«X-Technologies/X-Concepts»

Key Enablers of Further Performance Improvements in Power Electronics

Johann W. Kolar, et al.
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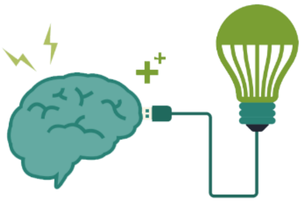
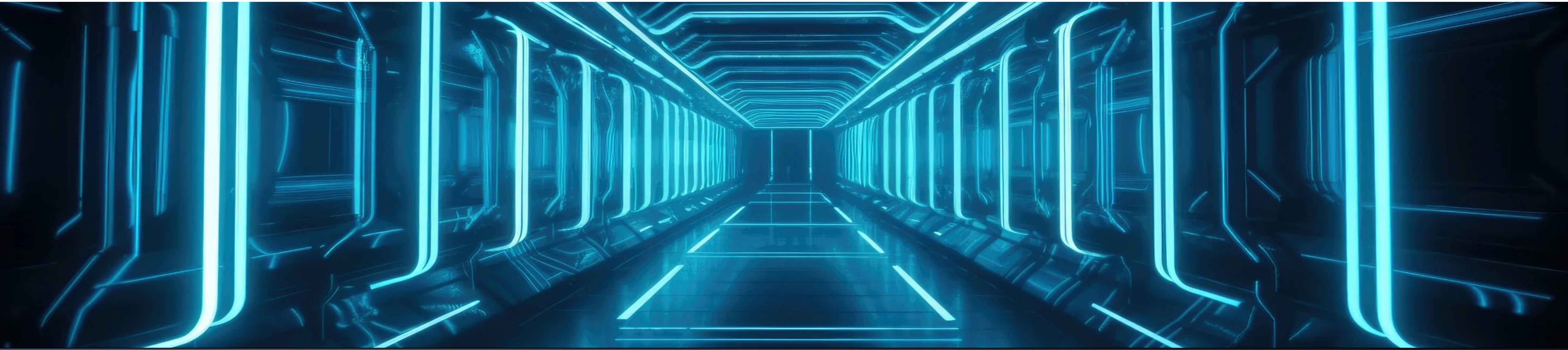


100th IFX Tech Talk
April 5, 2024



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Johann W. Kolar & Jonas Huber

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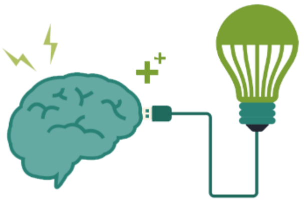

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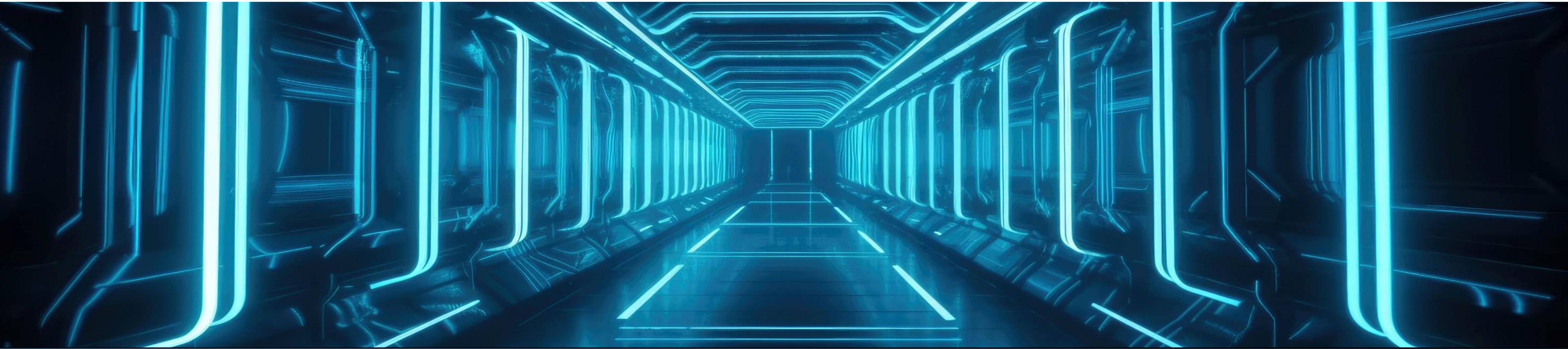


"X-Technologies / X-Concepts" – Key Enablers of Further Performance Improvements in Power Electronics

Abstract— Power electronics is a key technology for all forms of electrical energy generation and use in modern society, ranging from renewable energy systems and very diverse power supply applications, including fast charging of electric vehicles and hyper-scale data centers, to variable frequency motor drives for industrial automation. Progress in this area has been driven over the last 40 years by new concepts for power semiconductors and corresponding circuit topologies and modulation/control schemes, as well as the introduction of integrated circuits and microprocessors enabling digital signal processing and control.

We are now in the midst of another highly dynamic phase of development in power electronics, and it is interesting to reflect on the driving forces, in other words, to identify the "x-technologies" and "x-concepts" that will shape the field in the next decade. After a brief review of x-technology candidates such as monolithic bidirectional GaN switches, 3D-packaging and ML-supported multi-objective design optimization, the talk identifies key x-concepts, namely modularization, hybridization, synergetic association, functional integration and decentralization, and then demonstrates/verifies their capabilities using latest research results from the Power Electronic Systems Laboratory at ETH Zurich, like a 99.4% efficient multi-level PV inverter system, an ultra-compact 3-port automotive DC/DC converter system, a synergetically controlled ultra-wide output voltage range three-phase EV charger, a monolithic bidirectional GaN switch current DC-link AC/AC converter for motor integrated variable speed drives, a 4.8MHz switching frequency 100kHz bandwidth AC-source and a partial power processing DC/DC server power supply.

Finally, the urgency of transitioning from today's linear economy to a circular economy and/or of life cycle assessments, embodied energy analyses and design for repair, reuse and recyclability are highlighted as important "beyond tomorrow" topics for power electronics research to ensure that the widely accepted net-zero CO_2 target for 2050 is ultimately achieved on a sustainable basis.

Outline

- *Introduction*
- *X-Technologies*
- *X-Concepts*
- *Conclusions*

Acknowledgement

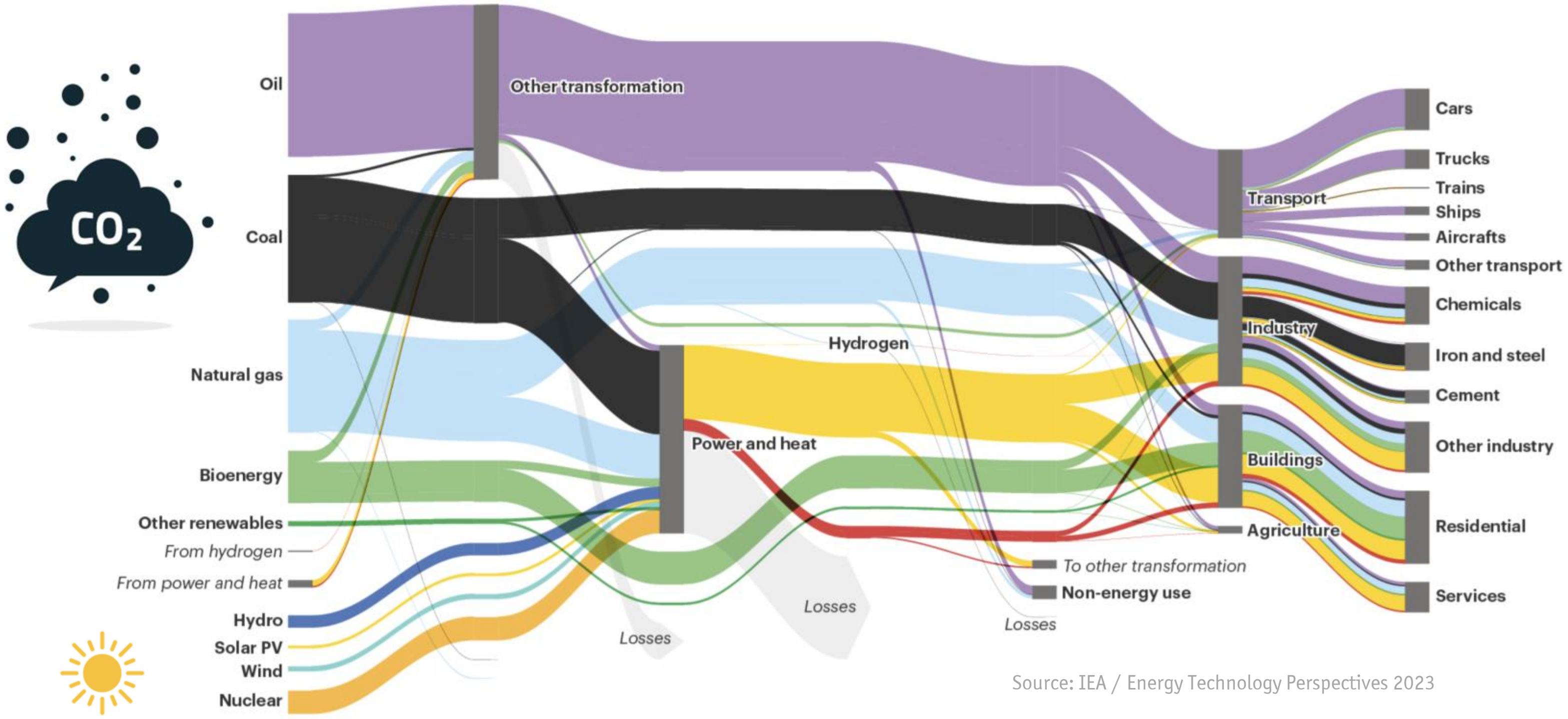
M. Antivachis
J. Azurza
J. Biela
D. Bortis
H. Ertl
T. Guillod
M. Haider
L. Imperiali
M. Kasper
J. Kaufmann
G. Knabben
F. Krismer
Y. Li
D. Menzi
S. Miric
J. Miniböck
N. Nain
D. Naumayr
P. Niklaus
J. Schäfer
L. Schrittwieser
F. Vollmaier
St. Waffler
S. Weihe
D. Zhang

Introduction

Clean Energy Transition
All-Electric Society

The Challenge

- *Global Energy Flows — 2021*



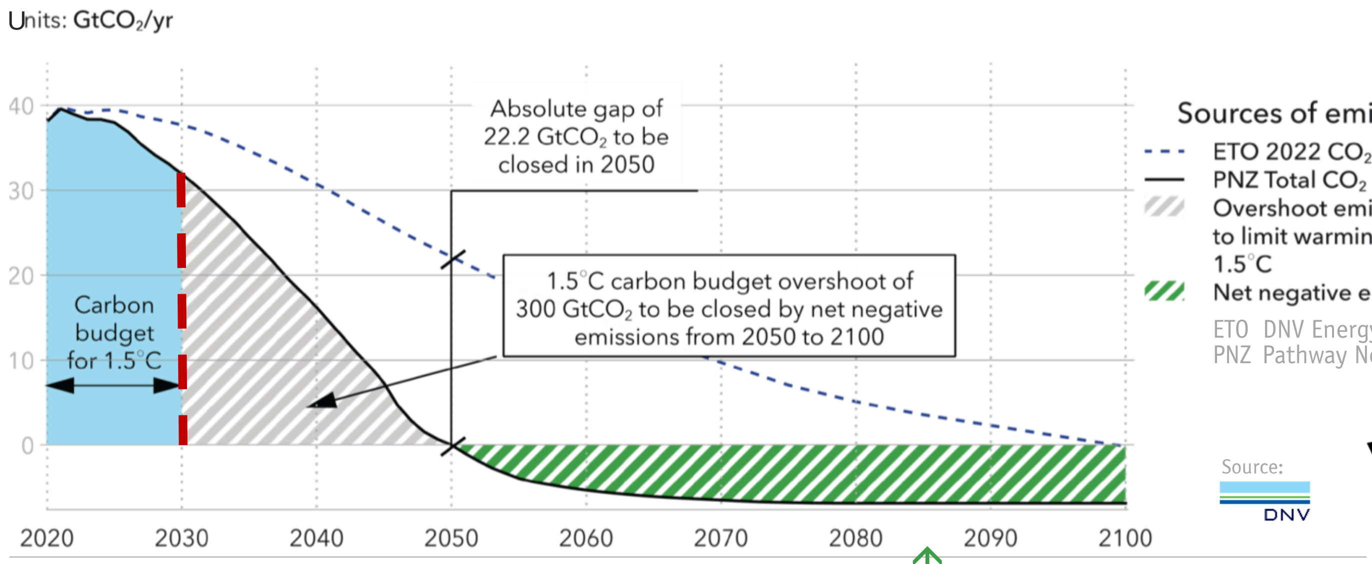
Source: IEA / Energy Technology Perspectives 2023

- *Large Share of Fossil Fuels (!)*

Decarbonization / Defossilization

- *"Net-Zero" Emissions by 2050 & Gap to be Closed*
- *50 $GtCO_{2eq}$ Global Greenhouse Gas Emissions / Year → 280 $GtCO_2$ Budget Left for 1.5°C Limit*

40 $GtCO_2$ →



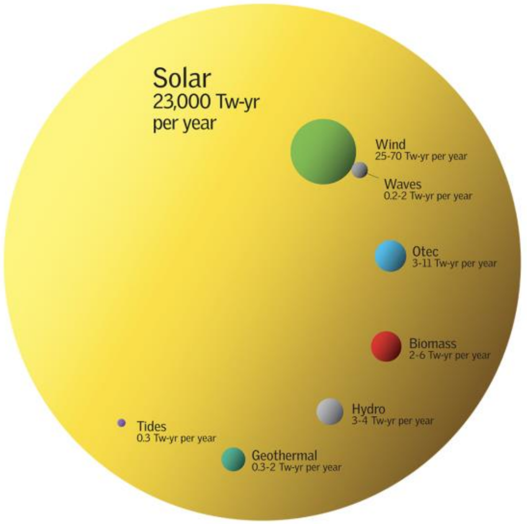
„Net-Negative"
Remove Overshoot
of 300 $GtCO_2$

- *Challenge of Stepping Back from Oil & Gas*
- *Human History — Transition from Lower to Higher Energy Density Fuel — Wood → Coal → Oil & Gas*

The Opportunity

(2009) 16 TW-yr —● 16 Tw-yr per year ●— *27 TW-yr (2050)*

Renewable energy resources per year



100% Conv. Efficiency
Excl. Oceans

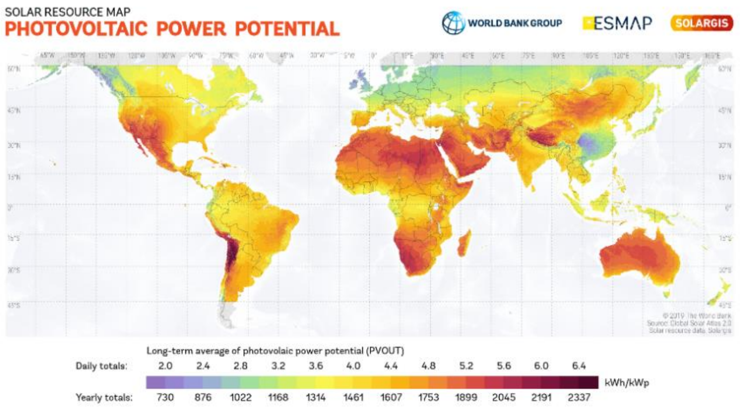
Note: Graphical Representation Assumes Spheres Not Circles

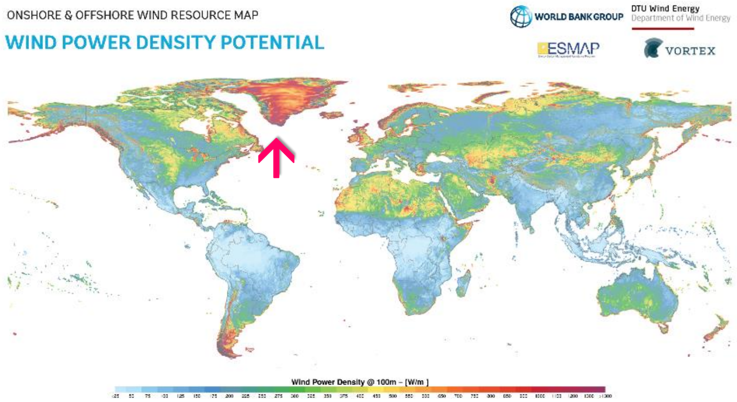
Primary Consumption:
16 TW-yr → 27 TW-yr
Final Consumption:
11 TW-yr → 15 TW-yr

Source: R. Perez et al., IEA SHC Program Solar Update (2009)

Fossil energy resources - total reserve left on earth

■ *Global Distribution of Solar & Wind Resources*

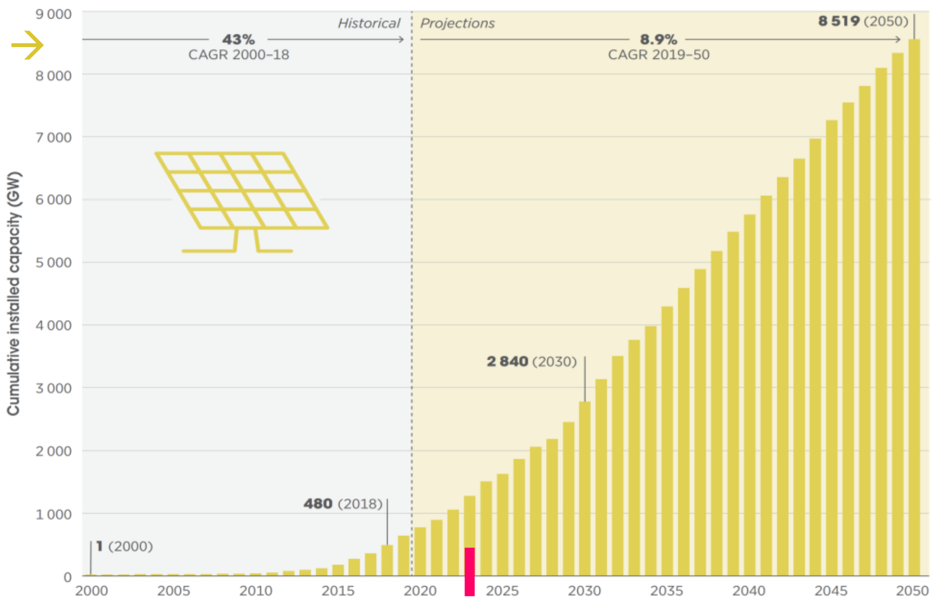




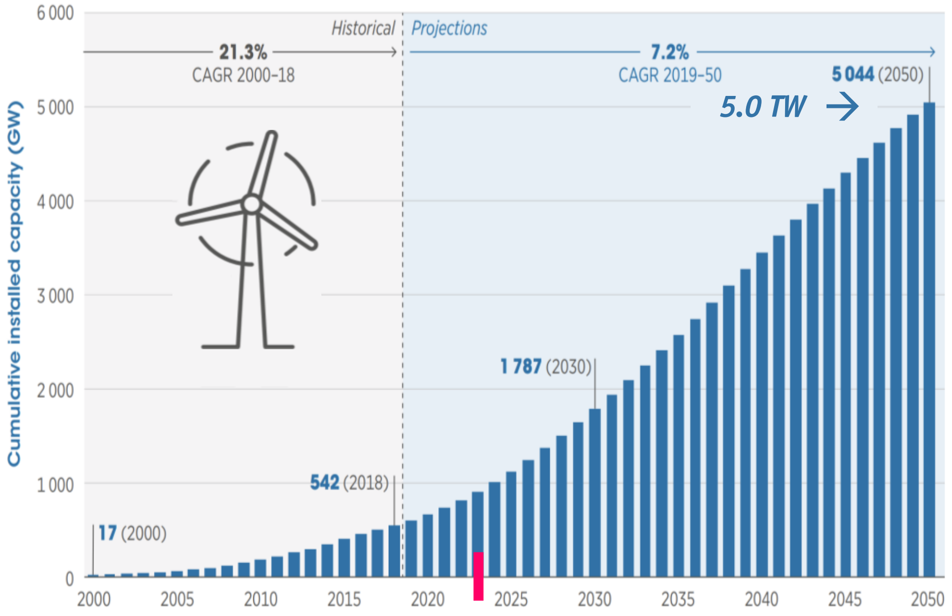
The Approach

- *Outlook of Global Cumulative Installations Until 2050 / Add. 1000 GW Off-Shore Wind Power*
- *In 2050 Deployment of 370 GW/Year (PV) & 200 GW/Year (On-Shore Wind) incl. Replacements*

8.5 TW →



Sources: Historical values based on IRENA's renewable energy statistics (IRENA, 2019c) and future projections based on IRENA's analysis (2019a).

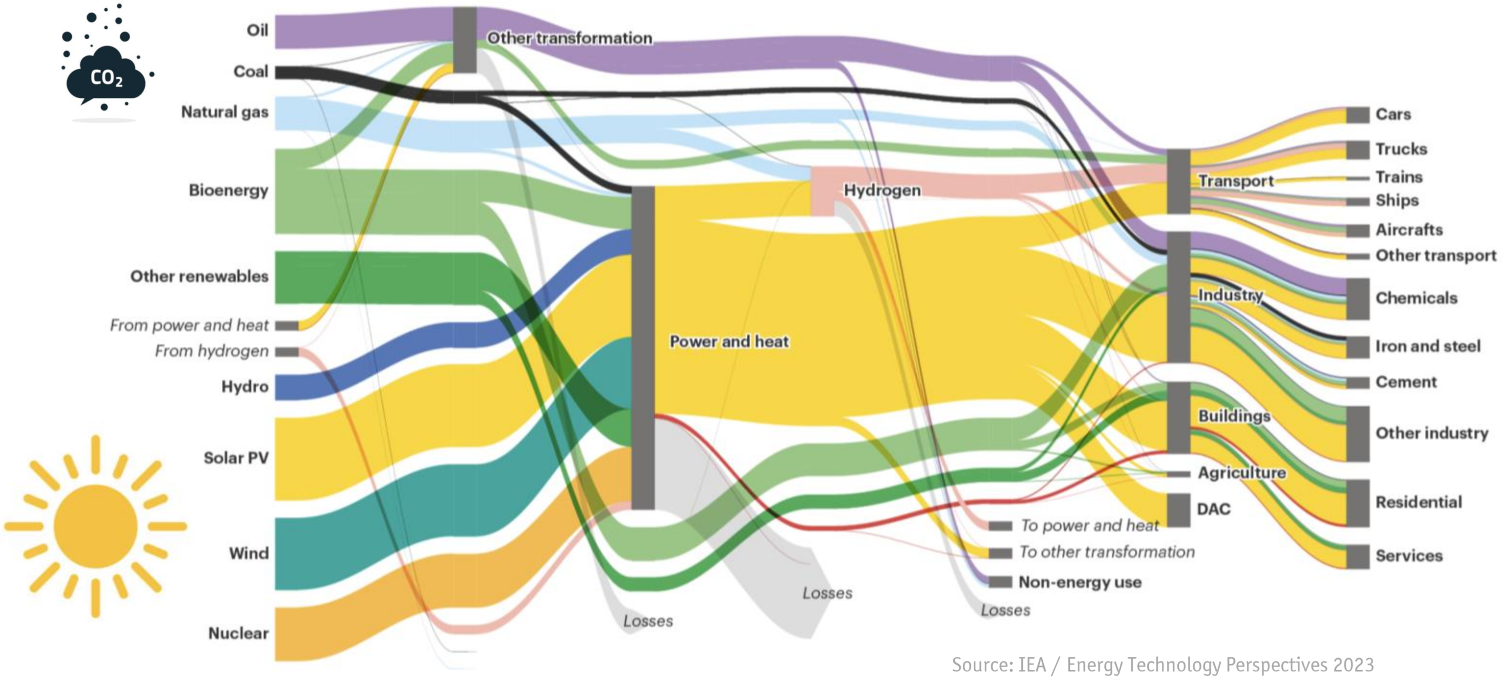


Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

- *CAGR of ≈9% up to 2050 → 8500 GW*
- *CAGR of ≈7% up to 2050 → 5000 GW*

Net-Zero CO_2 by 2050

- *Global Energy Flows — 2050 / Net-Zero Scenario*

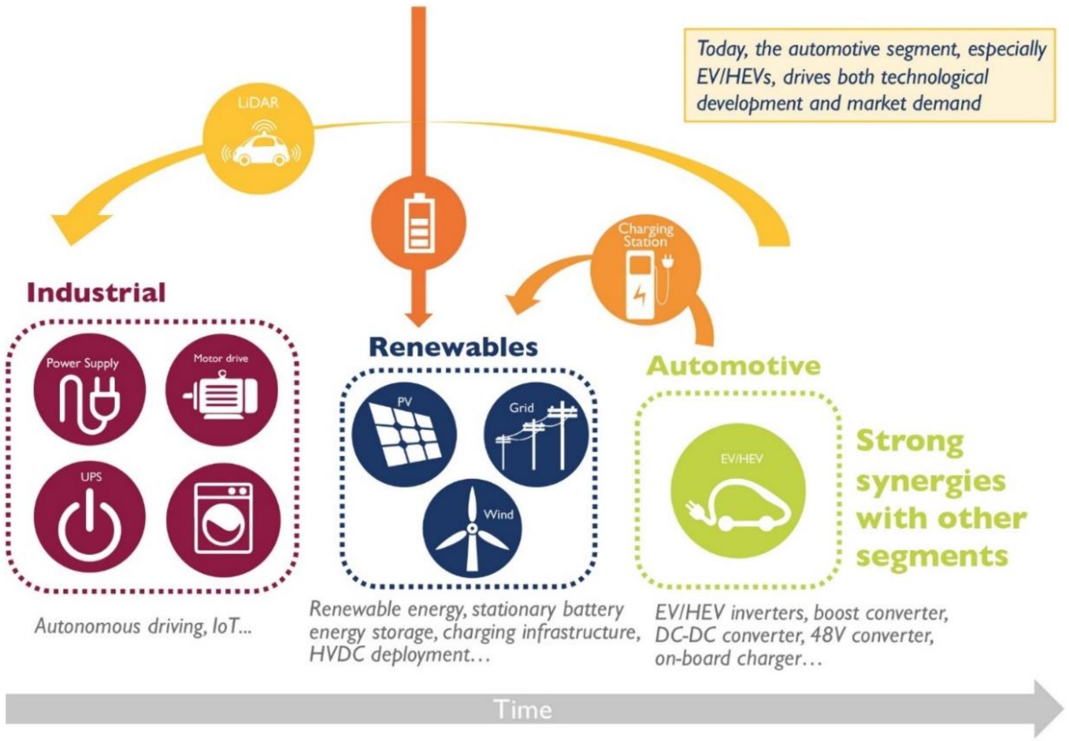


Source: IEA / Energy Technology Perspectives 2023

- *Dominant Share of Electric Energy — Power Electronics as Key Technology (!)*

Fundamental Role of Power Electronics

- *Global MEGA-Trends → Industry Automation | Renewable Energy | Sustainable Mobility | Urbanization etc.*



Source: Status of Power Electronics Industry 2019 Report
YOLE Développement

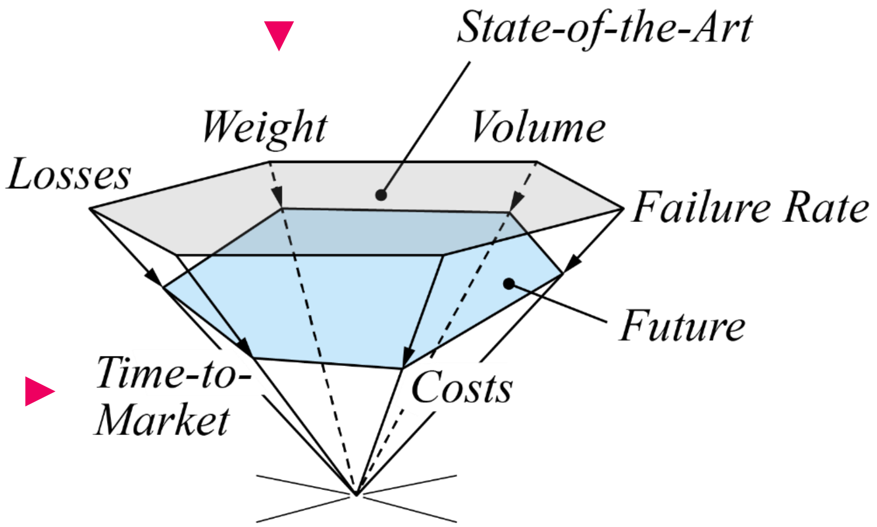
- *Clean Energy Transition → "All-Electric" Society*
- *UN Sustainable Development Agenda → There can be No "Plan B", because there is No "Planet B"* (Ban Ki-moon)

Performance Indicators / Trends

Environmental Impact & Material Usage ... [kg_{Fe} /kW]
[kg_{Cu} /kW]
[kg_{Al} /kW]
[cm^2_{Si} /kW]

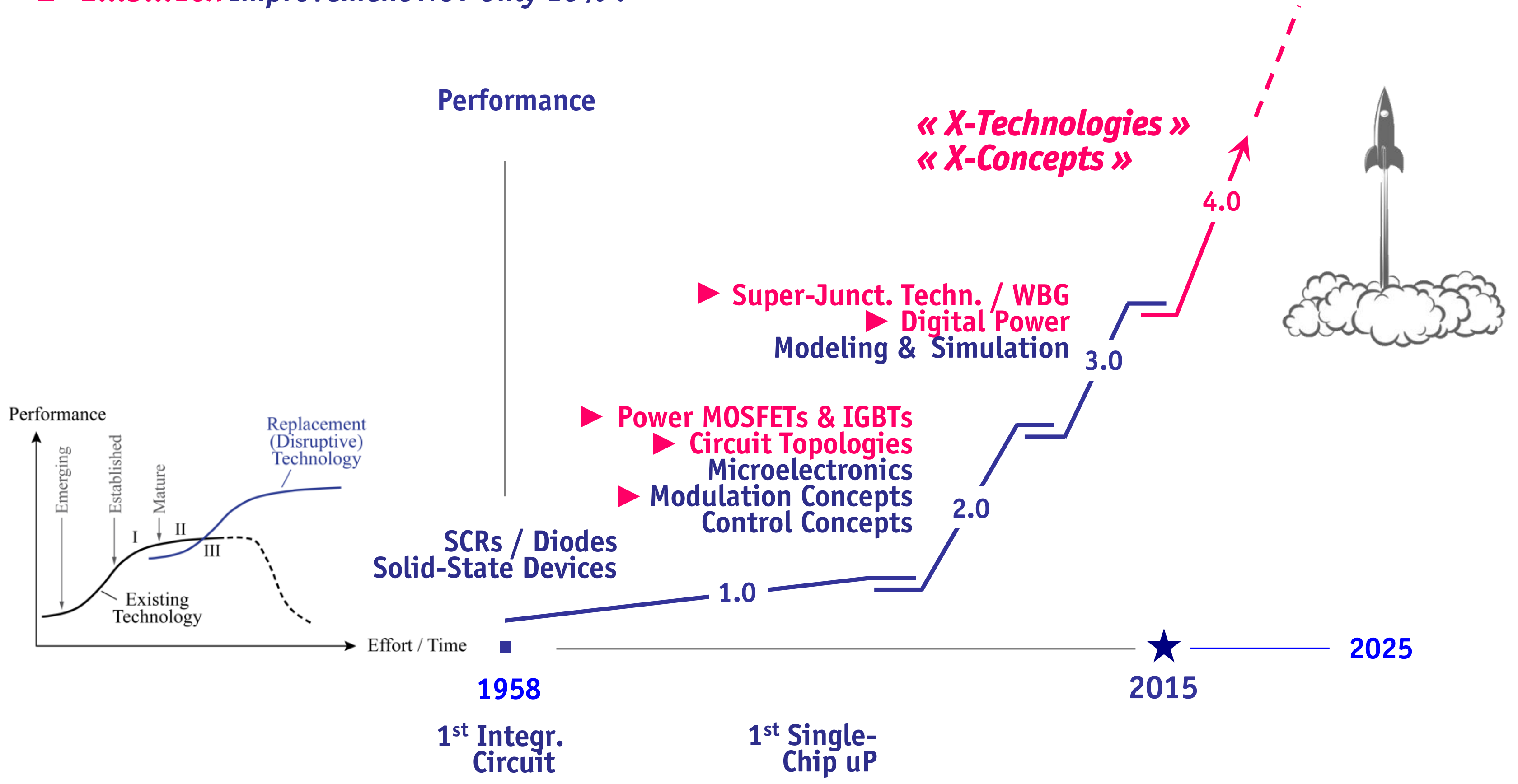
- Power Density [kW/dm^3]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h^{-1}]

- Manufacturability
- Recyclability / Sustainability
- Networked / IIoT



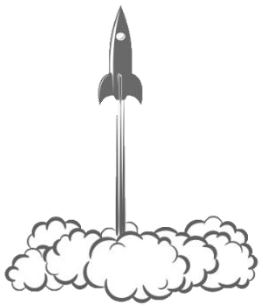
S-Curve of Power Electronics

- *« X-Technologies » / "Moon-Shot" Technologies*
- *« X-Concepts » → Full Utilization of Basic Scaling Laws & « X-Technologies »*
- *Power Electronics 1.0 → Power Electronics 4.0*
- *2…5…10x Improvement NOT Only 10% !*



X-Technologies

SiC | GaN
3D-Packaging & Integration
Digital Signal Processing

X-Technology  SiC | GaN

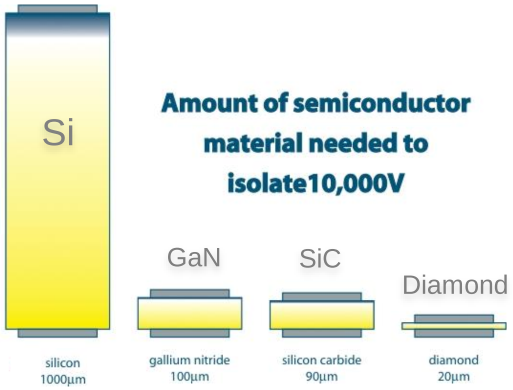
Low $R^*_{DS(on)}$ High-Voltage Devices

- *SiC MOSFETs / GaN HEMTs*
- *Low Conduction Losses*
- *High Efficiency*

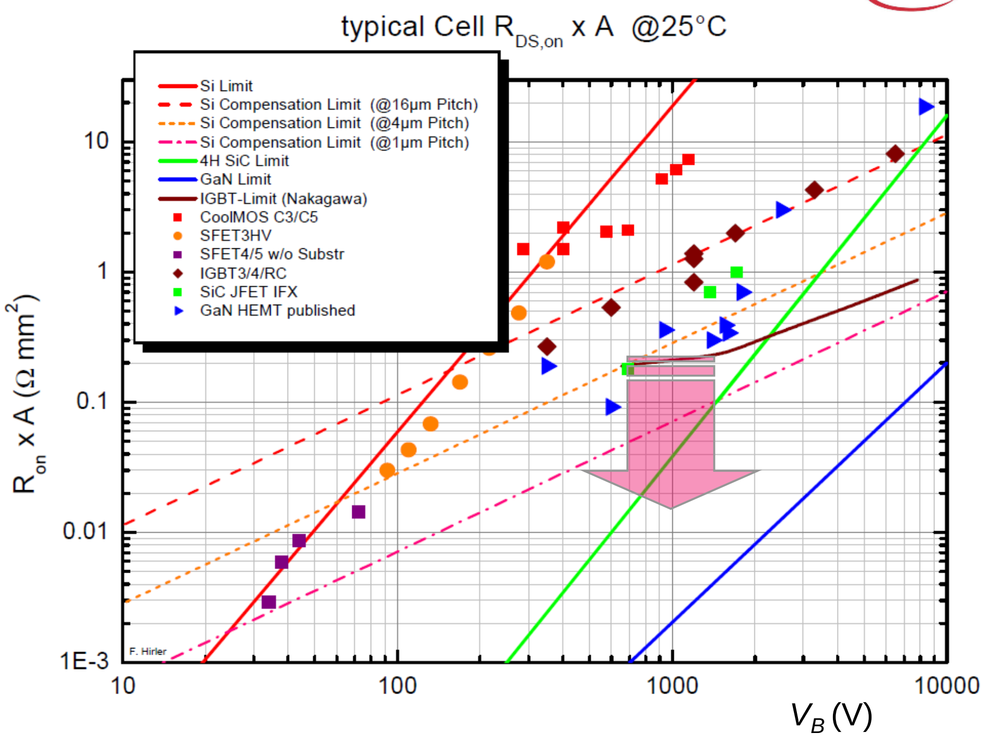
Source: www.evincetechnology.com

$$R^*_{on} = \frac{4V_B^2}{\varepsilon \mu_n E_C^3} \leftarrow$$

$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$



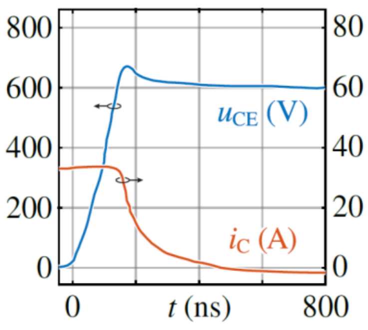
Source: Infineon



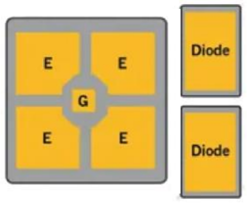
- *High Voltage Unipolar (!) Devices* → *Excellent Sw. Performance / High Power Density*

Si vs. SiC Switching Behavior

- *Si-IGBT* → *Const. On-State Voltage Drop / Rel. Low Switching Speed,*
- *SiC-MOSFETs* → *Resistive On-State Behavior / Factor 10 Higher Sw. Speed*

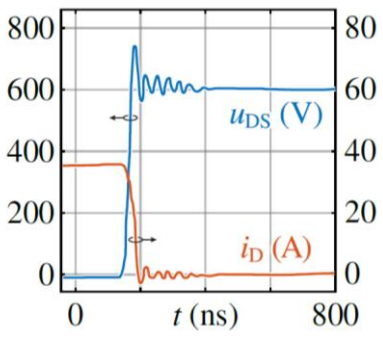


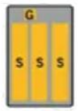
Source: Fuji Electric



1200V 100A
Die Size: 98.8mm² + 39.4mm²

Source: Infineon





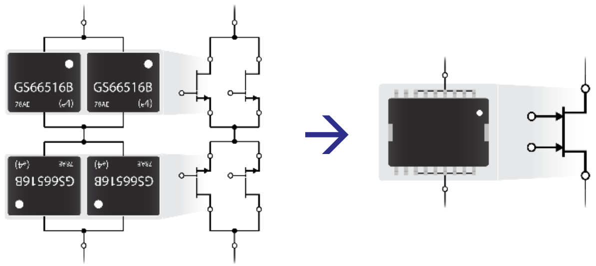
1200V 100A
Die Size: 25.6mm²

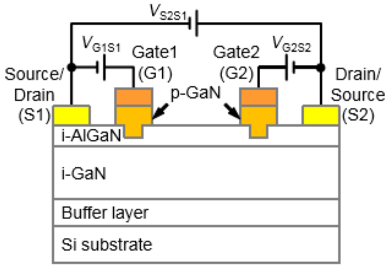
Source: Cree

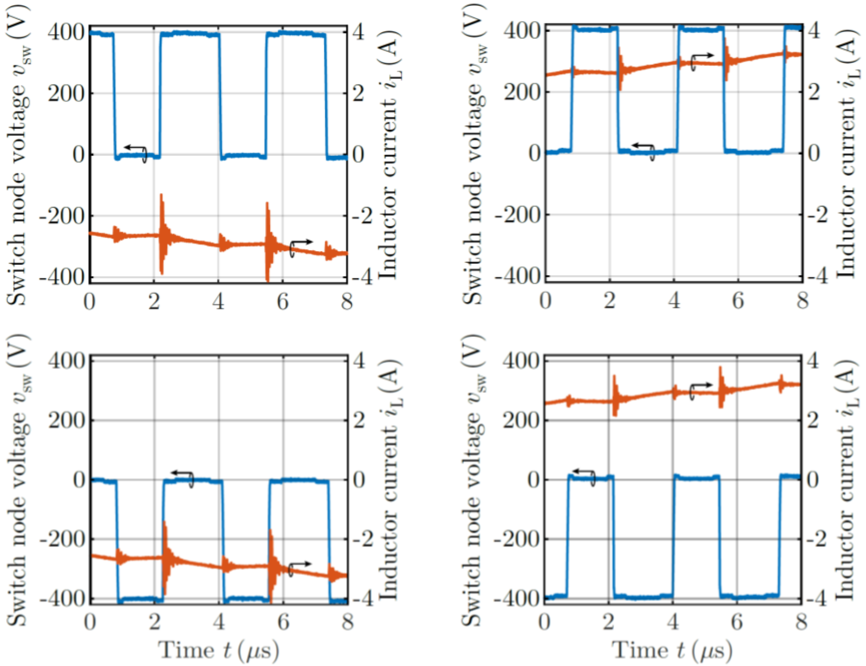
- *Extremely High di/dt & dv/dt* → *Challenges in Packaging / EMI*

Monolithic 600V GaN Bidirectional/Bipolar Switch

- PowerAmerica Program — Based on Infineon's CoolGaN™ HEMT Technology
- Dual-Gate Device / Controllability of Both Current Directions
- Bipolar Voltage Blocking Capability | Normally-On or -Off

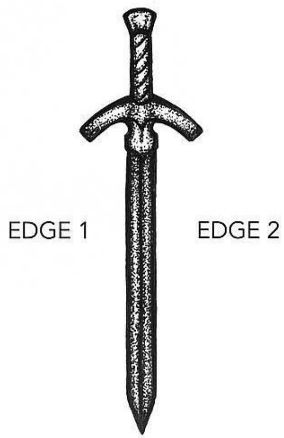






- Analysis of 4-Quardant Operation of $R_{DS(on)}$= 140mΩ | 600V Sample @ ± 400V

Challenges



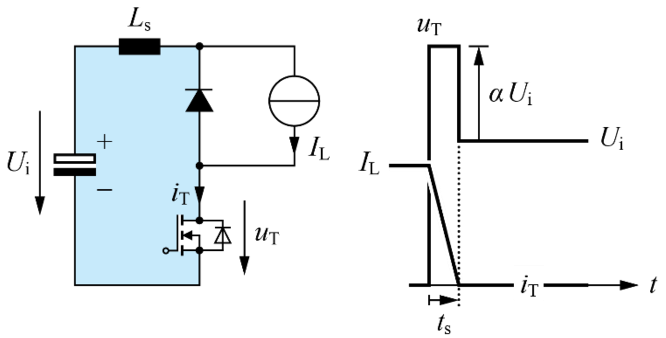
Circuit Parasitics

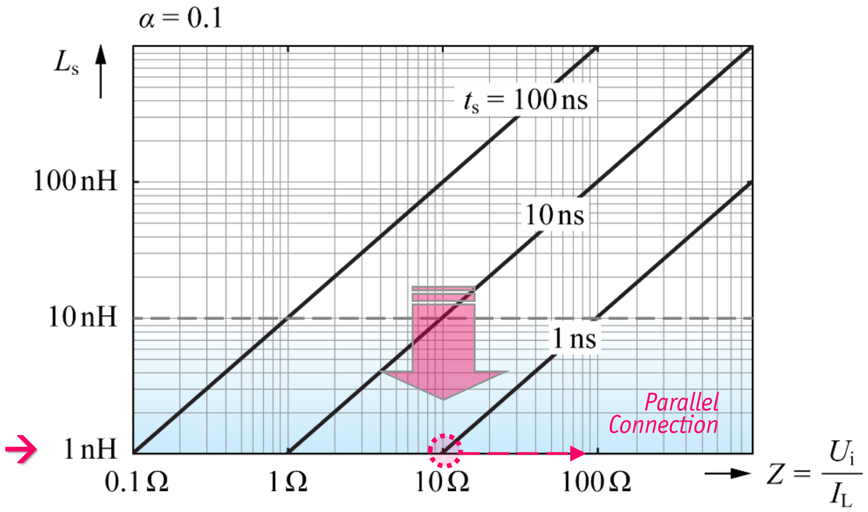
- *Extremely High di/dt*
- *Commutation Loop Inductance L_s*
- Allowed L_s Directly Related to Switching Time t_s →

$$L\frac{di}{dt}=u$$

$$L_s \le \frac{\alpha U_i}{\frac{I_L}{t_s}} = \alpha t_s \frac{U_i}{I_L}$$

Z



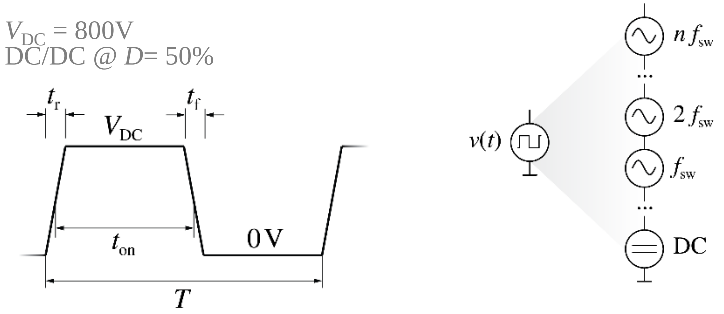


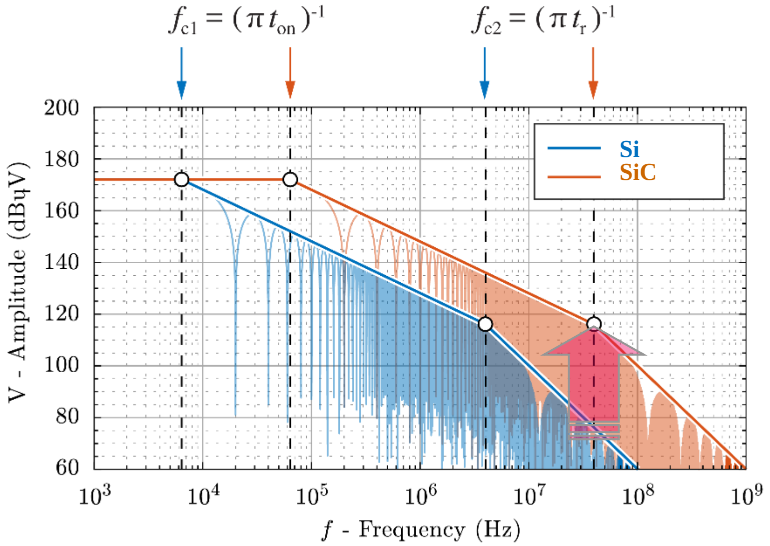
- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents*

Si vs. SiC EMI Emissions

- *Higher dv/dt* → *Factor 10*
- *Higher Switching Frequencies* → *Factor 10*
- *EMI Envelope Shifted to Higher Frequencies*

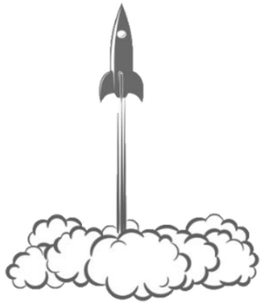
f_S = 10kHz & 5 kV/us for (Si IGBT)
f_S = 100kHz & 50 kV/us for (SiC MOSFET)





- *Higher Influence of Filter Component Parasitics & Couplings* → *Advanced Design*

X-Technology



3D-Packaging / Integration

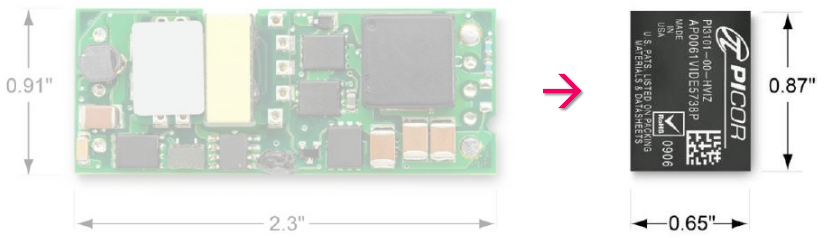
3D-Packaging / Heterogeneous Integration

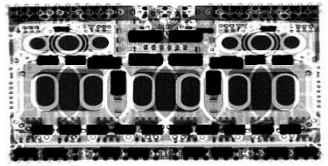
- *System in Package (SiP) Approach*
- *Minim. of Parasitic Inductances / EMI Shielding / Integr. Thermal Management*
- *Very High Power Density (No Bond Wires / Solder / Thermal Paste)*
- *PCBs Embedded Optic Fibres*
- *Automated Manufacturing*
- *Recycling (?)*

Source: VICOR

2.1 in² and 34 W/in²
72 Watts

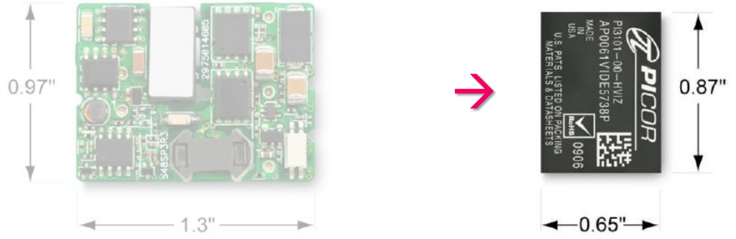
0.57 in² and 105 W/in²
60 Watts





1.26 in² and 26 W/in²
33 Watts

0.57 in² and 105 W/in²
60 Watts



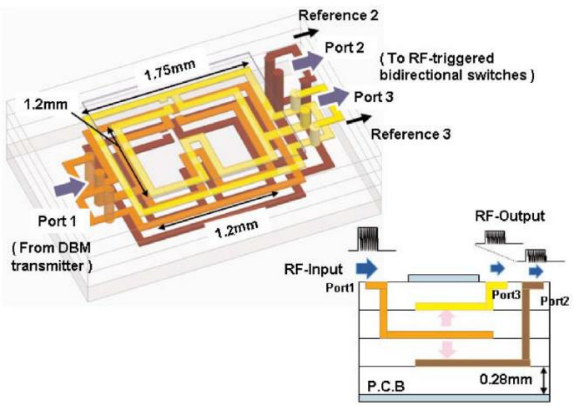
- *Future Application Up to 100kW (!)*
- *New Design Tools & Measurement Systems (!)*
- *University / Industry Technology Partnership (!)*

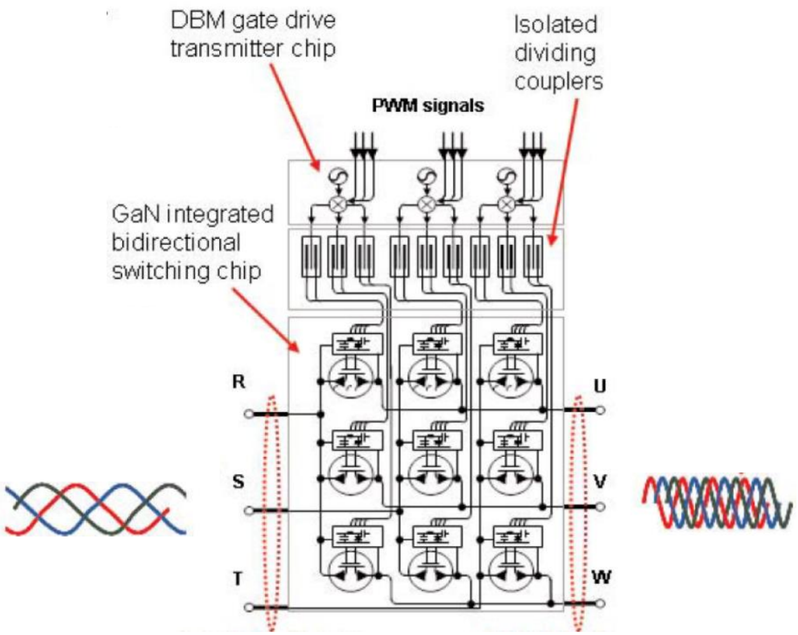
Monolithic 3D-Integration

Source: Panasonic ISSCC 2014

- GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology
  - 9 Dual-Gate GaN AC-Switches
  - DBM Gate Drive Transmitter Chip & Isolating Couplers
  - Ultra Compact → 25 x 18 mm² (600V, 10A – 5kW Motor)

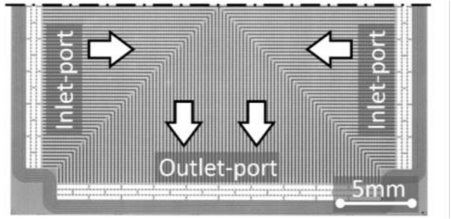
5.0GHz Isolated (5kVDC) Dividing Coupler

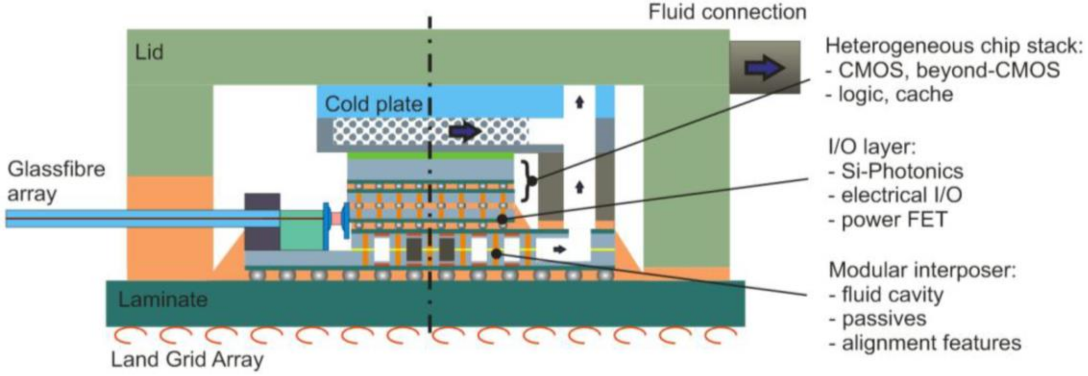


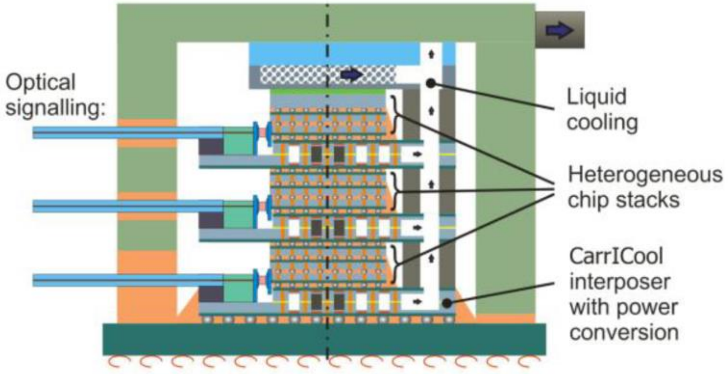


Remark Future uP Chip-Stack Packaging

- Slowing Transistor Techn. Node Scaling → Vertical & Heterogeneous Integr. of ICs for Performance Gains
- Extreme 3D-Integrated Cube-Sized Compute Nodes
- *Dual Side & Interlayer Microchannel Cooling*



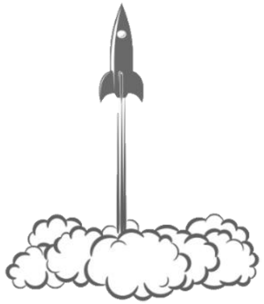




- Interposer Supporting *Optical Signaling* / *Volumetric Heat Removal* / *Power Conversion*

CarrICool
EU FP7 Project

X-Technology

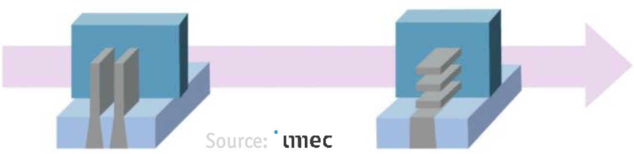


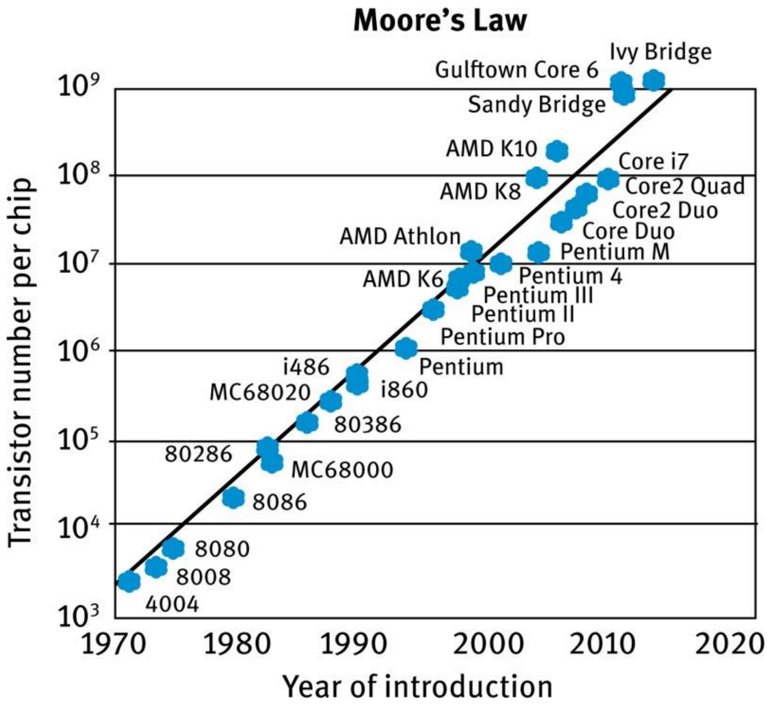
Digital Signal Processing

Digital Signal / Data Processing

- *Exponentially Improving uC / Storage Technology (!)*

— *Extreme Levels of Density (nm-Nodes) / Processing Speed*
— *Continuous Relative Cost Reduction*

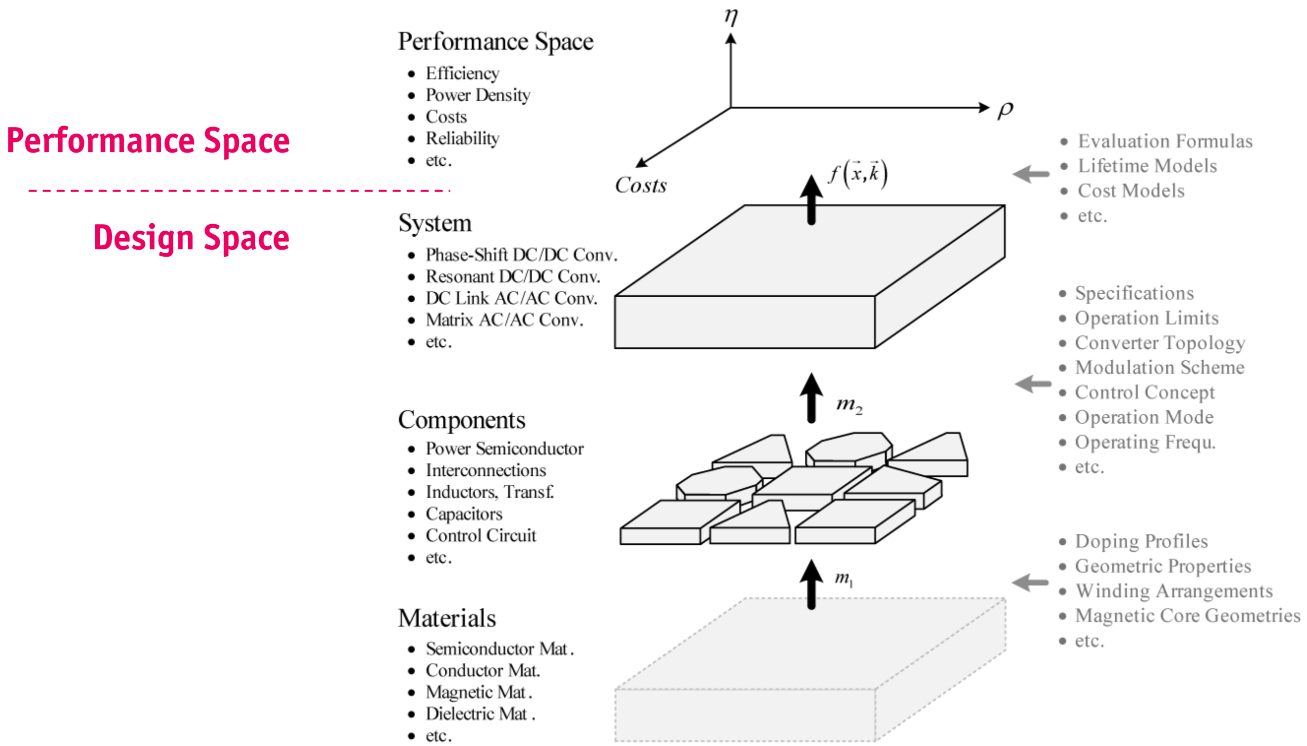




Source: Ostendorf & König /DeGruyter

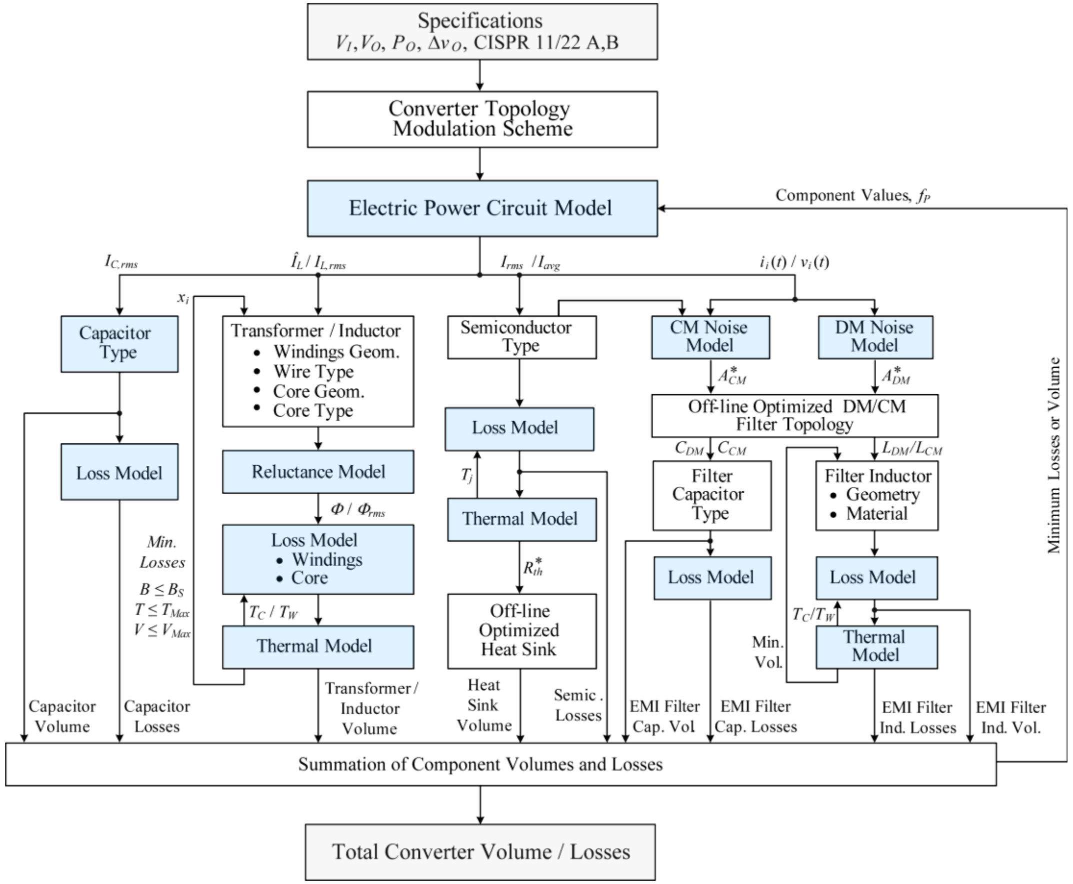
- *Distributed Intelligence*
- *Fully Digital Control of Complex Systems – AI-Based Design / Digital Twins / Industrial IoT (IIoT)*

Abstraction of Power Converter Design

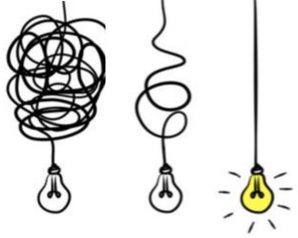


- *Mapping of Design Space" into Converter "η-ρ-σ-Performance Space"*
- *Design Space — Set of Selected Design- & Operating Parameters, Materials, Components, Topology, etc.*

Multi-Objective Optimization

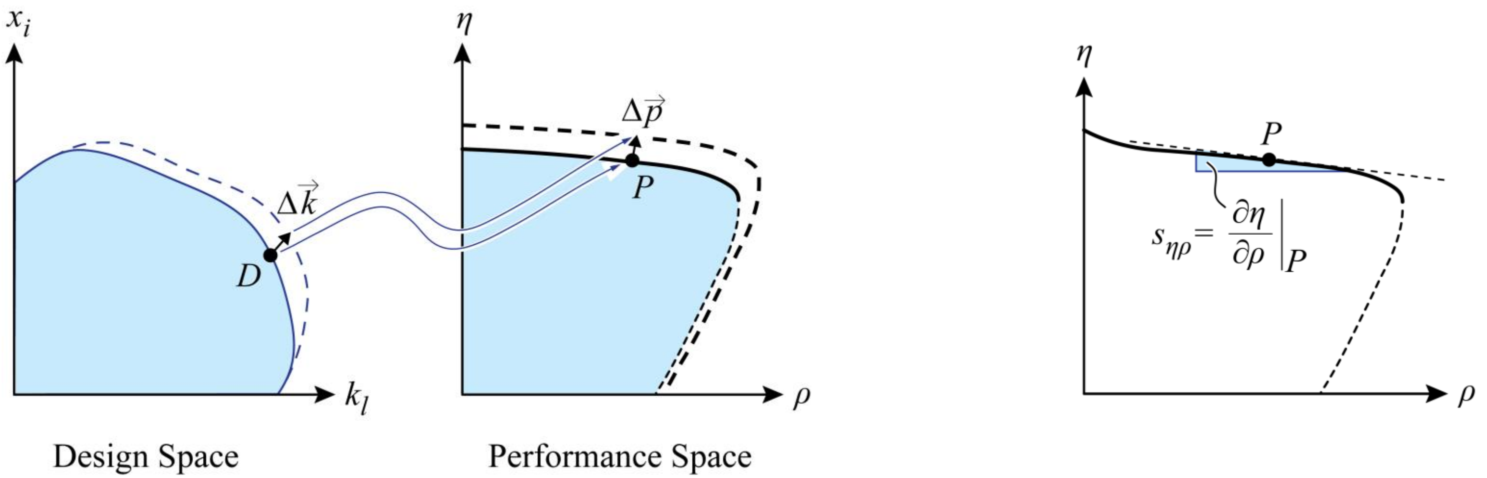


- *"Digital Twin"*
- *Multi-Objective Optimization* → ***Best Utilization of All Degrees of Freedom (!)***

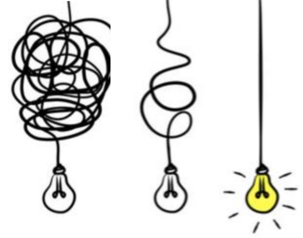


Multi-Objective Optimization

- *Based on Mathematical Model of the Technology Mapping*
- *Multi-Objective Optimization → Best Utilization of the "Design Space"*
- *Identifies Absolute Performance Limits → Pareto Front / Surface*

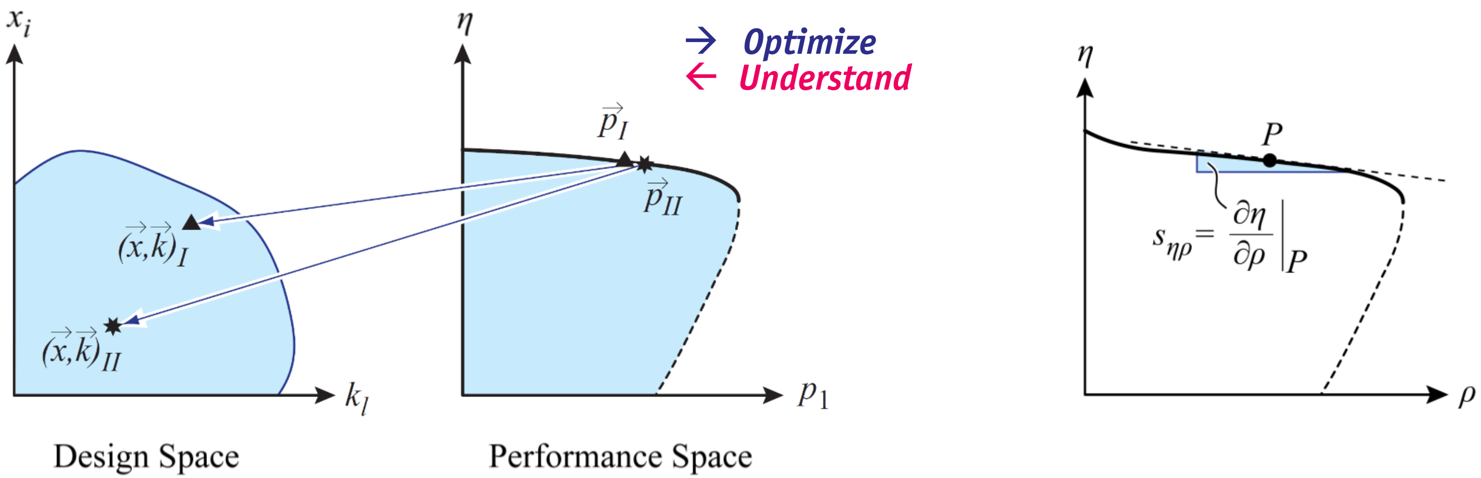


- Clarifies *Sensitivity* $\Delta\vec{p}\,/\,\Delta\vec{k}$ to Improvements of Technologies
- *Trade-Off Analysis*



Design Space Diversity

- *Equal Performance $\vec{p}_i$ for Largely Different Sets $(\vec{x},\vec{k})_i$ of Design Parameters*
- *E.g. Mutual Compensation of Volume or Loss Contributions (e.g. Cond. & Sw. Losses)*



- *Allows Consideration of Additional Performance Targets (e.g. Costs)*

Design Automation Roadmap

- *End-to-End Horizon — Cradle-to-Grave/Cradle — Modeling & Simulation*
- *Design for Cost / Volume / Efficiency / Manufacturing / Testing / Reliability / Recycling*

Autonomous Design → Design 4.0

– *Independent* Generation of Full Designs for Final Expert Judgement

Augmented Design

– *Suggestion* of Design Details Based on Previous Designs

Assisted Design ←

– *Support* of the User with Abstracted Database of Former Designs

State-of-the-Art

– *User Defined* Models and Simulation / Fragmented

- *AI-Based Summaries → No Other Way to Survive in a World of Exp. Increasing # of Publications (!)*

X-Concepts

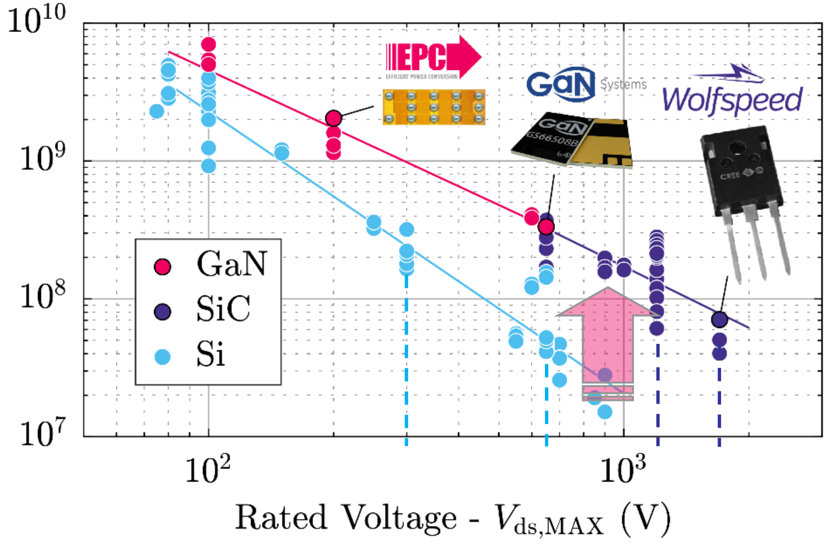
Modularization
Synergetic Association
Functional Integration
Hybridization
Decentralization

X-Concept  ***Modularization***

SiC/GaN Figure-of-Merit

- *Figure-of-Merit (FOM) Quantifies Conduction & Switching Properties*
- *FOM Determines Max. Achievable Efficiency @ Given Sw. Frequ.*

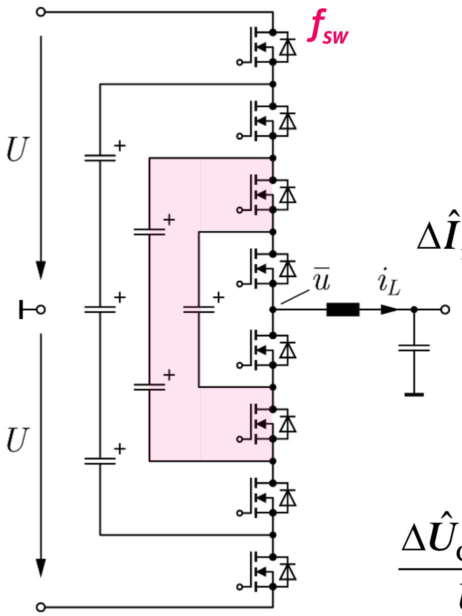
$$\mathrm{FOM} = \frac{1}{R_{\mathrm{ds,on}} Q_{\mathrm{oss}}}$$



- *Advantage of Multi-Level over 2-Level Converter Topologies*

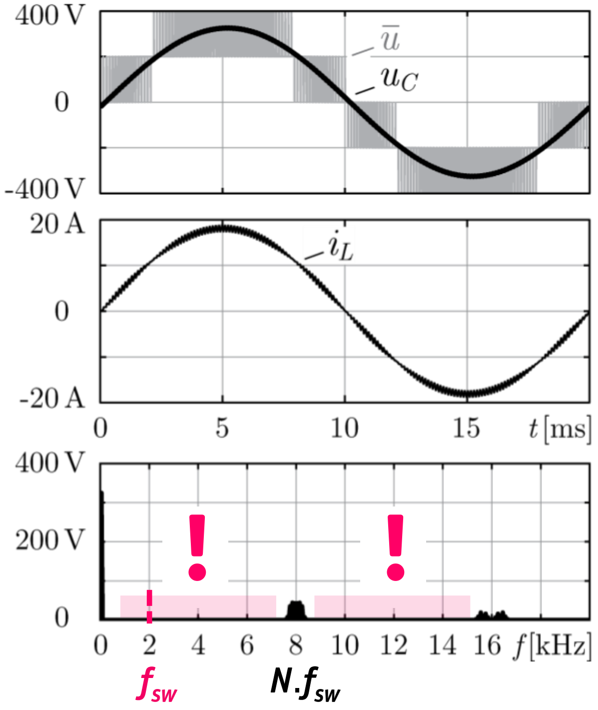
Scaling of Multi-Cell/Level Concepts

- *Reduced Ripple @ Same (!) Switching Losses*
- *Lower Overall On-Resistance @ Given Blocking Voltage*
- *Application of LV Technology to HV*



$$\Delta\hat{I}_{\max,N} = \frac{1}{N^2}\,\Delta\hat{I}_{\max,N=1}, \qquad \Delta\hat{I}_{\max,N=1} = \frac{U}{8 f_s L}$$

$$\frac{\Delta\hat{U}_{C,\max,N}}{U} = \frac{\pi^2}{32}\left(\frac{f_O}{f_S}\right)^2 \frac{1}{N^3}$$

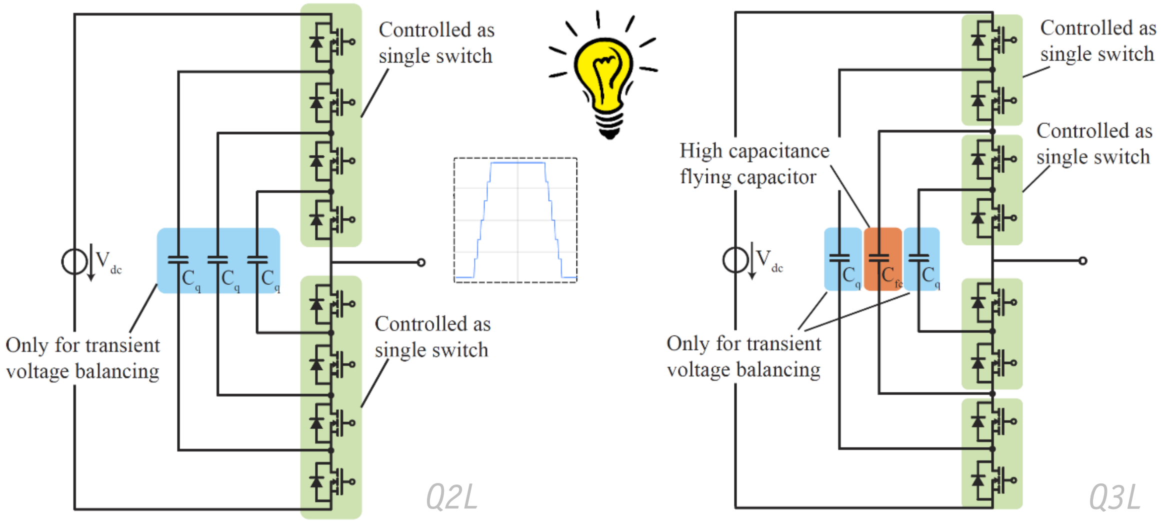


- *Scalability / Manufacturability / Standardization / Redundancy*

Quasi-2L & Quasi-3L Inverters

- *Operation of N-Level Topology in 2-Level or 3-Level Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*

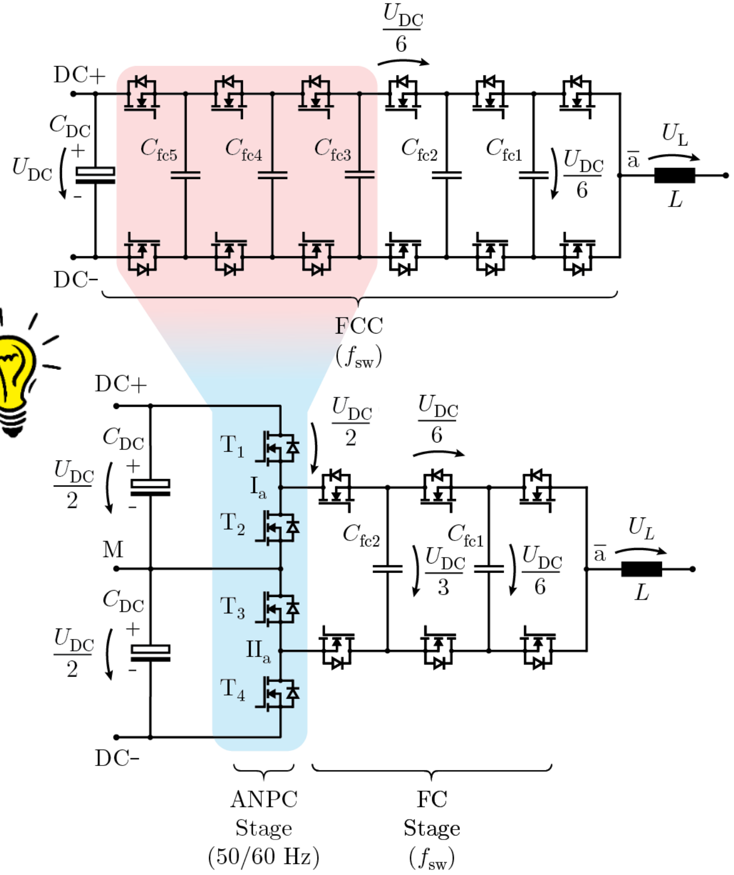
Source: M. Schweizer ABB

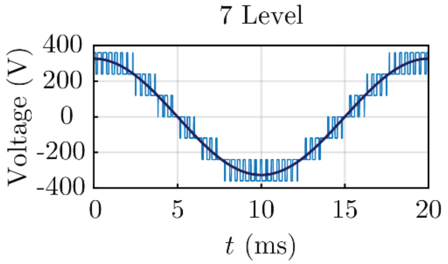


- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

3-Φ Hybrid Multi-Level Inverter

- *Realization of a 99%++ Efficient 10kW 3-Φ 400V$_{rms,ll}$ Inverter System*
- *7-Level Hybrid Active NPC Topology / LV Si-Technology*





99.35%
2.6kW/kg
56 W/in³

Infineon ETH

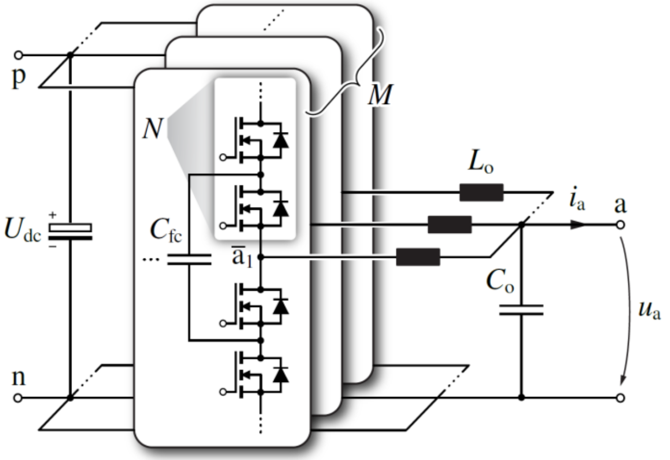
- *200V Si → 200V GaN Technology Results in 99.5% Efficiency*

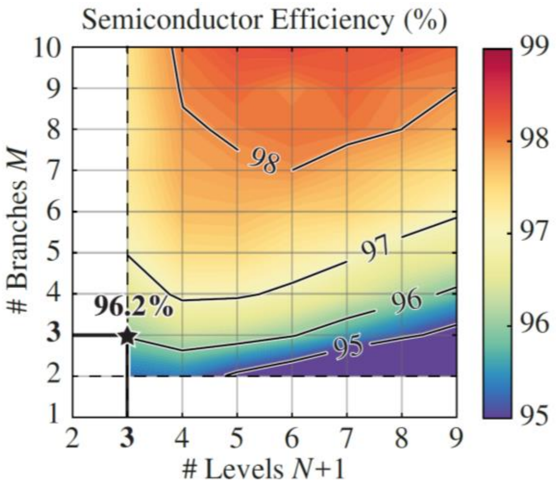
4.8MHz GaN Half-Bridge Phase Module

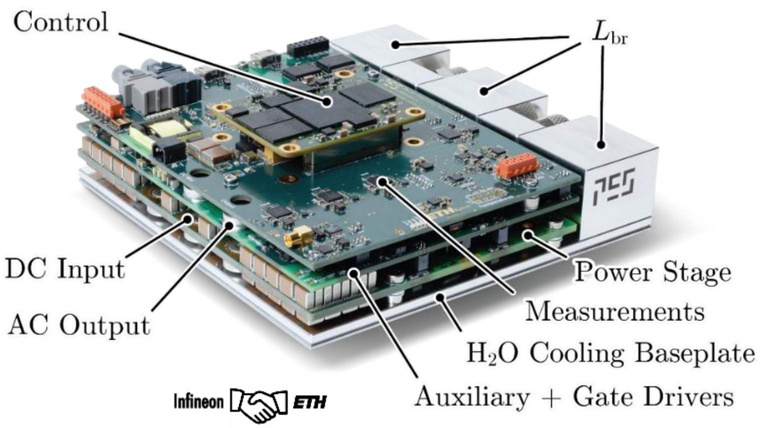
- *Combination of Series & Parallel Interleaving*

— *600V GaN Power Semiconductors, f_{sw}= 800kHz*
— *Volume of ≈180cm³ (incl. Control etc.)*
— *H_2O Cooling Through Baseplate*

★ *25 kW/dm³*







- *Operation @ f_{out}=100kHz / $f_{sw,eff}$ = 4.8MHz, 10kW, U_{dc}=800V*

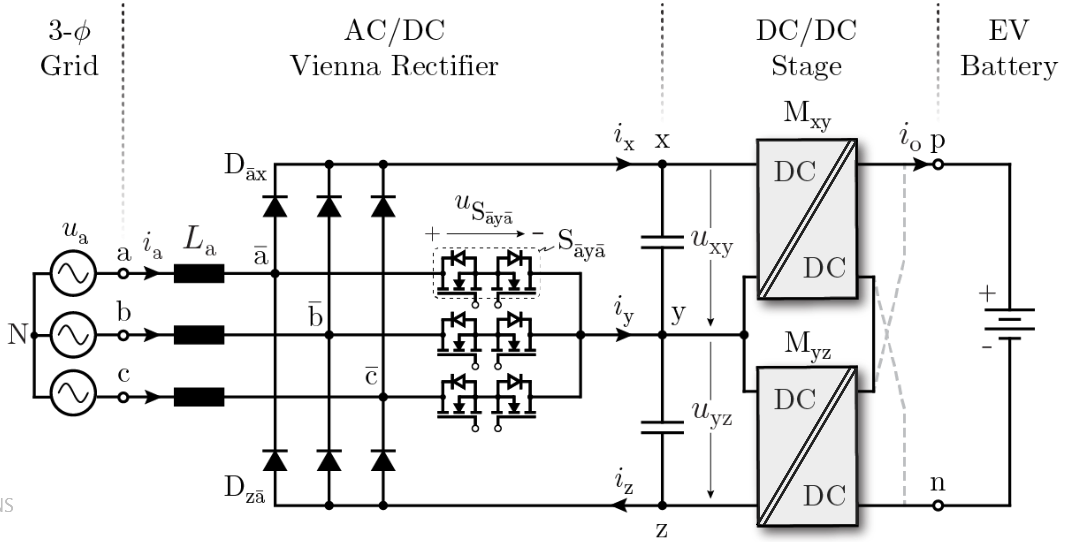
X-Concept

Synergetic Association

3-Φ EV-Charger Topology

- Isolated Controlled Output Voltage
- Buck-Boost Functionality & Sinusoidal Input Current
- *Applicability of 600V GaN Semiconductor Technology*
- *High Power Density / Low Costs*

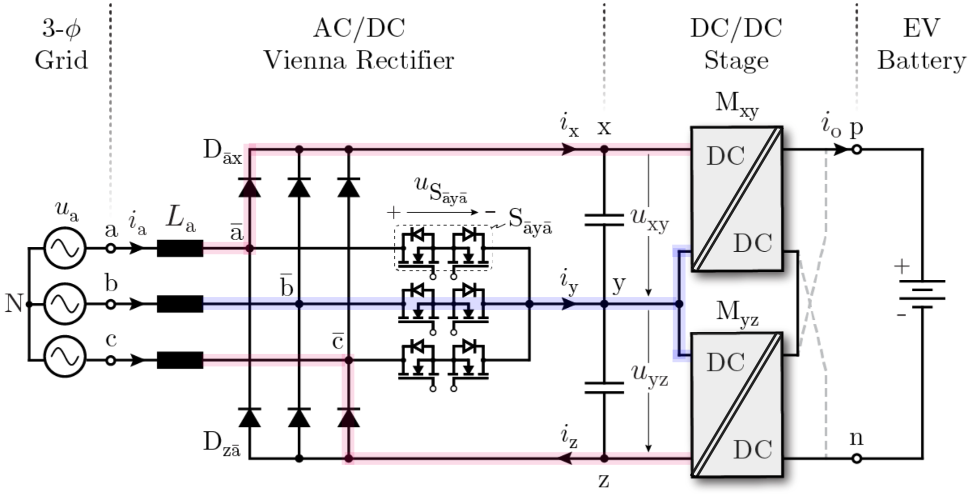
Source: SIEMENS

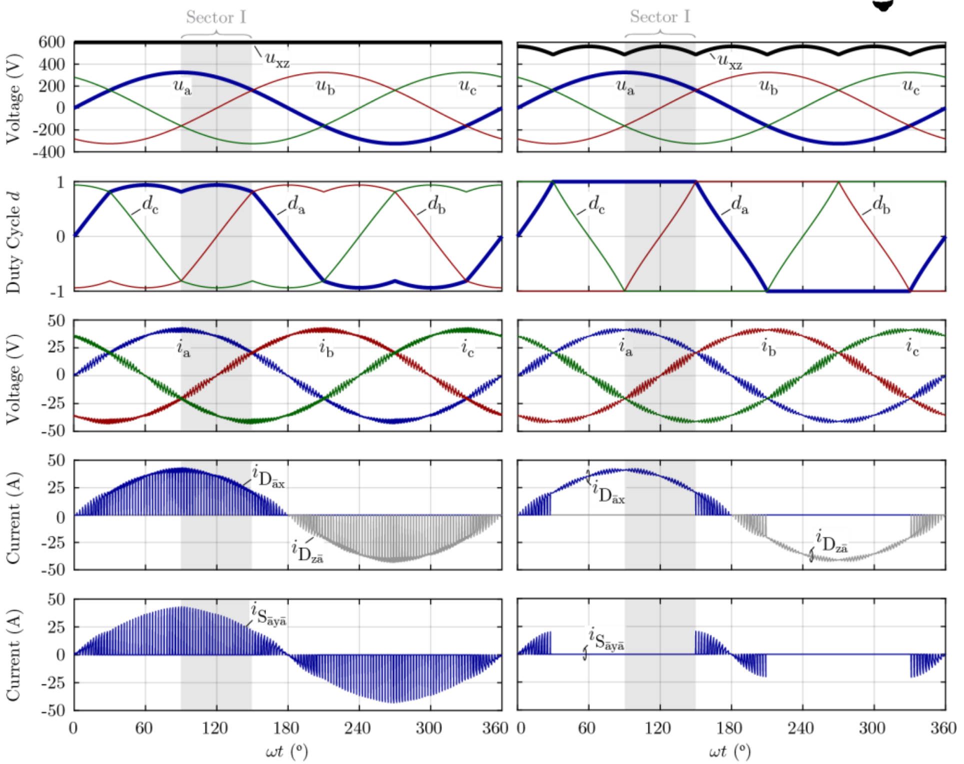


→ *Conventional / Independent* ***OR*** *"Synergetic Control" of Input & Output Stage*

Synergetic Association

- *1/3-Modulation → Significant Red. of Losses of the Power Switches Comp. to 3/3-PWM*
- *Conduction Losses of the Switches ≈ -80%*
- *Switching Losses ≈ -70%*





- *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

Synergetic Association

- *1/3-Modulation → Significant Red. of Losses of the Power Switches Comp. to 3/3-PWM*
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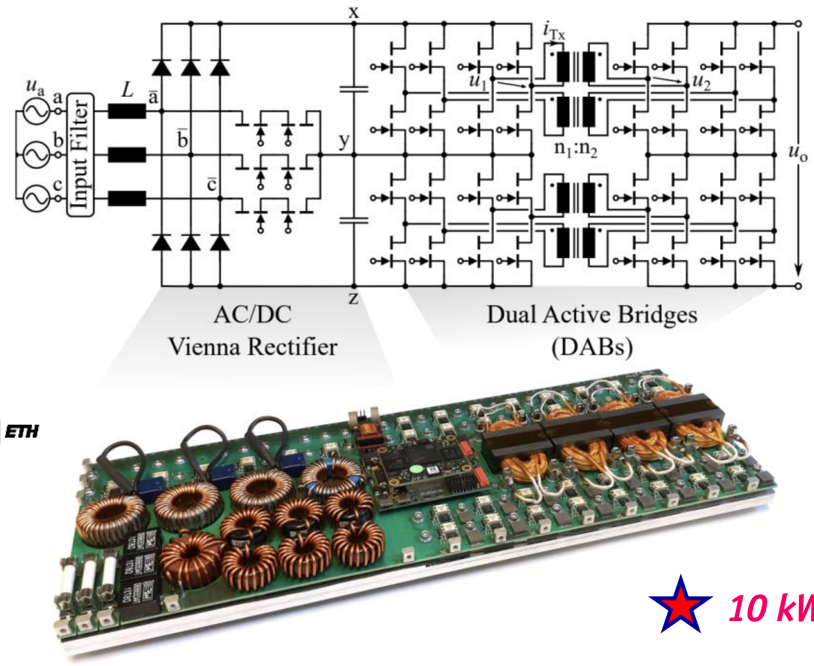
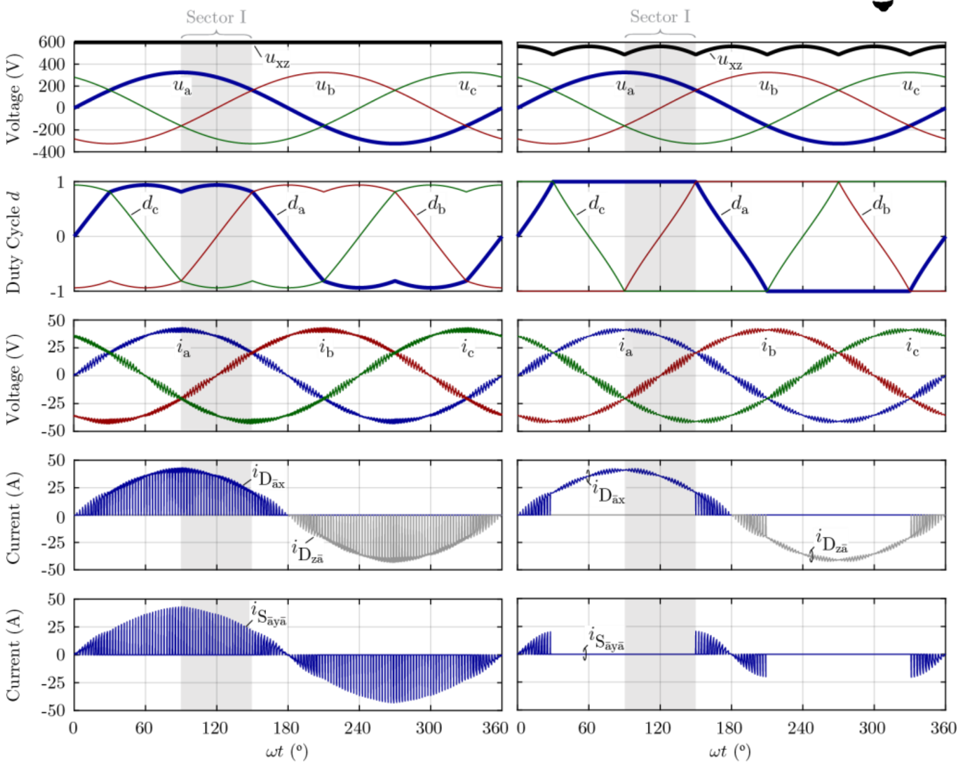


★ *10 kW/dm³*



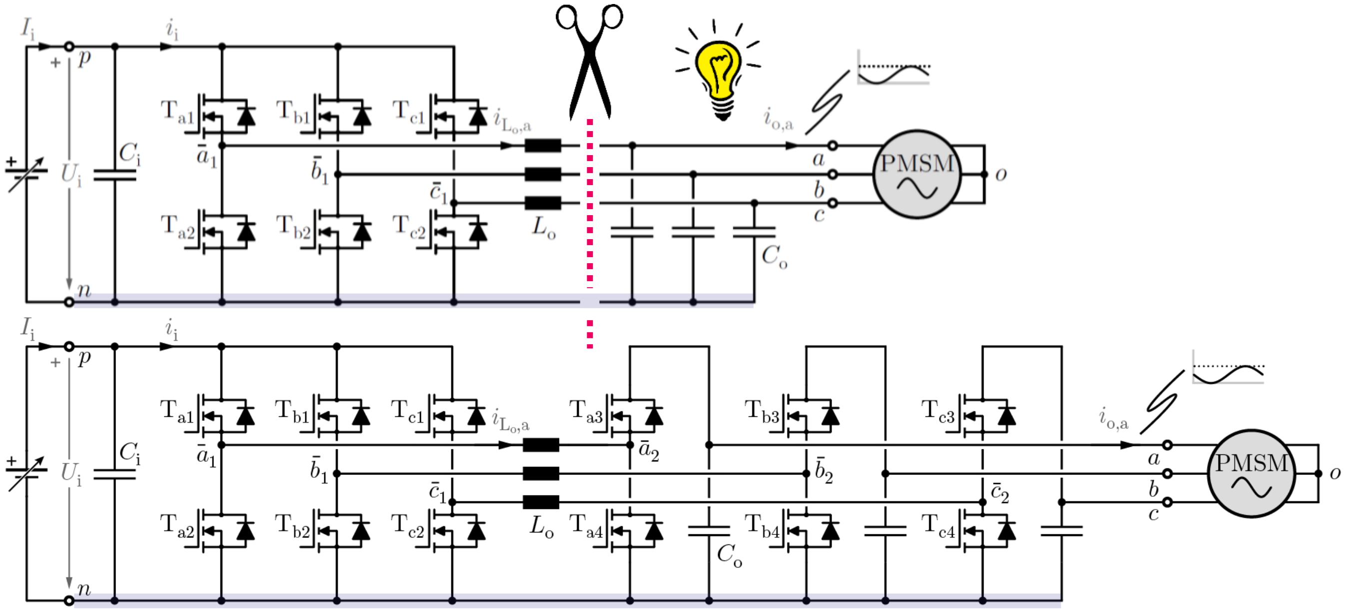
- *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

X-Concept

Functional Integration

Buck-Boost 3-Φ Variable Speed Drive Inverter

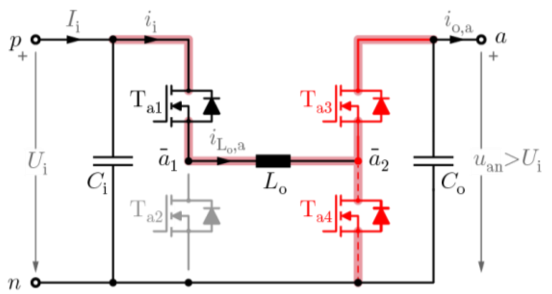
- *Generation of AC-Voltages Using Unipolar Bridge-Legs*
- *Utilize Filter Inductor for Boost Operation → Functional Integration*



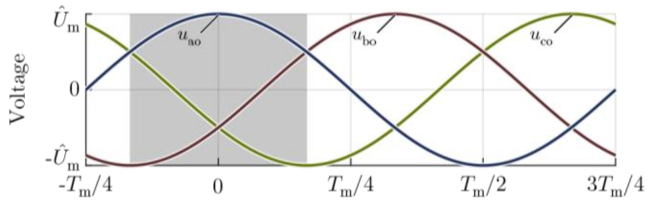
- *Switch-Mode Operation of Buck OR Boost Stage → Single-Stage Energy Conversion (!)*
- 3-Φ Continuous Sinusoidal Output / Low EMI → *No Shielded Cables / No Motor Insul. Stress*

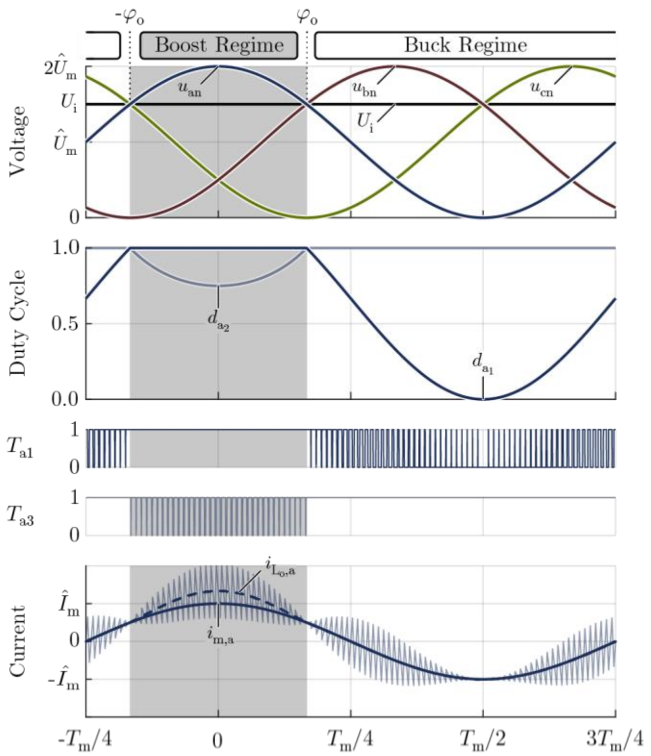
Boost-Operation $u_{an} > U_i$

- **Phase-Module**



- **Motor Phase Voltages**

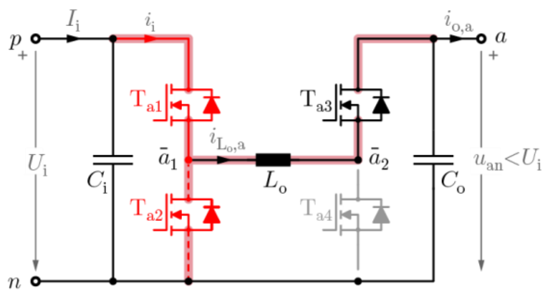




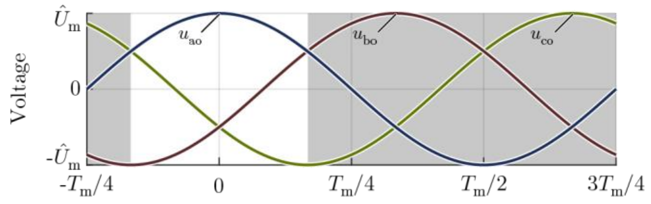
- *Current-Source-Type Operation*
- *Clamping of Buck-Bridge High-Side Switch* → *Quasi Single-Stage Energy Conversion*

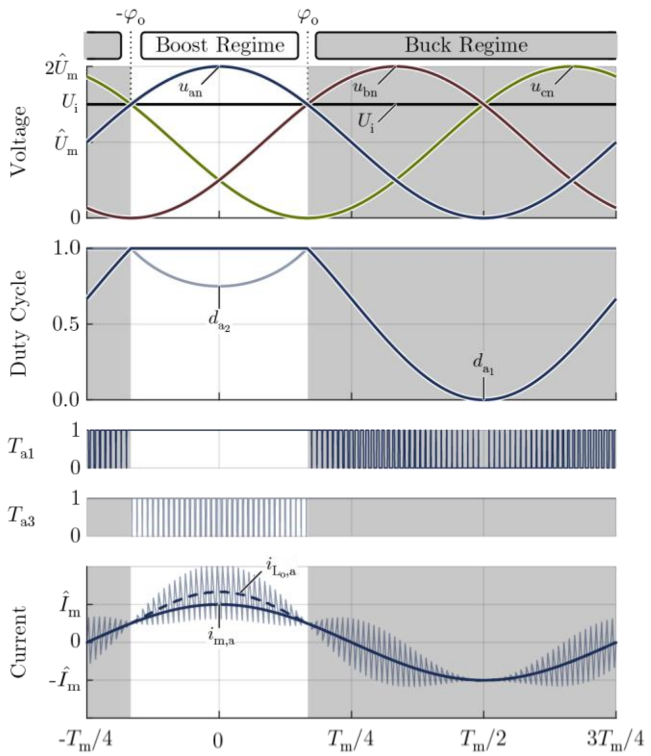
Buck-Operation $u_{an} < U_i$

- *Phase-Module*



- *Motor Phase Voltages*

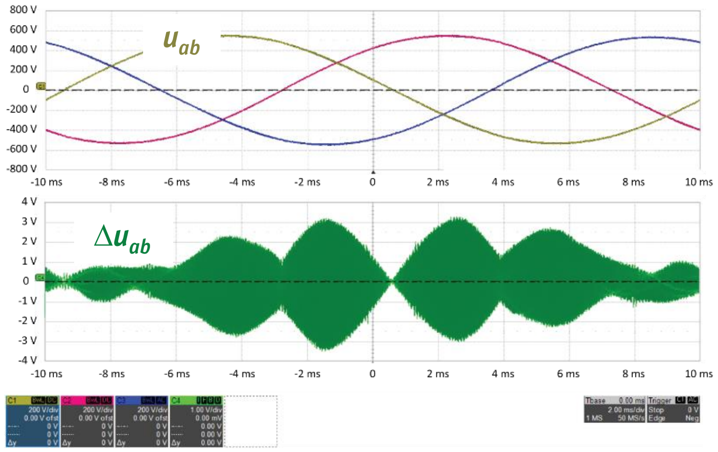




- *Voltage-Source-Type Operation*
- *Clamping of Boost-Bridge High-Side Switch → Quasi Single-Stage Energy Conversion*

SiC 3-Φ Buck-Boost Inverter Demonstrator

- DC Voltage Range 400...750V_{DC}
- Max. Input Current ± 15A
- Output Voltage 0...230V_{rms} (Phase)
- Output Frequency 0...500Hz
- Sw. Frequency 100kHz



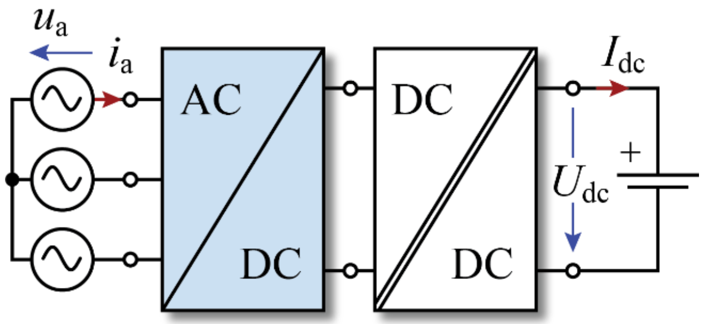
- *Dimensions → 160 x 110 x 42 mm^3*

★ *250 W/in^3*

Isolated 3-Φ AC/DC Converters

- *Conventional Approach* → *Two-Stage | 3-Φ PFC Rectifier & DC/DC Converter Stage*
- *Functional Integration* → *Utilizes AC/DC-Stage for Power Factor Corr. & HF AC Voltage Generation*
  → *Transformer Stray Inductance Used as Current Source*

Typ. 200...1000 V_{DC} EV Battery Voltage Range



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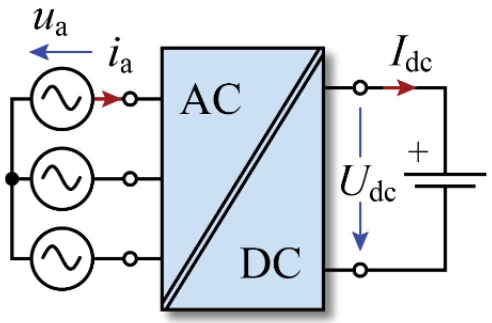


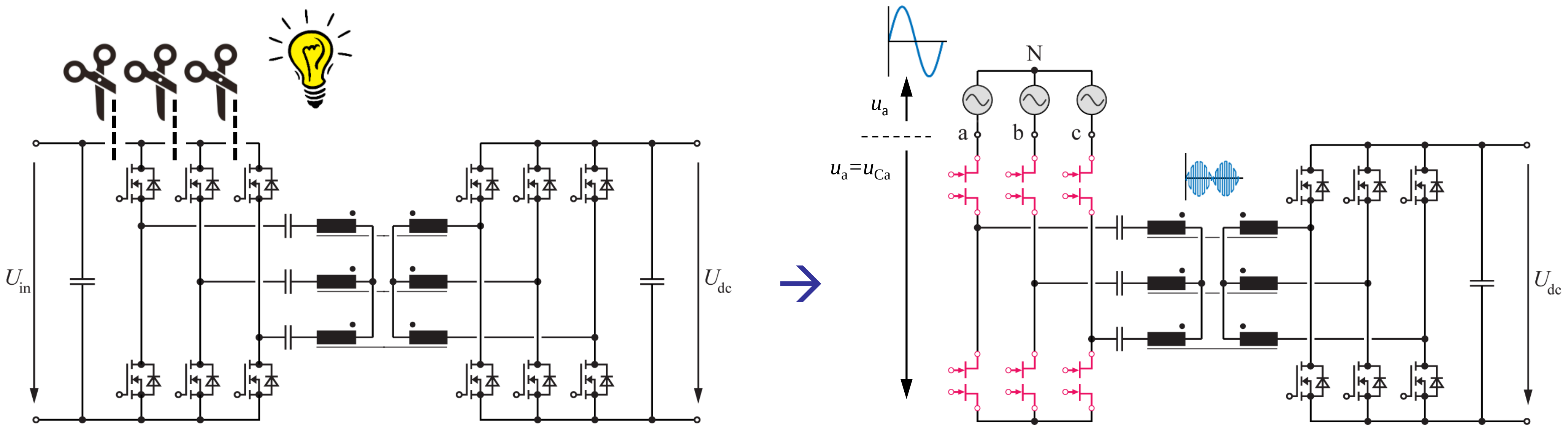
320...530 V_{rms} Line-to-Line

380 V_{DC} (260...400 V_{DC}) Datacenter Power Distribution

- *Elimination of DC/DC Converter Input Stage & DC-Link* → *Single-Stage Energy Conversion (!)*
- *Electric Vehicle Battery Charging | Datacenter Power Supply | AC Grid Interfaces of DC Micro-Grids*

3-Φ Input DAB-Type AC/DC Converter (1)

- *Modification of 3-Φ Xfrm DAB → Prim.-Side Phase-Modular AC/DC Converter Topology*
- *Synchronized (!) Prim.-Side Switching @ 50% Duty Cycle*



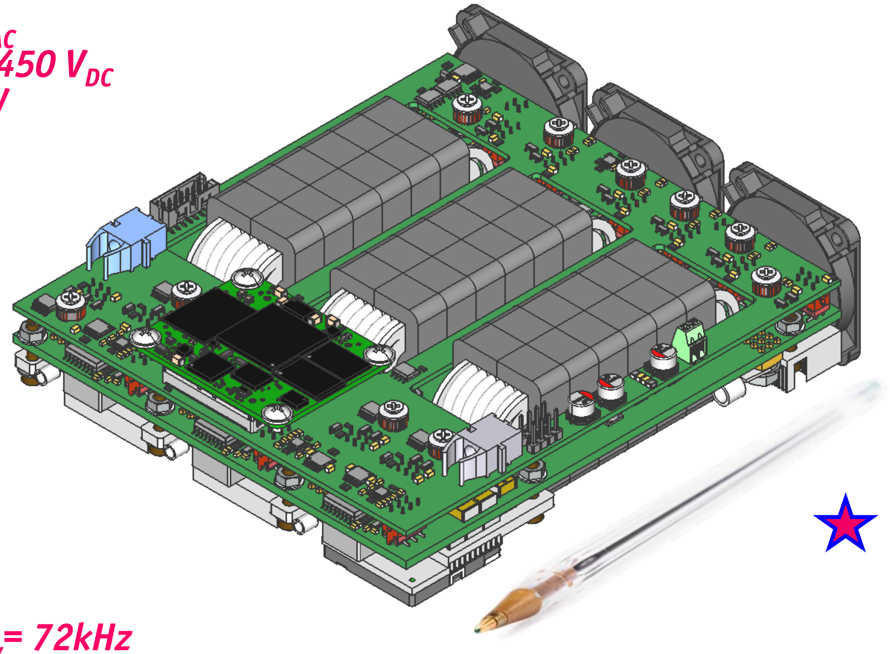
- *Voltage Stress on Prim.-Side AC Switches Determined by Peak Value of Grid PHASE Voltage (!)*
- *Bidirectional Power Flow*

3-Φ Input DAB-Type AC/DC Converter (2)

- *Voltage Stress on AC-Side Power Transistors Determined by PHASE Voltage Amplitude (!)*
- *600V GaN MBDS for 400V RMS Line-to-Line Grid ($U_{L\text{-}L,pk}$ = 560V)*
- *Unity Power Factor / Bidirectional*

- *Line-to-Line Input* 400 V_{AC}
- *DC Output* 250...450 V_{DC}
- *Rated Output Power* 6.6 kW

Infineon ETH

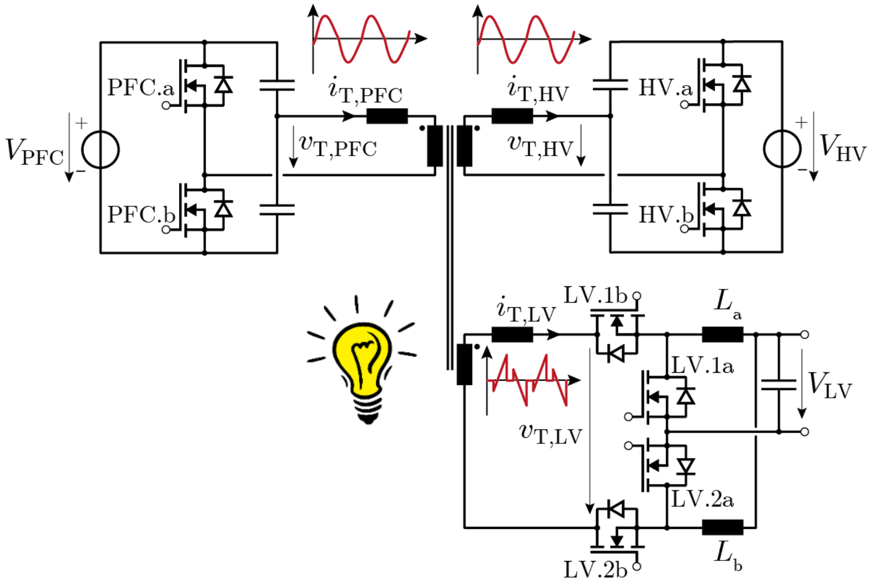


★ *98% (typ.) @ 8kW/dm³*

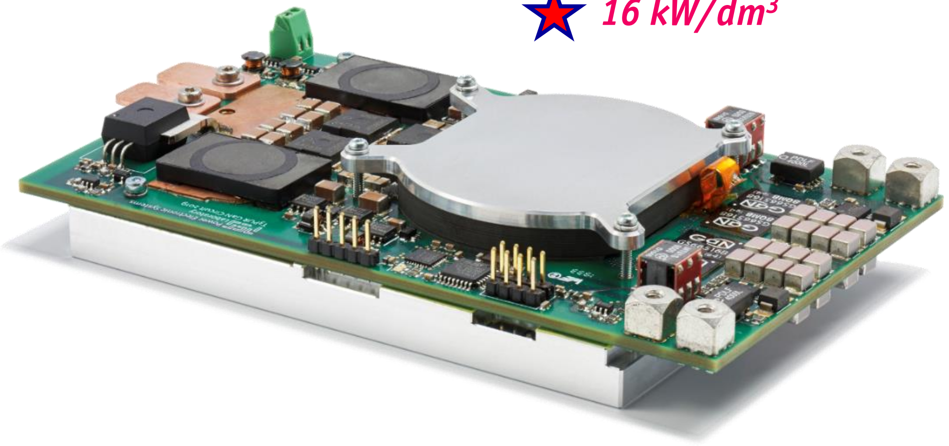
- *Prim.-Side Sw. Frequency f_{sw}= 72kHz*
- *14.5x13.1x3.7cm³/ 5.7x5.2x1.5in³*
- *Power Density w/ EMI-Filter ≈ 6kW/dm³ (98W/in³)*

3-Port Resonant GaN DC/DC Converter

- *Single Transformer & Decoupled Power Flow Control*
- *Charge Mode PFC → HV (250...500V) SRC DCX / Const. f_{sw}, Min. Series Inductance / ZVS*
- *Drive Mode HV → LV (10.5...15V) 2 Interleaved Buck-Converters / Var. f_{sw} / ZVS*
- *P = 3.6kW*



16 kW/dm³



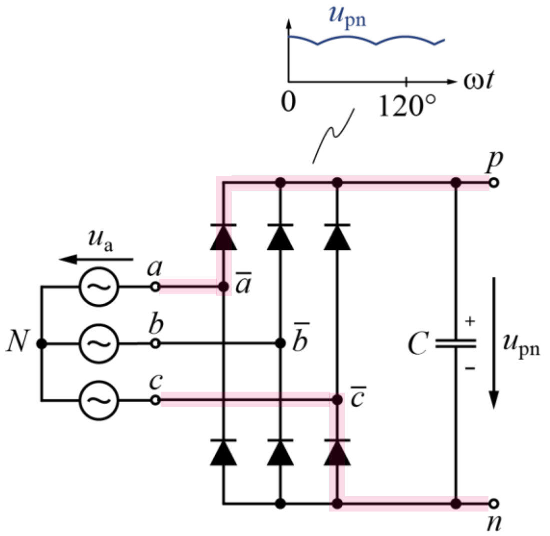
- *Peak Efficiency of 96.5% in Charge Mode / 95.5% in Drive Mode*
- *PCB-Based Windings / No Litz Wire Windings → Fully Automated Manufacturing*

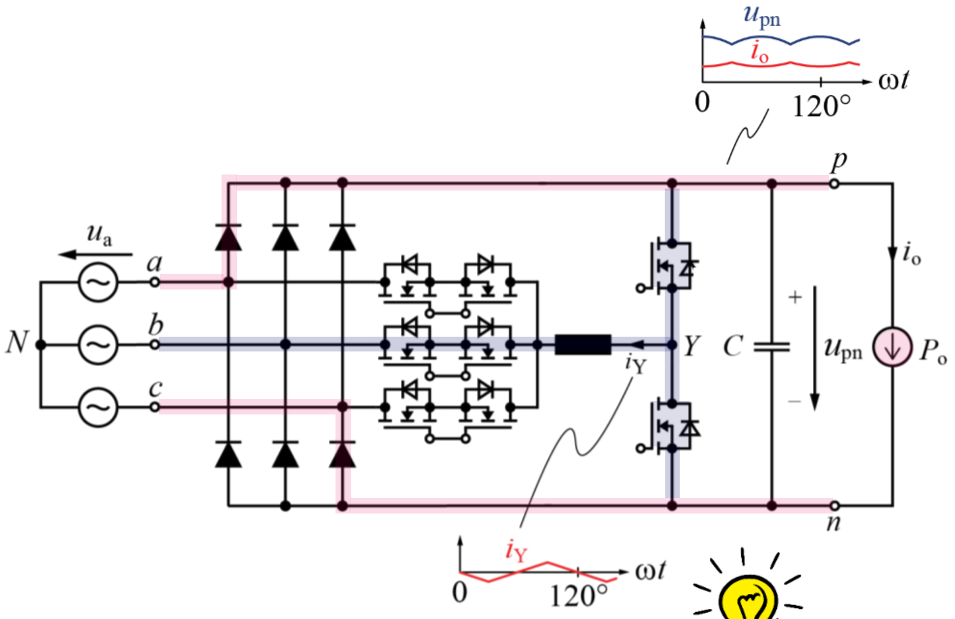
X-Concept

Hybridization

Hybrid Integrated Active Filter (IAF) PFC Rectifier

- *Hybrid Combination of Mains- and Forced-Commutated Converter*
- *3rd Harmonic Current Injection into Phase with Lowest Voltage*
- *Phase Selector AC Switches Operated @ Mains Frequency — 3-Φ Unfolder*



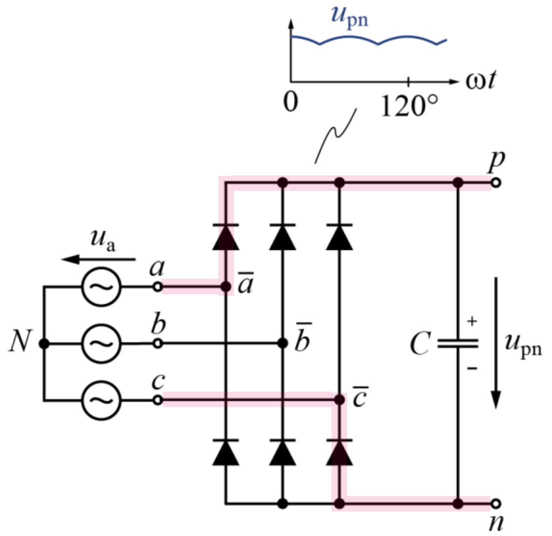


- *Non-Sinusoidal Mains Current*

→ *P_0= const. Required*
→ *Sinusoidal Mains Current*
→ *NO (!) DC Voltage Control*

Hybrid Integrated Active Filter (IAF) PFC Rectifier

- *Hybrid Combination of Mains- and Forced-Commutated Converter*
- *3rd Harmonic Current Injection into Phase with Lowest Voltage*
- *Phase Selector AC Switches Operated @ Mains Frequency — 3-Φ Unfolder*



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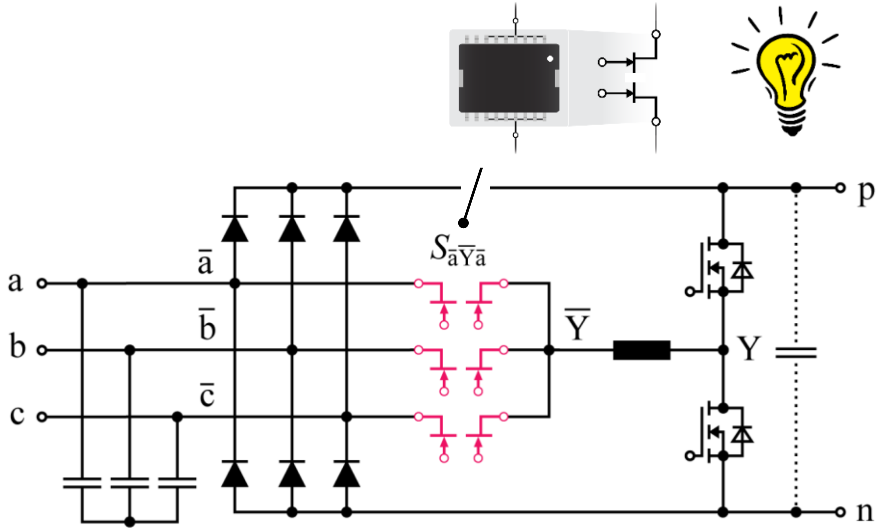


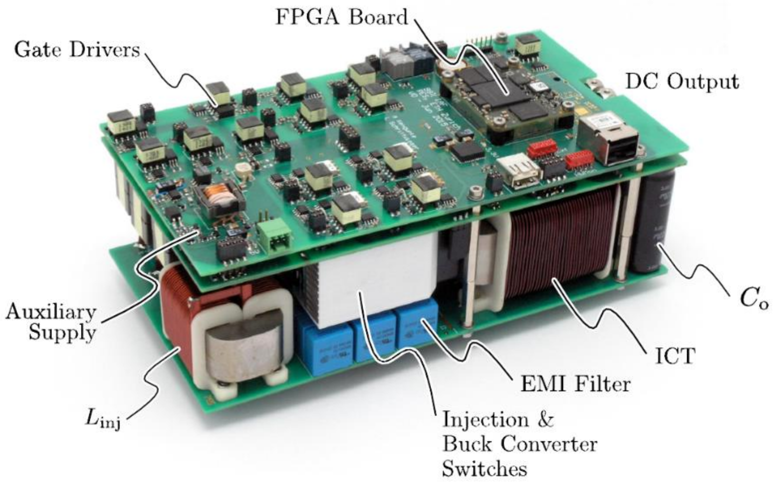
- *Non-Sinusoidal Mains Current*

→ *P_0= const. Required*
→ *Sinusoidal Mains Current*
→ *NO (!) DC Voltage Control*

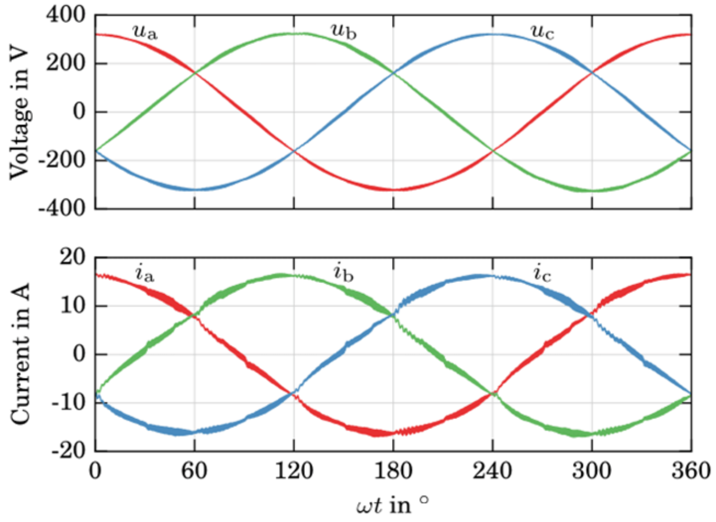
IAF PFC Rectifier & Buck Converter Demonstrator

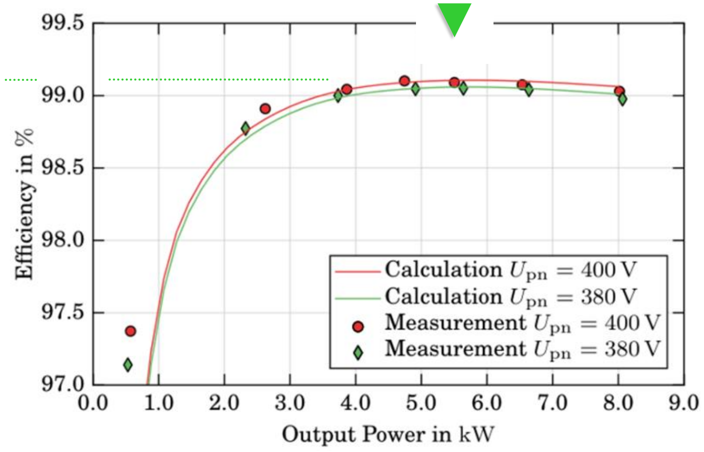
- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current THD_I ≈ 2% @ Rated Load*
- *Power Density ρ ≈ 4kW/dm³*

P_0 = 8 kW
U_N = 400V_{AC} → U_0 = 400V_{DC}
f_S = 27kHz

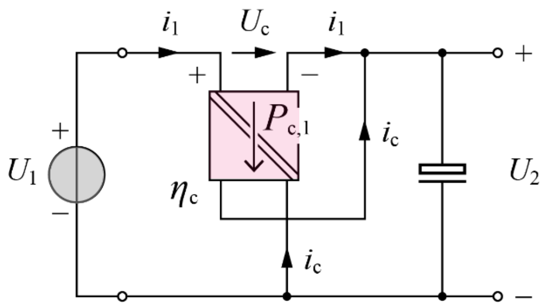


- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck Output Stages*
- *Controlled Output Voltage*





Partial/Differential Power Processing



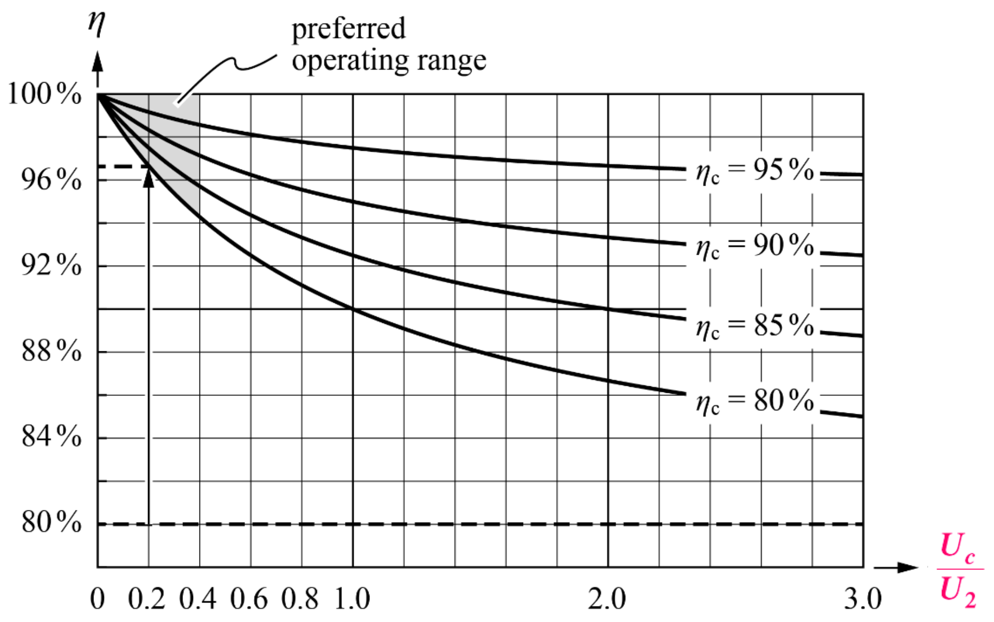
$$U_2 = U_1 - U_c$$

- *Reduced Converter Rating*

$$p_c = \frac{P_{c,1}}{P_1} = \frac{\frac{U_c}{U_2}}{1+\frac{U_c}{U_2}}$$

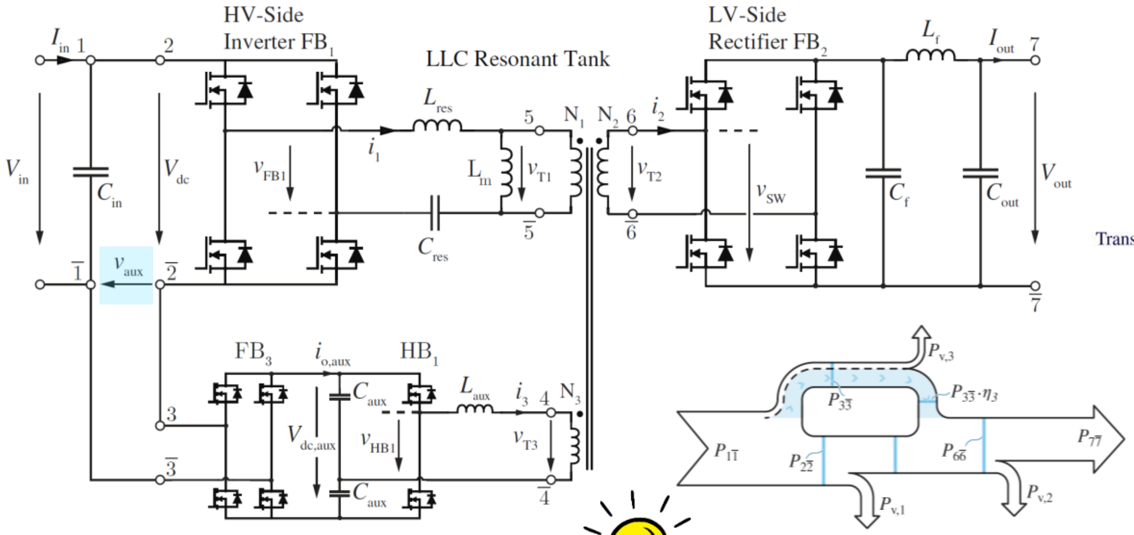
- *Low Influence of Converter Efficiency on Overall Efficiency*

$$\eta = \frac{P_2}{P_1} = \frac{(1+\frac{U_c}{U_2}\eta_c)}{(1+\frac{U_c}{U_2})}$$

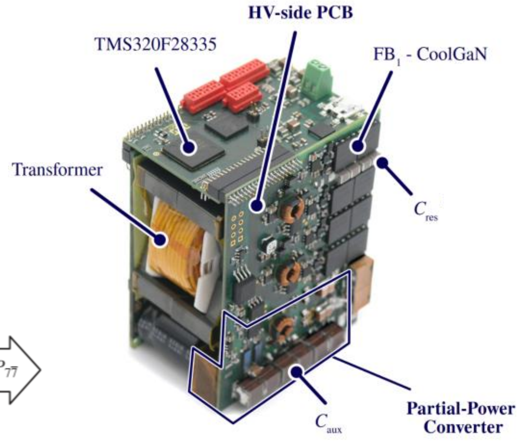


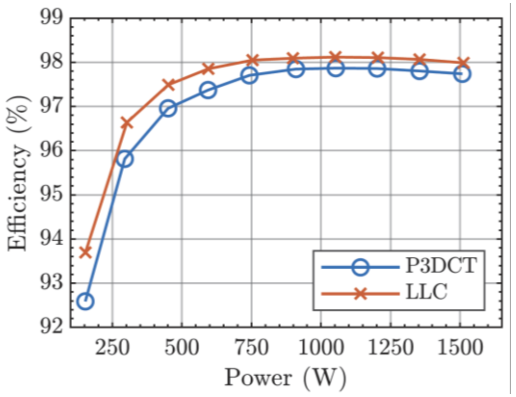
Partial-Power Pre-Regulated LLC DC-Transformer

- *Aux. Converter Stage for ± 10% V_{in} Compensation | V_{in} = 340V ... 420V*
- *Const. Voltage Transfer Ratio / High Efficiency LLC «DC/DC Transformer» @ Const. Frequency | f_{sw} = 100kHz*
- *Const. Output Voltage | V_{out} = 48V*



Partial-Power Pre-Regulation (P³) Converter



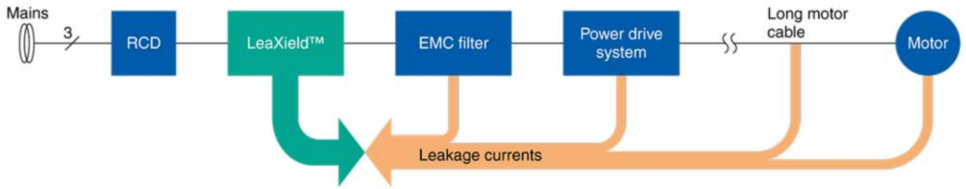


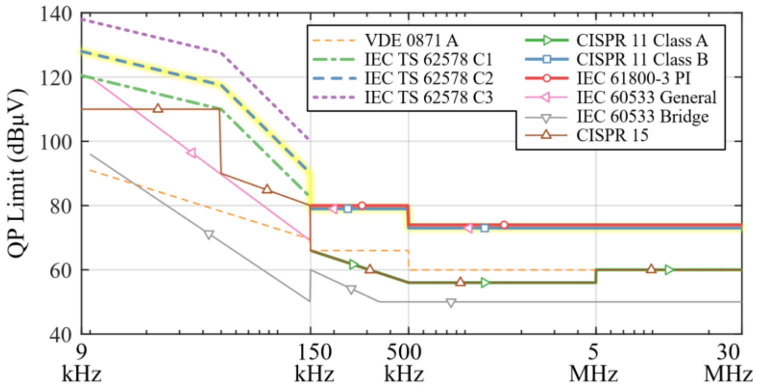
★ *140 W/in³*

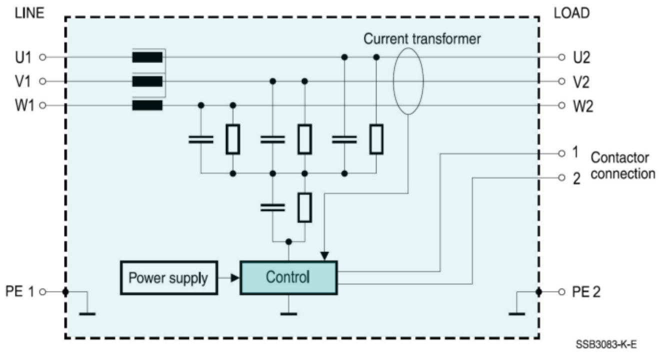
- *Rectangular Aux. Voltage Added or Subtracted (f_{aux} = 600kHz) from V_{in}*
- *Marginal Impact of Control on Overall Power Density & Efficiency*

Hybrid EMI-Filter / Leakage Current Reduction

- *Future Extension of EMI Limits — 9kHz ...150kHz | IEC TS 62578 Tech Spec. for Active Infeed Conv. Applications*
- *Earth Leakage Current "Compensation"*
- *Conducted CM EMI-Filter*





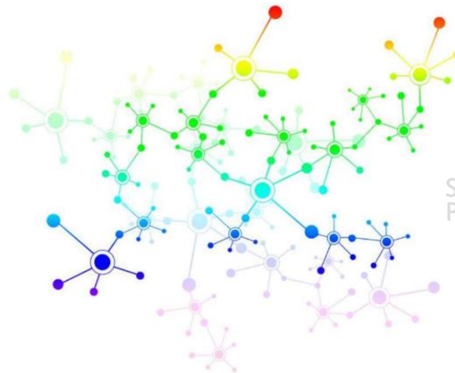


- *Prevents Unintentional Residual Current Device (RCD) Tripping w/o Isolation Transformer*
- *Attenuation of Cond. EMI Emissions in Wide Frequency Range 30/40/15dB @ 4/10/150kHz*

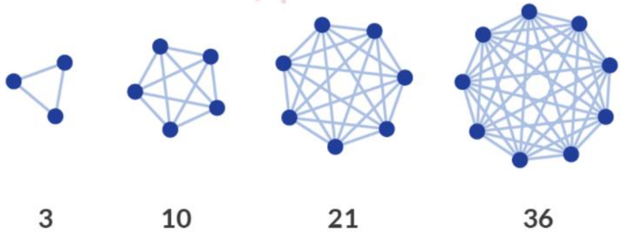
X-Concept  ***Decentralization***

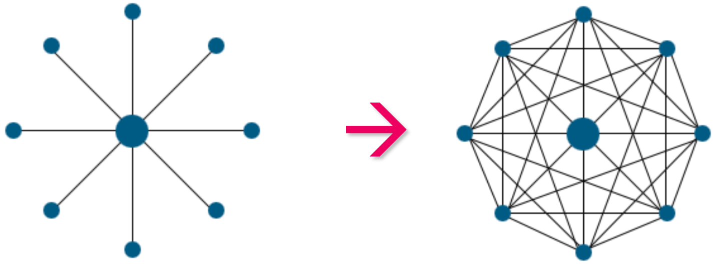
Networking Scaling

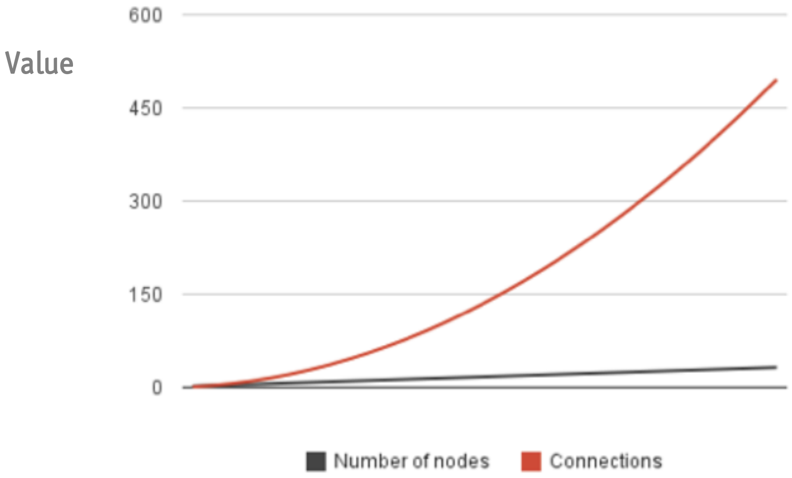
- Metcalfe's Law
  - Moving from Hub-Based Concept to Community Concept Increases Potential Network Value Over-Proportional → ~n(n-1) or ~n log(n)



Source: Pixabay

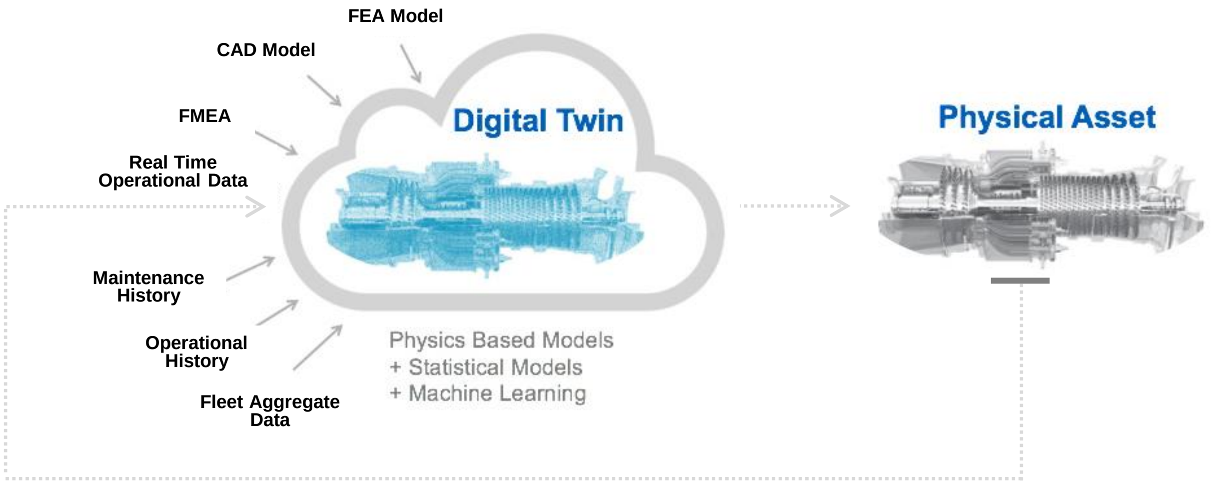






IIoT in Power Electronics

- *Digital Twin → Physics-Based "Digital Mirror Image"*
- *Digital Thread → "Weaving" Real/Physical & Virtual World Together*



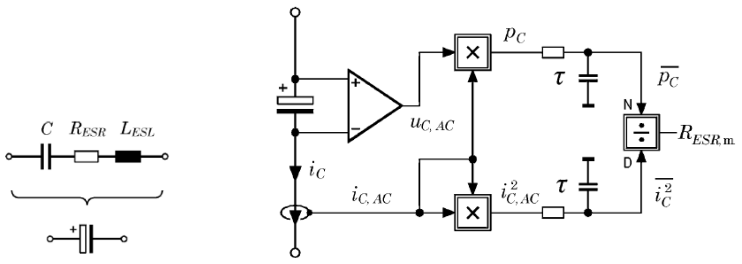
Source: www.railwayage.com

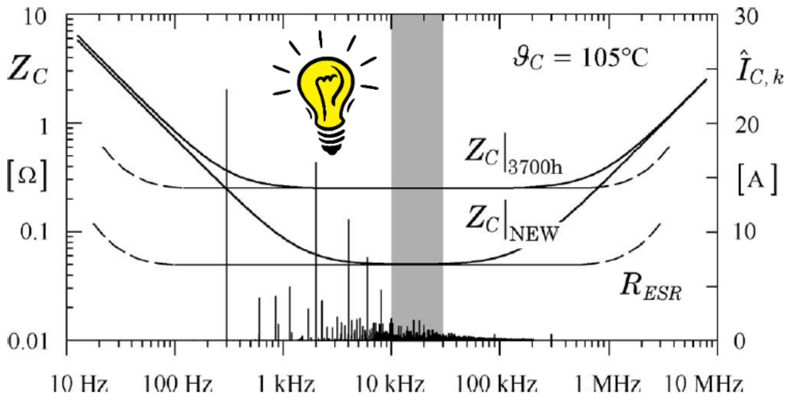
- *Requires Proper Interfaces for Models & Automated Design*
- *Model of System´s Past/Current/Future State → Design Corrections / Predictive Maintenance etc.*

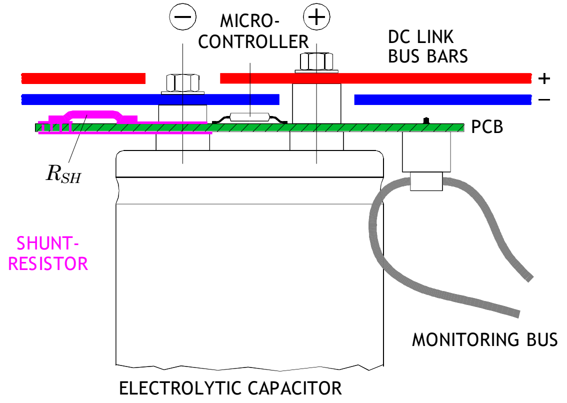
IIoT Starts with Sensors (!)

- *Condition Monitoring of DC Link Capacitors*
- *On-Line Measurement of the ESR in "Frequency Window" (Temp. Compensated)*
- *Data Transfer by Optical Fibre or Near-Field RF-Link*

Source: Prof. Ertl
TU Vienna, 2011



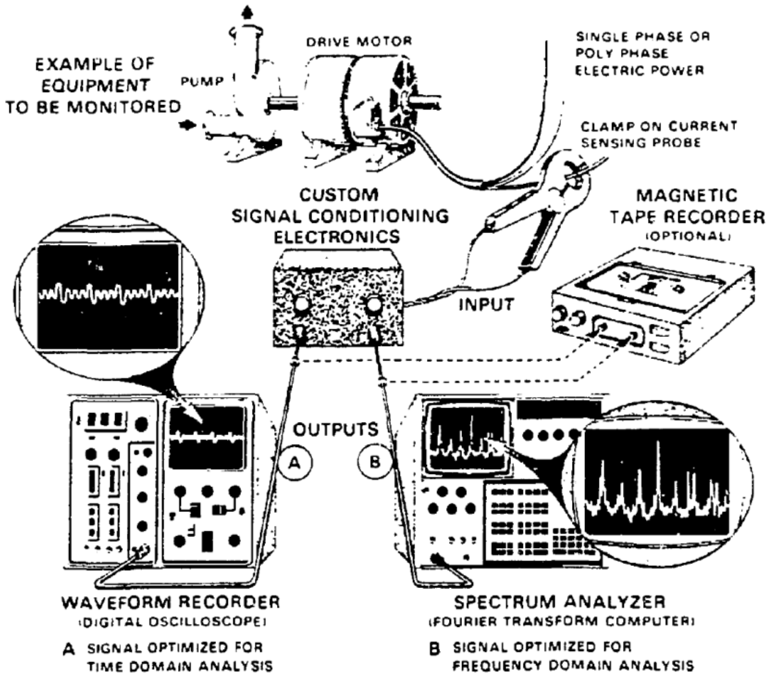




- *Possible Integration into Capacitor Housing or PCB*
- *Additionally features Series Connect. Voltage Balancing*

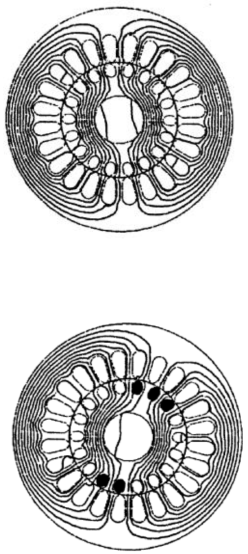
Motor Condition Monitoring / Fault Detection

- *Utilize the "Motor as Transducer" for Determining Aging / Wear of Motor and/or Mechanical Load*
- *Non-Intrusive Detection of Mechanical or Electrical - Bearings or Stator & Rotor - Abnormalities*
- *Motor Current Signature Analysis (MCSA) in Time & Frequency Domain*

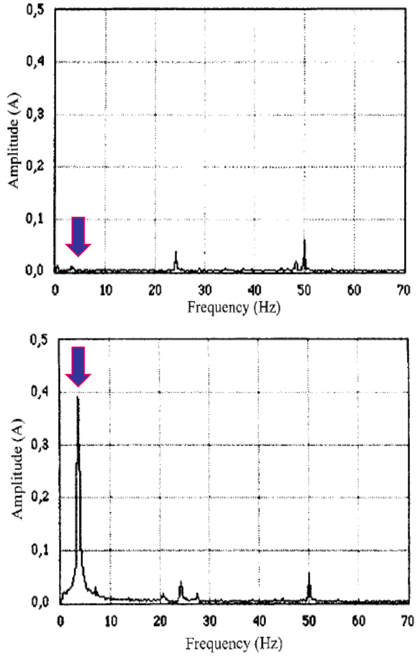


Source: ORNL, Kryter et al., 1989

Source: R. Fiser et al, 1997

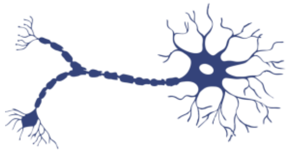


Source: S. Cruz et al, 1998



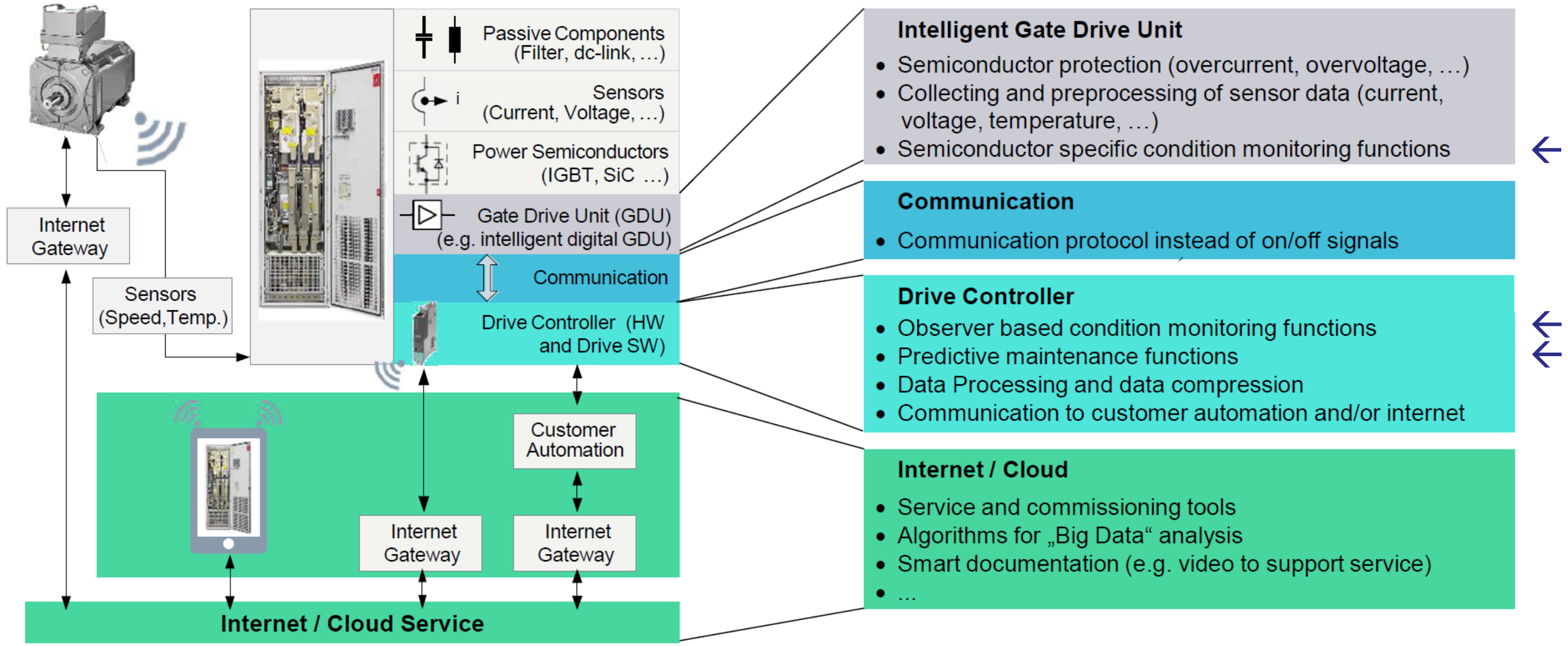
- *ORNL (1989) — MCSA Condition Monitoring of Motor-Valves in Nuclear Power Plant Safety Systems*
- *ANNs Discussed for Diagnostics since 25+ Years — Improvements w/ Computing Power of Modern Inverters*

Smart Inverter Concept



■ *Utilize High Computing Power and Network Effects in the Cloud*

Source: R. Sommer SIEMENS



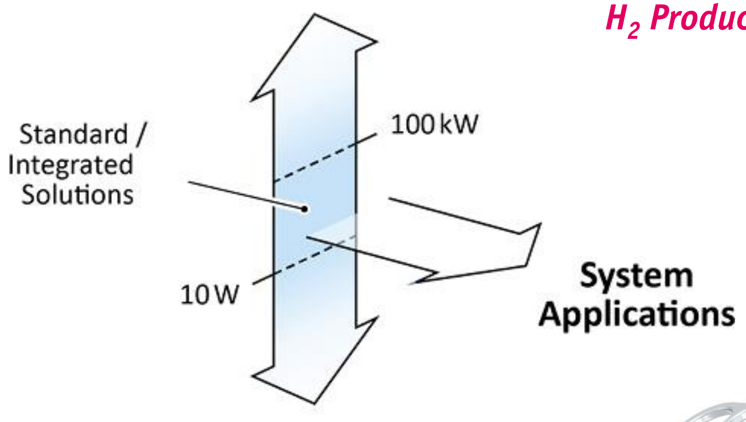
● *On-Line Protection / Monitoring / Optimization on Component | Converter | Drive | Application Level*

Conclusion

Future Application Areas

- *WBG Driven Extension to Medium Voltage | Extension to Micro-Power Electronics*
- *Extreme Cost Pressure for Standardized Solutions (!)*

Clustered AI Processors Vertical Power Delivery 100kA @ 0.75V ← *"There is Plenty of Room at the Top"* → *Medium Voltage & Frequency Solid-State Transformers Ultra-Fast EV Charging, Traction, H_2 Production, Datacenters, etc.*

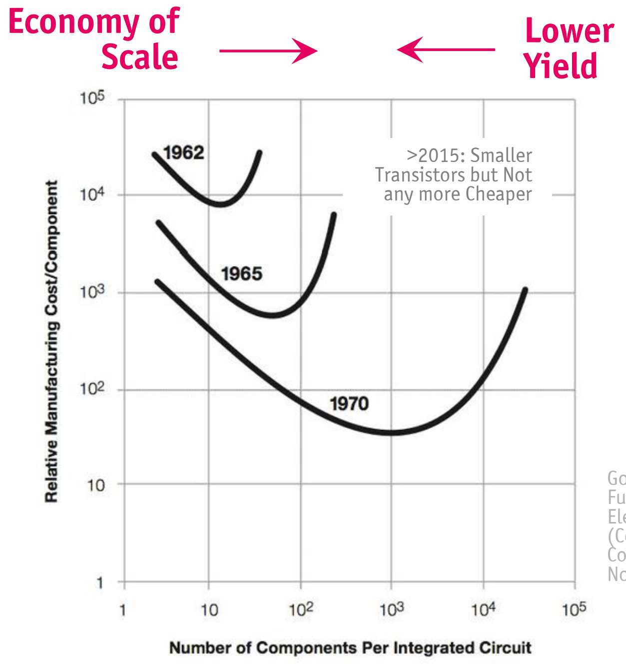


Power-Supplies on Chip ← *"There is Plenty of Room at the Bottom"*

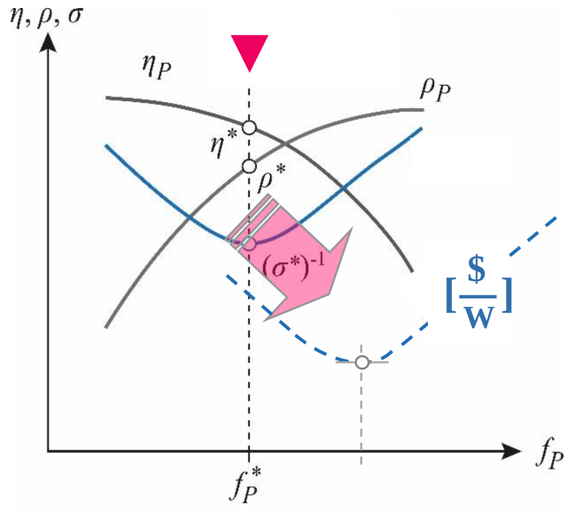
- *"There's Plenty of Room at the Bottom", Lecture by R. Feynman @ Caltech, 1959*
- *Key Importance of Technology Partnerships of Academia & Industry*

"Moore´s Law" of Power Electronics

- *"Moore´s Law" Defines Consecutive Technology Nodes Based on Min. Costs per Integr. Circuit (!)*
- *Complexity @ Min. Comp. Costs Increases approx. by Factor of 2 / Year*



Gordon Moore: The Future of Integrated Electronics, 1965 (Consideration of Three Consecutive Technology Nodes)



- *Potential Power Density Improvement — Factor 2 ... 5 Until 2030*
- *Definition of "η^*, ρ^*, σ^*, f_P^*– Technology Node" Must Consider Conv. Type / Operating Range etc. (!)*

Source:
www.roadtrafficsigns.com

Power Electronics → Electronic "Energy" Management

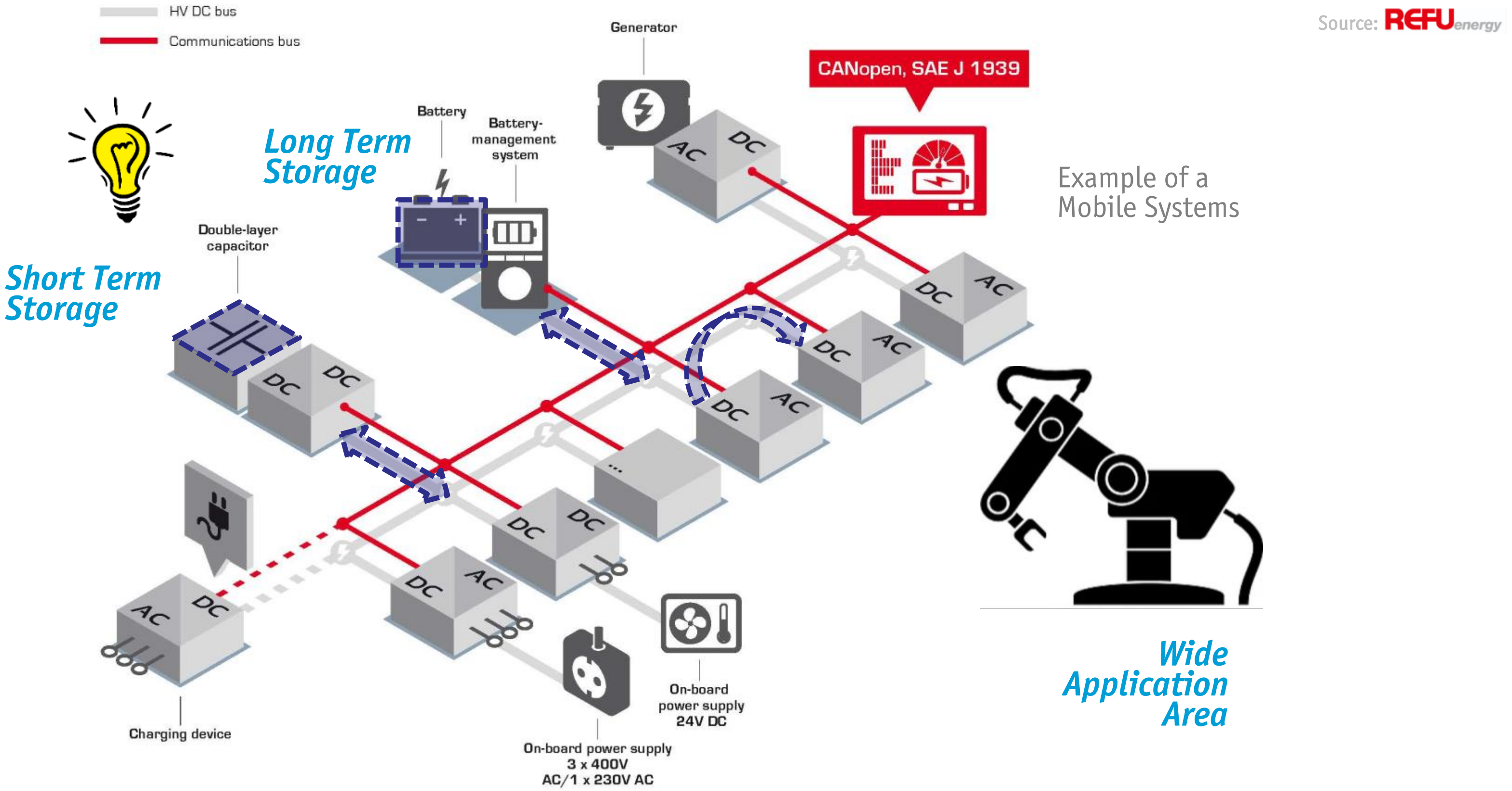
- Design Considering Converters as Standardized "Integrated Circuits" (PEBBs)
- Extend Analysis to Converter Clusters / Power Supply Chains / etc.

— "Converter" → "Systems" (Microgrid) or "Hybrid Systems" (Automation / Aircraft)
— "Time" → "Integral over Time"
— "Power" → "Energy"

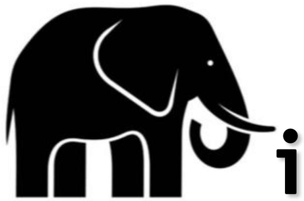
$$p(t) \rightarrow \int_0^t p(t)\,\mathrm{d}t$$

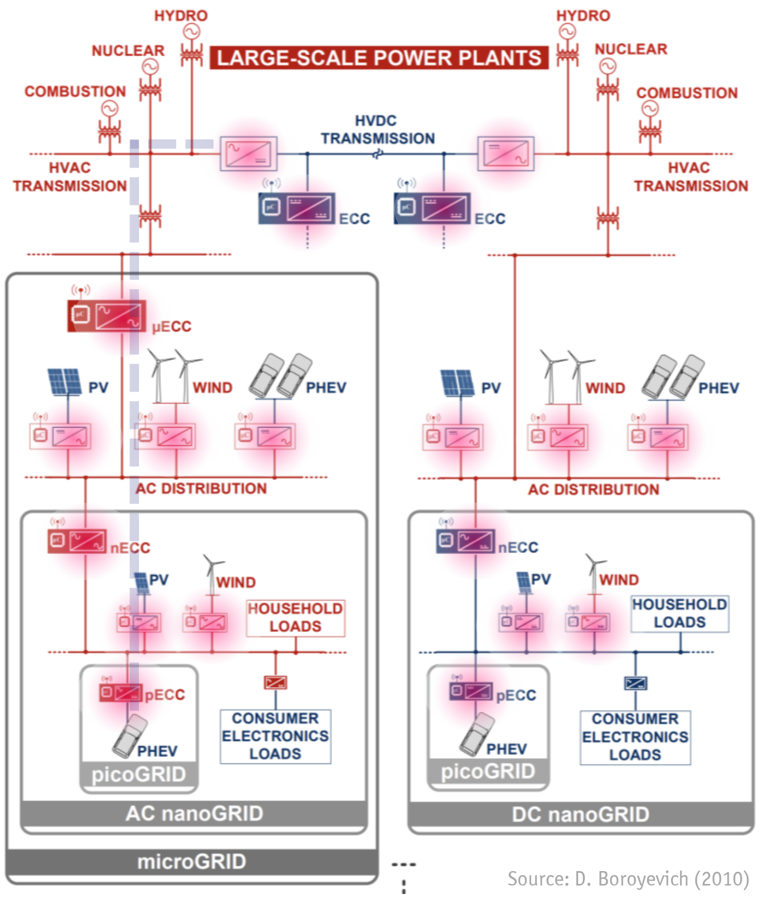
— Power Conversion → Energy Management / Distribution
— Converter Analysis → System Analysis (incl. Interactions Conv. / Conv. or Load or Mains)
— Converter Stability → System Stability (Autonom. Cntrl of Distributed Converters)
— Cap. Filtering → Energy Storage & Demand Side Management
— Costs / Efficiency → Life Cycle Costs / Mission Efficiency / Supply Chain Efficiency
— etc.

Energy Management — *DC Micro-/Nanogrids*



- *Renewable Energy Integration*
- *"Networked" — Bidir. Flow/Exchange of Energy & Signals/Data | Distrib. Autonom. Cntrl & Protect.*
- *Hybrid Power Solutions — Combin. of Electric / Hydraulic / etc. Systems | Continuous Opt. & Diagnosis*

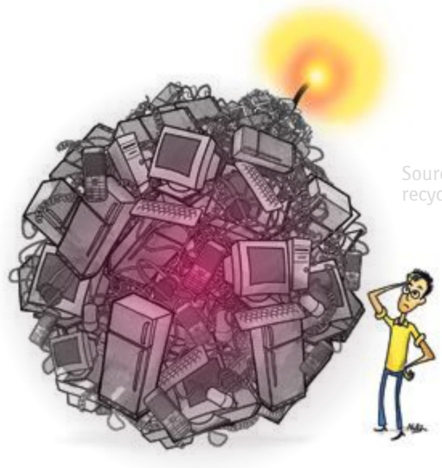
The  in the Room



Source: D. Boroyevich (2010)

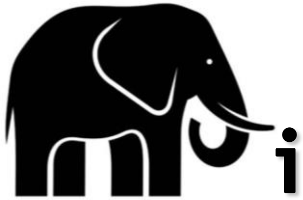
- *25´000 GW Installed Ren. Generation in 2050*
- *15´000 GWh Batt. Storage*

- *4x Power Electr. Conversion btw Generation & Load*
- *100´000 GW of Installed Converter Power*
- *20 Years of Useful Life*



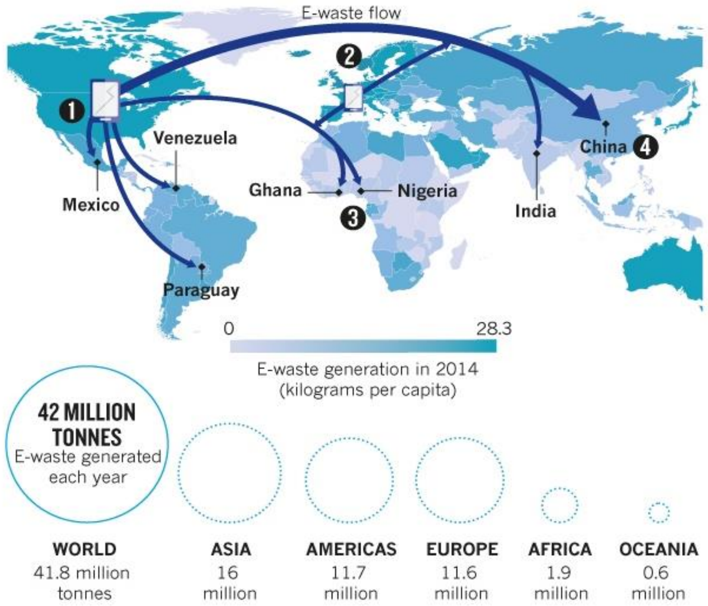
Source: www.e-waste-recyclers.co.in

- *5´000 GW_{eq} = 5´000´000´000 kW_{eq} of E-Waste / Year (!)*
- *10´000´000´000 $ of Potential Value*

The  in the Room

- *52´000´000 Tons of Electronic Waste Produced Worldwide in 2021 → 74´000´000 Tons in 2030*
- *Increasingly Complex Constructions → No Repair or Recycling*

Source: Green IT Solution



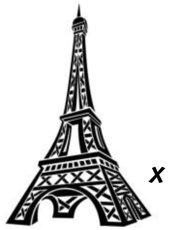
Source: nature

- *Growing Global E-Waste Streams → Regulations Mandatory (!)*

The Paradigm Shift (1)

- *Growing Global E-Waste Streams / < 20% Recycled*
- *120´000´000 Tons of Global E-Waste in 2050*

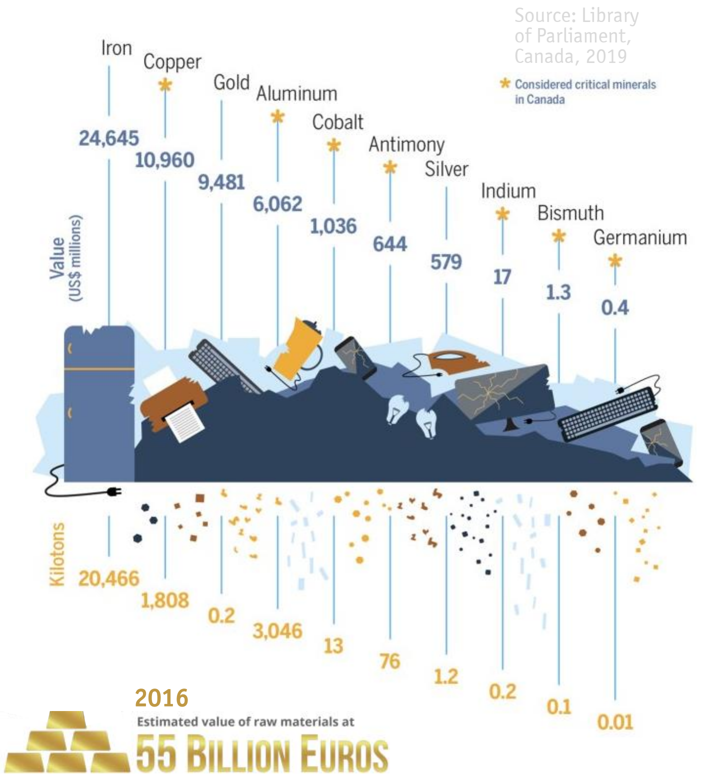
← 52 Mt (!)



x 5´200

Source: The Global E-waste Monitor 2020

unitar

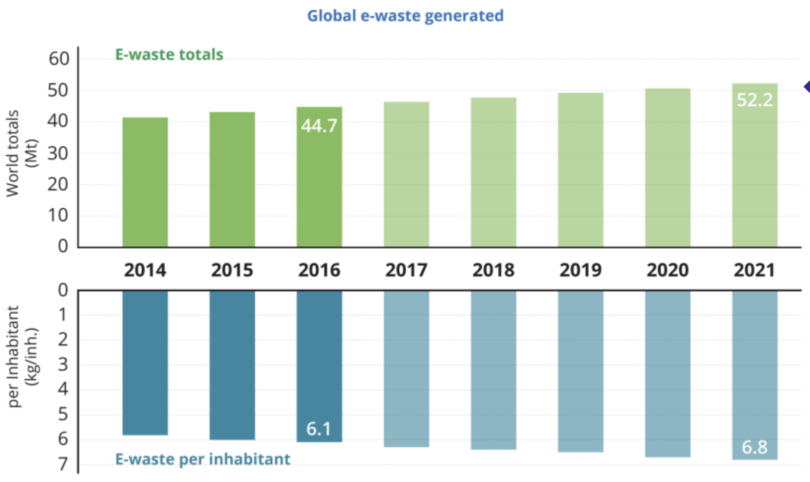


Global / 2019

- *"Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources*
- *Resources Returned into the Product Cycle at the End of Use*
- *E-Waste Represents an "Urban Mine" w/ Great Economic Potential*

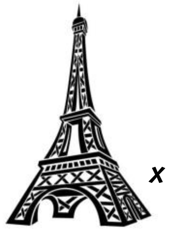
The Paradigm Shift (2)

- *Growing Global E-Waste Streams / < 20% Recycled*
- *120´000´000 Tons of Global E-Waste in 2050*



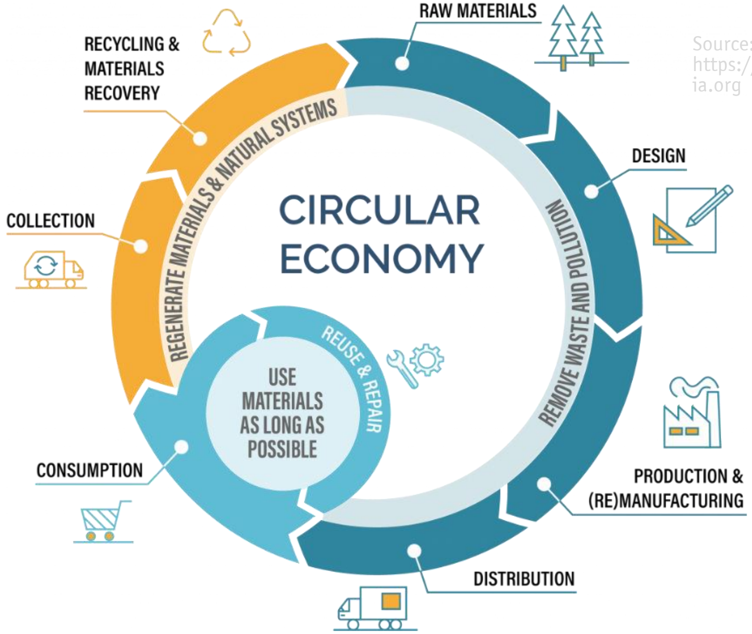
Note: 2017-2021 are estimates

← 52 Mt (!)



x 5´200

Source: The Global E-waste Monitor 2020

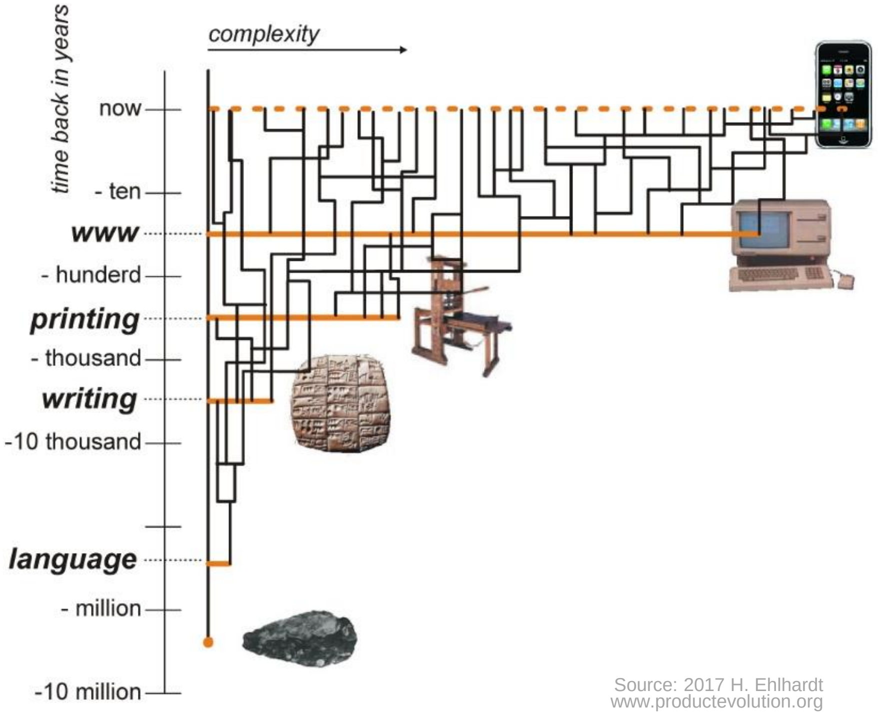


Source: https://circularphiladelphia.org

- *"Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources*
- *Resources Returned into the Product Cycle at the End of Use*

Complexity Challenge

- *Technological Innovation — Increasing Level of Complexity & Diversity of Modern Products*
- *Exp. Accelerating Technological Advancement (R. Kurzweil)*



Source: 2017 H. Ehlhardt
www.productevolution.org

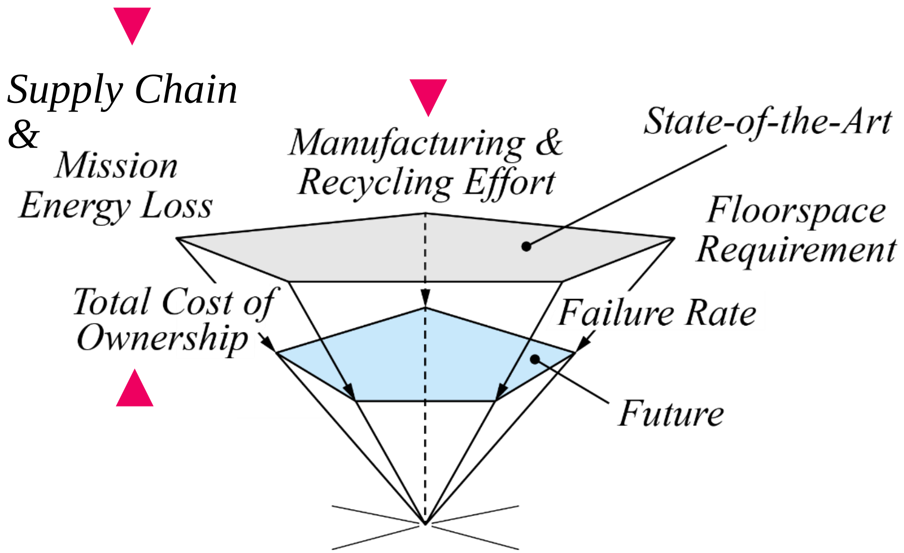
- *Ultra-Compact Systems / Functional Integration — Main Obstacle for Material Separation*

Performance Indicators / Trends

- Energy Systems / Electronics

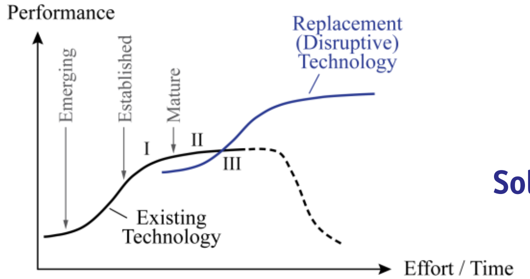
- *Complete Set of New Performance Indices*

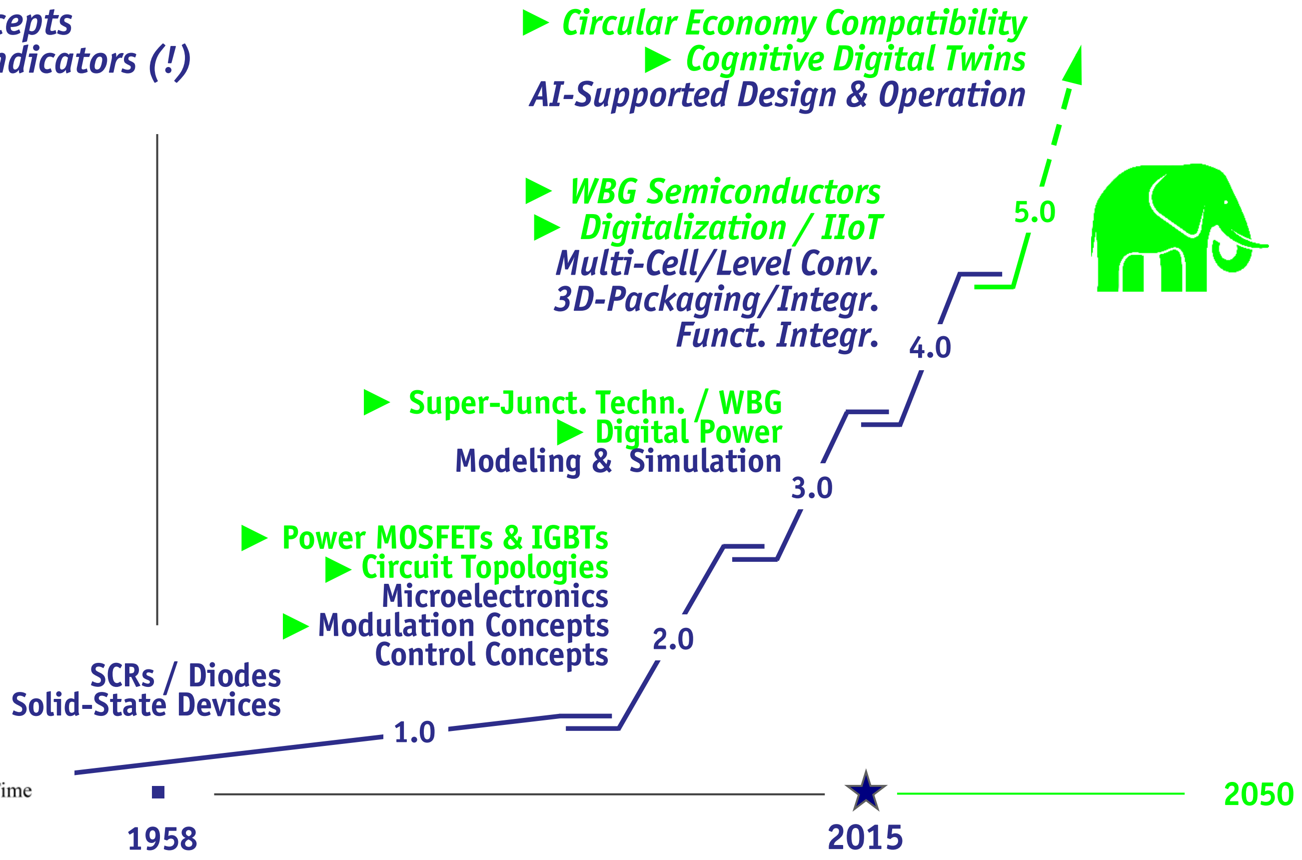
— Power Density [kW/m^2]
— Energy Density [kWh/m^3]
— Environmental Impact [$kg\,CO_2eq/kW$]
— TCO [$/kW]
— Mission Efficiency [%]
— Failure Rate [h^{-1}]



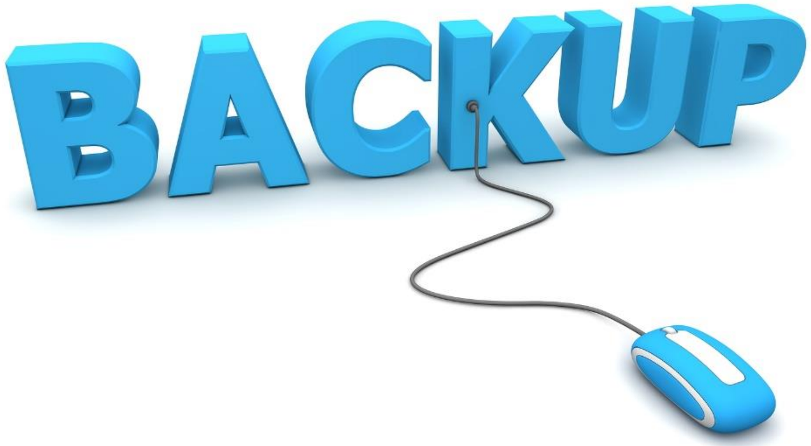
Power Electronics 5.0

- *Power Electronics 1.0 → Power Electronics 5.0*
- *X-Technologies & X-Concepts*
- *New Main Performance Indicators (!)*



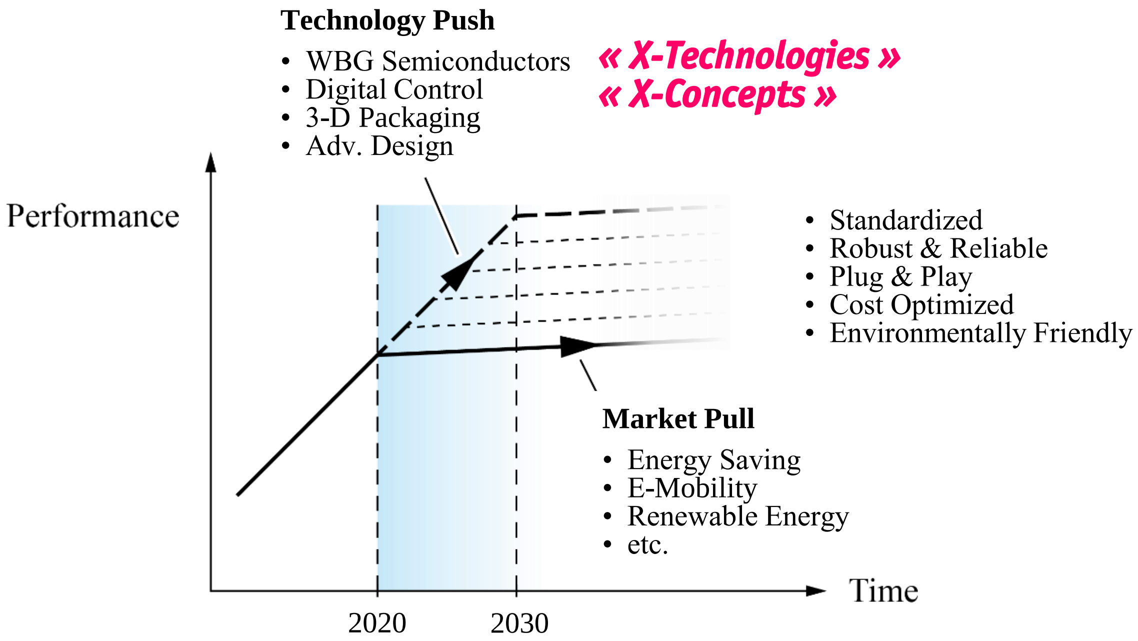


Thank you!


BACKUP

Future Development / Trends

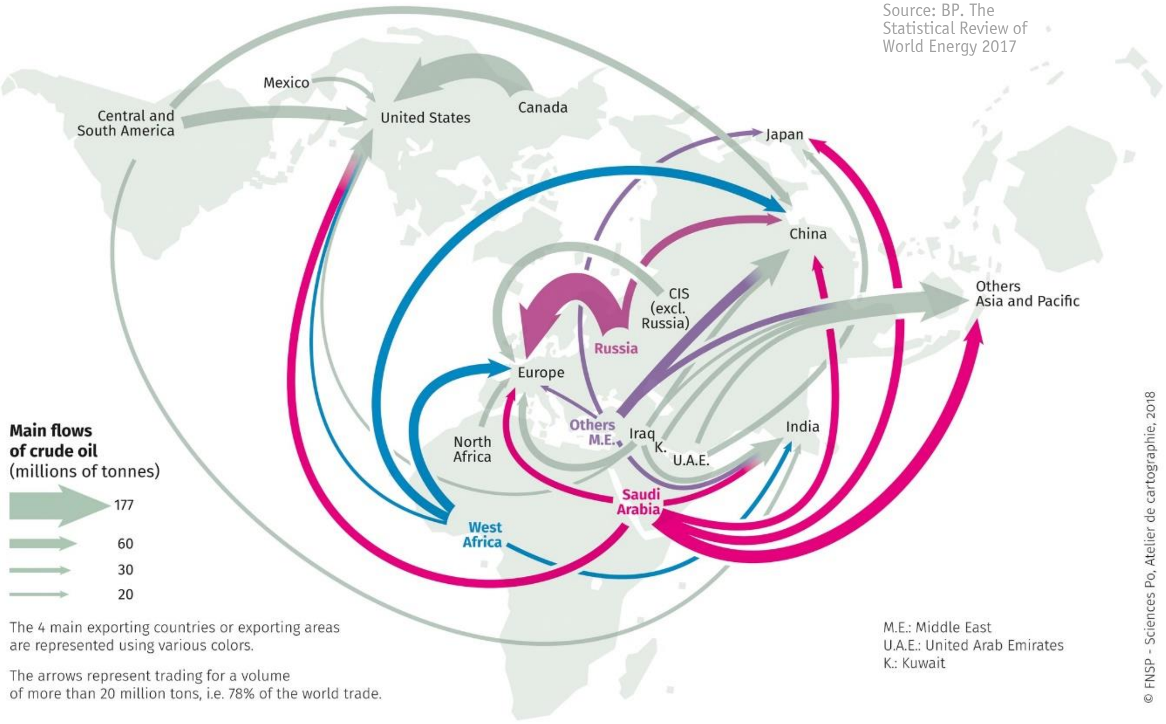
- *MEGA-Trends — Renewable Energy / Energy Saving / E-Mobility / "SMART XXX"*
- *Power Electronics will Massively Spread in Highly Diverse Applications*

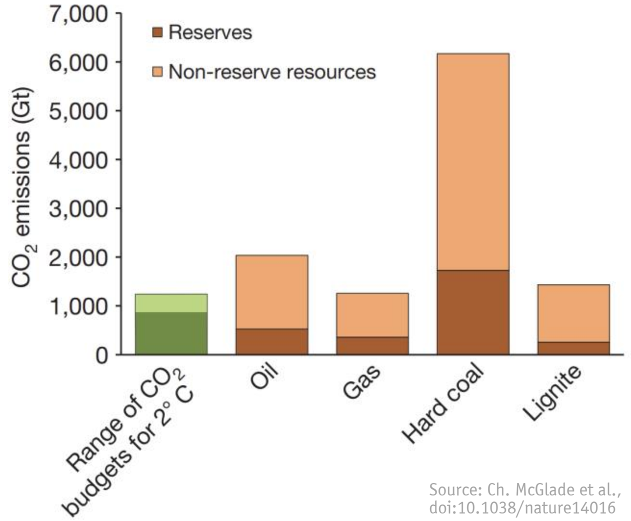


- *More Application Specific Solutions*
- *More Specific Requirements – High Peak/Avg. Ratio, Wide Volt. Range etc.*
- *Cost Optimization @ Given Performance Level for Standard Solutions*
- *Design / Optimize / Verify (All in Simulation) — Faster / Cheaper / Better*

Energy Independence / Security of Supply

- *Global Oil Trade (2016) — High Import Dependency of Leading Economies*



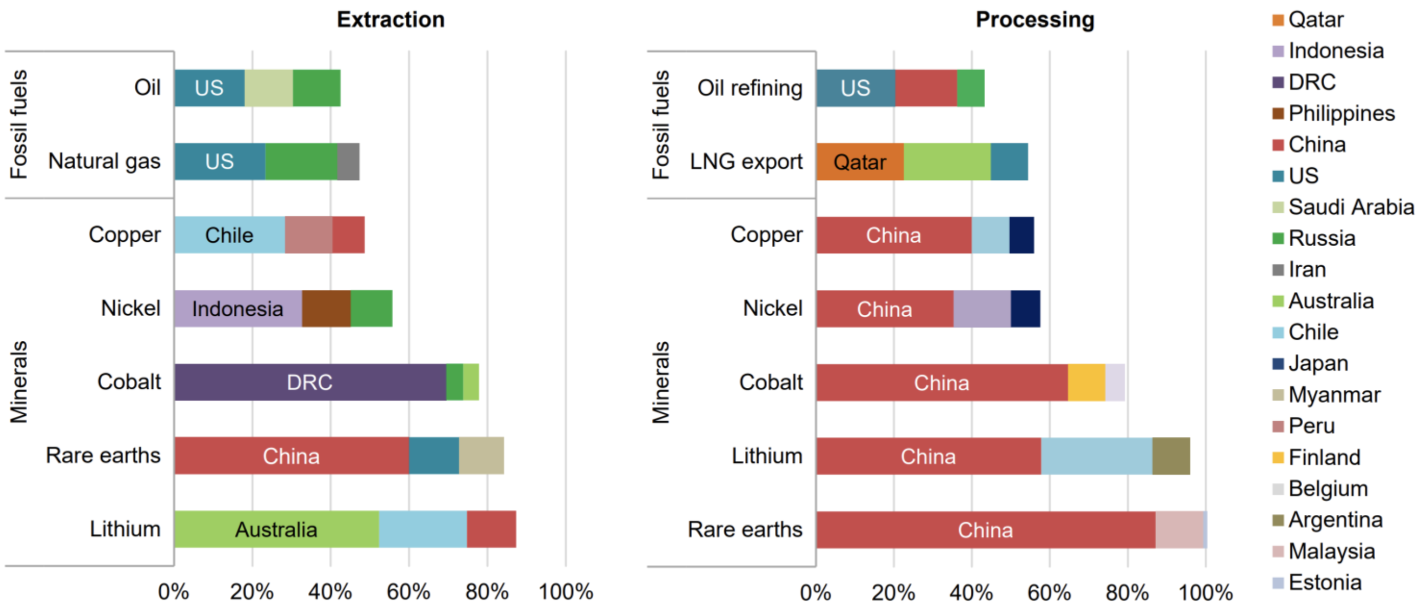


Source: Ch. McGlade et al., doi:10.1038/nature14016

- *2°C Target → Globally, 30% of Oil Reserves | 50% Gas Reserves | > 80% Coal Reserves Should Remain Unused (!)*
- *"The Stone Age Didn't End for Lack of Stone — The Oil Age will End Long Before the World Runs Out of Oil"*

Critical Minerals

- *Production of Selected Minerals Critical for the Clean Energy Transition*



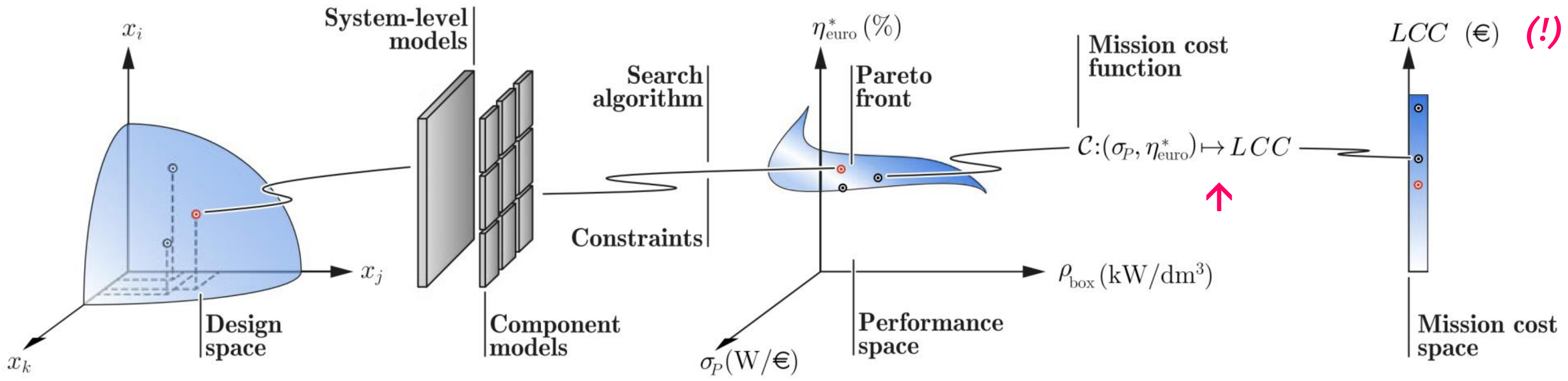
Shares of top three producing countries, 2019

Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

- *Extraction & Processing More Geographically Concentrated than for Oil & Nat. Gas (!)*

Multi-Objective Optimization

- *Typ. Performance Indices — Efficiency η [%] | Power Density ρ [kW/dm³] | Rel. Cost σ [kW/$]*
- *Consideration of Specific Operating Points OR Mission Profile*

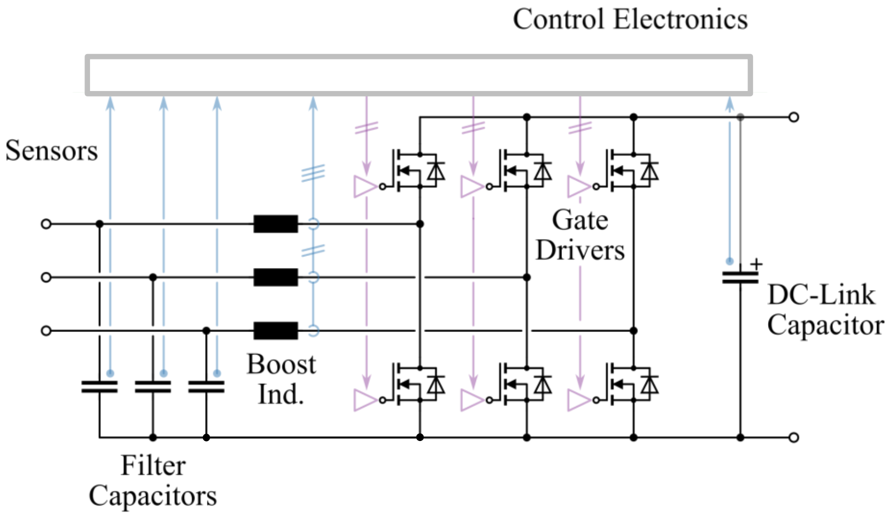


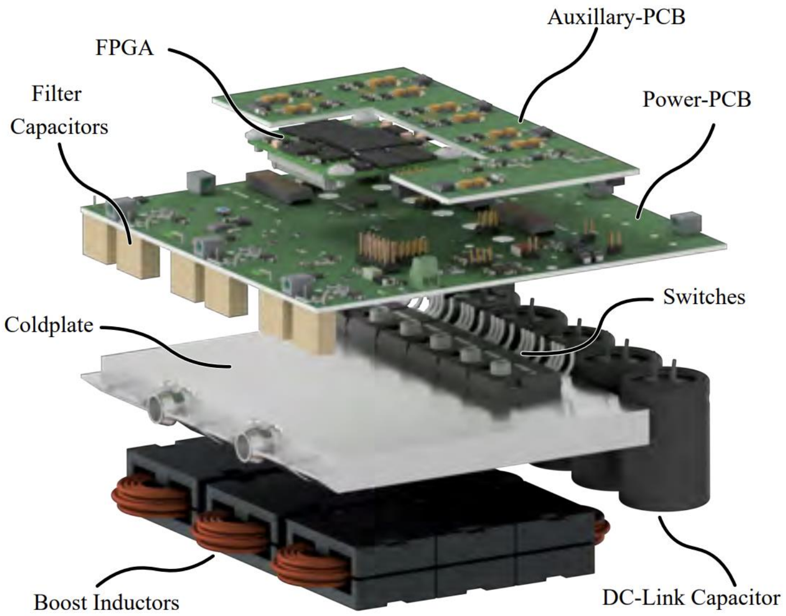
- *Mission Profile — Power Loss → Energy Loss / Life-Cycle Cost (!)*

Example — Three-Phase AC/DC PEBB

- *Key Power Electronics Building Block (PEBB) for Three-Phase PFC Rectifiers & Inverters*

10 kW
400 V_{AC} Mains
800 V_{DC} Output
1200 V SiC



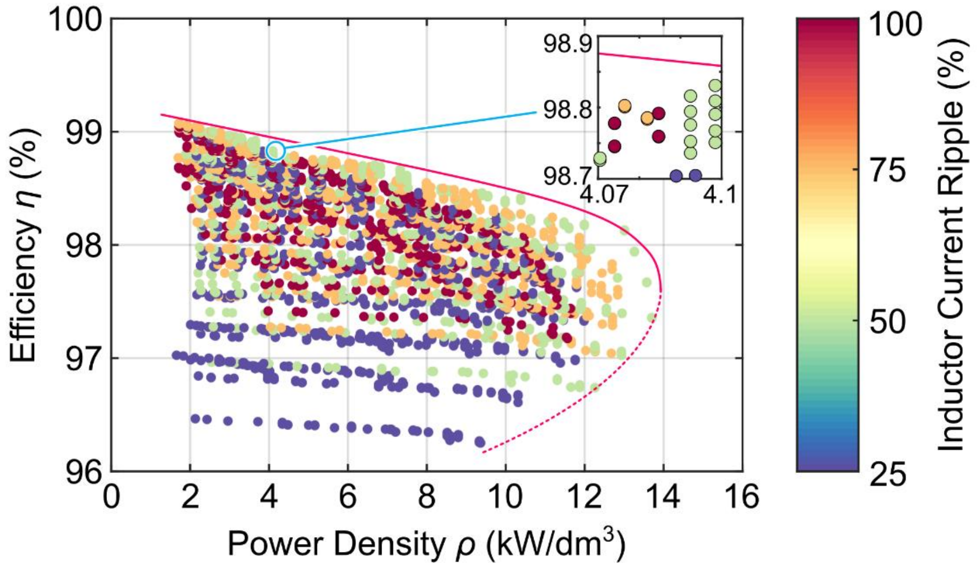


- *Main Components Considered (Losses, Volume, CO_{2eq})*
- *Power Trans., Heat Sink, Boost Ind., DC-Link Cap., Filter Cap., Gate Drivers, Sensors, Contr. Electr., PCBs*

η-ρ-Multi-Objective Optimization

- Design Space Diversity — Optimiz. for Min. Environmental Impact w/o Compromising Eff. or Power Density (!)
- Example of a Three-Phase Two-Level AC-DC PEBB w/ LC-Input Filter

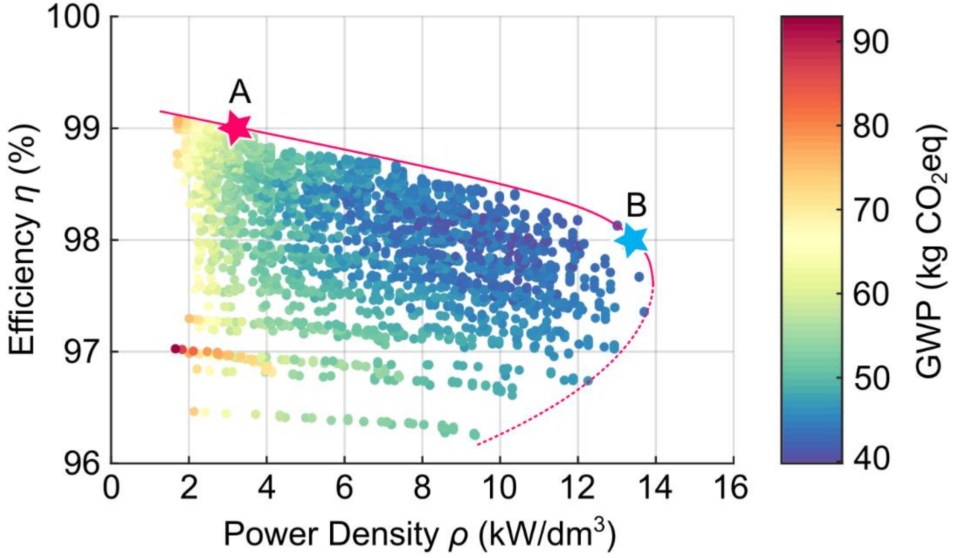
10 kW
400 V_{AC} Mains
800 V_{DC} Output
1200 V SiC

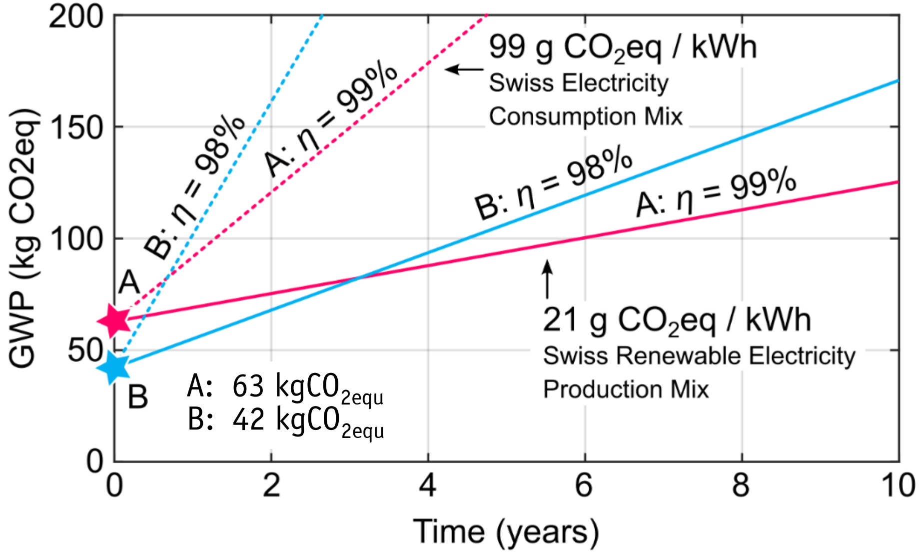


- **Degrees of Freedom**
  - Switching Frequency [25...200 kHz]
  - Rel. Ind. Peak Current Ripple [0.25...1]
  - Variable Transistor Chip Area
  - Variable Ind. Size (N87; Solid/Litz Wire)
- **Assumptions**
  - Junction Temp. @ 120 °C
  - Ambient Temp. 40 °C
  - Necessary Heat Sink Vol. via CSPI = 25 W/(K·dm³)

Efficiency vs. Operating Time Carbon Footprint

- *Global Warming Potential GWP [kg CO_{2eq}] as Add. Performance Indicator*
- *Mission Matters — Example 8 Hours Full Load per Day Over 10 Years*
- *Electricity Mix Matters — Carbon Intensity*

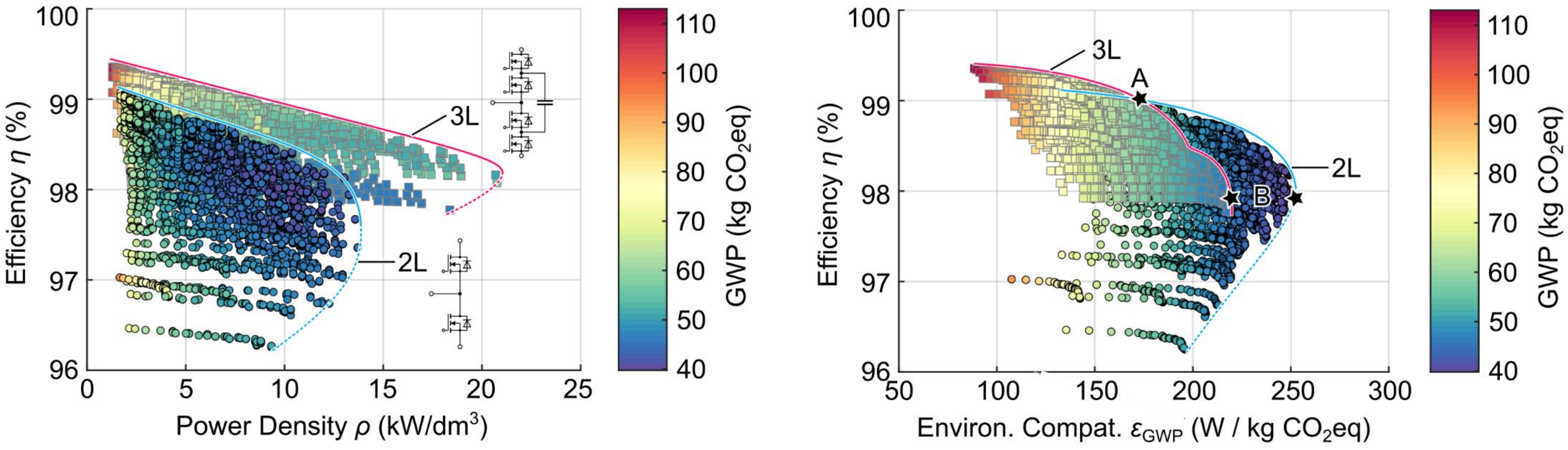




- *Energy Losses During Use Phase Contribute to Overall GWP*
- *More Eff. Designs w/ Higher Initial GWP Outperform Less Eff. Designs for Longer Operating Times*

2-Level vs. 3-Level PEBB Evaluation

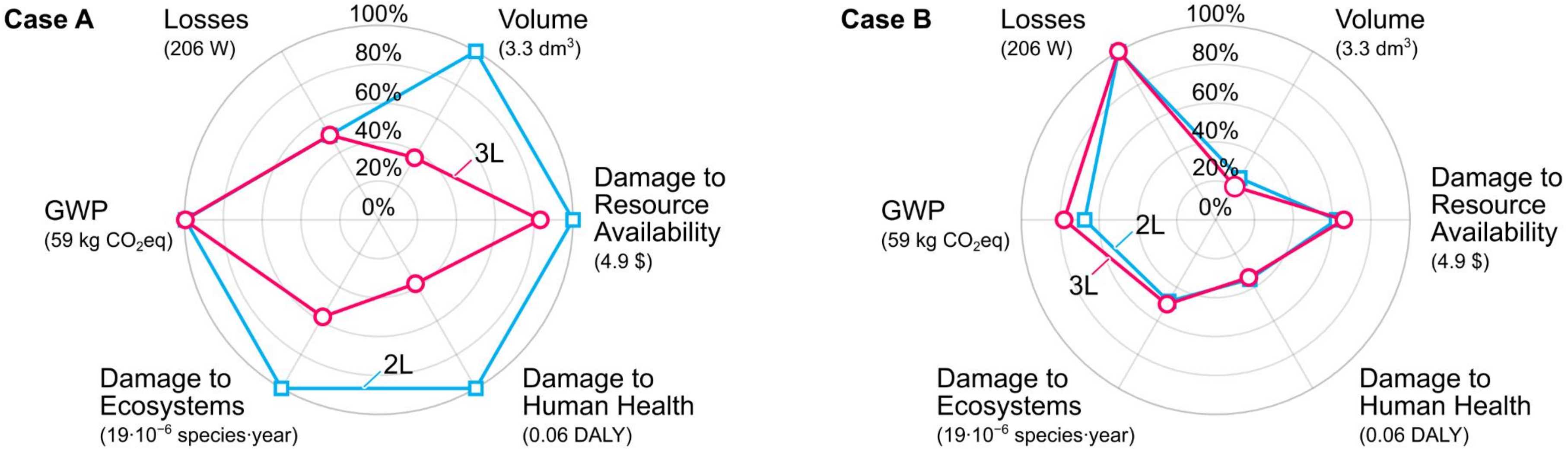
- *3-Level Flying-Capacitor Bridge-Legs w/ 650 V SiC MOSFETS / 2-Level Bridge-Legs w/ 1200 V SiC MOSFETs*
- *400 V_{AC} Mains | 800 V_{DC} | 10 kW | LC-Filter w/ Same Capacitor Voltage Ripple*



- *Higher 3L Inverter Eff. & Power Density BUT Lower Environm. Compatibility [W/kgCO_{2eq}]*
- *Higher 3L Initial GWP Due to Higher # of Power Semiconductors*

Comprehensive Environmental Impact Profile

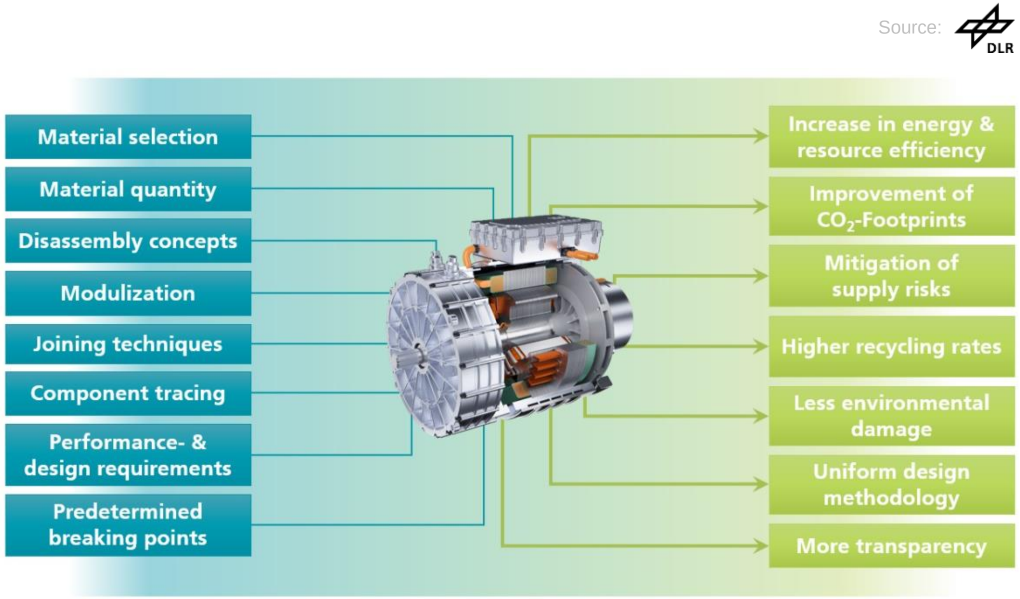
- *Further Environm. Impact Indicators — Volume & ReCiPe 2016 Areas of Protection*
- *Human Health | Ecosyst. Quality | Resource Scarcity*
- *Comparative Evaluation of 2L vs. 3L PEBB*



- *Case A — 99% Eff. @ Equal GWP — Significantly Diff. Volumes & Diff. ReCiPe Performance*
- *Case B — 98% Eff. @ Highest Rel. Environm. Compatibility — Similar Volumes & Environm. Impacts*

Design for Repairability & Circularity

- *Eco-Design — Reduce Environmental Impact of Products, incl. Energy Consumption Over Life Cycle*
- *Re-Pair / Re-Use / Disassembly / Sorting & Max. Material Recovery, etc. Considered*
- *EU Eco-Design Guidelines (!)*



- *FAIRPHONE — Modular Design | Man. Replaceable Parts | 100% Recycl. of Sold Products | Fairtrade Materials*
- *80% of Sustainability / Environmental Impact of Products are Locked-In at the Design Phase*

CEC-Power Electronics Roadmap

- *Environmental Awareness as Integral Part of Power Electronics Design*

Circular-Economy-Compatible (CEC) Power Electronics

"Net-Zero CO_2 is Not Enough"
- Max. Repairability | Reusability | Recyclability
- Min. Scarce Materials, Min. Toxic Waste

Full Environmental Footprint Based on Smart Datasheets
- Seamless Integr. of Comp. Models in Multi-Obj. Opt.
- Full A-Priori LCIA / Environmental Footprint
- Standardization / Single Source of Truth

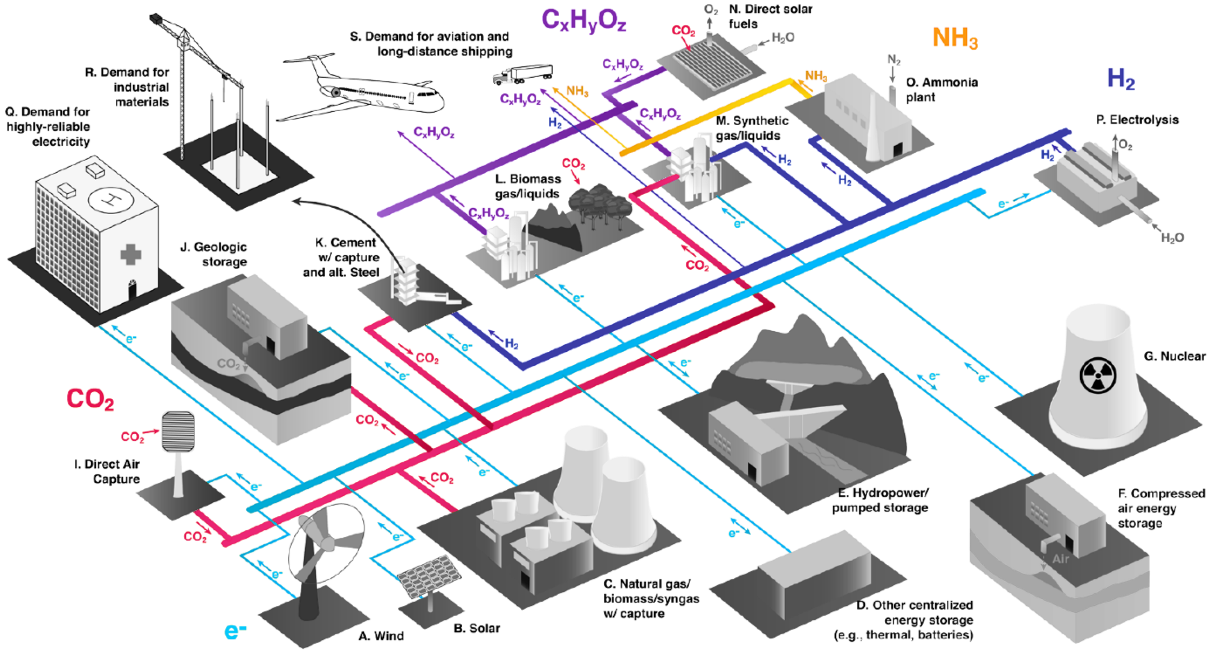
Generic Life-Cycle Impact Analysis (LCIA)
- New KPIs in Multi-Obj. Opt.
- Data Sources / Quality / Abstraction / Generalization as Key Challenges

Classical $\eta\rho$-Pareto Optimization / Design
- Manual A-Posteriori LCA of Complete Converters

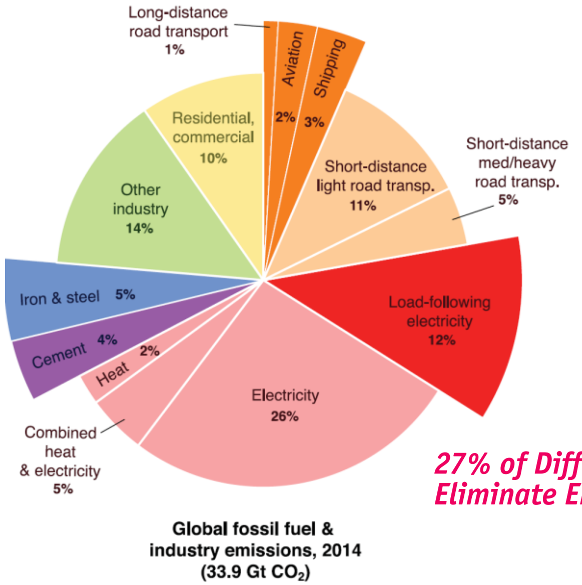
- *Automated Design | On-Line Monitoring | Prev. Maintenance | Digital Product Passport*

The Comprehensive Solution (!)

- *CO_2-Free Electricity / Electrification — Viable Pathway for Reducing Emissions !&! Costs (Long Term)*
- *E-Fuels & P2X for Long-Haul Transport / Aviation / etc. & Short Term / Seasonal Storage*



Science
S.J. Davis et al.
(2018)

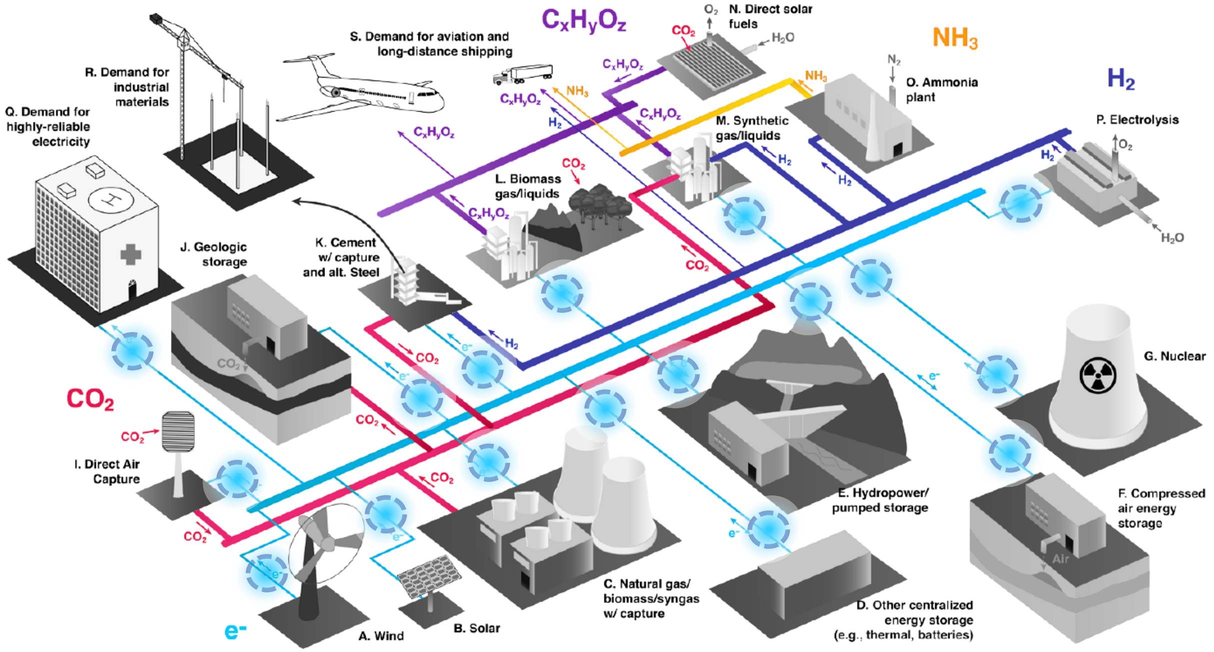


27% of Difficult-to-Eliminate Emissions

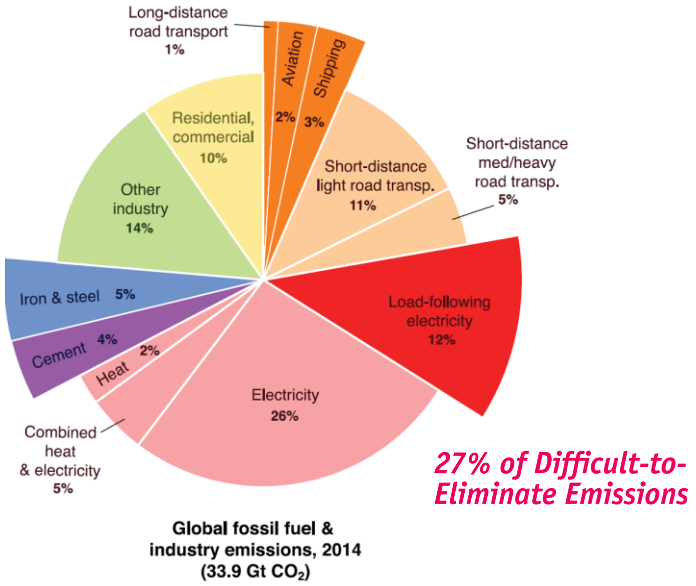
- *Integrated Net-Zero Multi-Carrier Energy System — E-Energy | Heat & Cold (N.N.) | etc. | Storage | CO_2C&S*
- *Missing Multi-Discipl. Research on Cross-Sector Converters / Technologies / Geogr. Diversity / Economics etc.*

The Comprehensive Solution (!)

- *Power Electronics ◌ A Key Enabler !*



Science
S.J. Davis et al.
(2018)

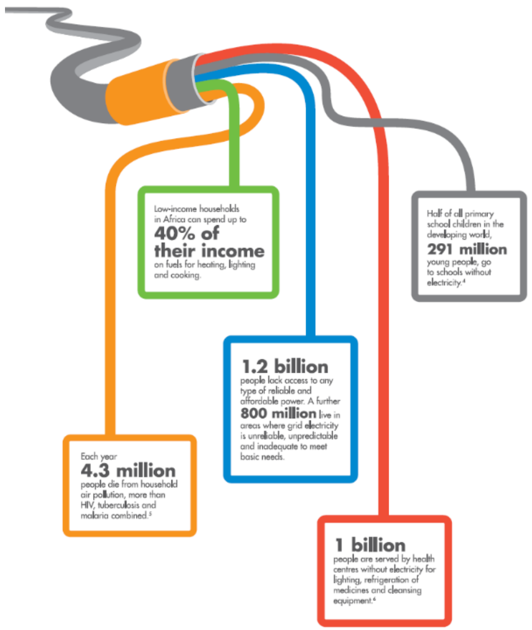


27% of Difficult-to-Eliminate Emissions

- *Ren. Gen. & Cross-Sector Conv. — Heat-Pumps / Electrolyzers / FCs / etc. → All Power Electronics Dependent !*

Remark Bottom-of-the-Pyramid

- *2 Billion People are Lacking Access to Clean Energy*
- *Urgent Need for Rural Electrification*



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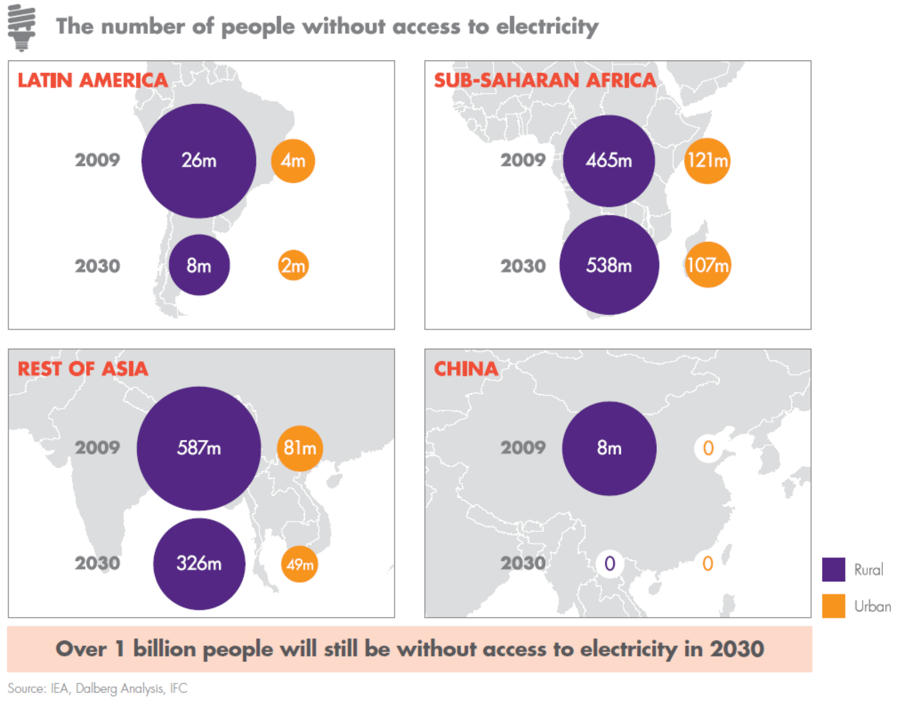
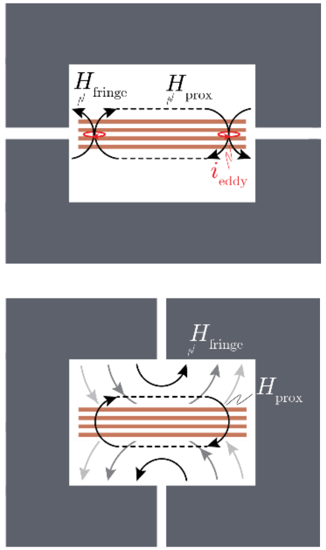
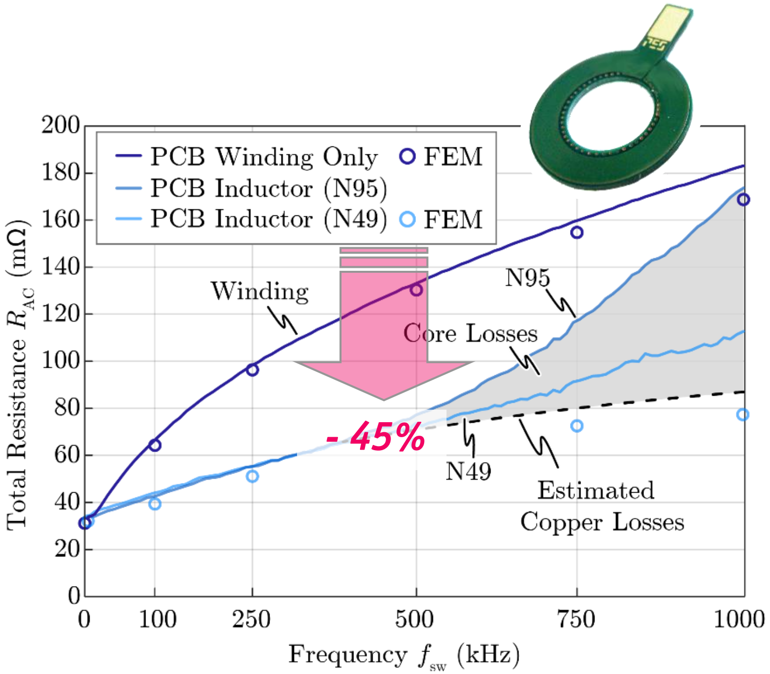


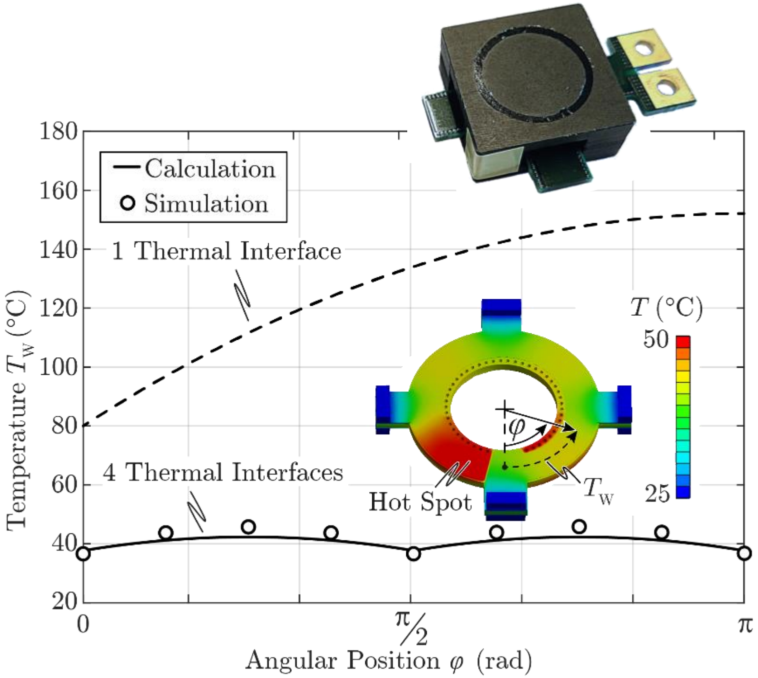
- *2 US$ / Household / Month (!) for 2 LED Lights & Mobile-Phone Charging*

Low-Loss PCB-Winding Inductor

- *Conv. PCB Windings & Airgaps → Skin / Proximity / Fringing Field ⊥ to PCB → Current Displacement*
- *Arrangement of Airgaps for Mutual Field Compensation*
- *Thermal Interfaces for Efficient Cooling*







- *Optimal Positions & Wdg Distance of Airgaps for Multi-Airgap / Multi-Layer Inductors*
- *Factor of 3 Red. of Skin & Prox. Losses*