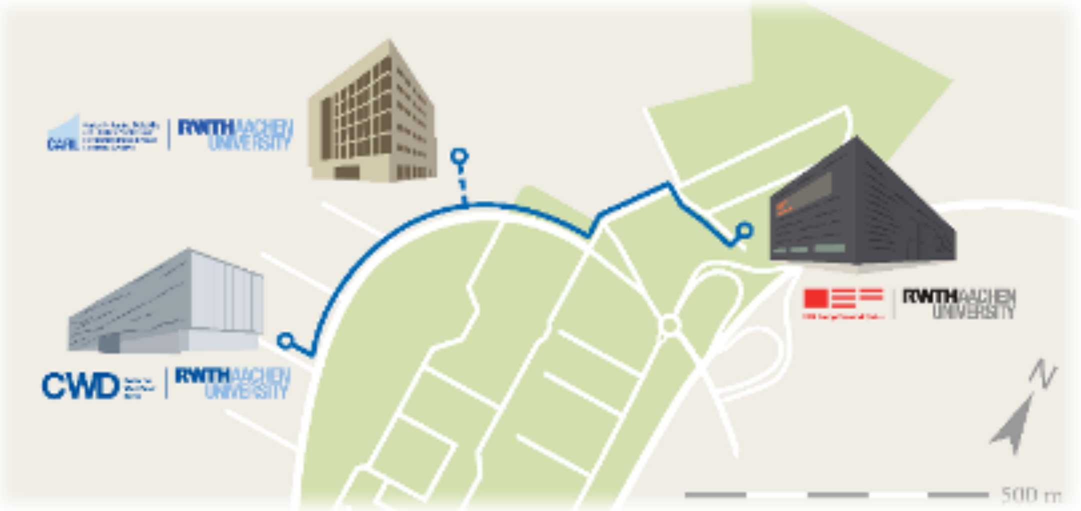


Demo & Test Infrastructure – FEN Medium-Voltage DC Grid at RWTH CAMPUS

- First medium-voltage DC grid

- Research Demonstrator for:
  - Protection strategies
  - Hybrid circuit breaker testing
  - Breakerless grid concepts
  - Advanced DC converter technology and control

- Facts:
  - Power: 5 MW
  - Voltage +- 2.5 kV
  - Total length: 1,025m - Underground: 731m, Indoor: 294 m
  - Several high-power and medium-voltage converter systems
  - Connects two AC 11 kV substations (avoiding high tariffs of peak loads)
  - Payback potentially less than 3 years



Underground DC-cables

Demo & Test Infrastructure – FEN Medium-Voltage DC Grid at RWTH CAMPUS

- Construction
  - □ Total length 1,025 m
    - Underground 731 m
    - Indoor 294 m
- Connects two AC 11 kV substations
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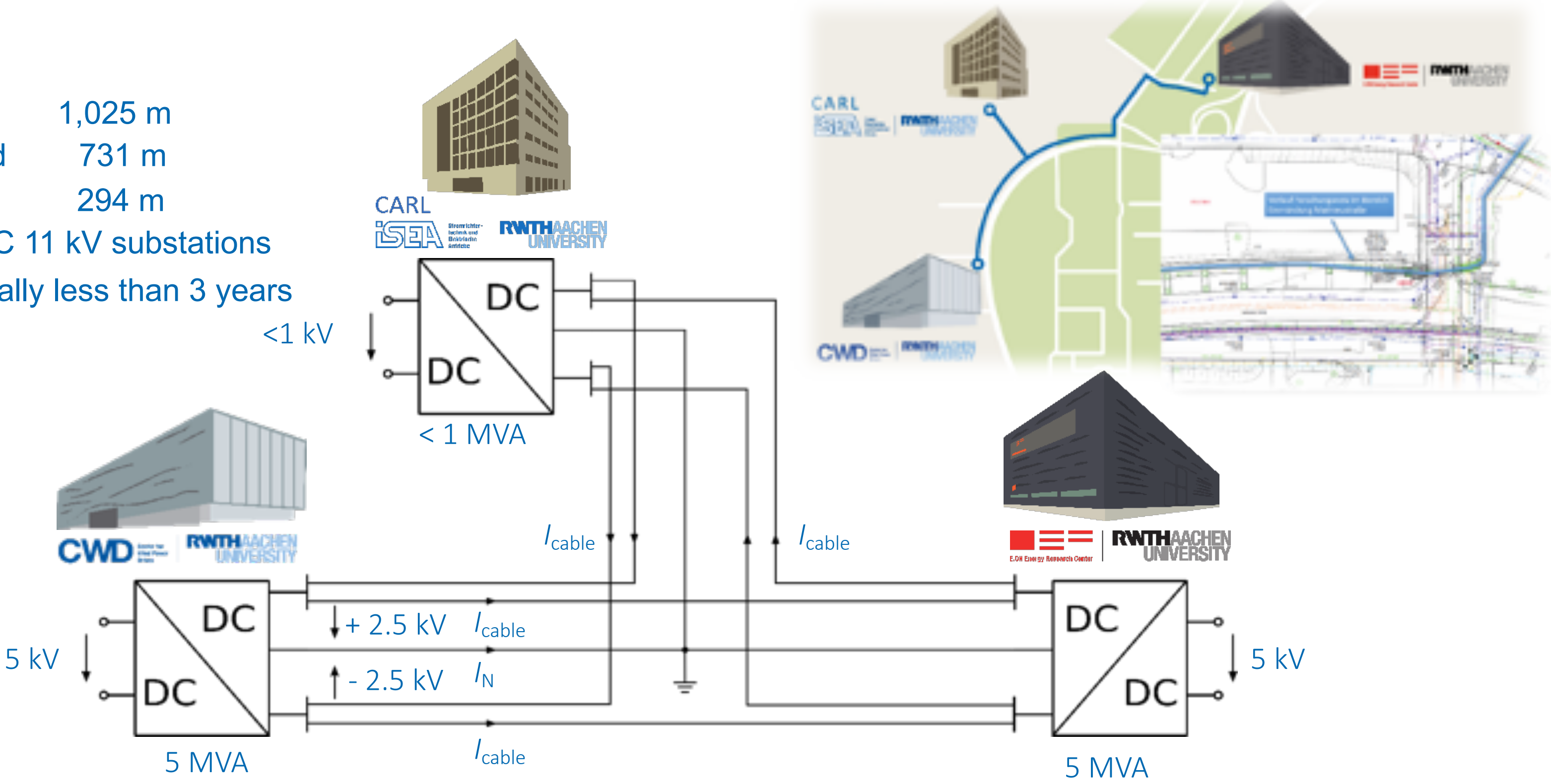
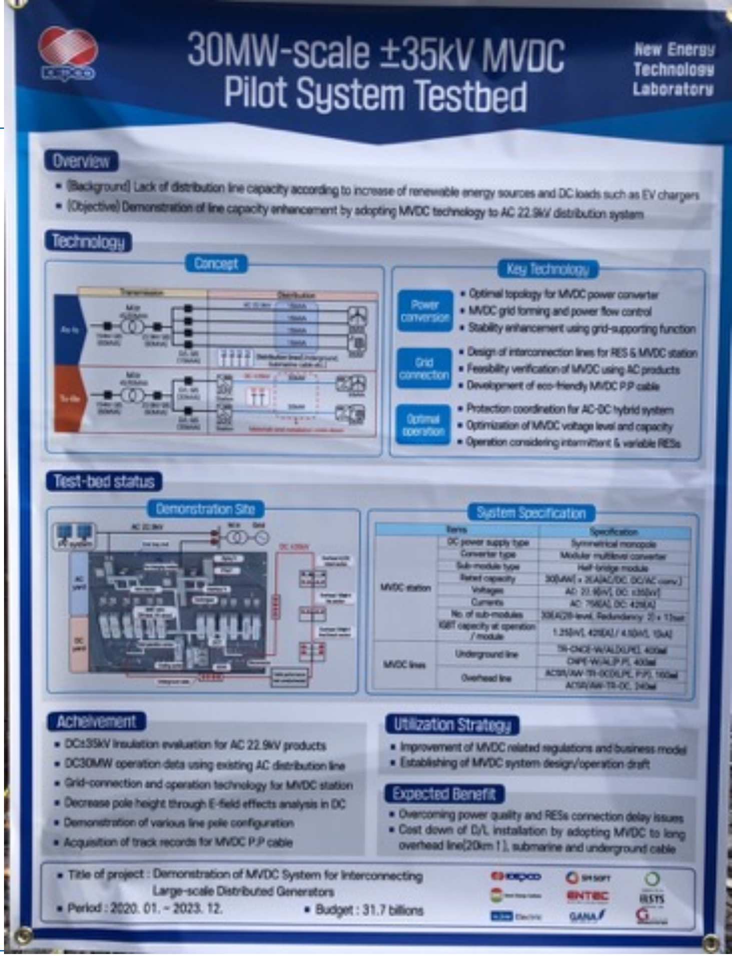


MVDC Grid already implemented in Korea by KEPCO



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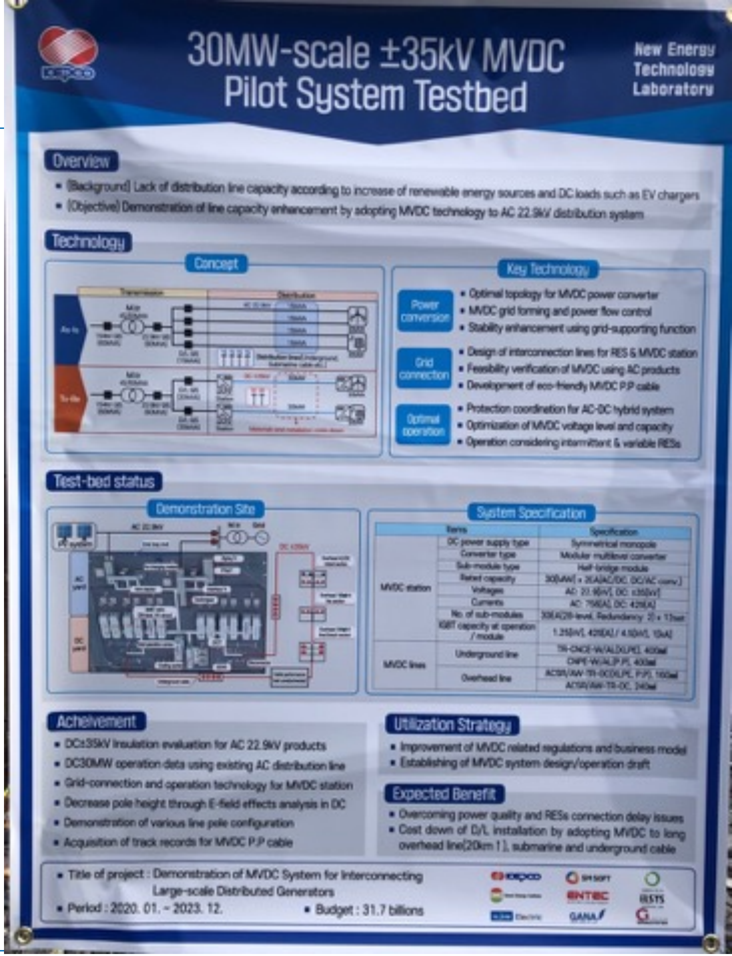
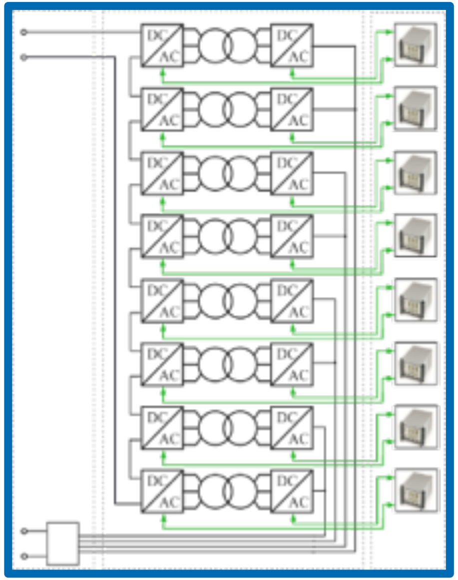
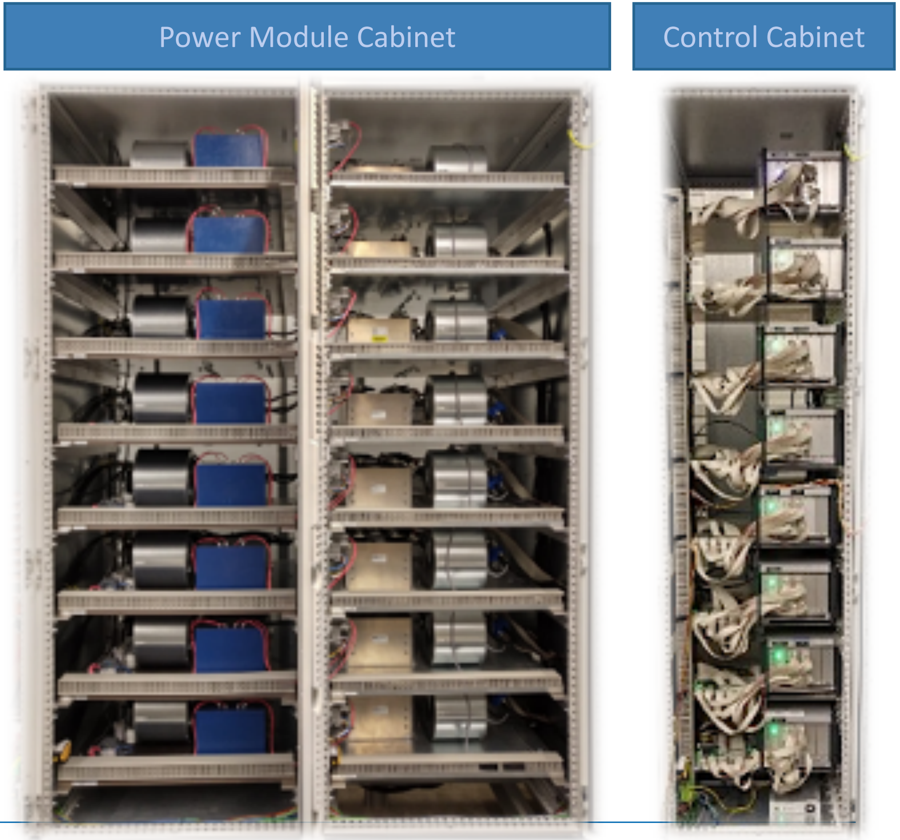


Modular Dual-Active Bridge Converter (5 kV input to 8 x 375 V LVDC)

- Various Input configurations
  - Up to 8 modules in series or parallel
  - Input voltage $U_{\text{in}} = 5\ \text{kV}\ (\pm 2.5\ \text{kV})$
- Various output configurations
- Double usage of real-time simulation platform
- Distributed RT-simulation for control-hardware-in-the-loop
- Adaptable to DC collectors for PV, Fuel cells and electrolyzers.



8P
4P2S
2P4S



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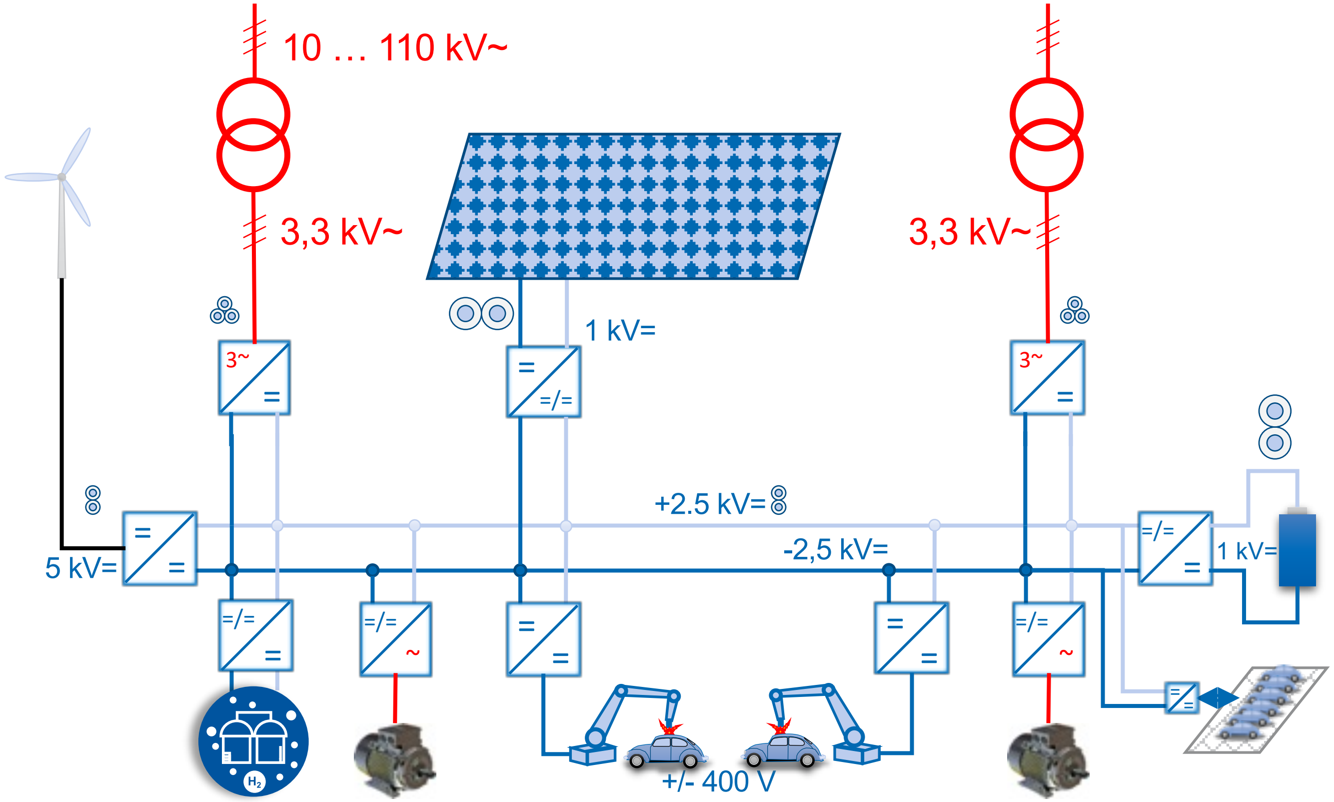
- Various output configurations
- Double usage of real-time simulation platform
- Distributed RT-simulation for control-hardware-in-the-loop
- Adaptable to DC collectors for PV, Fuel cells and electrolyzers
- Direct connection for factories, building and homes to MVDC grid

The LVDC Engineering Building at Seoul National University

The 1970 Engineering Building at Seoul National University (top left) was completely remodelled in 2012 to become energy efficient. It is equipped with a 36 kWpeak PV system (top right). Prof. S. Sul explains the 380 Vdc power line to which EV chargers, all electronic loads and the AC distribution system are coupled (bottom left). The 380 Vdc system is electronically protected and also has 380 DC circuit breakers (bottom right) (pictures taken by Prof. De Doncker, with permission of SNU)

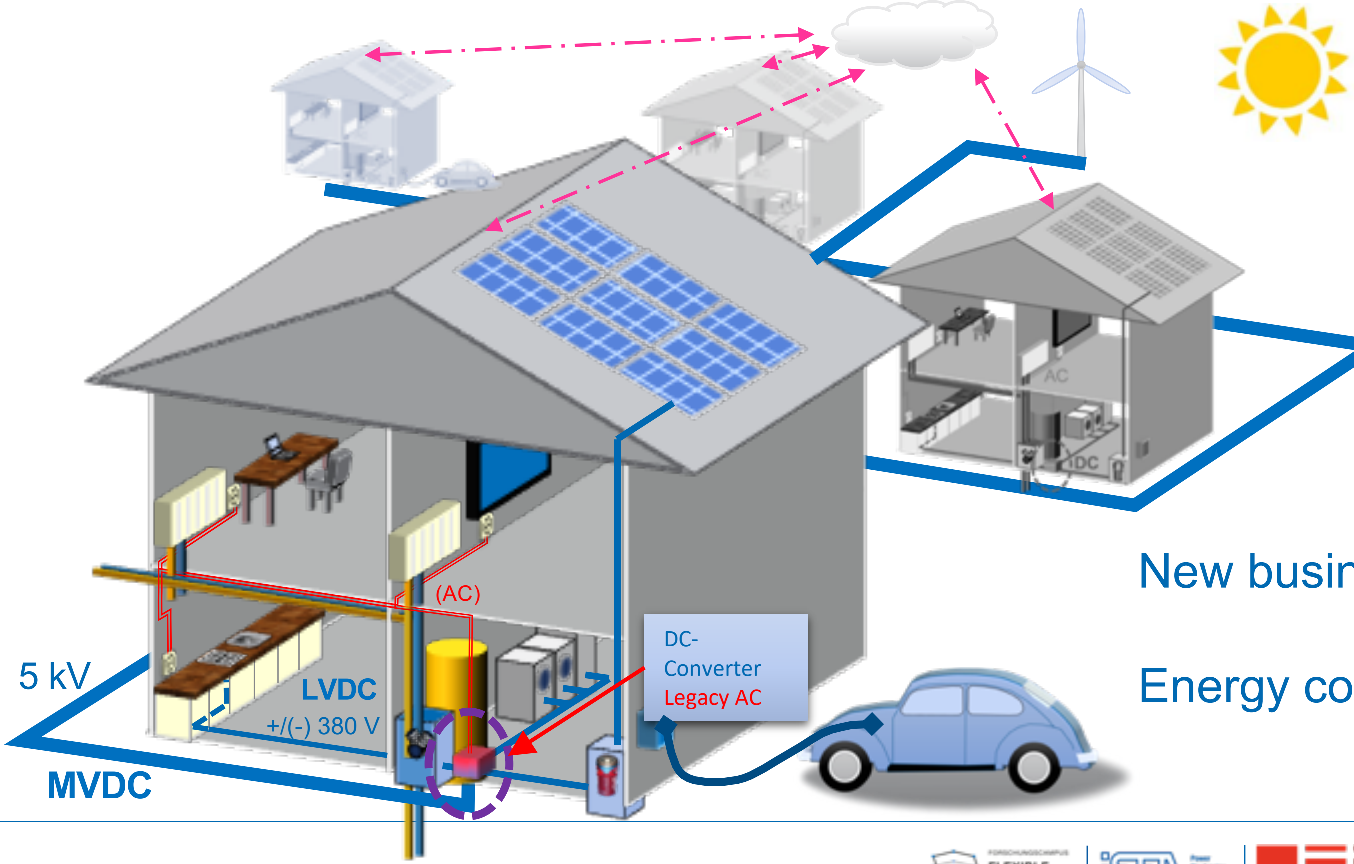
DC-Factory - Power Grid Concept MVDC for Steel Manufacturers, Automotive OEMs

Redundancy through PEL modularity, multiple power feed-in from grid, on-site REN and H_2 production



DC-Grid and Energy Management in DC city quarter

Lower infrastructure costs, higher efficiency and bidirectional power flow for prosumers



New business models
&
Energy communities

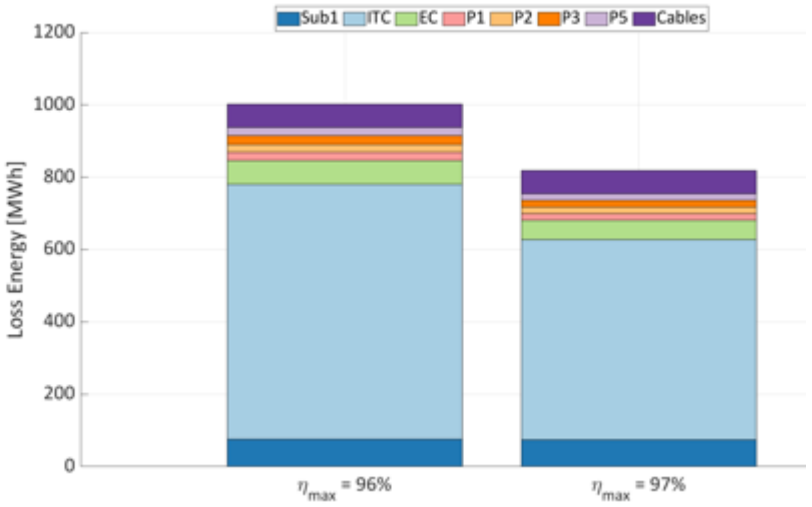
The RWTH MVDC Campus West Grid

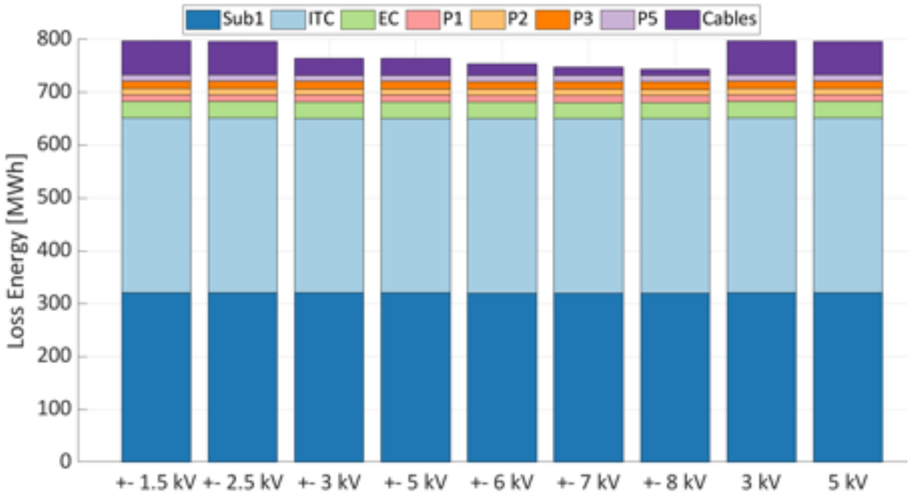
- Based on results from the Campus West project[1]
- PV generation on parking rooftops
  - Ca. 400 kW each – in total 1.7 MW
- 4 parking buildings with charging facilities for EV
  - 20,5% of all parking spots for EV
  - Mix of 11 kW AC, 22 kW AC and 50 kW DC charging points
  - 4.8 MW (P C1), 4.2 MW (P C2), 5.3 MW (P C3), 4.4 MW (P C5.1)[1]
- IT – Center
  - 1.6 MW
- Energy Center
  - Power geothermal pumps (heating) ~ 250 kW
  - Power heat pump (cooling) ~ 1.4 MW
- AC-DC connection for DC-grid:
  - 3 substations
  - Connected to public 10 kV AC grid

[1] „Konzept für elektrische Energieversorgung in verschiedenen Ausbaustufen des Campus West der RWTH Aachen“ , ACS

Results: Efficiency – System Level

- DC concepts are more efficient than the 6/10 kV AC-System
  - Even though DC substation losses are much higher





- AC-Substation:
  - Losses ~72 MWh
  - average Efficiency: 99,51%
  - P_{nom} = 4 MW

- DC-Substation:
  - Losses ~320 MWh
  - average Efficiency: 97,8%
  - P_{nom} = 4 MW

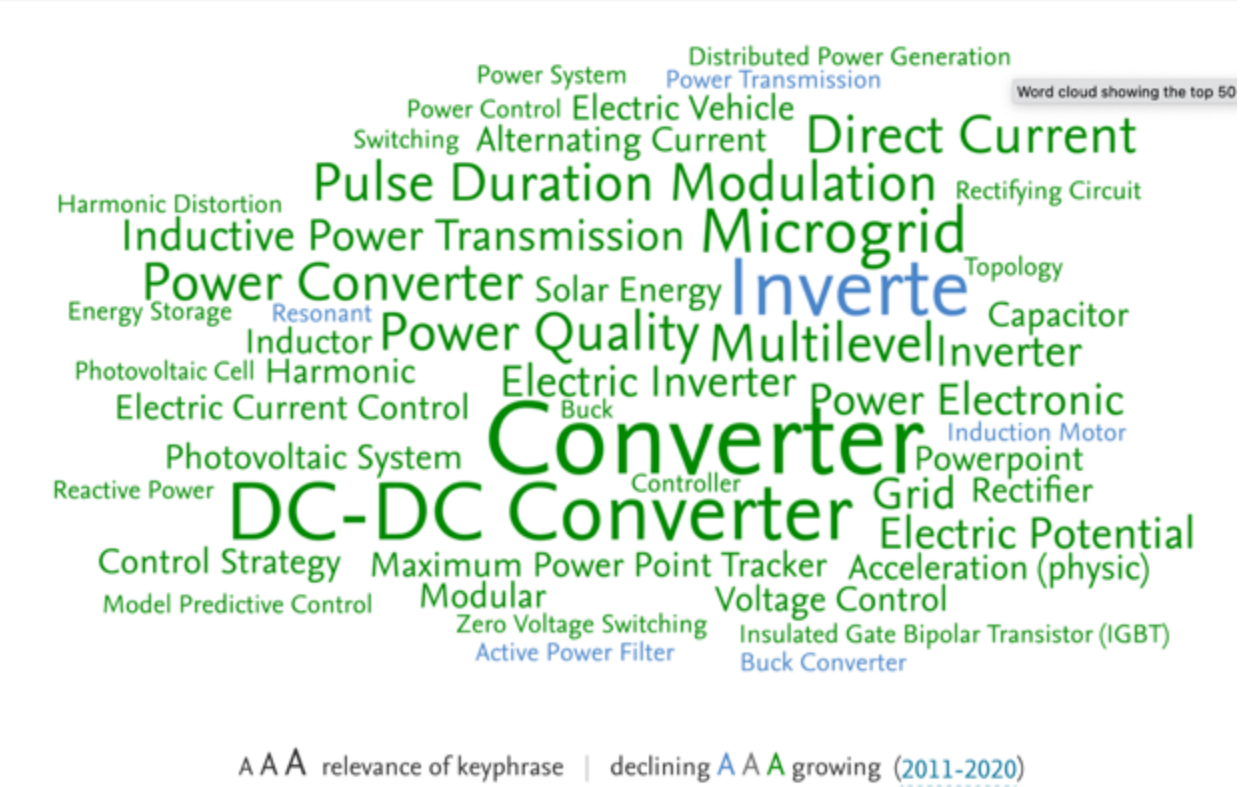
Conclusions

- Bi-directional DC converters wit galvanic isolation (DABs) are well developed and can be produced using existing power electronic technologies, building DC Solid State Transformers

- Higher frequency operation of DC-SST avoids Peak Copper, enabling a global Energy Transition

We are on the right track

DC – DC converters are currently most relevant keywords in R&D in Electrical Power Engineering (SciVal)



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Thank you for your attention







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