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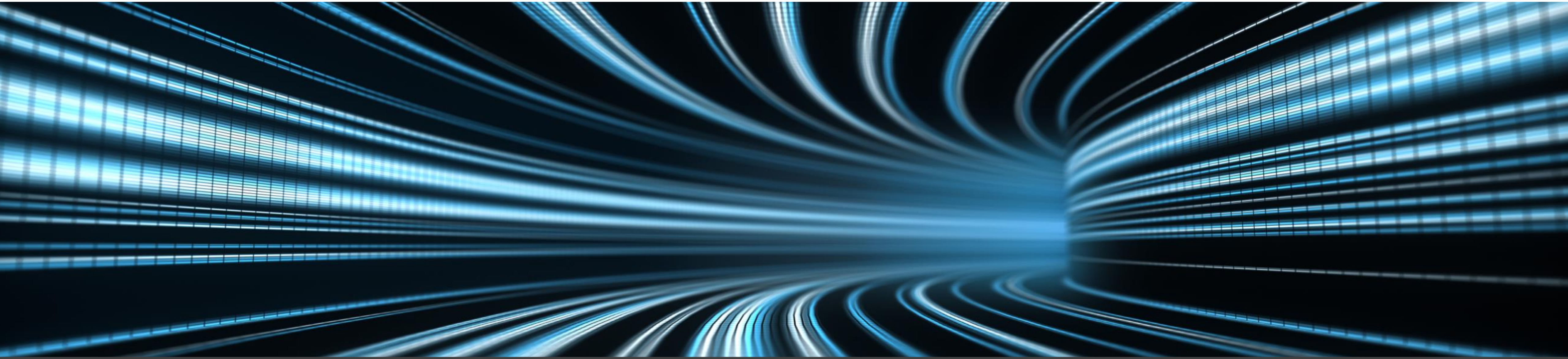
«X-Technologies/X-Concepts»

Key Enablers of Further Performance Improvements in Power Electronics

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Sept. 17, 2024



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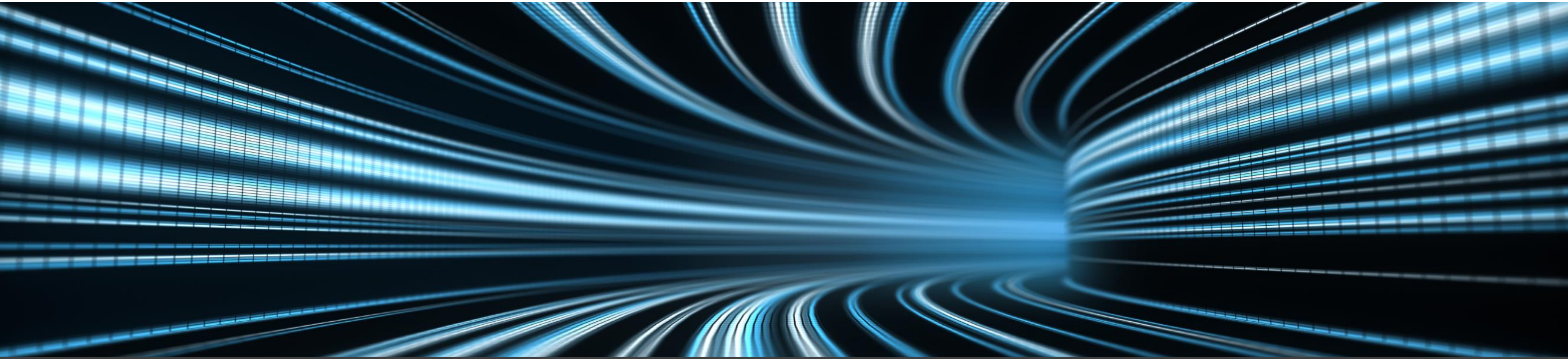

Outline

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

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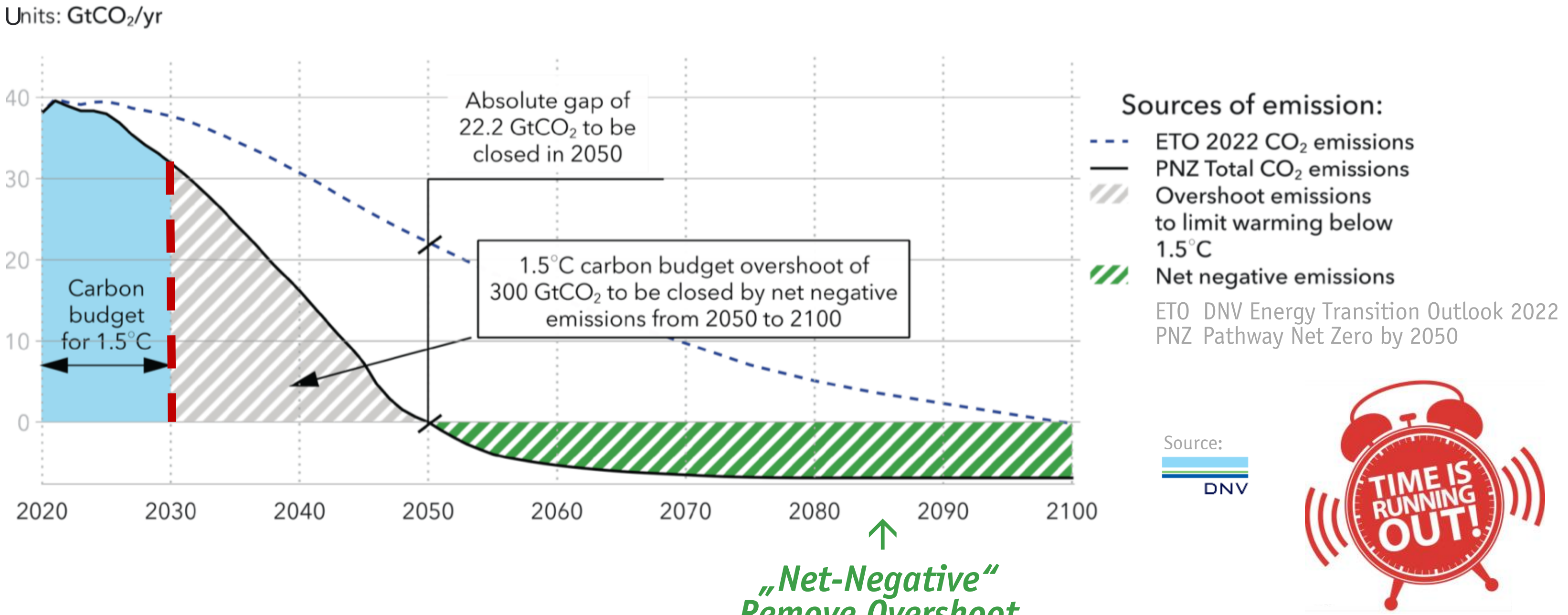
Introduction

Clean Energy Transition
All-Electric Society

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 $GtCO_2$ →



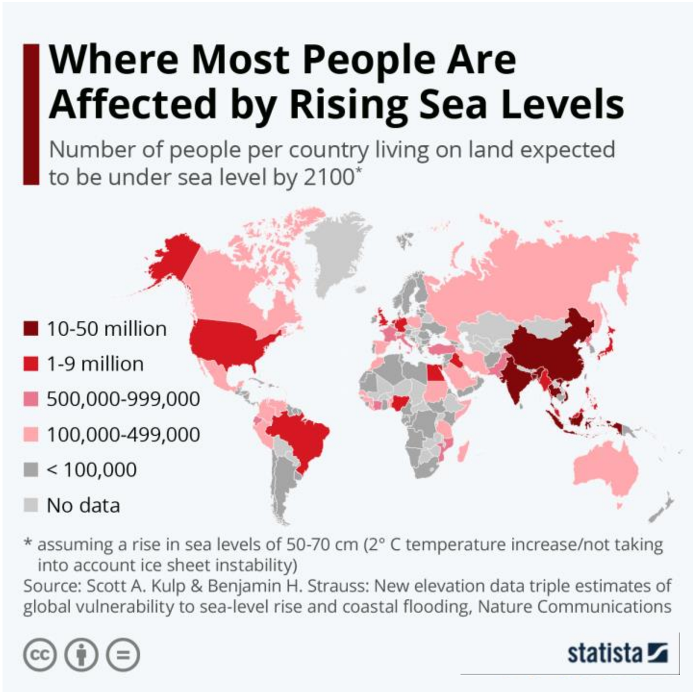
↑
„Net-Negative"
Remove Overshoot
of 300 $GtCO_2$

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

Global Sea Levels by 2100

- *Rising Sea Levels Due to Global Warming*

@ 2°C Temp. Increase

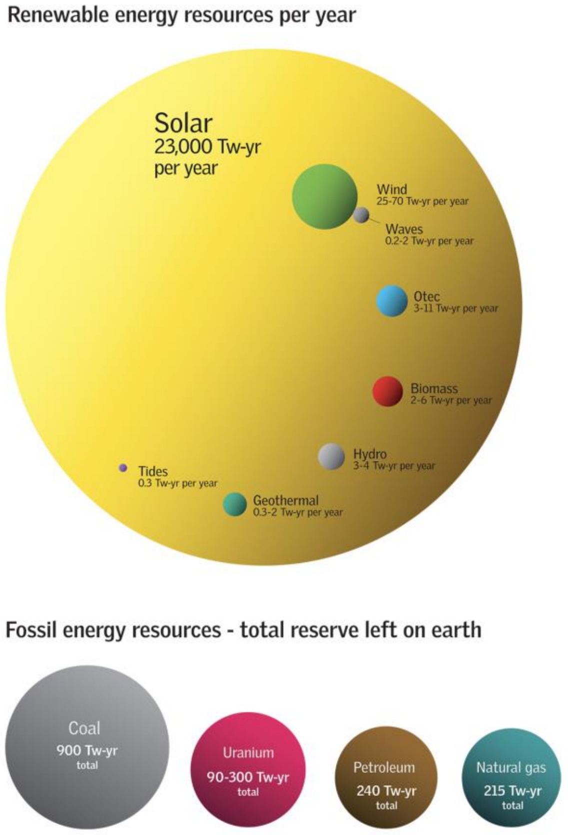


- *North Sea Enclosure Dyke — Mammoth Dams Envisioned to Protect 25 Million Europeans — €250 bn ... €500 bn*

The Opportunity

(2009) 16 TW-yr  *27 TW-yr (2050)*

100% Conv. Efficiency
Excl. Oceans

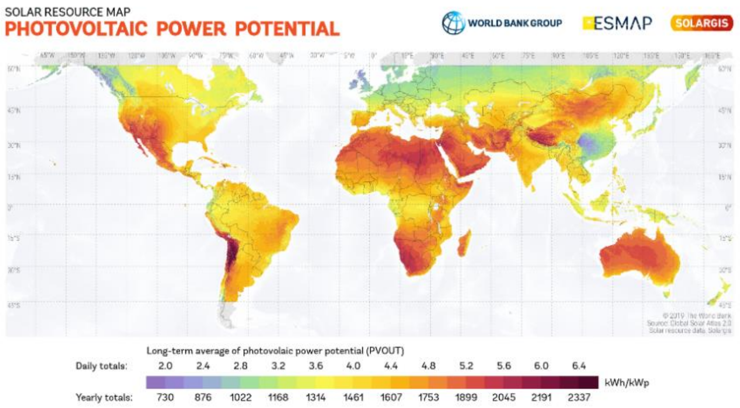


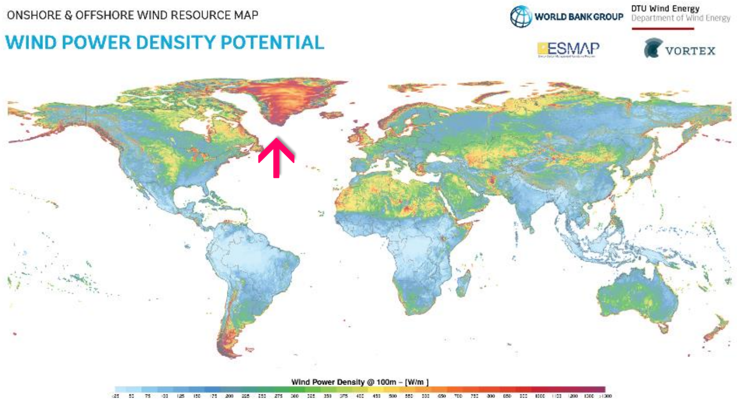
Note: Graphical Representation Assumes Spheres Not Circles

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)

- ***Global Distribution of Solar & Wind Resources***

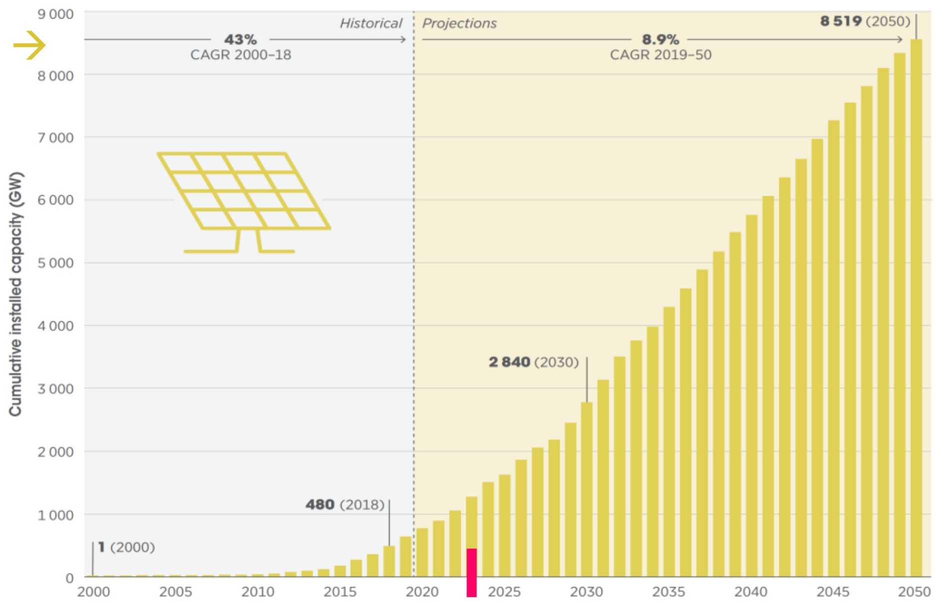




The Approach

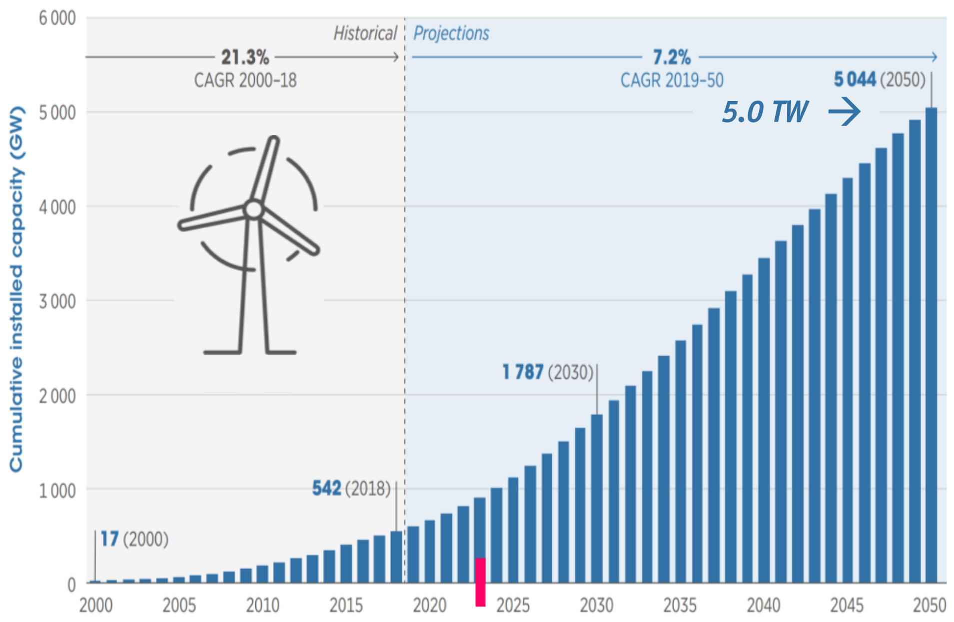
- *Outlook of Global Cumulative Installations Until 2050 / Add. 1000 GW Off-Shore Wind Power*
- *In 2050 Deployment of 370 GW/Year (PV) & 200 GW/Year (On-Shore Wind) incl. Replacements*

8.5 TW →



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

5.0 TW →

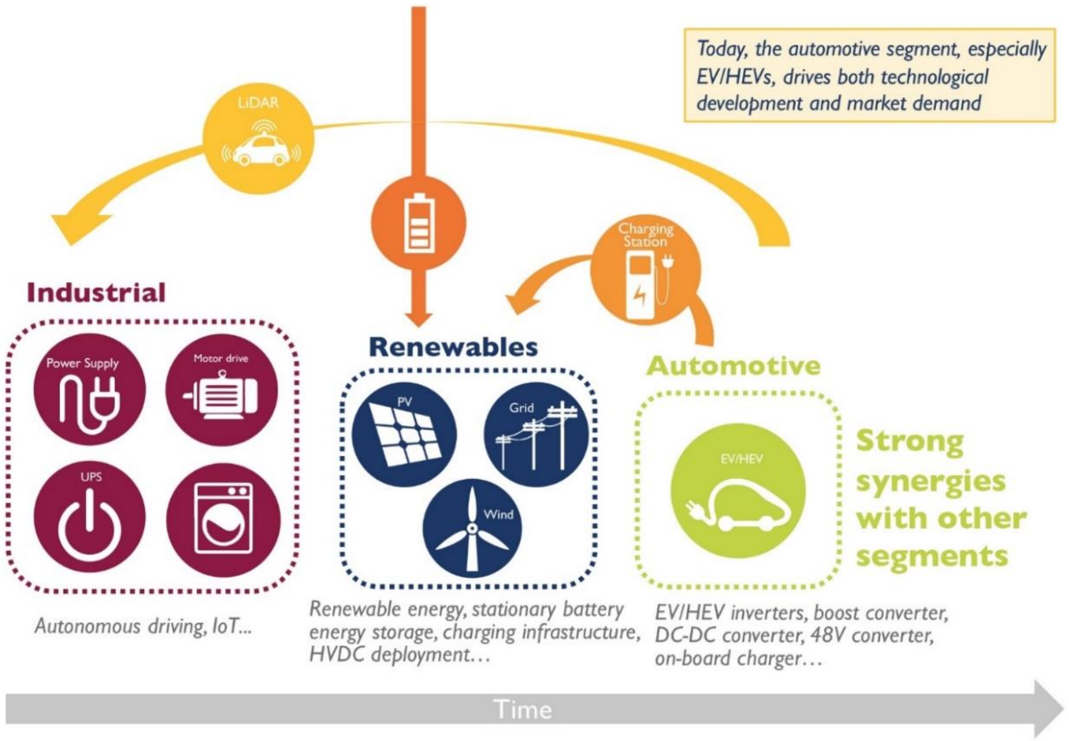


Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

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

Fundamental Role of Power Electronics

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

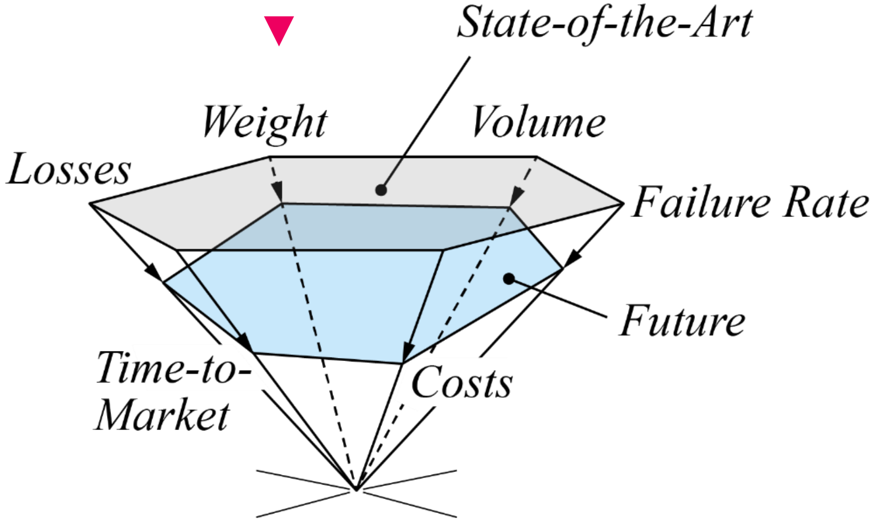


Source: Status of Power Electronics Industry 2019 Report YOLE Développement

- *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]

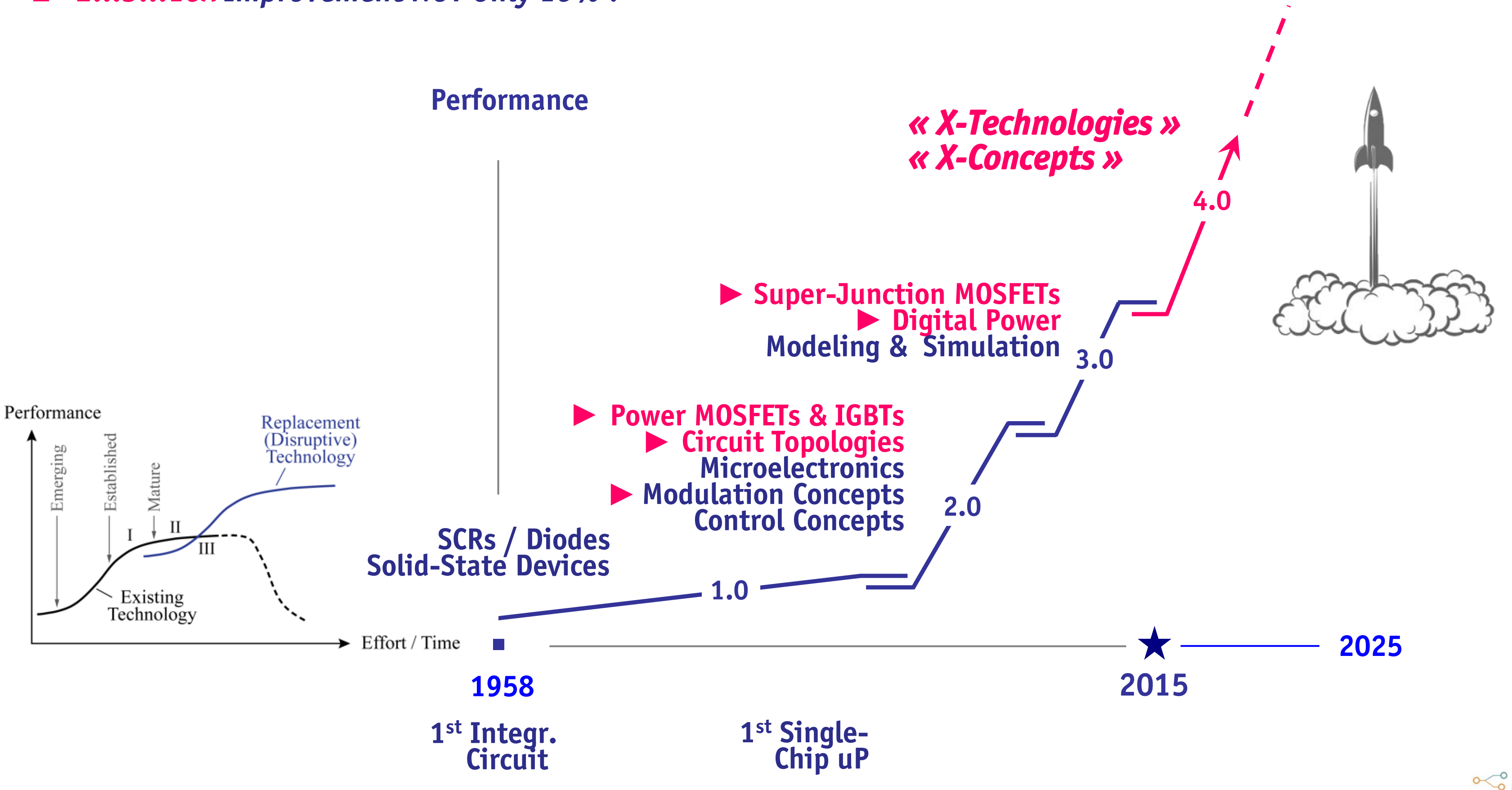


- Power Density [kW/dm^3]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h^{-1}]

- Manufacturability
- Recyclability / Sustainability
- Networked / IIoT

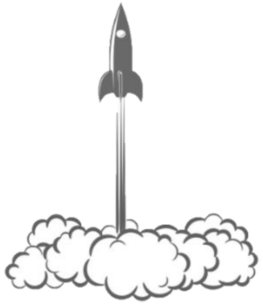
S-Curve of Power Electronics

- « 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*

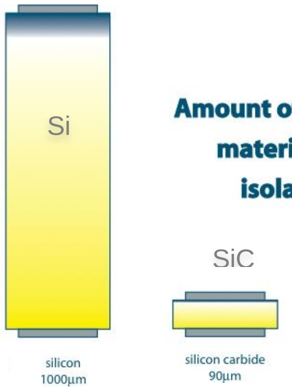
Low $R^*_{DS(on)}$ High-Voltage Devices

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

Source: www.evincetechnology.com

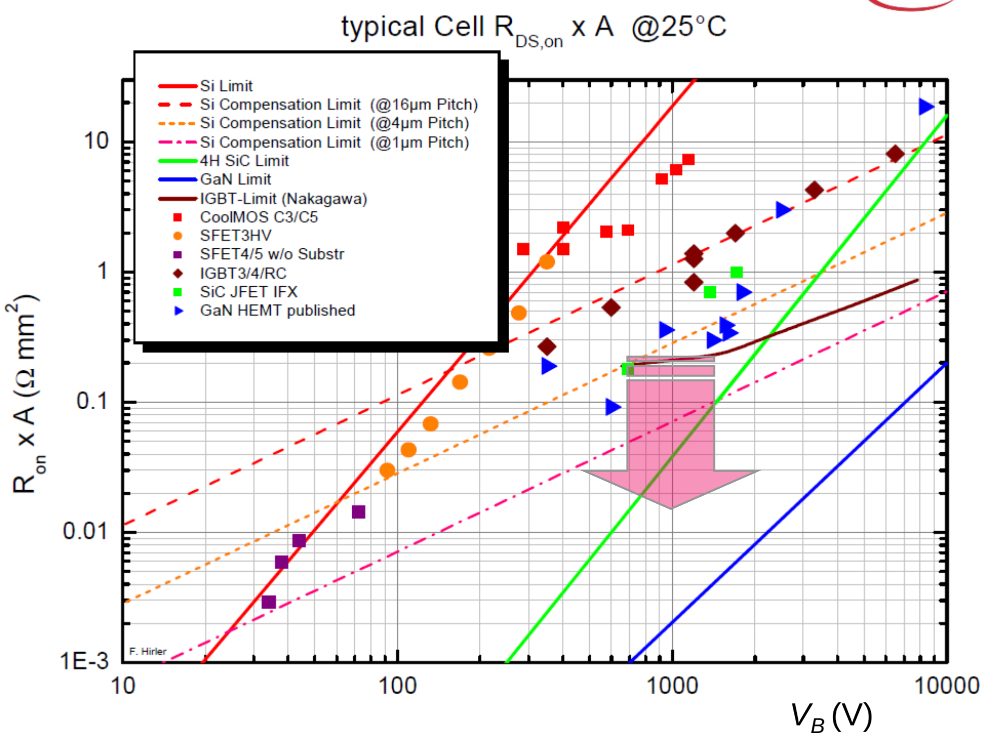
$$R^*_{on} = \frac{4V_B^2}{\varepsilon \mu_n E_C^3} \leftarrow$$

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



Amount of semiconductor material needed to isolate10,000V

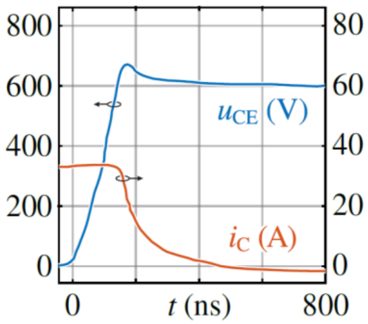
Source: Infineon



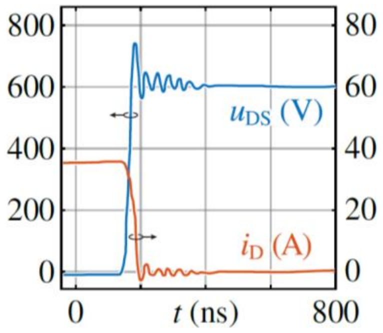
- High Voltage Unipolar (!) Devices → Excellent Sw. Performance / High Power Density

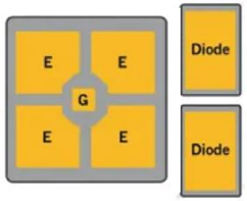
Si vs. SiC Switching Behavior

- *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: 98.8 mm² + 39.4 mm²

Source: Infineon

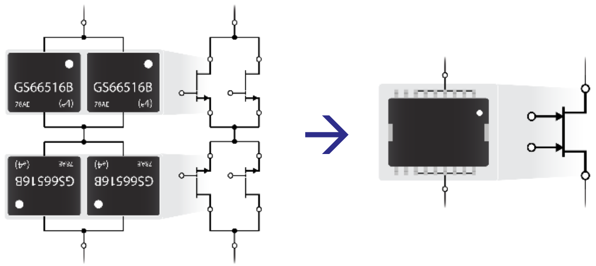
1200V 100A
Die Size: 25.6 mm²

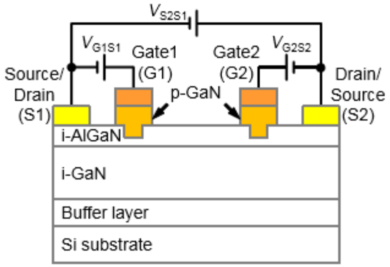
Source: Cree

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

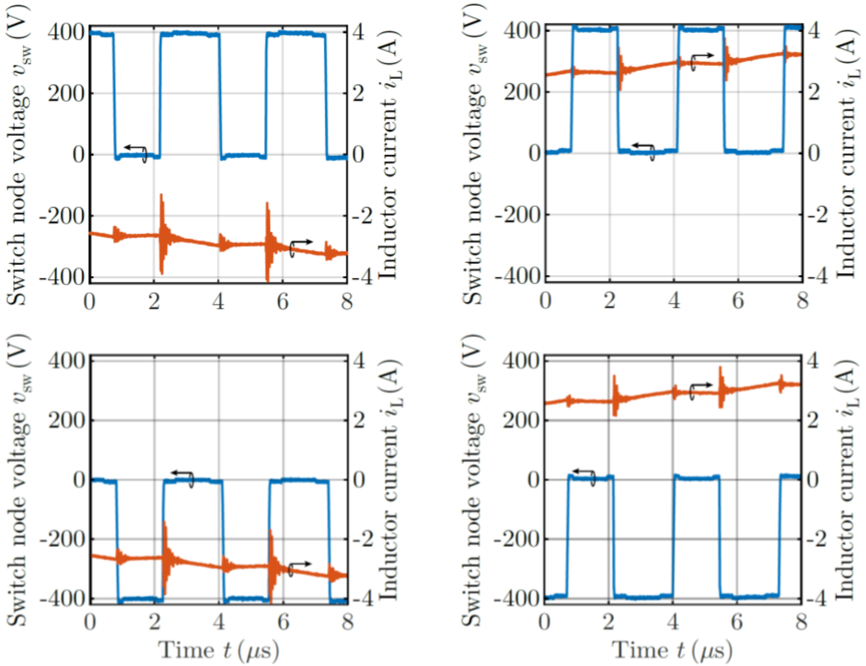
Monolithic 600V GaN Bidirectional/Bipolar Switch

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



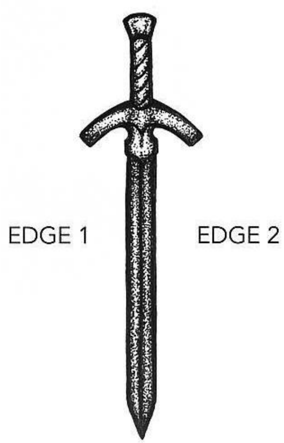


Source: Panasonic ideas for life



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

Challenges

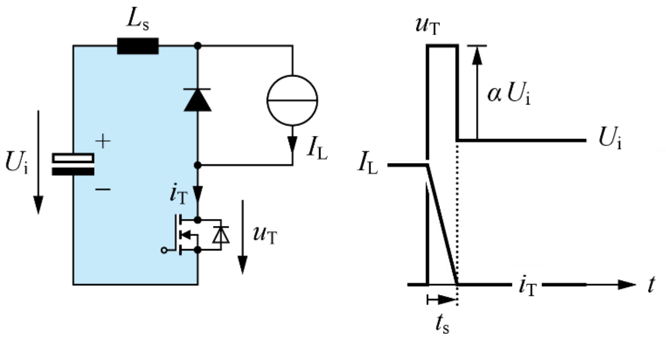


Circuit Parasitics

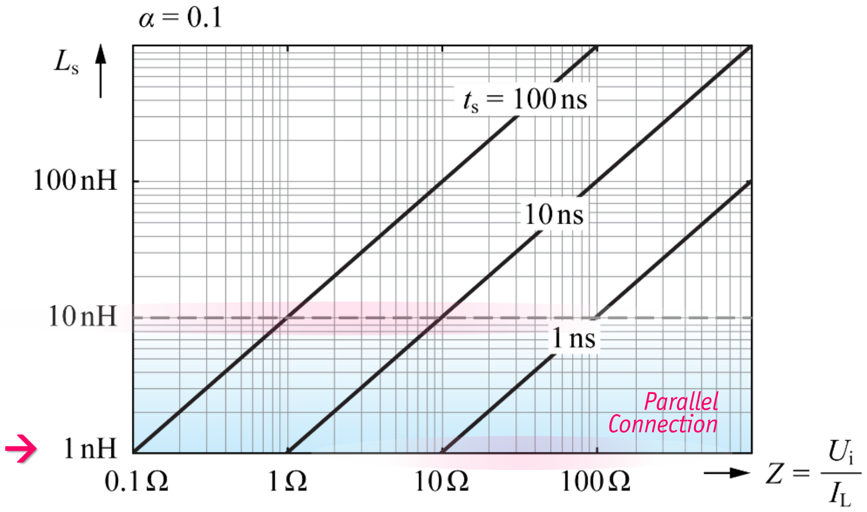
$$L\frac{di}{dt} = u$$

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

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



→

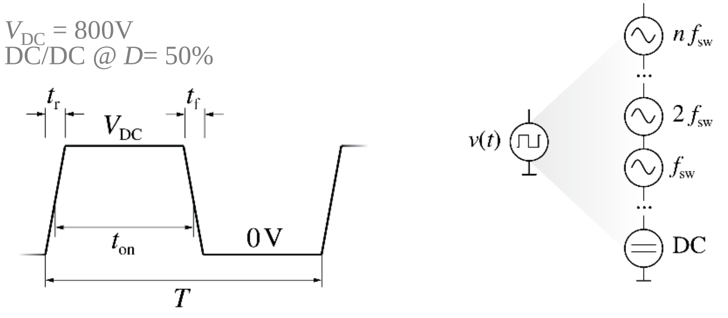


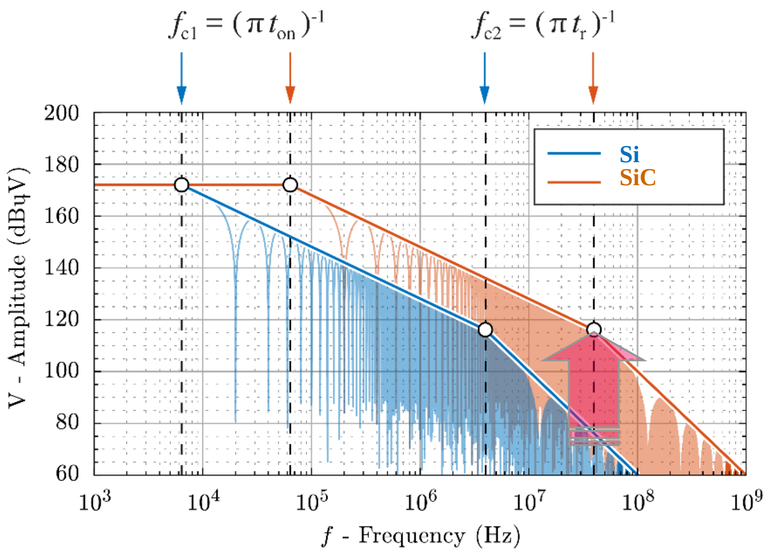
- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents (Z-Matching)*

Si vs. SiC EMI Emissions

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

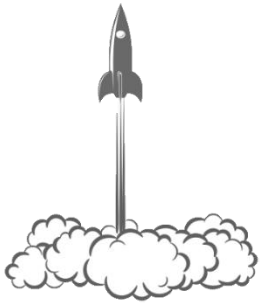
f_S= 10 kHz & 5 kV/us for (Si IGBT)
f_S= 100 kHz & 50 kV/us for (SiC MOSFET)





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

X-Technology

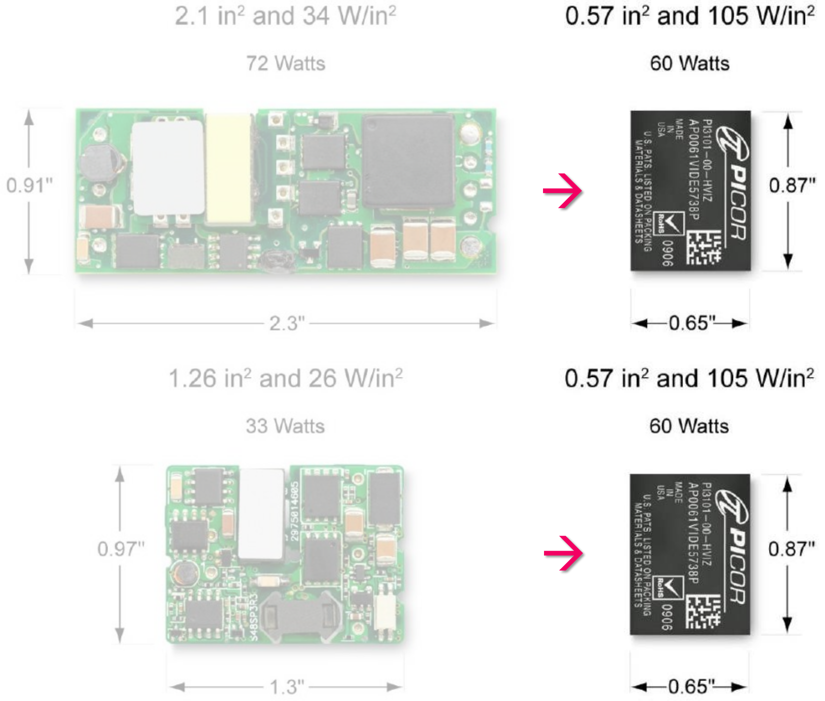


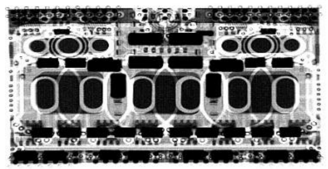
3D-Packaging / Integration

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 Fibers*
- *Automated Manufacturing*
- *Recycling (?)*

Source: VICOR





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

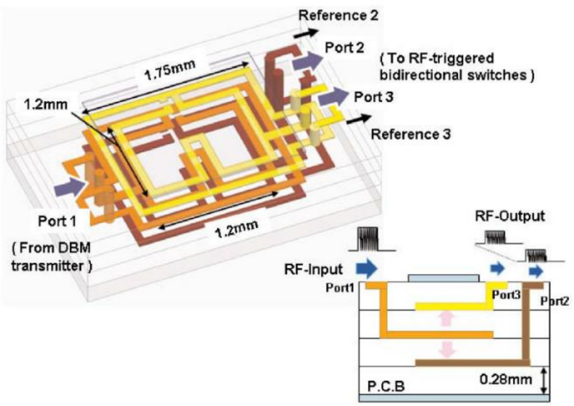
Monolithic 3D-Integration

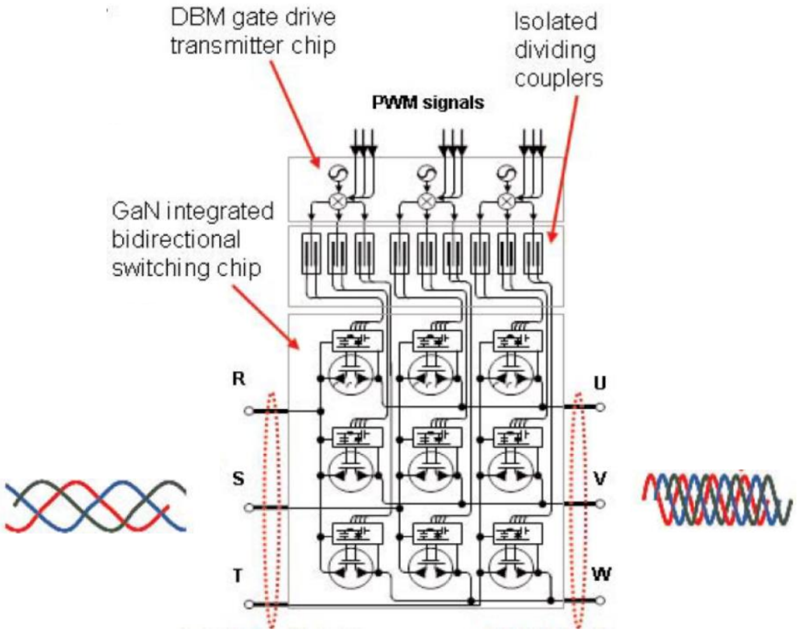
Source: Panasonic ISSCC 2014

- *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 (600 V, 10 A – 5 kW Motor)*

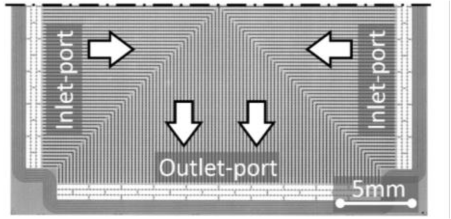
5.0GHz Isolated (5kVDC) Dividing Coupler

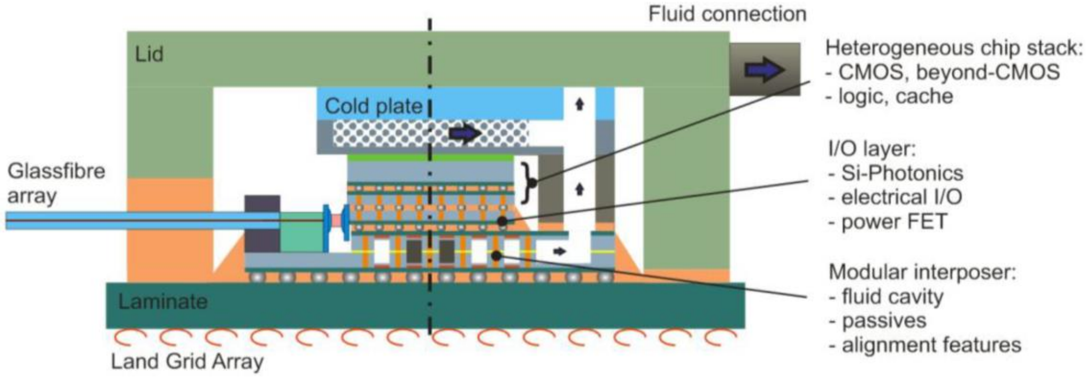


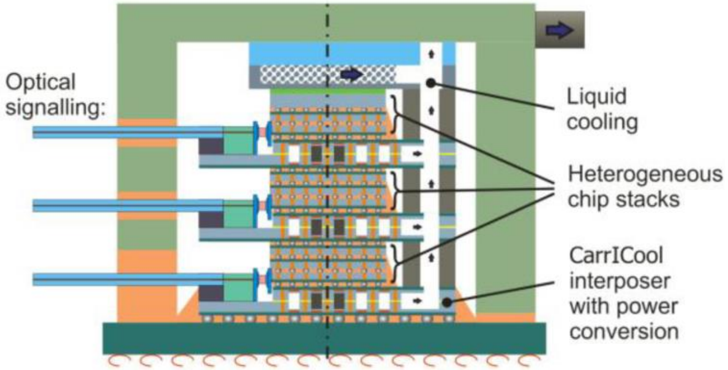


Remark Future uP Chip-Stack Packaging

- *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*



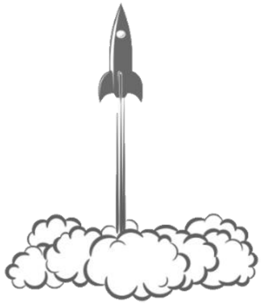




- *Interposer Supporting Optical Signaling / Volumetric Heat Removal / Power Conversion*

CarrICool
EU FP7 Project

X-Technology

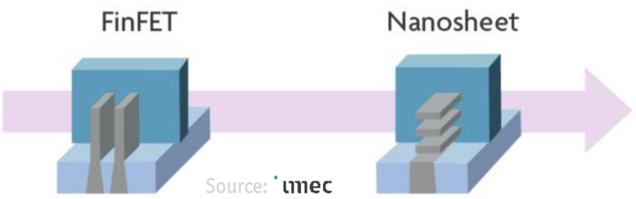


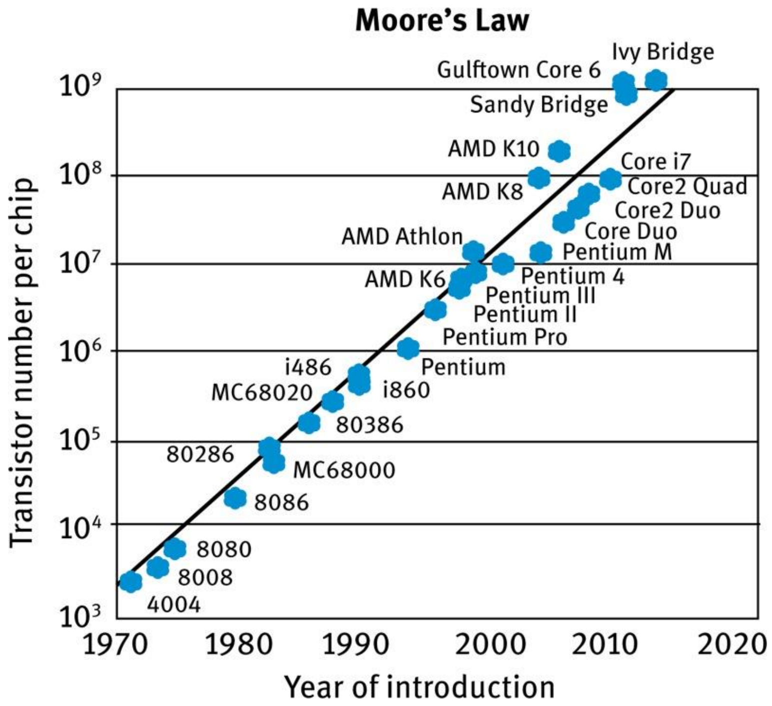
Digital Signal Processing

Digital Signal / Data Processing

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

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

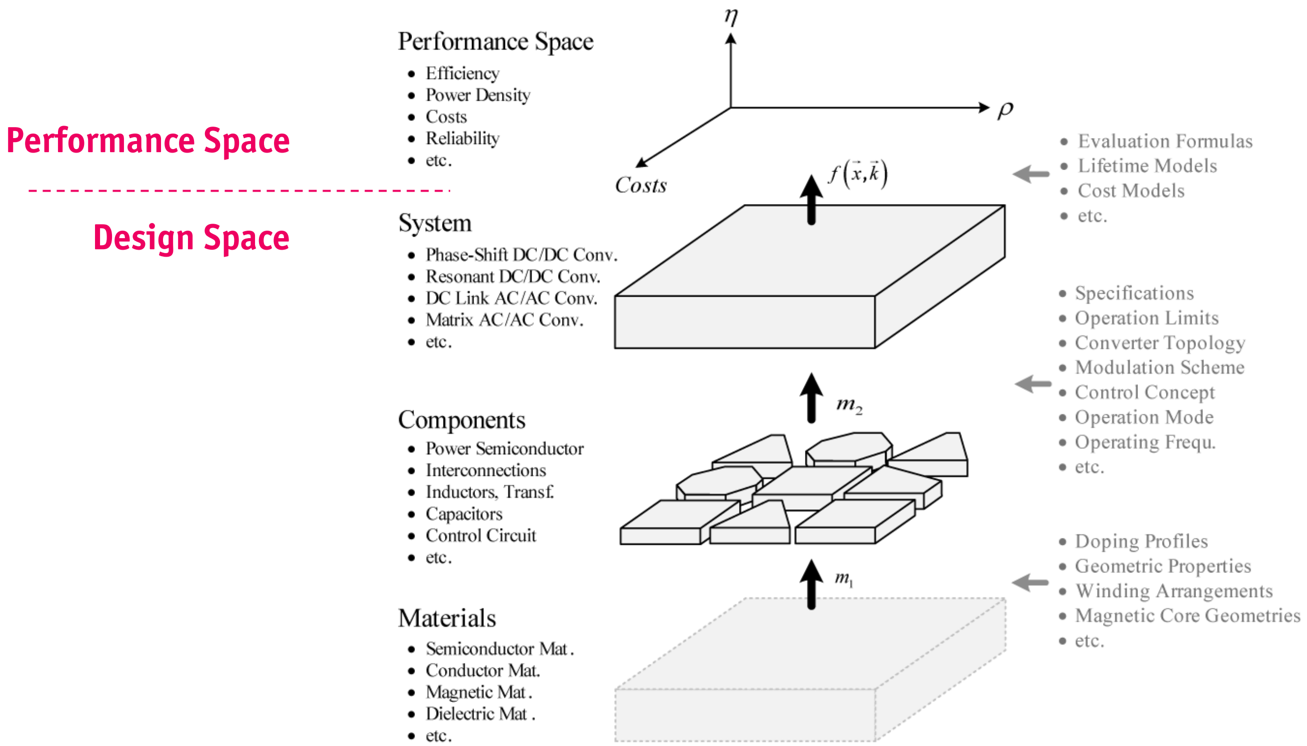




Source: Ostendorf & König /DeGruyter

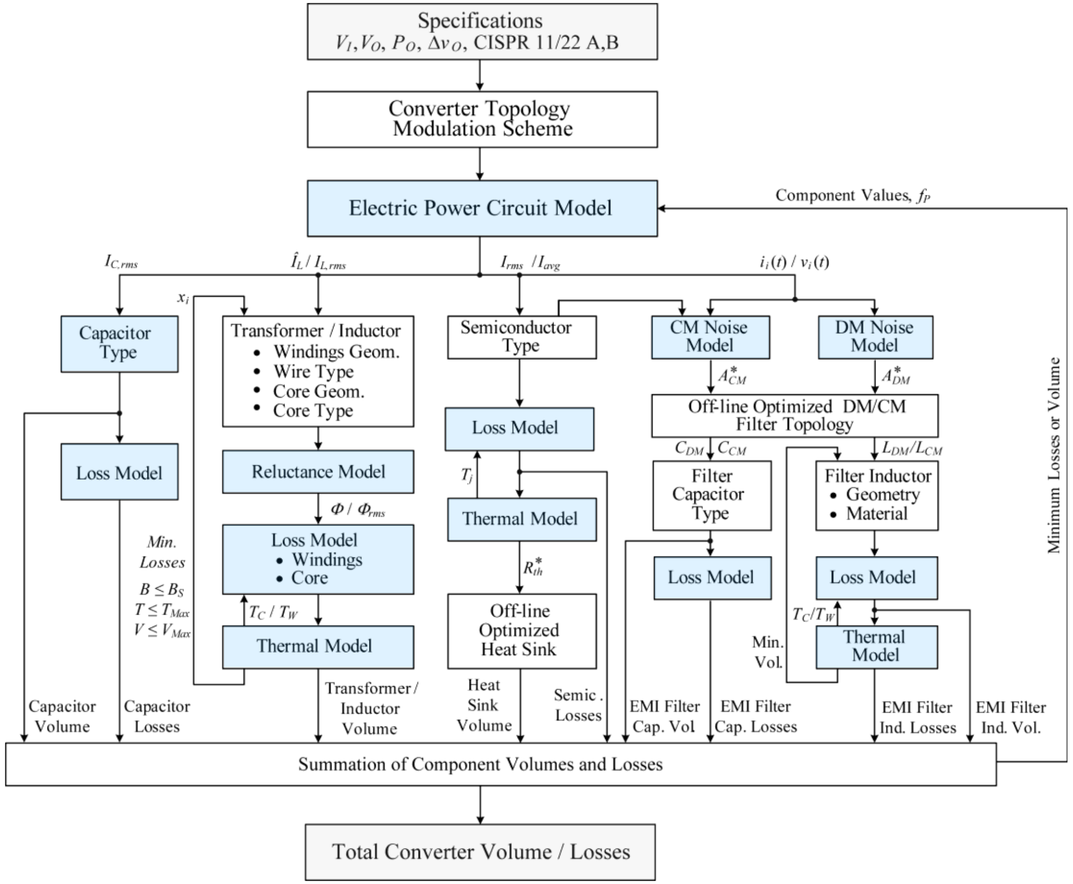
- *AI-Based Design & Fully Digital Control of Complex Systems*
- *Distributed Intelligence / Digital Twins / Industrial IoT (IIoT)*

Abstraction of Power Converter Design

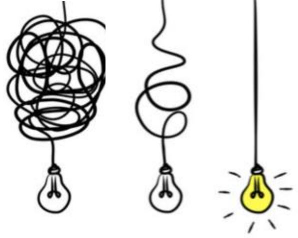


- *Mapping of "Design Space" into Converter "η-ρ-σ-Performance Space"*
- *Design Space — Set of Selected Design- & Operating Parameters, Materials, Components, Topology, etc.*

Multi-Objective Optimization

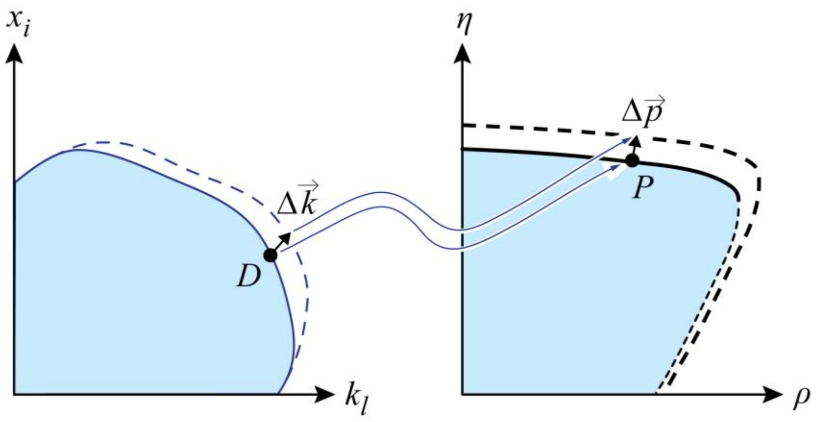


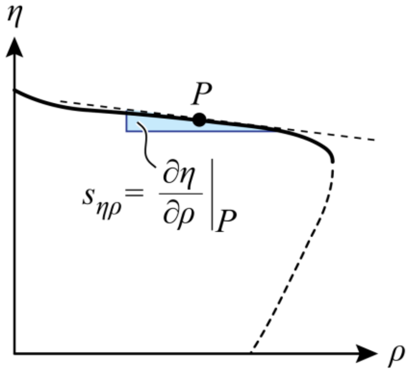
- *"Digital Twin"*
- *Multi-Objective Optimization* → ***Best Utilization of All Degrees of Freedom*** **(!)**



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

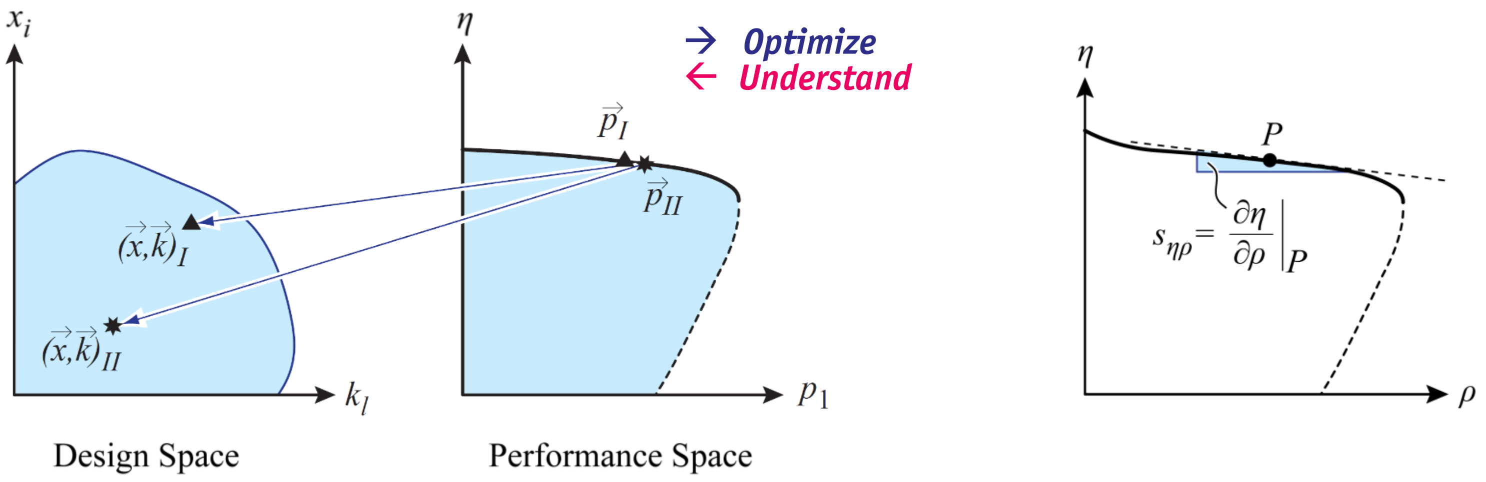




- Clarifies Sensitivity $\Delta\vec{p}\ /\ \Delta\vec{k}$ to Improvements of Technologies
- Trade-Off Analysis

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

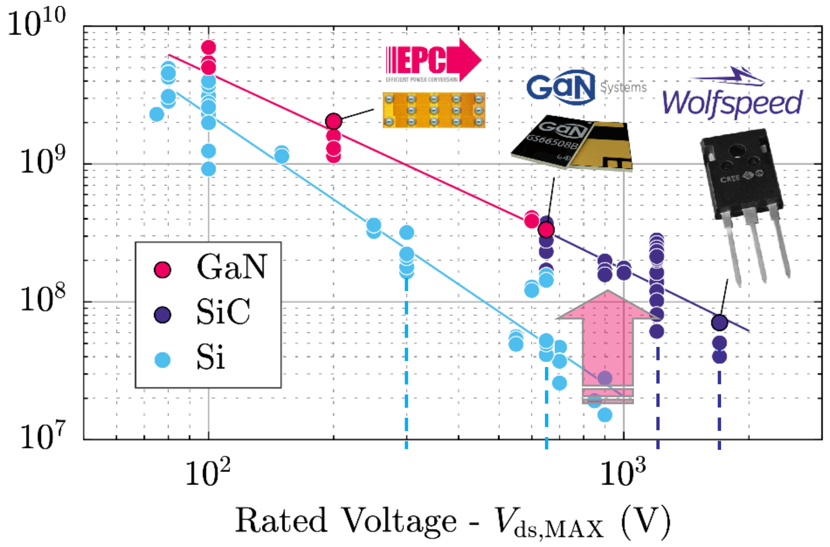
Modularization
Synergetic Association
Functional Integration
Hybridization
Decentralization

X-Concept  *Modularization*

SiC/GaN Figure-of-Merit

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

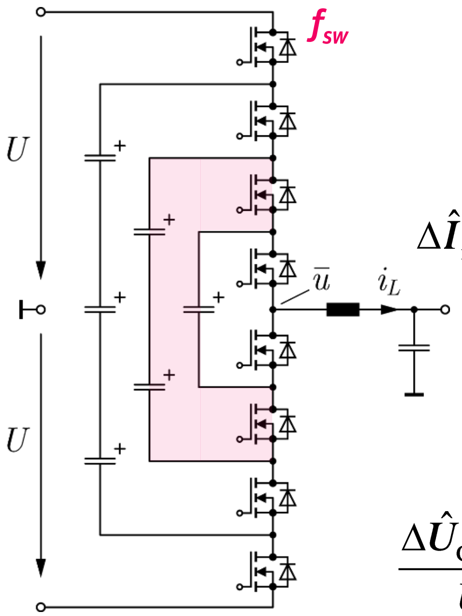
$$\mathrm{FOM} = \frac{1}{R_{\mathrm{ds,on}} Q_{\mathrm{oss}}}$$



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

Scaling of Multi-Cell/Level Concepts

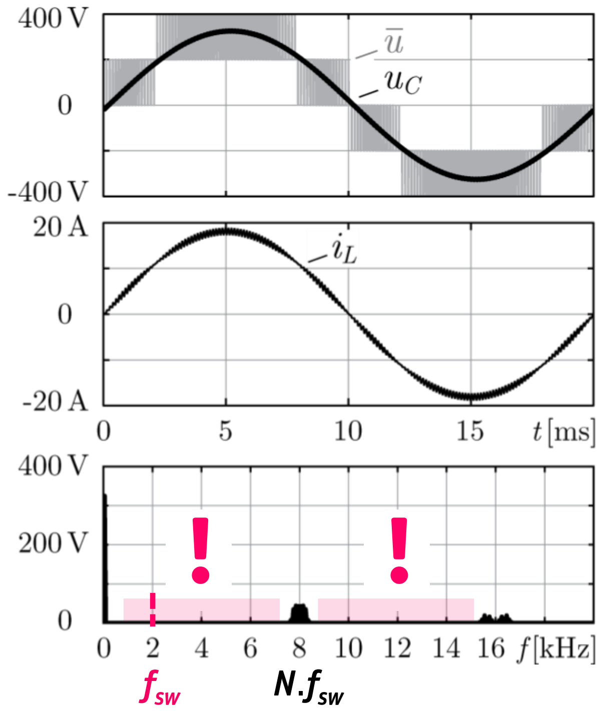
- Reduced Ripple @ Same (!) Switching Losses
- Lower Overall On-Resistance @ Given Blocking Voltage
- Application of LV Technology to HV



$$\frac{U}{8 f_s L}$$

$$\Delta \hat{I}_{\max,N} = \frac{1}{N^2} \Delta \hat{I}_{\max,N=1}$$

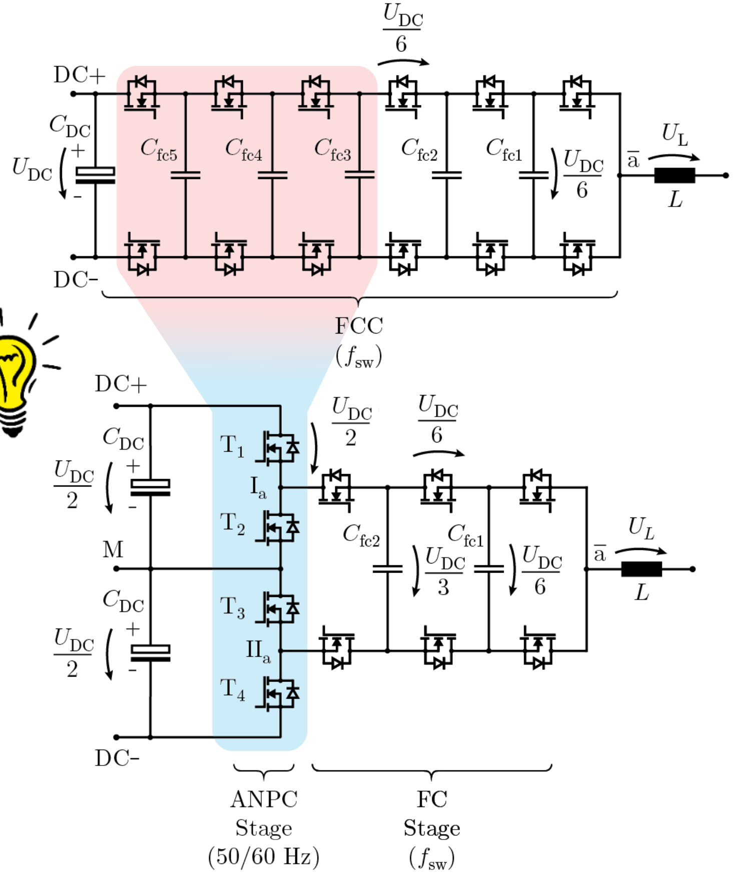
$$\frac{\Delta \hat{U}_{C,\max,N}}{U} = \frac{\pi^2}{32} \left(\frac{f_O}{f_S}\right)^2 \frac{1}{N^3}$$

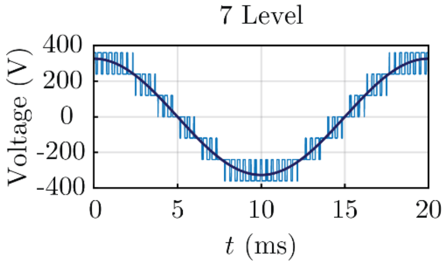


- Scalability / Manufacturability / Standardization / Redundancy

3-Φ Hybrid Multi-Level Inverter

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





★ *99.35%*
2.6 kW/kg
56 W/in³

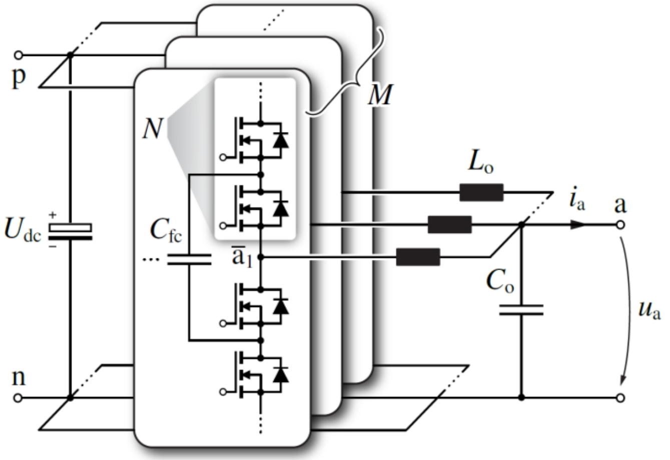
- *200 V Si → 200 V GaN Technology Results in 99.5% Efficiency*

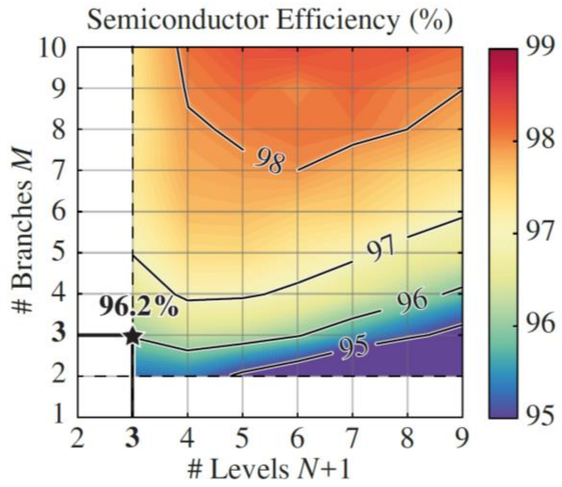
4.8MHz GaN Half-Bridge Phase Module

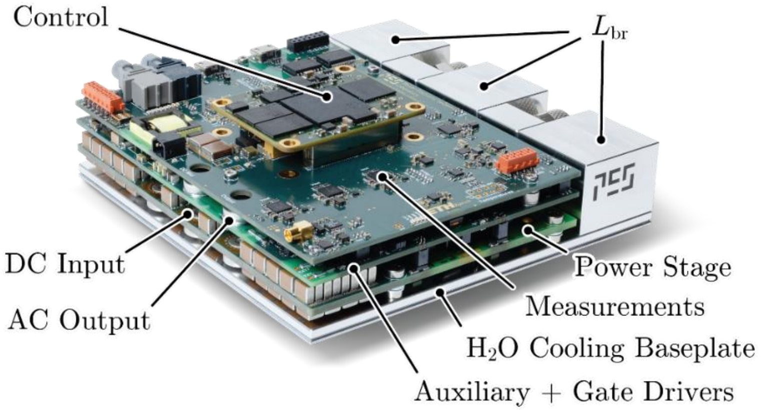
- *Combination of Series & Parallel Interleaving*

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

★ 25 kW/dm³







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

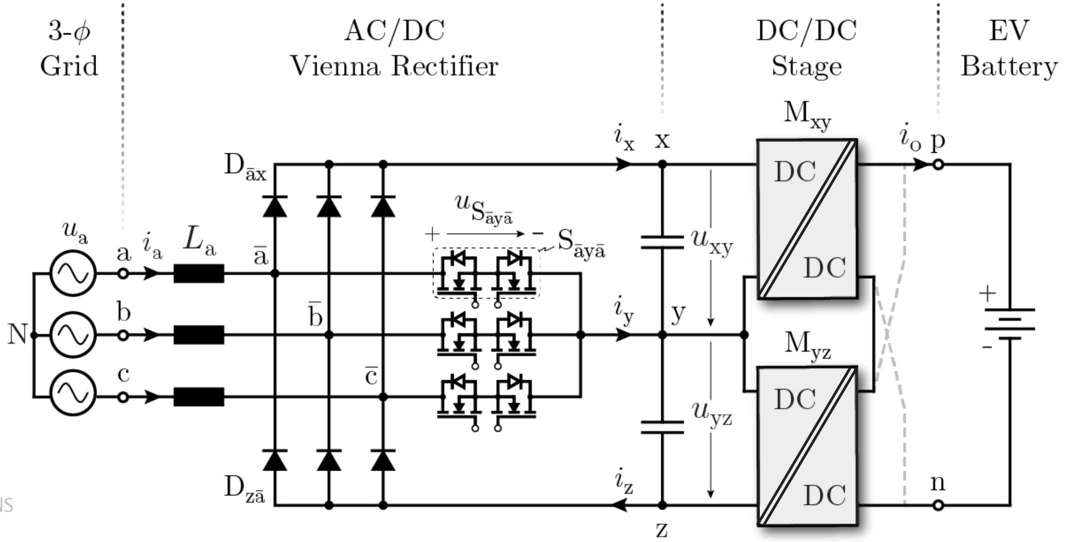
X-Concept

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

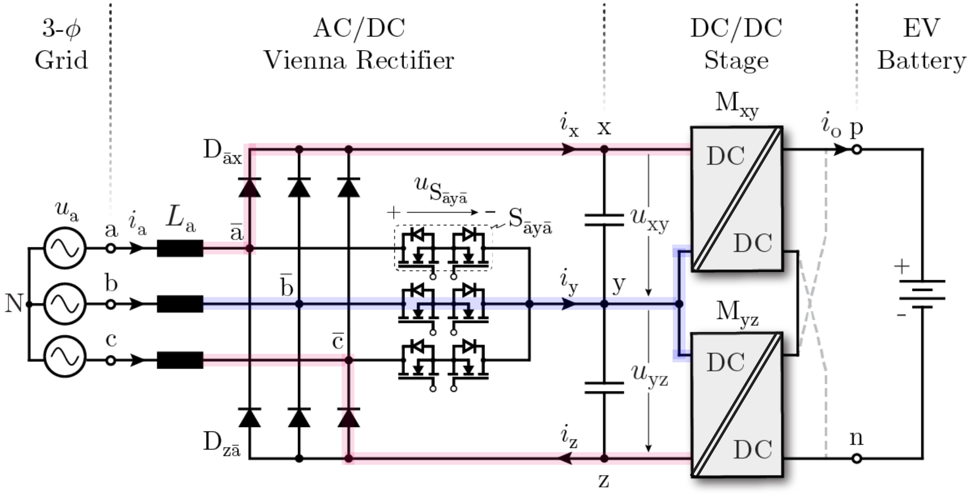


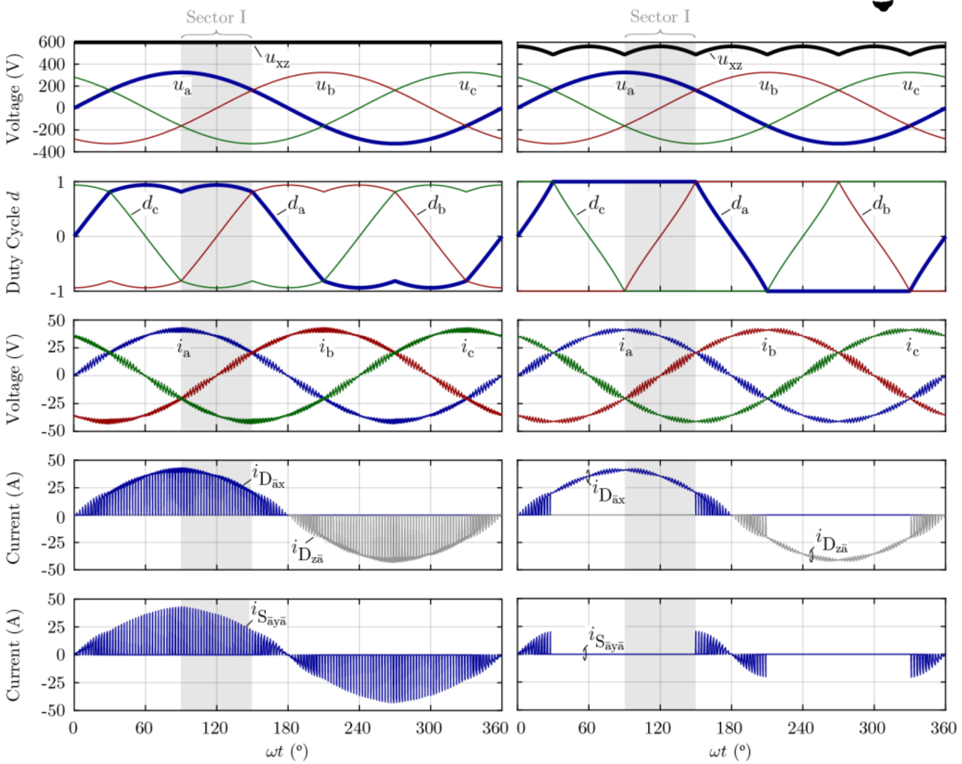
→ *Conventional / Independent* *__OR__* *"Synergetic Control" of Input & Output Stage*

Synergetic Association 1/2

- *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%*

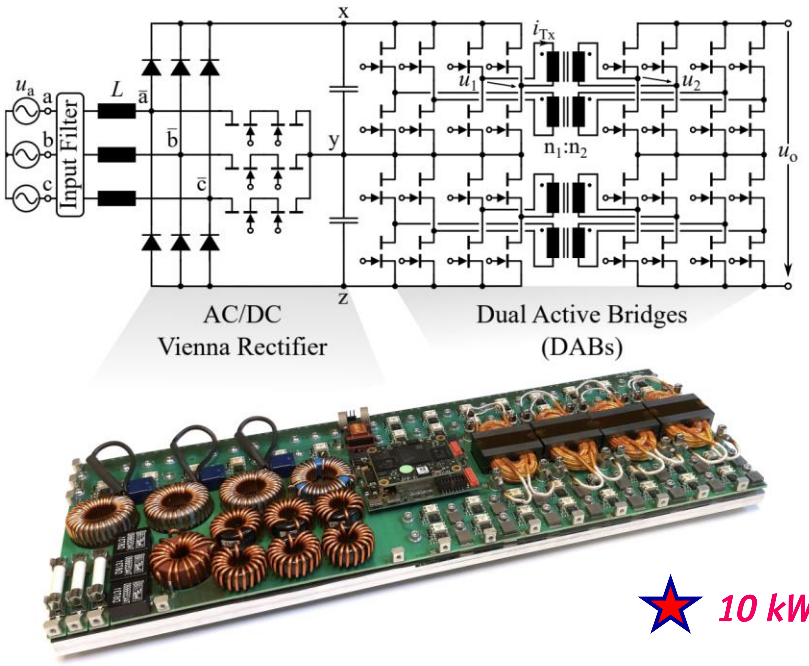




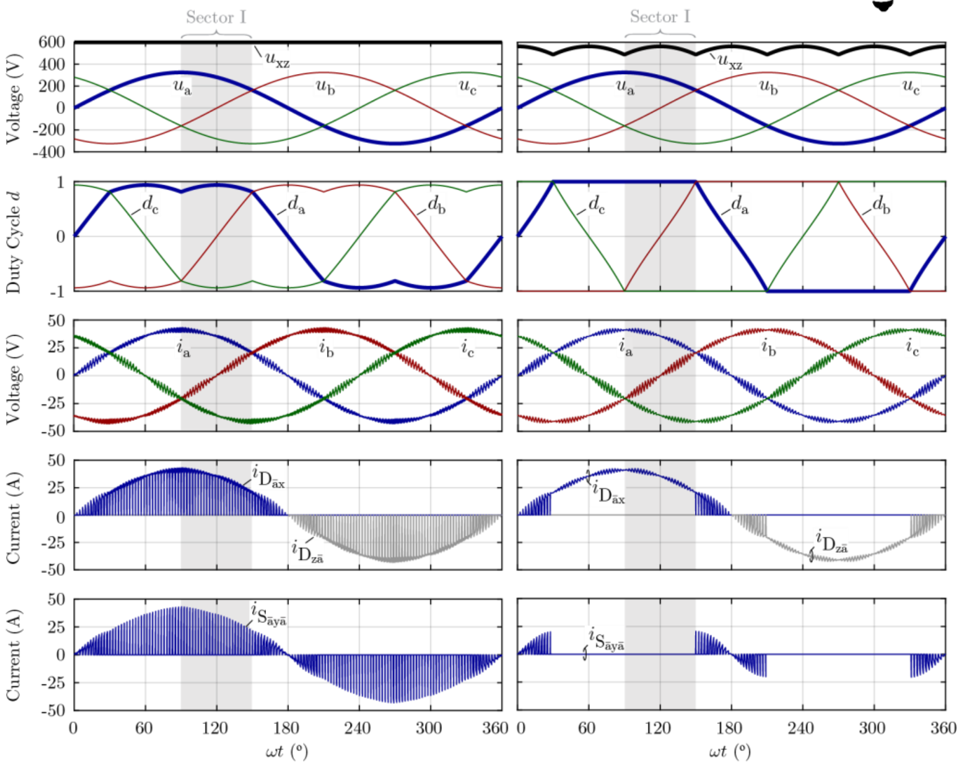
- *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

Synergetic Association 2/2

- *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%*



10 kW/dm³



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

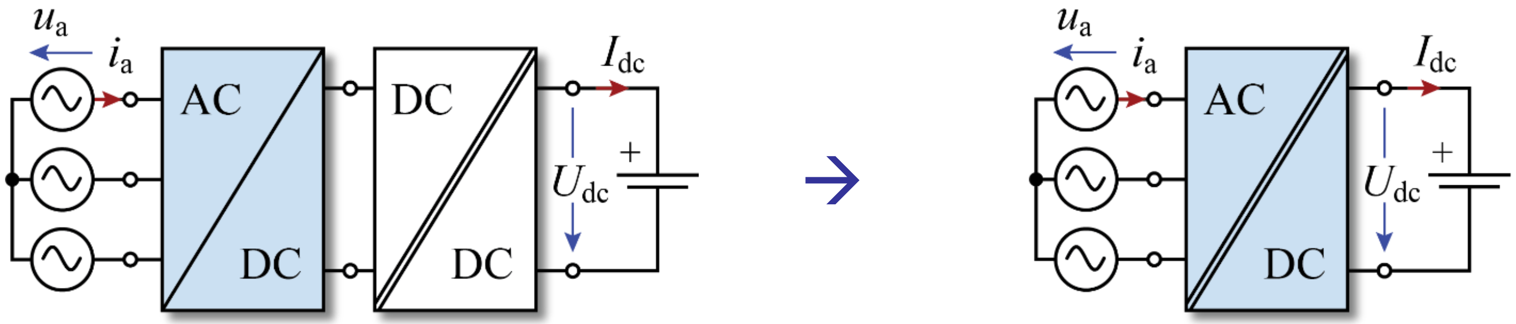
X-Concept

Functional Integration

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



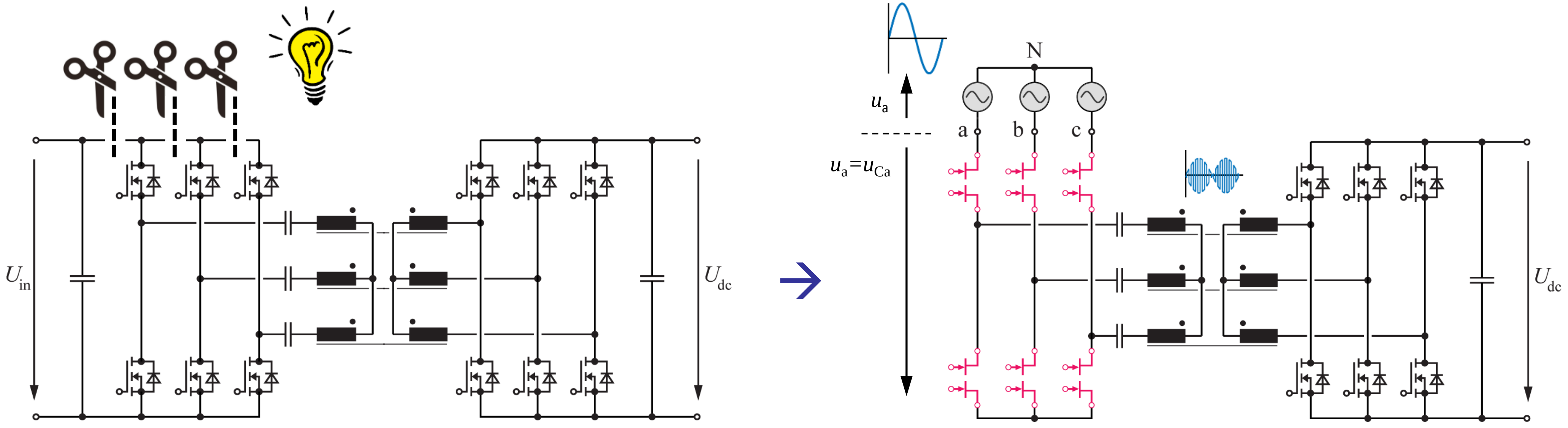
320...530 V_{rms} Line-to-Line

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 1/2

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

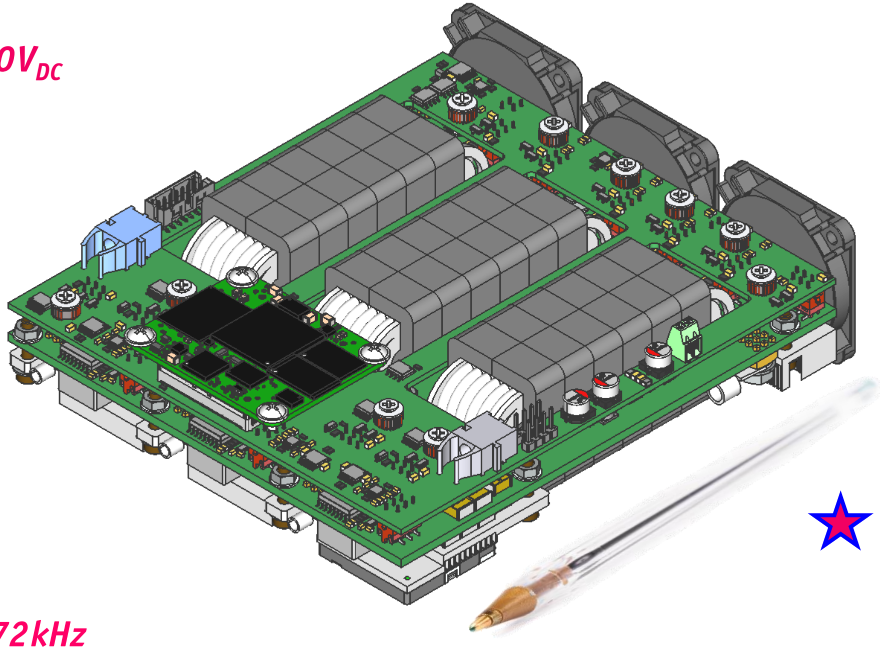


- Voltage Stress on Prim.-Side AC Switches Determined by Peak Value of Grid PHASE Voltage (!)
- Bidirectional Power Flow

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

- 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 400V_{AC}
- DC Output 250...450V_{DC}
- Rated Output Power 6.6kW

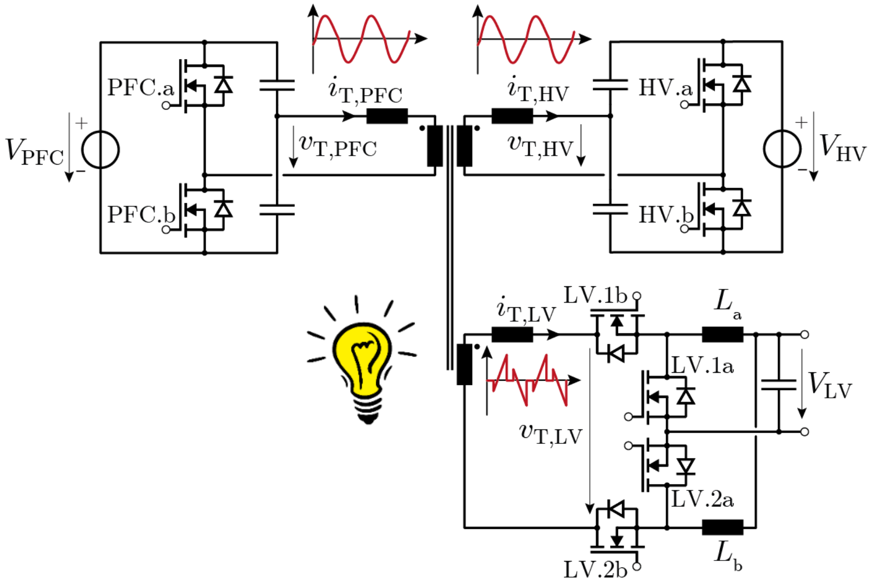


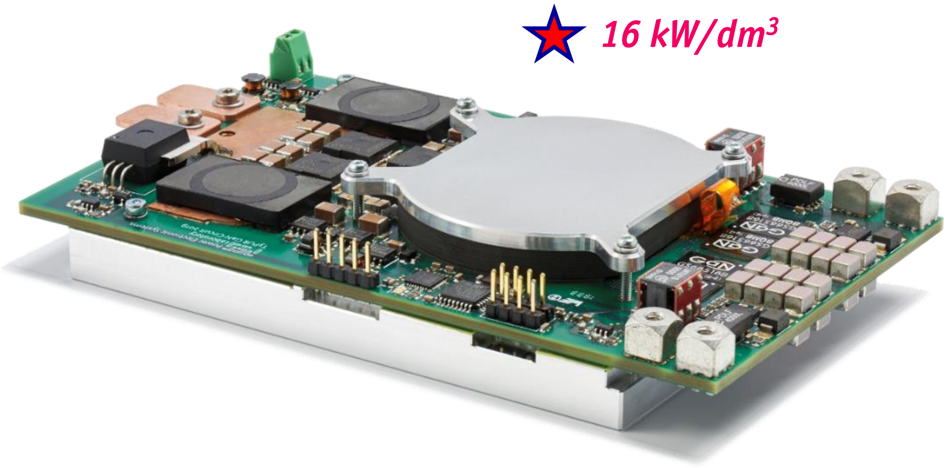
★ 98% (typ.) @ 8kW/dm³

- Prim.-Side Sw. Frequency f_{sw}= 72kHz
- 14.5 x 13.1 x 3.7cm³/ 5.7 x 5.2 x 1.5in³
- 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 = 3.6 kW*



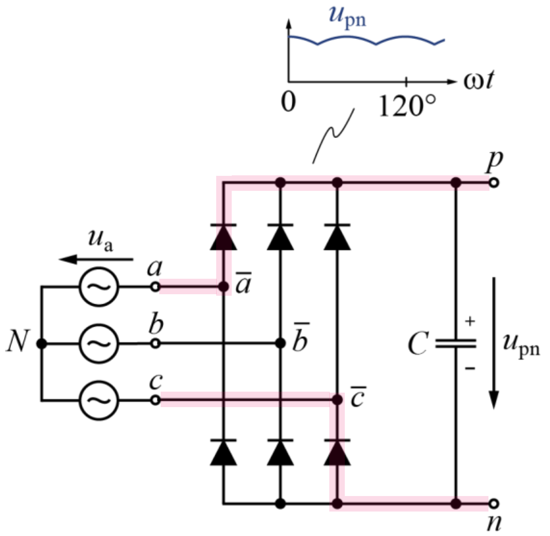


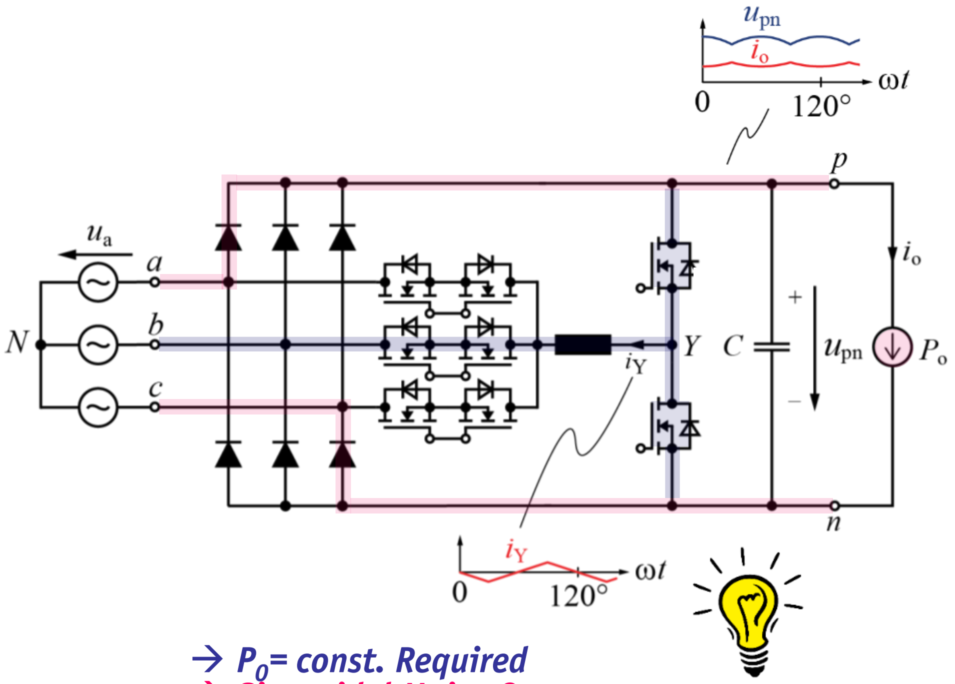
- *Peak Efficiency of 96.5% in Charge Mode / 95.5% in Drive Mode*
- *PCB-Based Windings / No Litz Wire Windings → Fully Automated Manufacturing*

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*



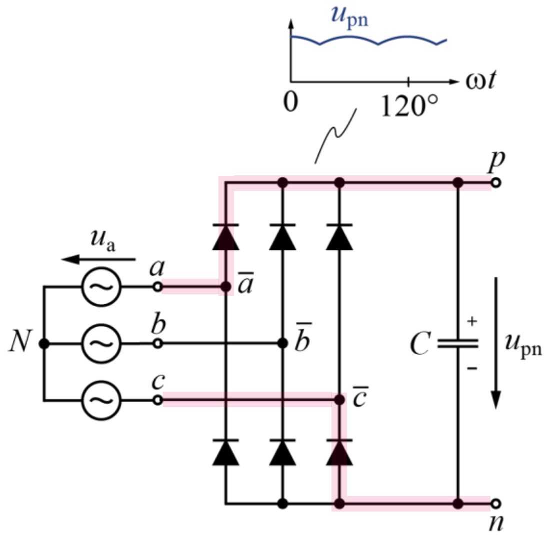


- *Non-Sinusoidal Mains Current*

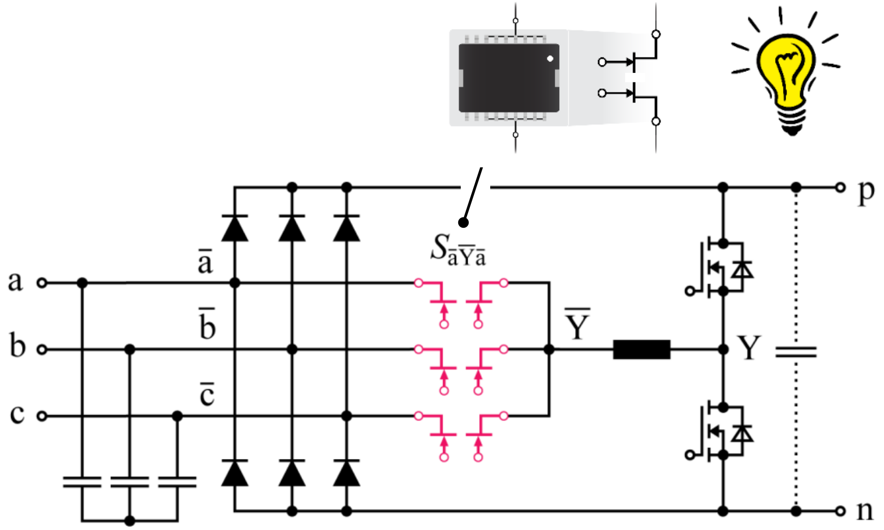
→ *P_0= const. Required*
→ *Sinusoidal Mains Current*
→ *NO (!) DC Voltage Control*

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*



→



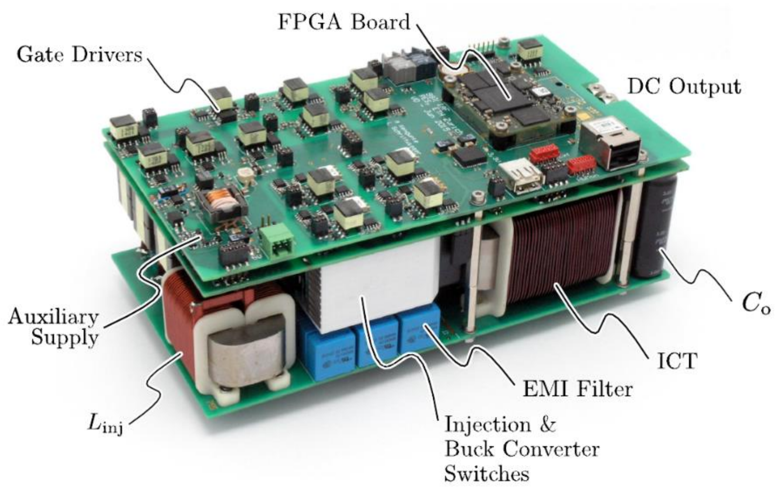
- *Non-Sinusoidal Mains Current*

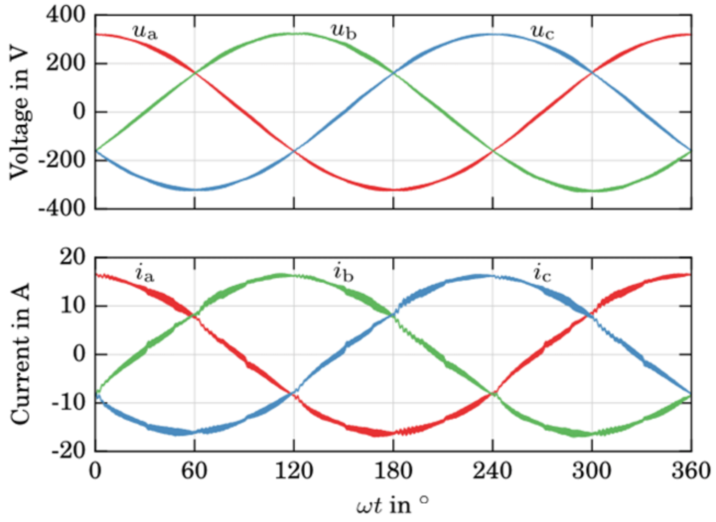
→ *P_0= const. Required*
→ *Sinusoidal Mains Current*
→ *NO (!) DC Voltage Control*

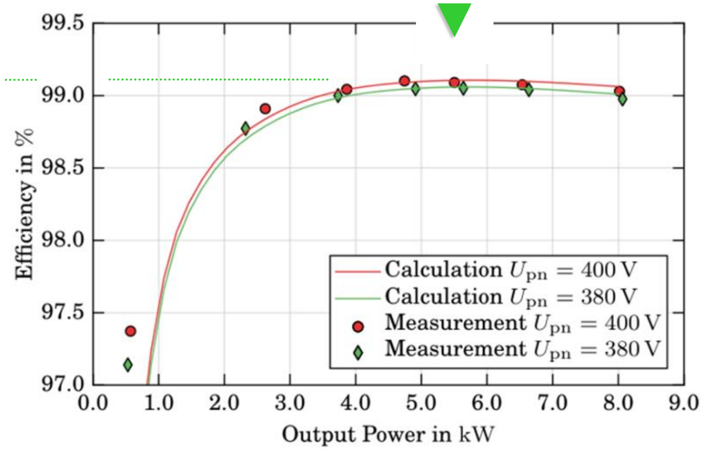
IAF PFC Rectifier & Buck Converter Demonstrator

- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current $THD_I \approx 2\%$ @ Rated Load*
- *Power Density $\rho \approx 4\,kW/dm^3$*

$P_0 = 8\,kW$
$U_N = 400V_{AC} \rightarrow U_0 = 400\,V_{DC}$
$f_S = 27\,kHz$





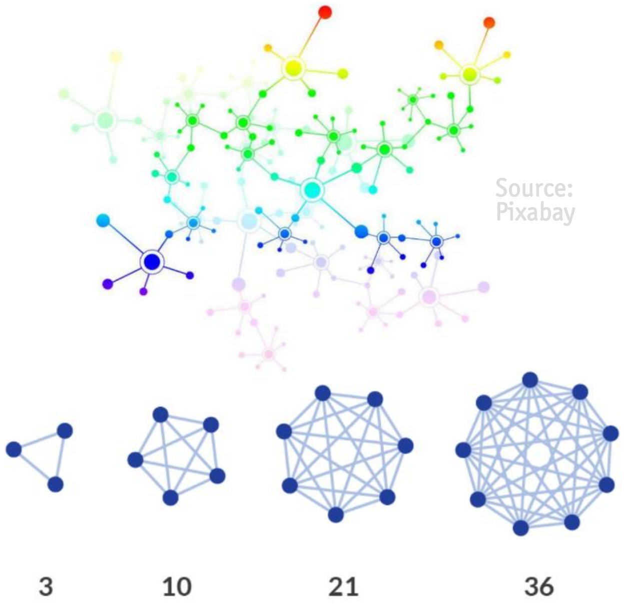


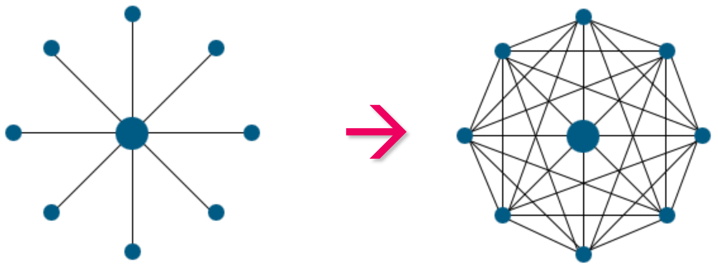
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck Output Stages*
- *Controlled Output Voltage*

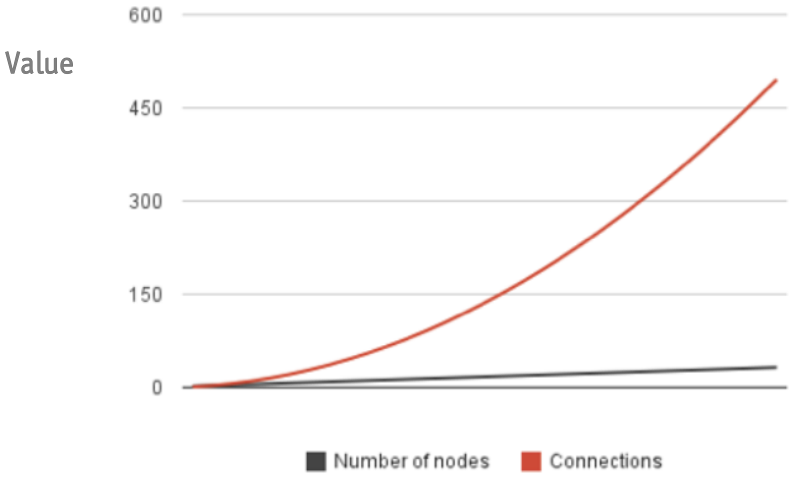
X-Concept  *Decentralization*

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)

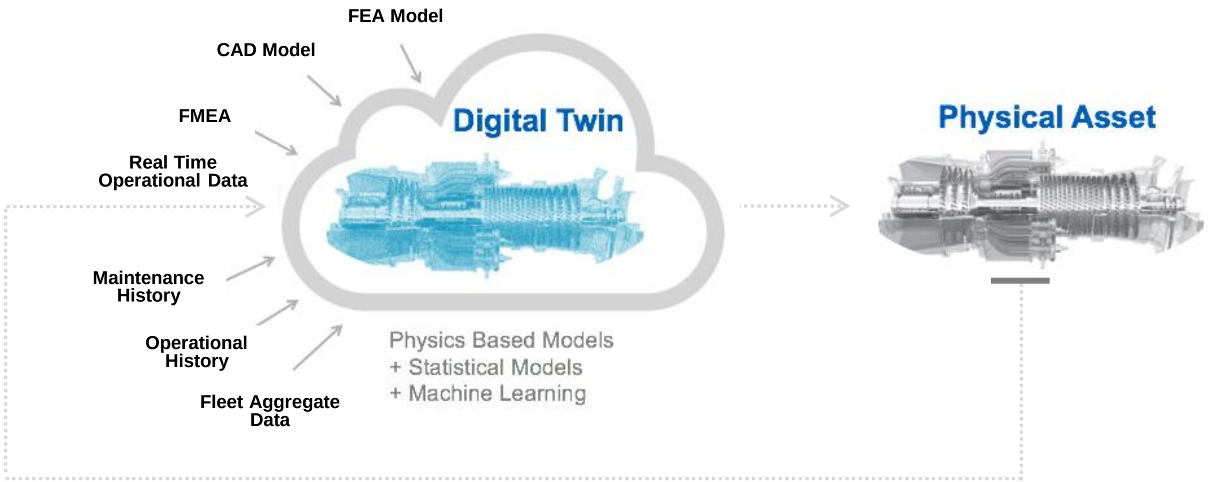






IIoT in Power Electronics

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



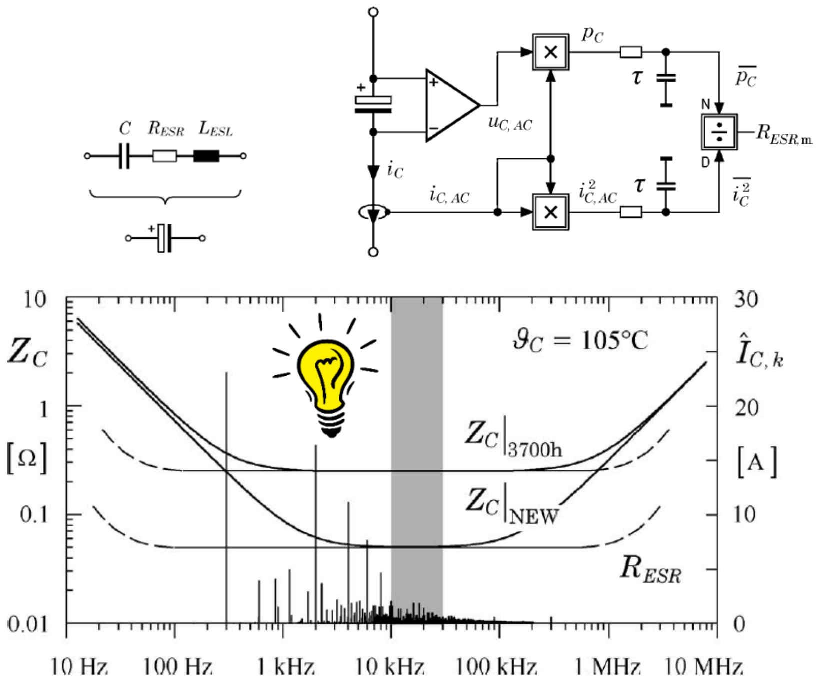
Source: www.railwayage.com

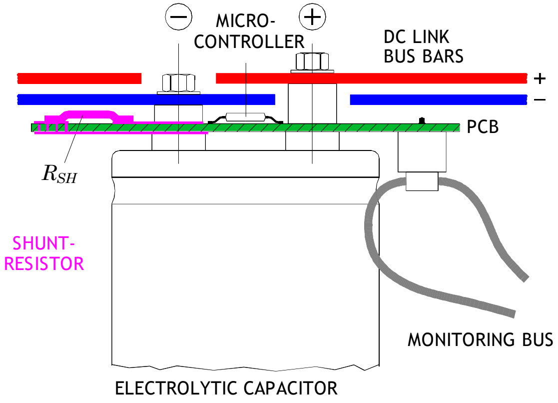
- *Requires Proper Interfaces for Models & Automated Design*
- *Model of System´s Past/Current/Future State → Design Corrections / Predictive Maintenance etc.*

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

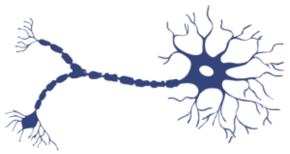
TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria
Source: Prof. Ertl
TU Vienna, 2011





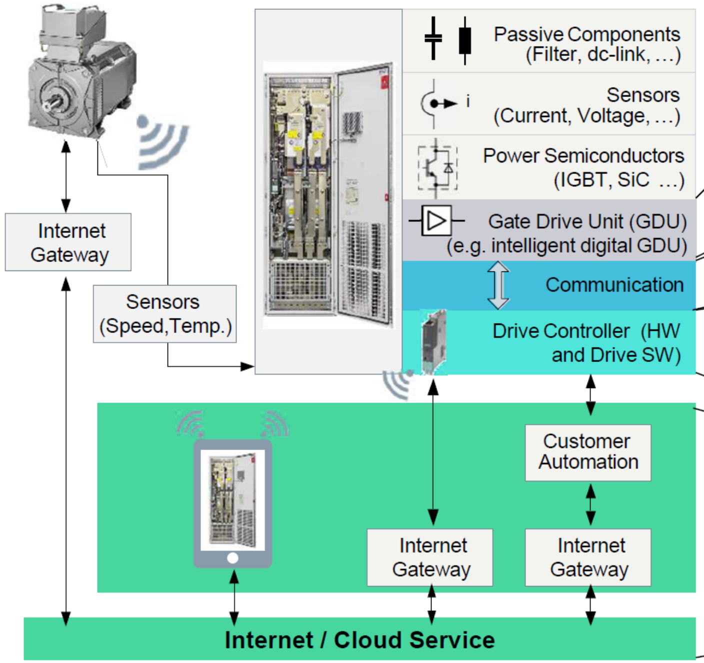
- Possible Integration into Capacitor Housing or PCB
- Additionally features Series Connect. Voltage Balancing

Smart Inverter Concept



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

Source: R. Sommer
SIEMENS



Intelligent Gate Drive Unit

- Semiconductor protection (overcurrent, overvoltage, …)
- Collecting and preprocessing of sensor data (current, voltage, temperature, …)
- Semiconductor specific condition monitoring functions

Communication

- Communication protocol instead of on/off signals

Drive Controller

- Observer based condition monitoring functions
- Predictive maintenance functions
- Data Processing and data compression
- Communication to customer automation and/or internet

Internet / Cloud

- Service and commissioning tools
- Algorithms for „Big Data“ analysis
- Smart documentation (e.g. video to support service)
- …

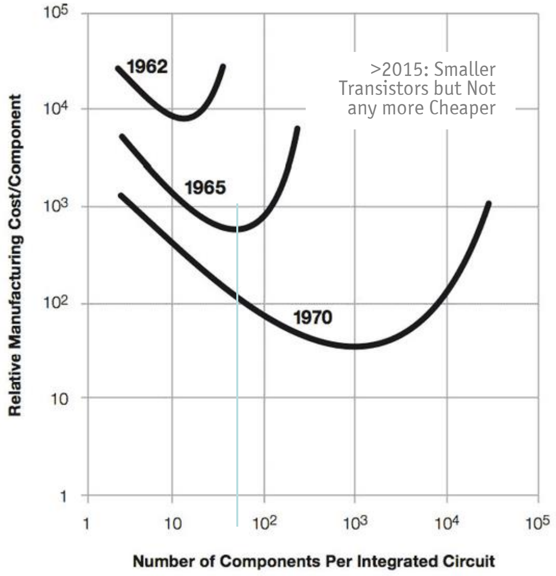
- *On-Line Protection / Monitoring / Optimization on Component | Converter | Drive | Application Level*

Conclusion

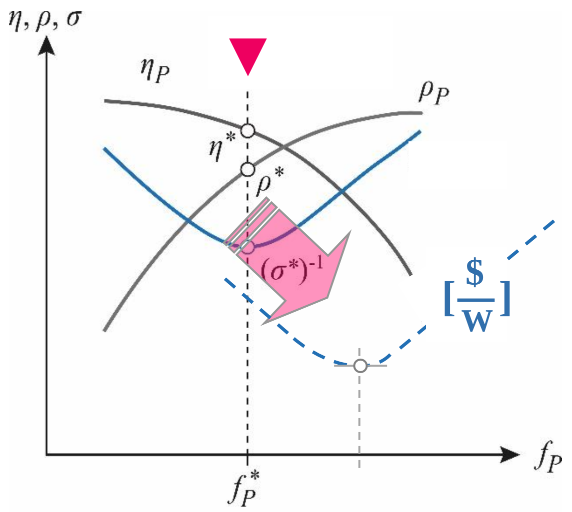
"Moore´s Law" of Power Electronics

- *"Moore´s Law" Defines Consecutive Technology Nodes Based on Min. Costs per Integrated Circuit (!)*
- *Prediction in 1965: Number of Transistors on a Chip will Double Every ≈2 Years w/ Minimal Increase in Cost*

Economy of Scale → ← Lower Yield



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

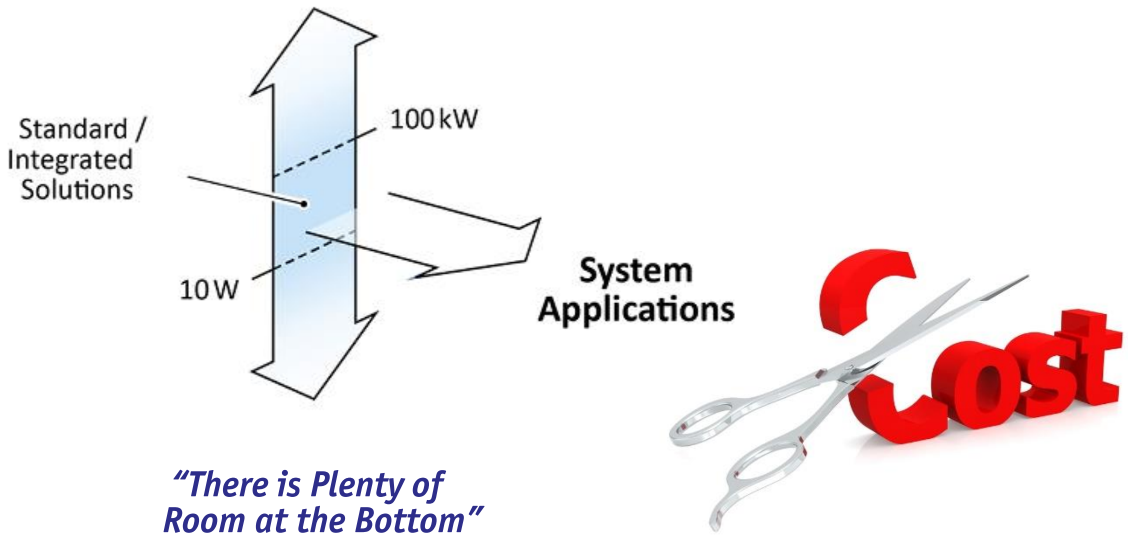


- *Potential Power Density Improvement — Factor 2 ... 5 Until 2030*
- *Definition of "η^*, ρ^*, σ^*, f_P^*– Technology Node" Must Consider Conv. Type / Operating Range etc. (!)*

Future Application / Research Areas

- *WBG Driven Extension to Medium Voltage — There is Plenty of Room at the Top (SSTs, XF EV Charging etc.)*
- *Extreme Cost Pressure for Standardized Solutions (!)*

"There is Plenty of Room at the Top"



"There is Plenty of Room at the Bottom"

- *"There's Plenty of Room at the Bottom" (R. Feynman @ Caltech, 1959) – Monolithic Integr. etc.*
- *Key Importance of Technology Partnerships of Academia & Industry*

Source:
www.roadtrafficsigns.com

Power Electronics → Electronic "Energy" Management

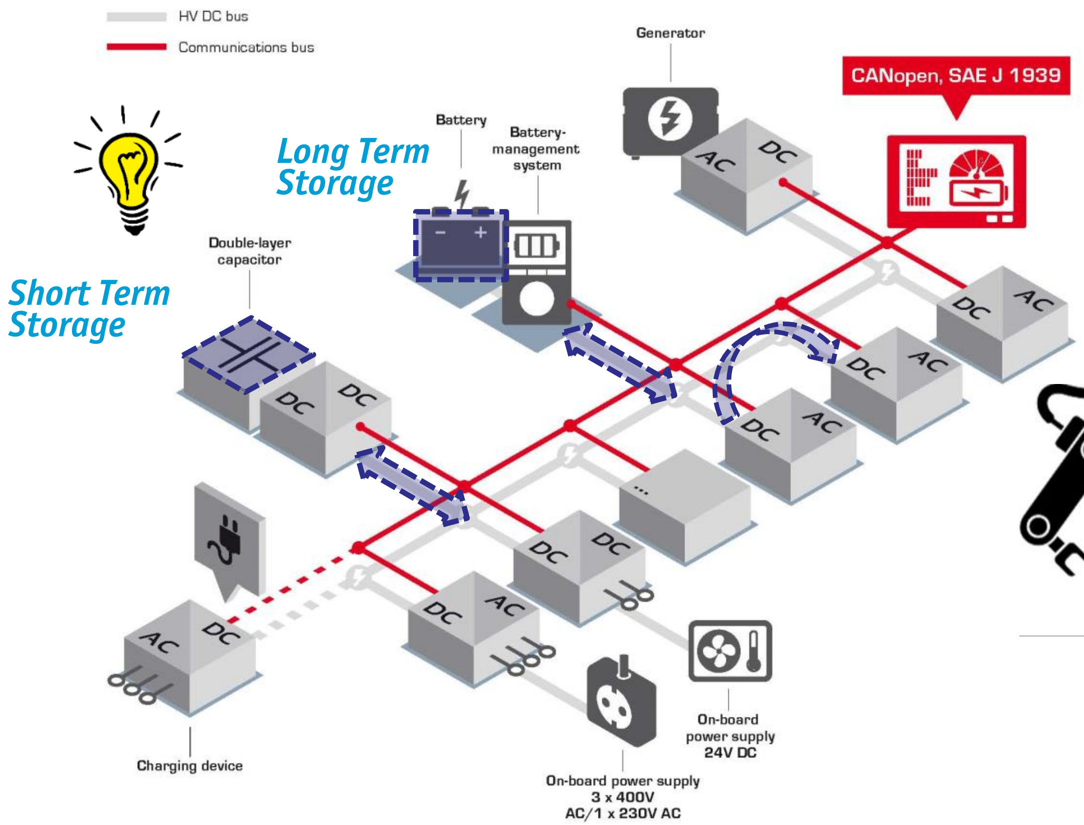
- *Design Considering Converters as Standardized "Integrated Circuits" (PEBBs)*
- *Extend Analysis to Converter Clusters / Power Supply Chains / etc.*

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

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

— *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*

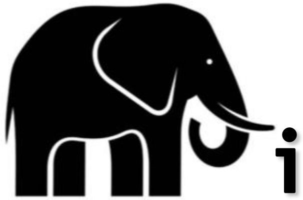


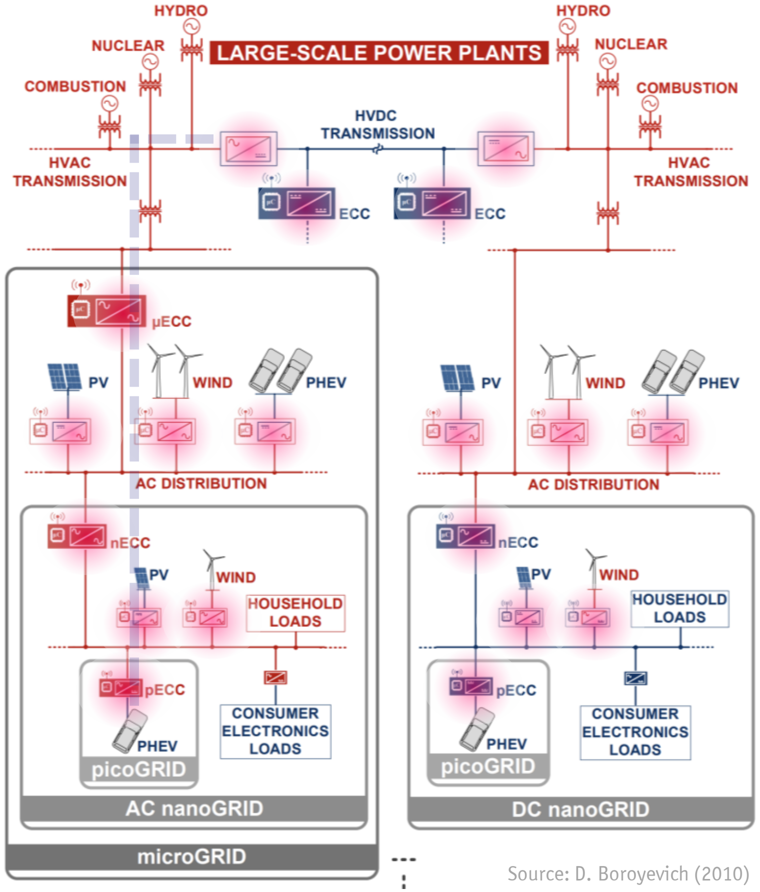
Source: REFU energy

Example of a Mobile Systems

Wide Application Area

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

The  in the Room



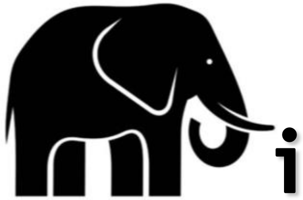
Source: D. Boroyevich (2010)

- *Global Population by 2050 — 10bn 2.5 kW/Capita*
- *25´000 GW Installed Ren. Generation in 2050*

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

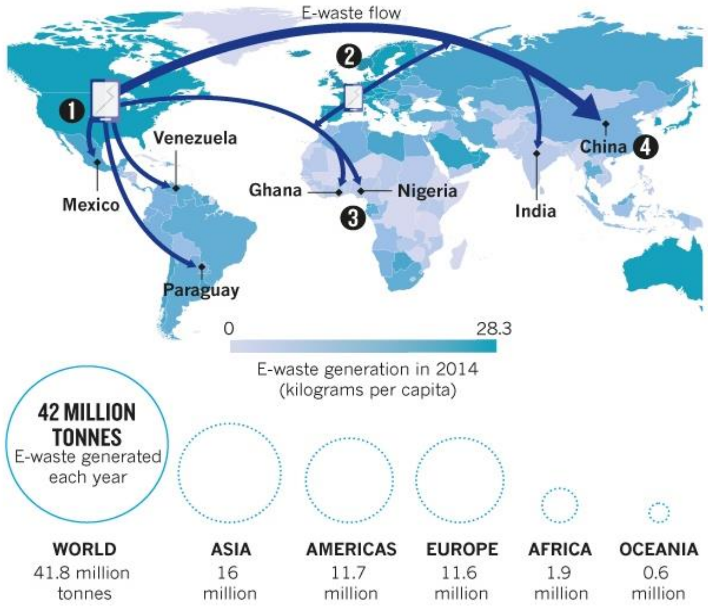
Source: www.e-waste-recyclers.co.in

- *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



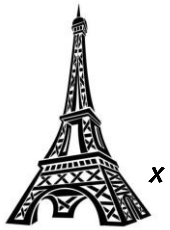
Source: nature

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

The Paradigm Shift

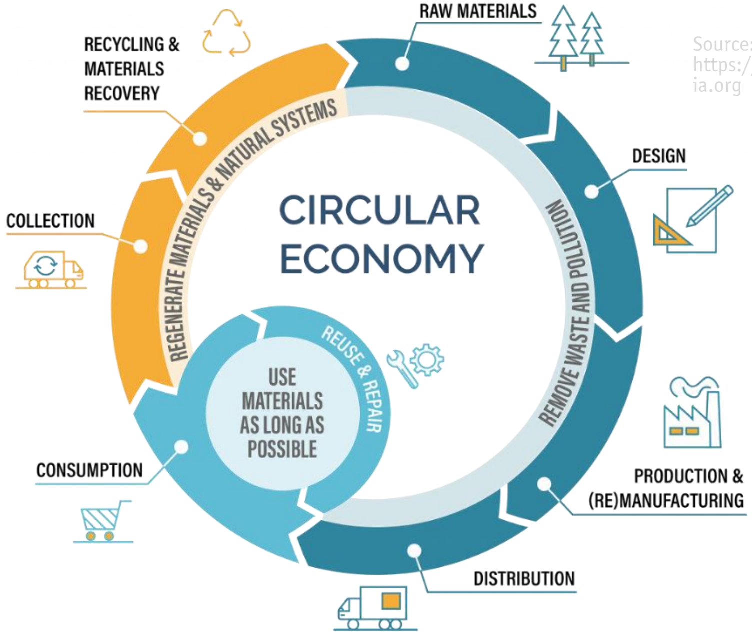
- *Growing Global E-Waste Streams / < 20% Recycled*
- *120´000´000 Tons of Global E-Waste in 2050*

← 52 Mt (!)



x 5´200

Source: The Global E-waste Monitor 2020

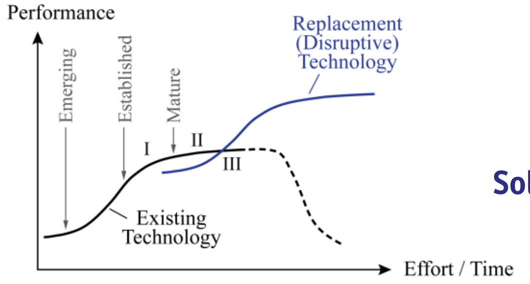


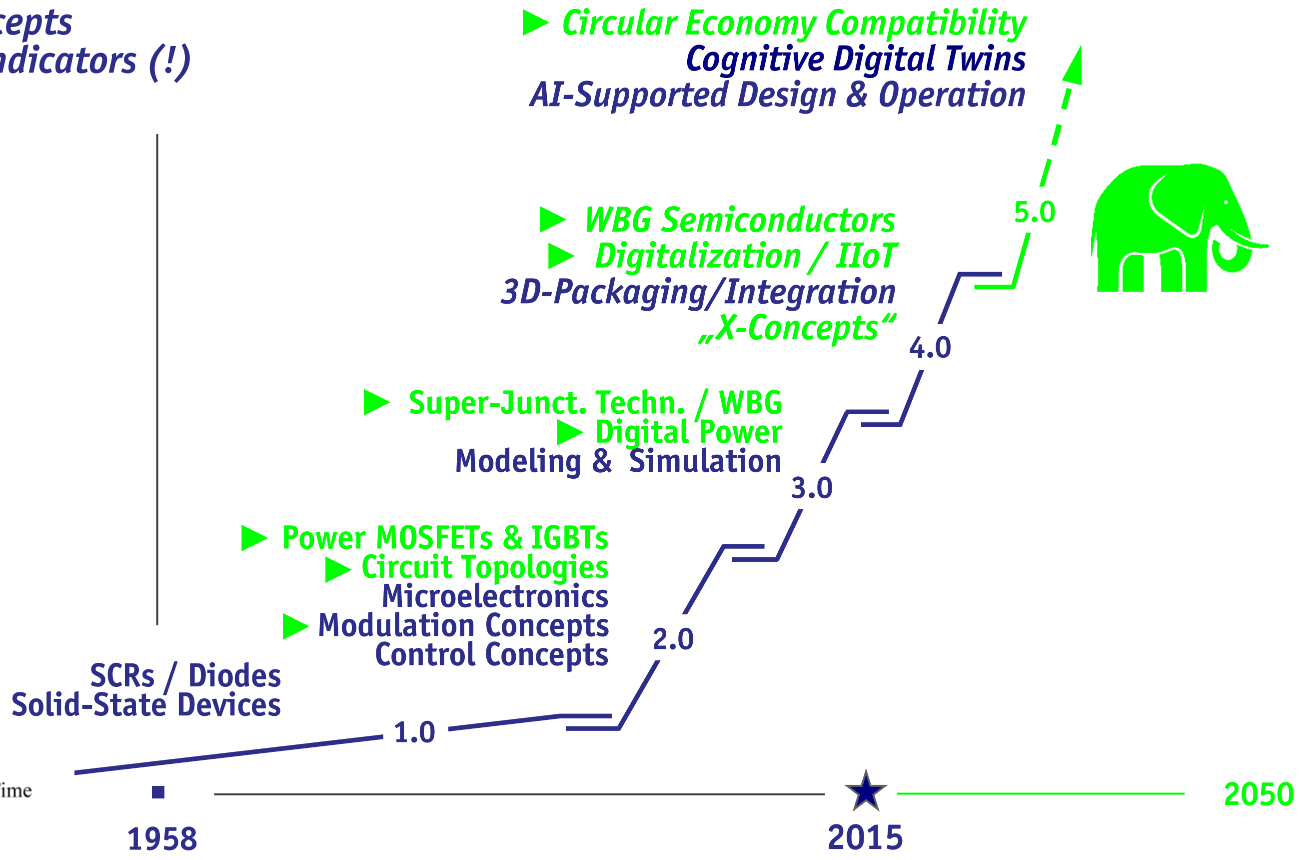
Source: https://circularphiladelphia.org

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

Power Electronics 5.0

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





Thank you!