E.ON Energy Research Center

FLEXIBLE ELEKTRISCHE NETZE

RWTH AACHEN UNIVERSITY

Power Electronics – key enabling technology for for the Energy Transition



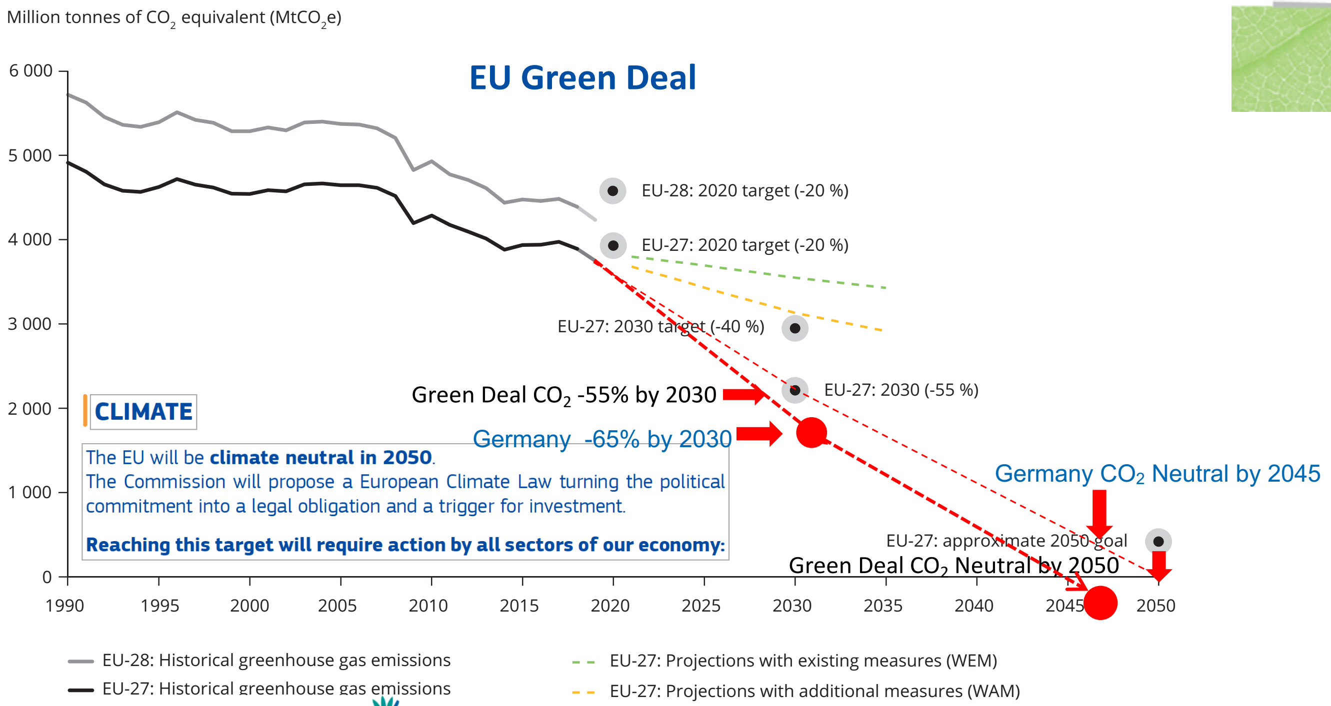




Rik W. De Doncker
Director E.ON Energy Research Center & Research Campus FEN
RWTH Aachen University

2nd PEEC Workshop, Washington, USA
April 1-2, 2023

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

Print ISBN 978-92-76-13661-3 doi:10.2775/97540 NA-03-19-927-EN-C
PDF ISBN 978-92-76-13629-3 doi:10.2775/275924 NA-03-19-927-EN-N

European Commission

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

FORSCHUNGSCAMPUS FLEXIBLE ELEKTRISCHE NETZE | E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

IEEE Spectrum
Oct. 2022

Cost:

275 trillion$
or
9 trillion$/year

= 10 % World economic product

but

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

engl.: trillion = deutsch Billion = 1.000.000.000.000

BY VACLAV SMIL

Decarbonization Is Our Costliest Challenge

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

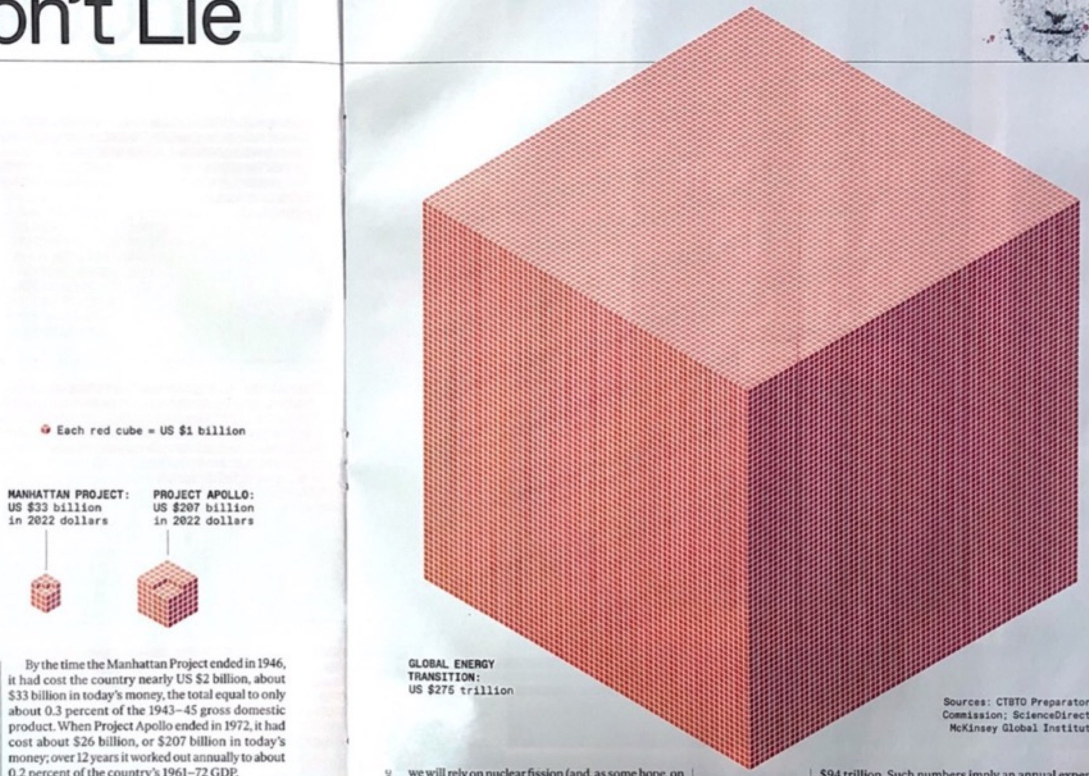
In his 1949 book *The Concept of Mind*, Gilbert Ryle, an English philosopher, introduced the term "category mistake." He gave the example of a visitor to the University of Oxford who sees colleges and a splendid library and then asks, "But where is the university?" The category mistake is obvious: A 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.



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.

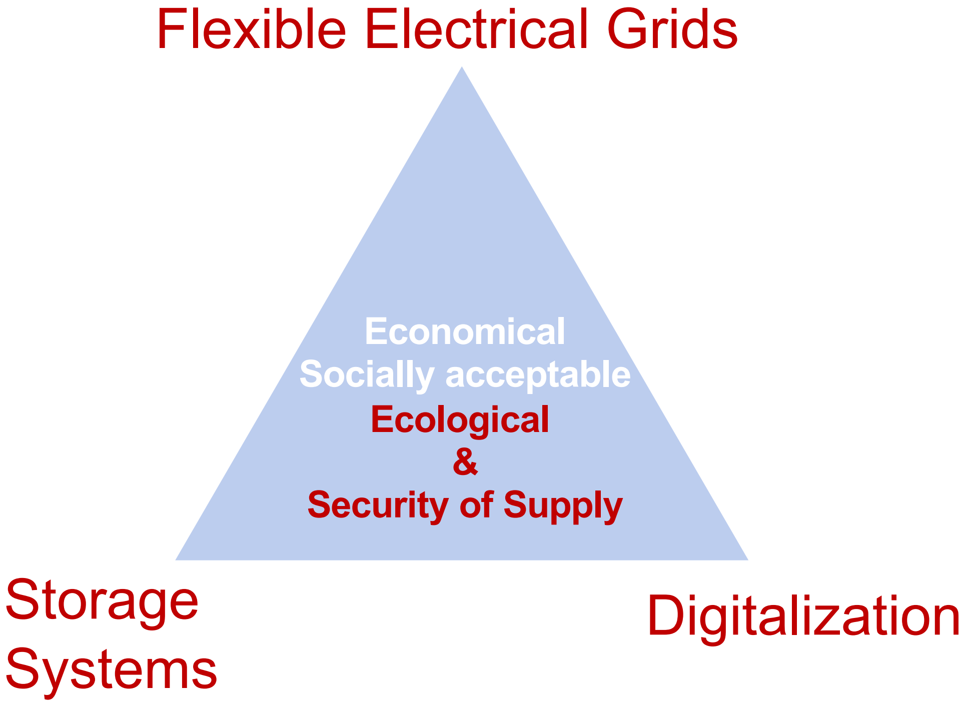
Of course, nobody can provide a reliable account of the eventual cost of global energy transition because we do not know the ultimate composition of the new primary energy supply. Nor do we know what shares will come from converting natural renewable flows, whether we will use them to produce hydrogen 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. ■

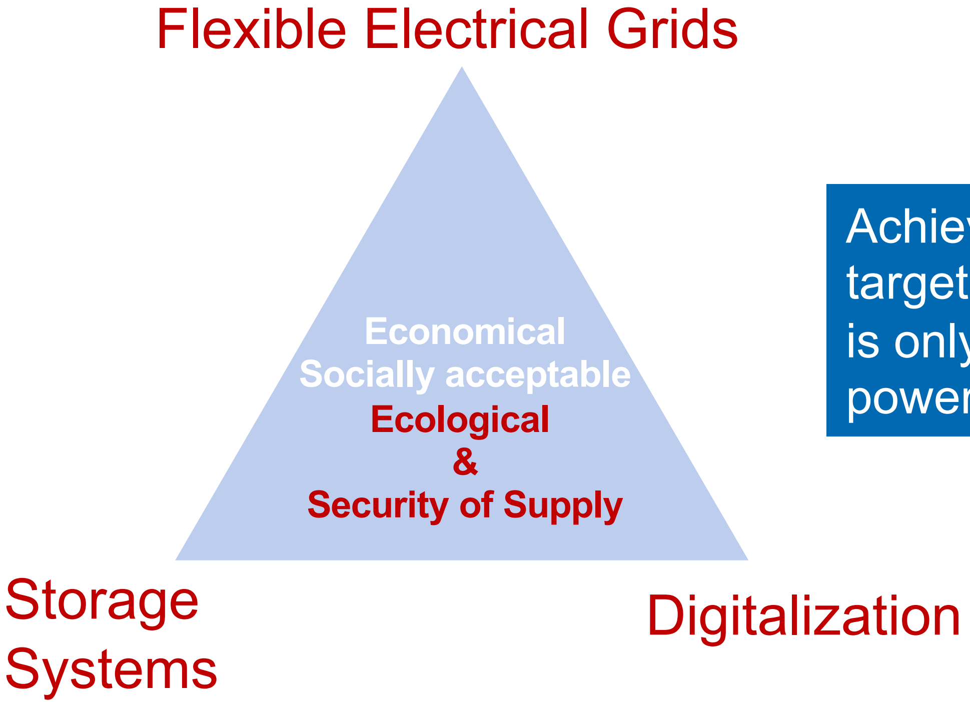
PORTRAIT: SERGIO ALBIAC

Illustration by Chris Philpot

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



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



Achieving Green Deal targets & lowering costs is only possible with power electronics.

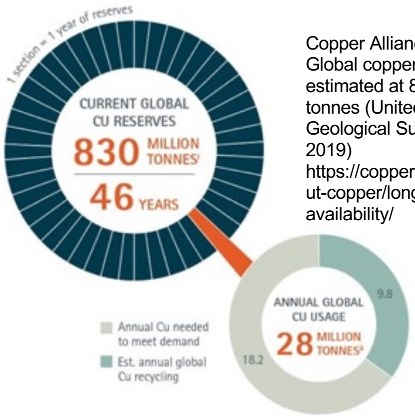
Urgency to innovate in all sectors to meet EU Green targets

More Silicon, less Copper and Steel!

- Saving material resources using power electronics and higher frequencies in DC solid state transformers (SST) is needed to reach climate goals
  - Recycling of PEL components
  - New materials to increase power density

- 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 more copper use



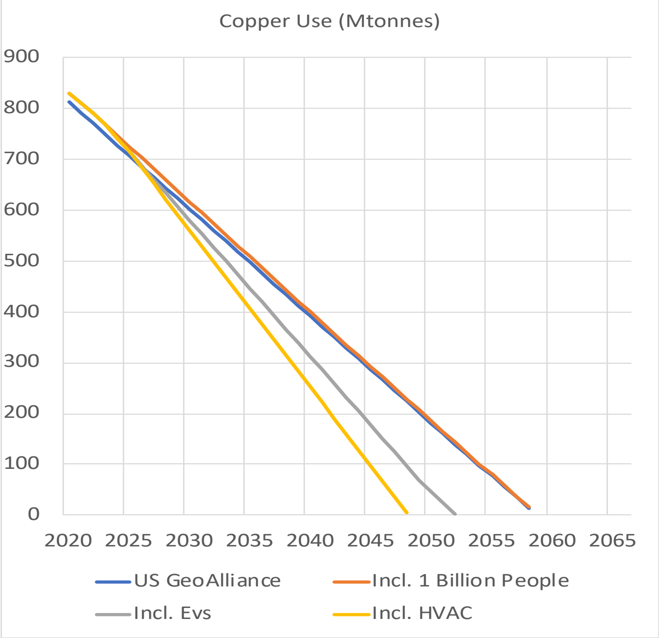
Copper Alliance,based on Global copper reserves are estimated at 830 million tonnes (United States Geological Survey [USGS], 2019) https://copperalliance.org/about-copper/long-term-availability/

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!

- Saving material resources using power electronics and higher frequencies in DC solid state transformers (SST) is needed to reach climate goals
  - Recycling of PEL components
  - New materials to increase power density



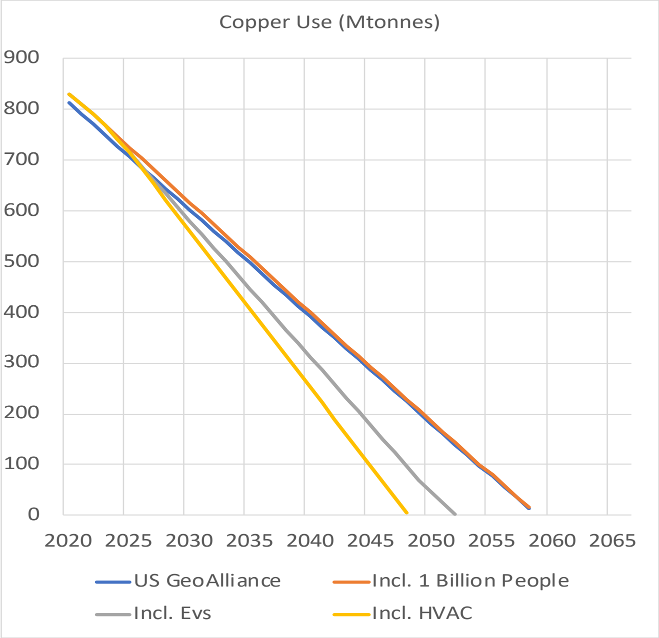
- Standard of living (and emissions) is correlated to electricity use
- About 1 Billion people have limited or no access to electricity
  - Requires 12,5 MioTons Cu extra when using 50 Hz grids (Time out 2057)
- Electrification of all sectors will increase massively more copper use
  - Electrification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

Urgency to innovate in all sectors to meet EU Green targets

More Silicon, less Copper and Steel!

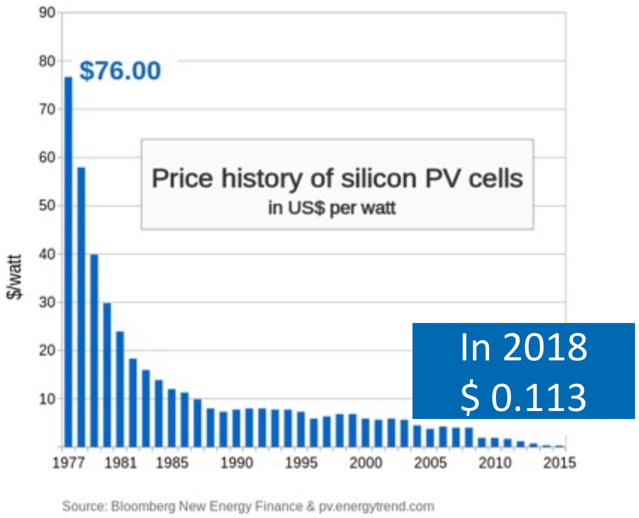
- Saving material resources using power electronics and higher frequencies in DC solid state transformers (SST) is needed to reach climate goals
  - Recycling of PEL components
  - New materials to increase power density

- 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 more 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)



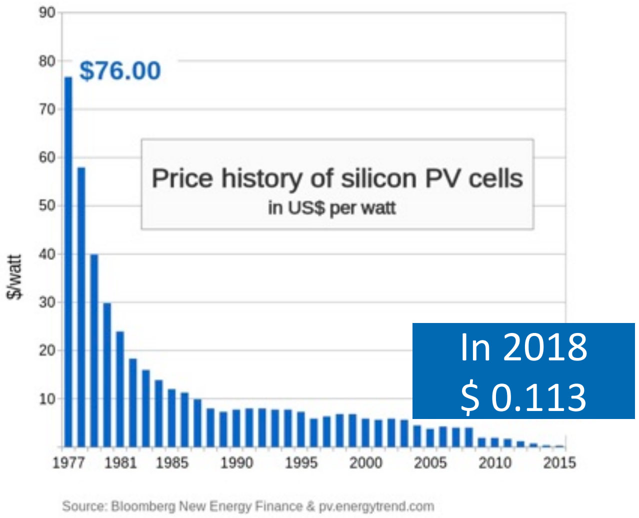
- Innovation needs to be accelerated to meet EU Green Deal targets
- Electrification of developing countries for geopolitical stability
- China State Grid may deploy UHVDC technology (more than +/- 1 MV) and is considering an “Electrical Silk Route” from China to EU -> HVDC can and will go global. We all must work together.

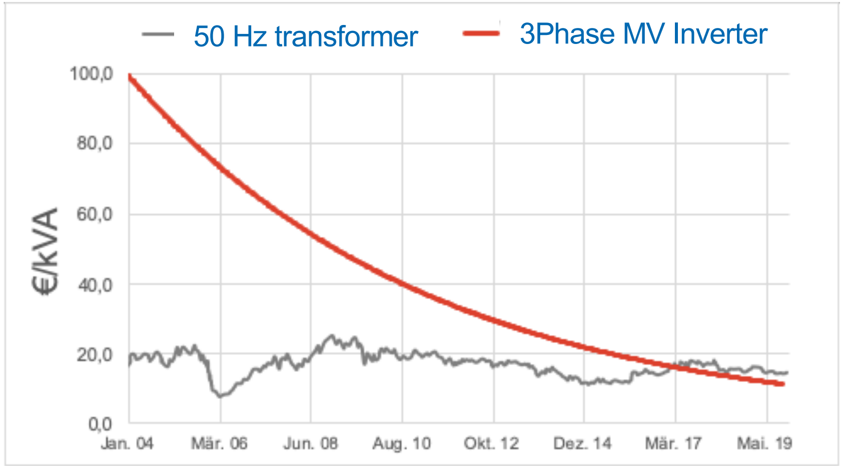
Security of supply – saving materials
Price of copper has already doubled over past five years (LMEx)



It is expected that price of silicon will keep going down while price of metals, in particular copper price is already increasing.
(best investment according to The Economist).

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



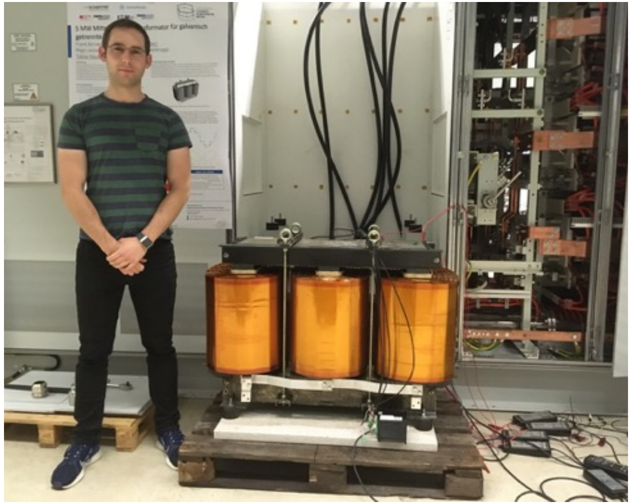


Silicon is made of SiO_2 (i.e. sand, an abundant material) and **energy**
Energy is produced by **PV**
PV energy is controlled and converted by **power electronics** made of **silicon**

DC Transition with DC Solid State Transformers

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

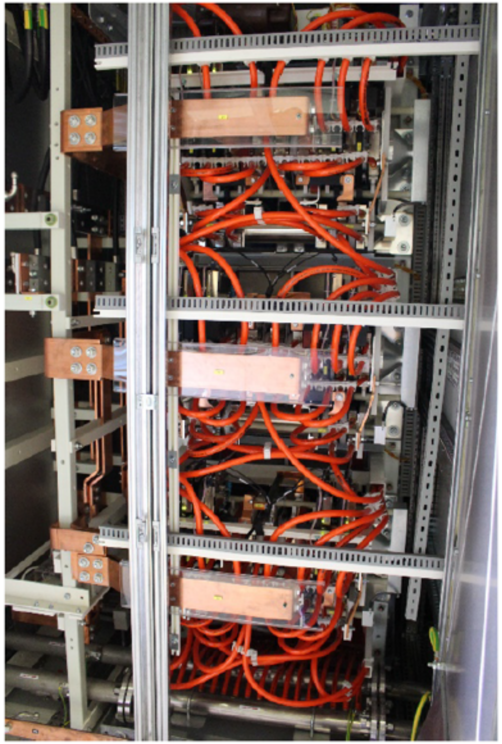
4,5 MVA, 50 Hz Transformer
11.500 kg (2,5 kg/kVA)

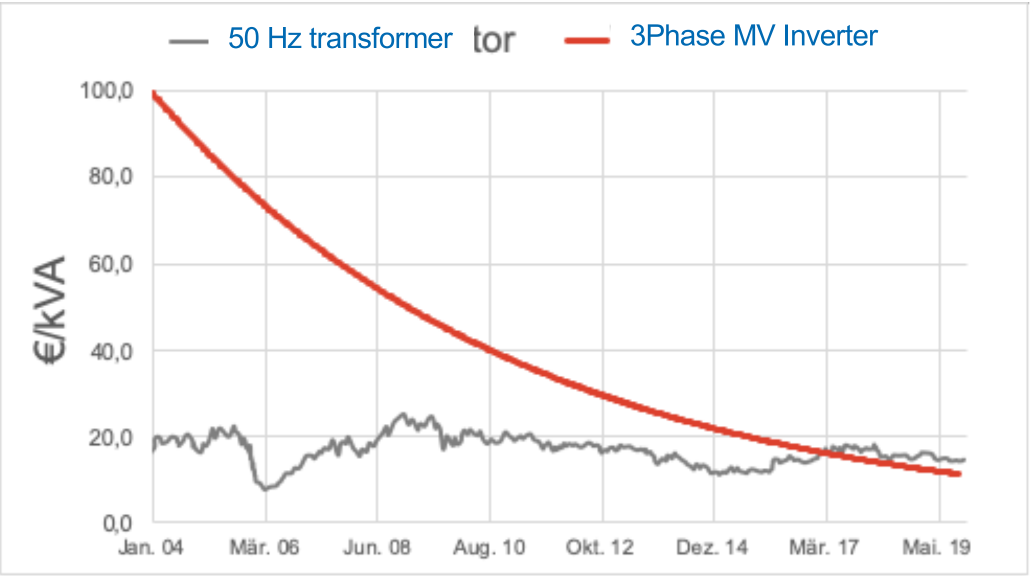


5,0 MVA, 1.000 Hz Transformer
675 kg (0,14 kg/kVA)

- Solid State DC transformers reduce significantly our CO2-foot print
  Estimated Transformer use; AC@50 Hz >25,000 ton/GVA, DC@1 kHz Grid < 1,500 ton/GW

Power electronic inverters are progressively having lower costs than 50 Hz transformers



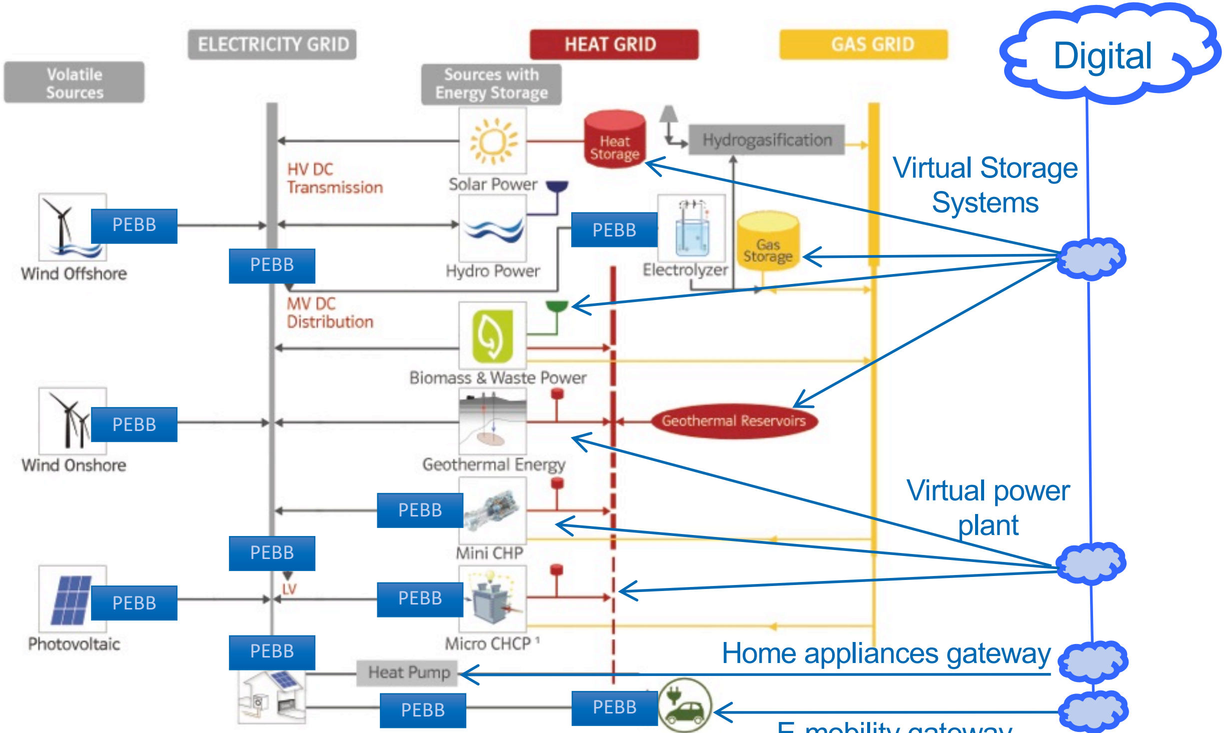


Estimated cost for 2021

Automotive inverter 3 €/kVA

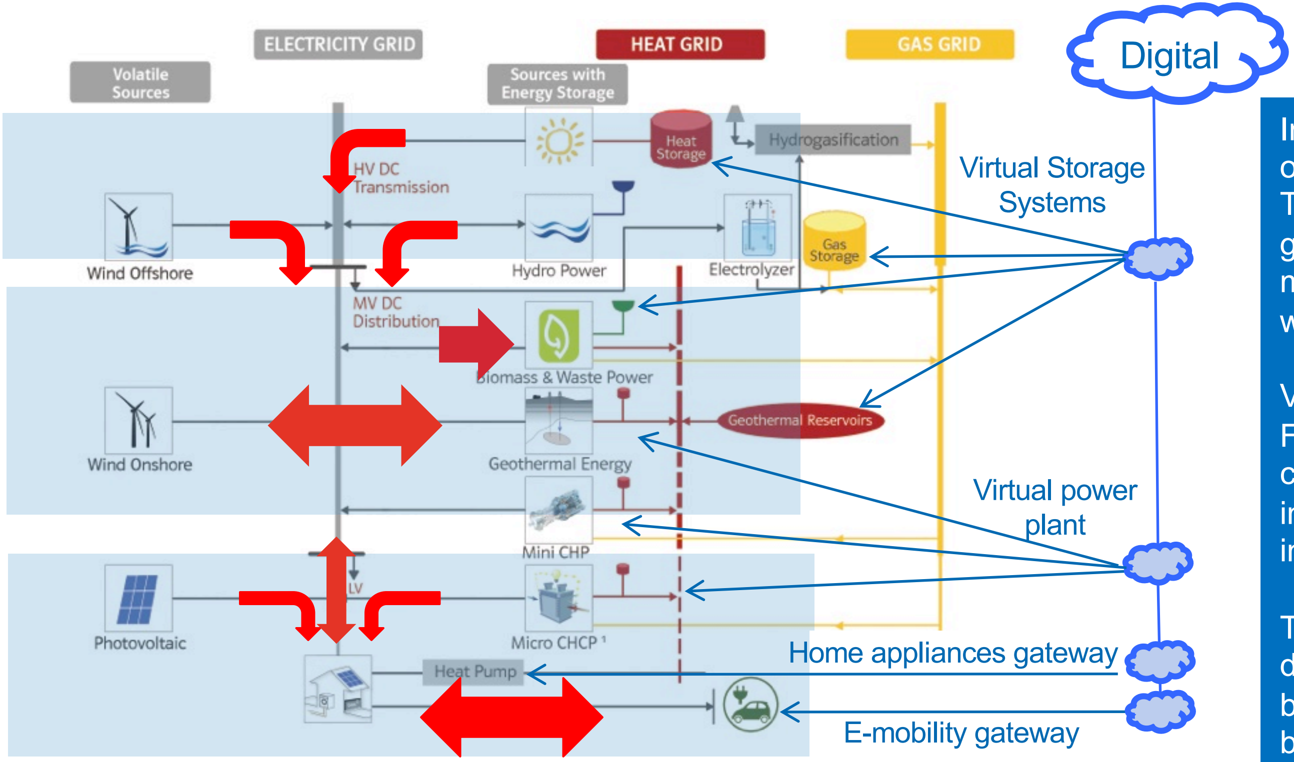
DC Solid-State DC Transformer 9 €/kW

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.

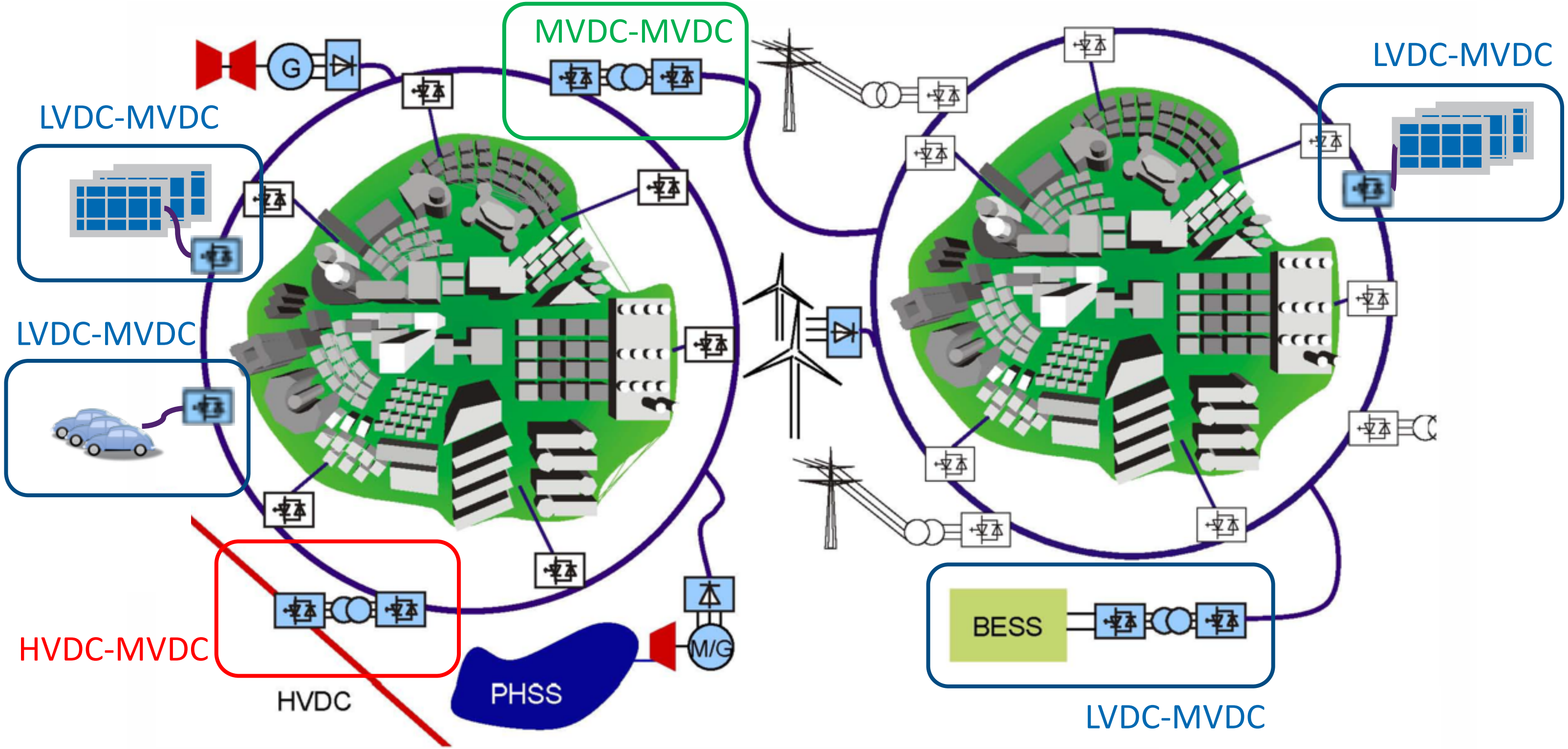
VDE ETG Task Force expects less cost for DC integration in infrastructure.

The MV distribution grid will become bottleneck.

PEBB : Power Electronic building Block

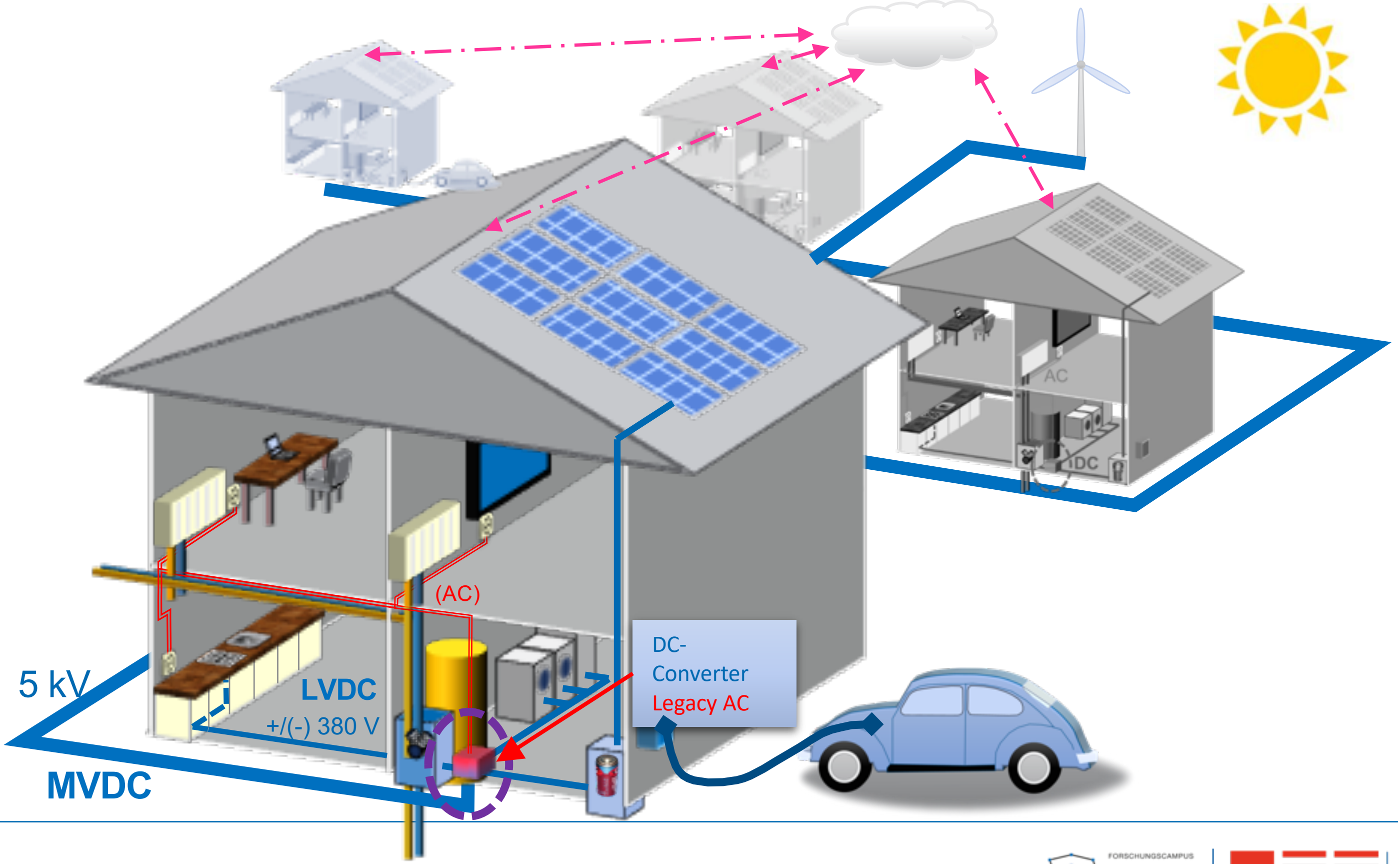
Flexible Grids for Decentralized Power Generation

Cellular Grid Topologies, Sector Coupling and DC Intelligent Substations



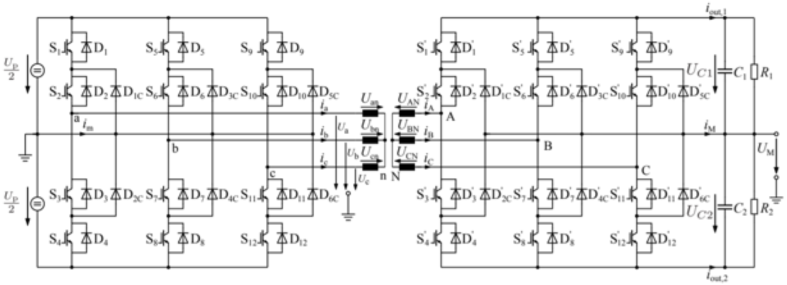
DC-Grid and Energy Management in DC city quarter

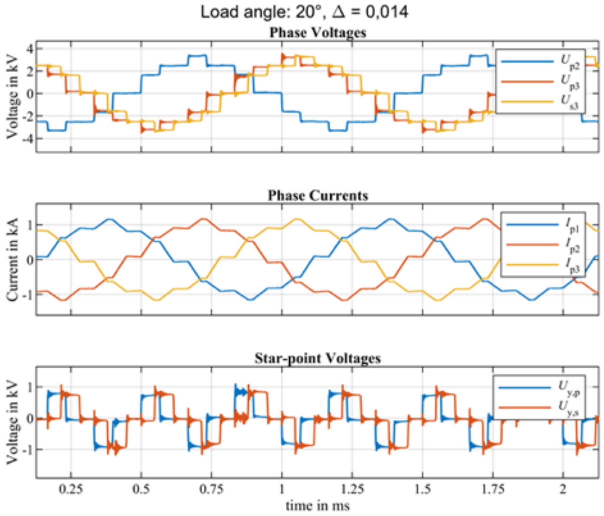
Lower infrastructure costs, higher efficiency and bidirectional power flow for prosumer



Medium-Voltage High-Power DC-DC-Converters at PGS

- Modular three-phase dual active bridge
  - $P = 5\ \mathrm{MW}, V_{\mathrm{DC}} = 5\ \mathrm{kV} \pm 10\%$
  - 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





Conclusion – Key components (DAB) are production ready!

- Additional issues of DAB solved (see references, patents)
  - 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 ➡ a true DC PEBB for multiple voltage and power levels

➡ **Three-phase DABs can be built today, using existing converters (TRL 8)**

Conclusion and Outlook

- The 3-phase DAB offers high efficiency and power density
- The control algorithms have been fully developed to make the 3-phase DAB a suitable, robust DC transformer for LV and MV DC distribution grids

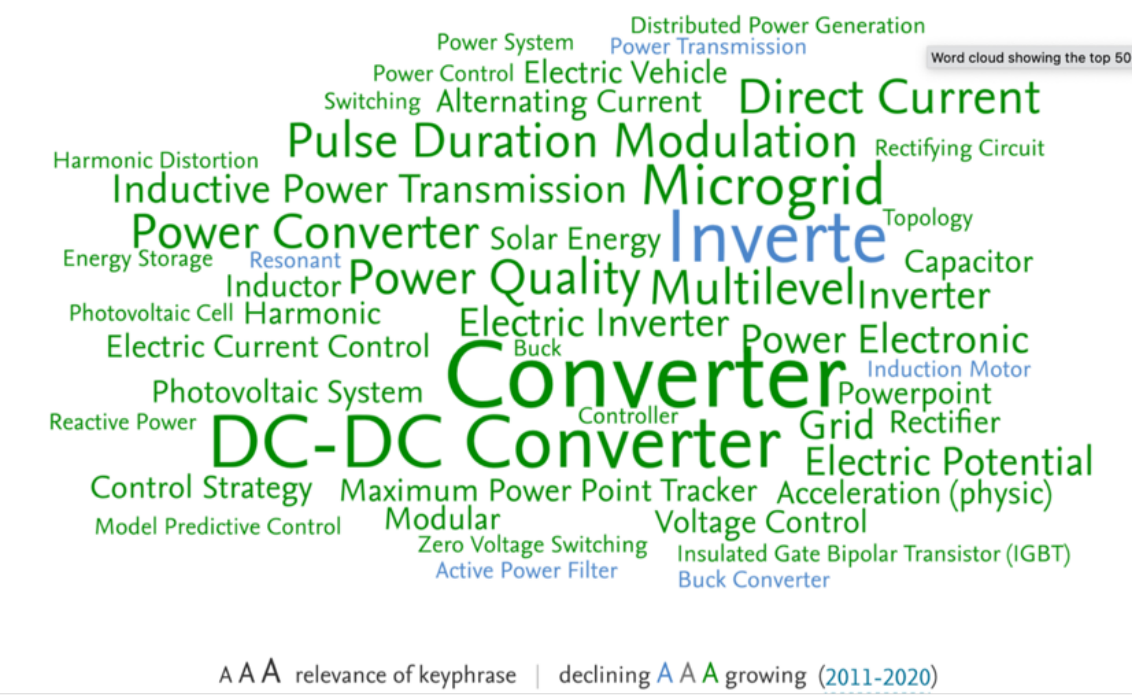
- New wide bandgap devices (SiC) will increase switching frequencies, increasing power densities further, in particular in MVDC-LVDC applications

- Development and design of symmetrical MF & HF 3-phase transformers, with integrated leakage inductances, will further reduce control complexity

- Development of suitable insulation (BiL) and cooling systems for MF & HF 3-Phase transformers

We are on the right track

DC – DC converters are currently most relevant topics in Electrical Power Engineering (SciVal)



Furthermore

- Three-level, three-phase DAB converters offer more degrees of freedom to extend ZVS
  - S. Thomas, “A medium voltage multi-level DC/DC converter with high voltage transformation ratio”, PhD thesis, RWTH Aachen, 2014, ISBN 978-3-8440-2605-4

- Dead time compensation in 3p-DAB
  - H. Siddique, “The three-phase dual-active bridge converter family : modeling, analysis, optimization and comparison of two-level and three-level converter variants”, PhD Thesis, RWTH Aachen, 2019, DOI: 10.18154/RWTH-2020-01205

- HVDC to MVDC 3p-DAB – MMC & 3p-DAB
  - S. Cui, “Modular multilevel DC-DC converters interconnecting high-voltage and medium-voltage DC grids”, PhD Thesis, RWTH Aachen, 2019, DOI: 10.18154/RWTH-2019-05892

- Multi-port Active Bridges for multi-terminal distribution grids
  - M. Neubert, “Modeling, synthesis and operation of multiport-active bridge converters”, PhD Thesis, RWTH Aachen, 2020, DOI: 10.18154/RWTH-2020-10814

List of References

- R. W. DeDoncker, D. M. Divan and M. H. Kheraluwala, "A three-phase soft-switched high-power-density DC/DC converter for high-power applications, Proceedings of the Annual Meeting of the IEEE Industry Applications Society, Pittsburgh, PA, October, 1988, also in IEEE Transactions on Industry Applications, vol. 27, no. 1, pp. 63-73, Jan.-Feb. 1991, doi: 10.1109/28.67533.
- R. W. De Doncker, D. M. Divan and M. H. Kheraluwala, "Power conversion apparatus for DC/DC conversion using dual active bridges,“ US patent US5027264A
- R. W. De Doncker, "Power electronic technologies for flexible DC distribution grids," 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima, 2014, pp. 736-743, doi: 10.1109/IPEC.2014.6869670.
- Madlener R., De Doncker R.W. (2008) Investing in Power Generation. In: Bausch A., Schwenker B. (eds) *Handbook Utility Management*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-79349-6_17
- M. Stieneker, J. Butz, S. Rabiee, H. Stagge and R. W. D. Doncker, "Medium-Voltage DC Research Grid Aachen," International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age, Bonn, Germany, 2015, pp. 1-7.
- R. W. De Doncker, A. Monti, A. Moser, E.M. Jakobs (eds), "DC Technology in Utility Grids - Survey Report“, *Research CAMPUS Flexible Electrical Networks Report*, 1st Edition, 2020, ISBN 978-3-946143-08-6
- 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
- J. Voss, “Multi-megawatt three-phase dual-active bridge DC-DC converter: extending soft-switching operating range with auxiliary-resonant commutated poles and compensating transformer saturation effects”, Diss., RWTH Aachen University, E.ON ERC, 2019
- J. Hu, PhD Thesis, “Modulation and dynamic control of intelligent dual-active-bridge converter based substations for flexible dc grids," RWTH Library Open Access http://publications.rwth-aachen.de/record/763285, DOI: 10.18154/RWTH-2019-06213.
- Senghui Cui, ” Modular multilevel DC-DC converters interconnecting high-voltage and medium-voltage DC grids”; PhD thesis , RWTH Aachen University, 2019, DOI: 10.18154/RWTH-2019-05892
-] J. Hu, S. Cui and R. W. De Doncker, "DC Fault Ride-Through of a Three-Phase Dual-Active Bridge Converter for DC Grids," *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, Niigata, 2018, pp. 2250-2256, doi: 10.23919/IPEC.2018.8507672.

Xing.FENaachen.net

Linkedin.FENaachen.net

@FENaachen

YouTube.FENaachen.net

Thank you for your attention.

Contact:
Univ.-Prof. Dr. ir. Dr. h.c. Rik W. De Doncker

Flexible Elektrische Netze FEN GmbH
Campus-Boulevard 79, 52074 Aachen
info@fenaachen.net

E.ON ERC – RWTH Aachen University
Mathieustraße 10, 52074 Aachen
Tel. : +49 241 80 49667
post_pgs@eonerc.rwth-aachen.de

FORSCHUNGS CAMPUS
öffentlich-private Partnerschaft für Innovationen

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

FORSCHUNGSCAMPUS
FLEXIBLE ELEKTRISCHE NETZE