ETH zürich

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Winter School
02/27 – 03/03/2017
Villach, Austria

Multi-Objective Optimization in Power Electronics

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www.pes.ee.ethz.ch

Power Electronic Systems Laboratory @ ETH Zurich

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Wireless Power	Advanced Mechatronics	Magnetic Levitation
D. Bortis	**F. Krismer**					**A. Tüysüz**	**Th. Nussbaumer**
M. Leibl D. Neumayr D. Rothmund J. Schäfer L. Schrittwieser	J. Böhler D. Boillat Th. Guillod J. Huber	P. Bezerra	Ch. Gammeter M. Guacci	J. Azurza	O. Knecht	M. Antivachis M. Flankl M. Mauerer S. Miric	Th. Holenstein P. Püntener M. Schuck T. Wellerdieck

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

22 Ph.D. Students
4 Post Docs → *1:5 PostDoc/Doc - Ratio*

ECPE Competence Centre

EPSMA

Leading Univ.
in Europe

Examples of
Research Activities in

Mechatronics

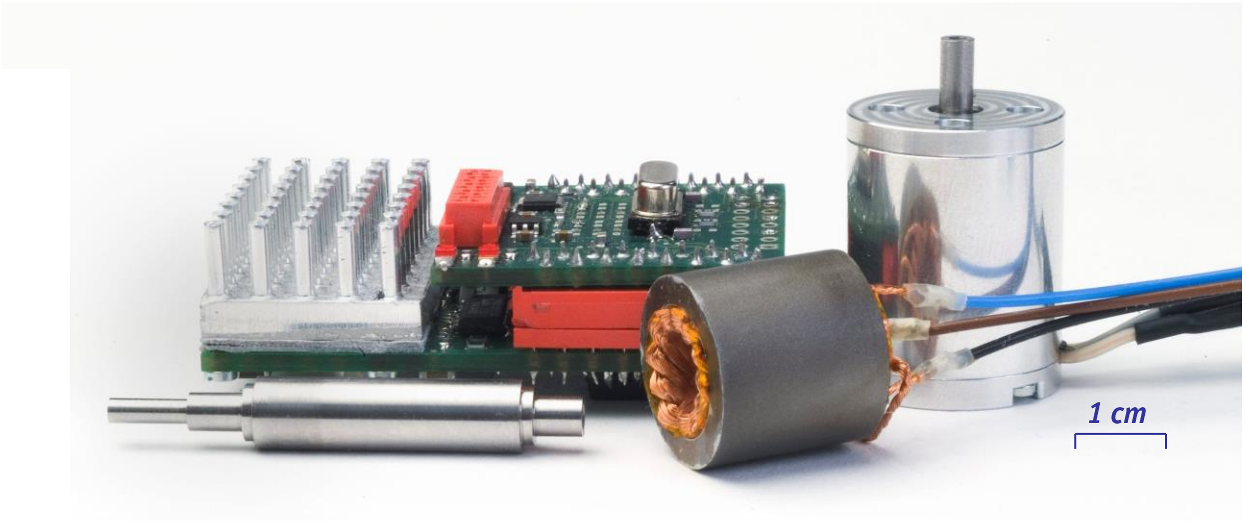
- Ultra High Speed Drives
- Bearingless Machines

Ultra High Speed Drive Systems

- µm-Scale PCB Drilling
- Dental Technology
- Laser Measurement Technology
- Turbo-Compressor Systems
- Air-to-Power
- Artificial Muscles
- Mega Gravity Science

World Record !

100W @ 1‘000‘000 rpm

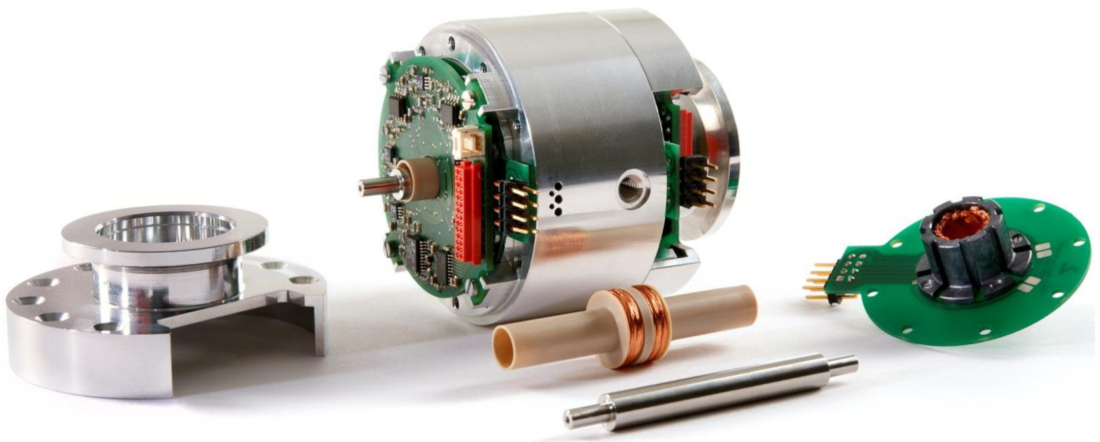


Ultra High Speed Magnetically Levitated Drive Systems

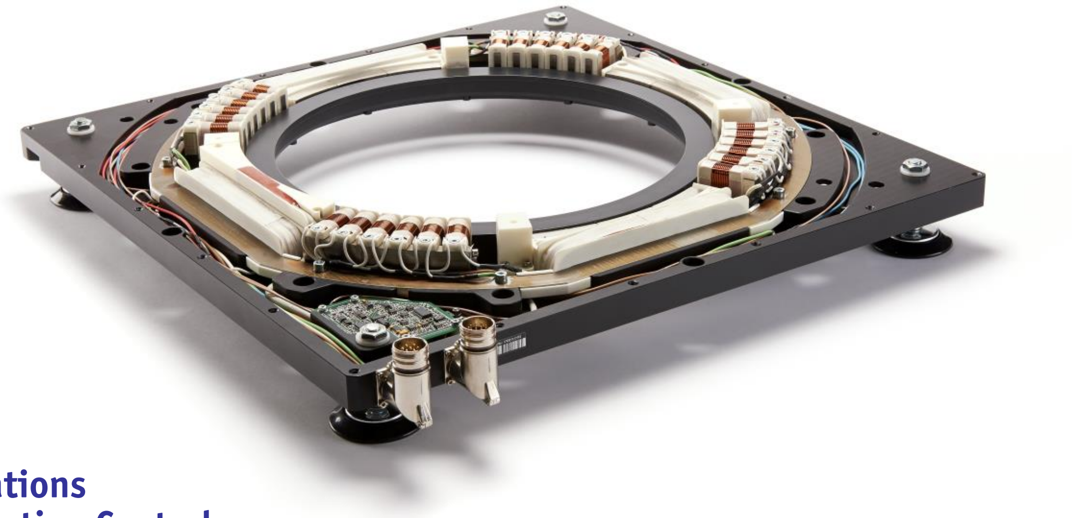
World Record !

500'000 rpm

- Laser Measurement Technology
- Active Damping of Air Bearings
- Satellite Attitude Control

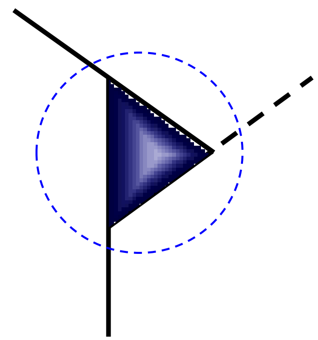


Bearingless Motors



- Maximum Speed 2000rpm
- High Acceleration Capability (3.8s from 0 → 2000rpm)
- 7mm Air Gap
- Two Phase Winding Configurations
- Adaptive Unbalance Compensation Control

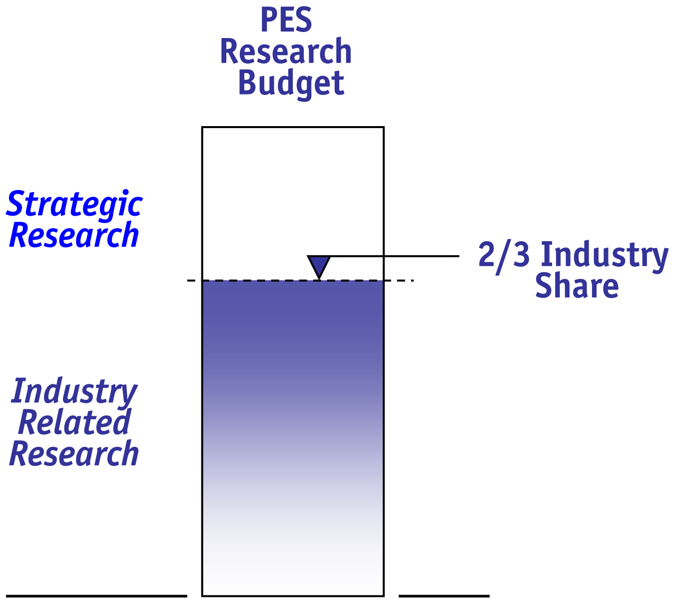
PES Research Scope



- *Airborne Wind Turbines*
- *Micro-Scale Energy Systems*
- *Wearable Power*
- *Exoskeletons / Artificial Muscles*
- *Hybrid Systems*
- *Pulsed Power*

Industry Collaboration

- ► Core Application Areas
  - Renewable Energy
  - UPS
  - Smart Grid
  - Automotive Systems
  - More-Electric Aircraft
  - Medical Systems
  - Industry Automation
  - Semiconductor Process Technology
  - Etc.
- ► *16 International Industry Partners*



Outline

- ▶ Global Megatrends
- ▶ Resulting Requirements for Power Electronics
- ▶ *Multi-Objective Optimization Approach*
- ▶ *Optimization Application Examples*
- ▶ Power Electronics 2.0
- ▶ Summary

Acknowledgement
D. Bortis
R. Bosshard
R. Burkart
F. Krismer

Global Megatrends

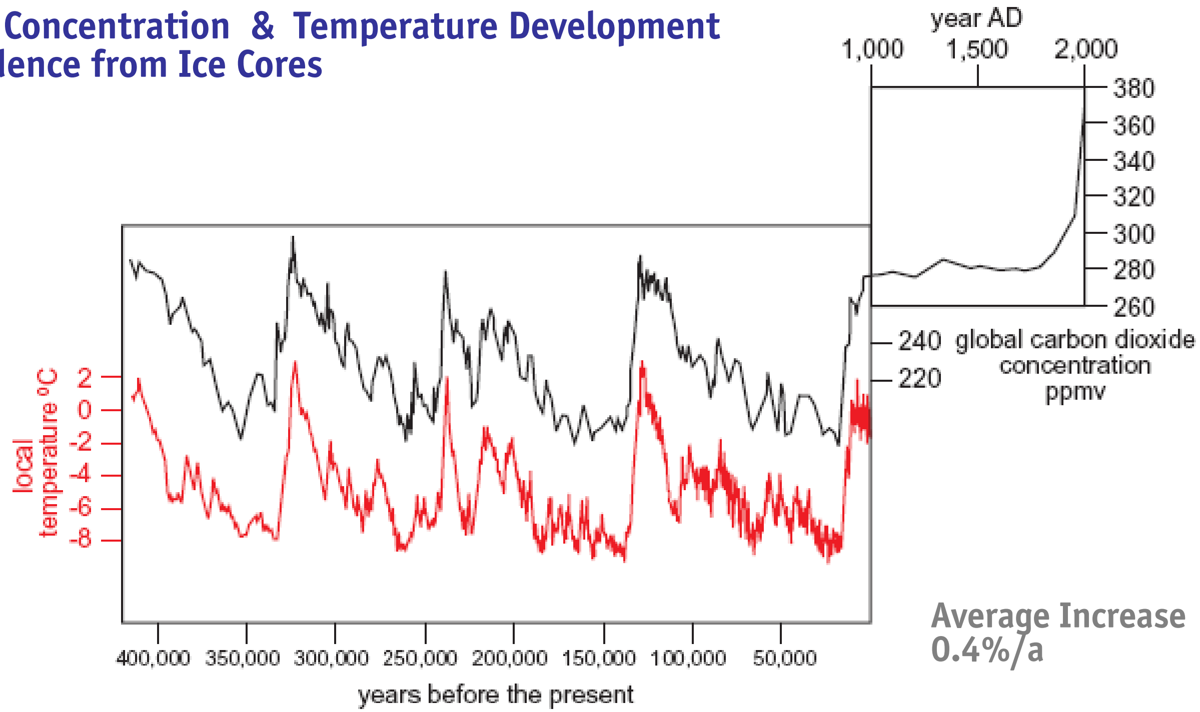
Climate Change
Digitalization
Sustainable Mobility
Urbanization
Alleviate Poverty
Etc.

Global Megatrends

Climate Change →
Digitalization
Sustainable Mobility
Urbanization
Alleviate Poverty
Etc.

► Climate Change

- CO_2 Concentration & Temperature Development
- Evidence from Ice Cores



Average Increase
0.4%/a

► Reduce CO_2 Emissions *Intensity* (CO_2/GDP) to Stabilize Atmospheric CO_2 Concentration
► 1/3 in 2050 → less than 1/10 in 2100 (AIST, Japan @ IEA Workshop 2007)

▶ Climate Change

- CO_2 Concentration & Temperature Development
- Evidence from Ice Cores

Source: H. Nilsson
Chairman IEA DSM Program
FourFact AB

▶ Reduce CO_2 Emissions *Intensity* (CO_2/GDP) to Stabilize Atmospheric CO_2 Concentration
▶ 1/3 in 2050 → less than 1/10 in 2100 (AIST, Japan @ IEA Workshop 2007)

→ *Utilize Renewable Energy* (1)

■ Enabled by Power Electronics

— Higher Reliability (!)
— Lower Costs

Source: M. Prahm / Flickr

Medium-Voltage Power
Collection and Connection
to On-Shore Grid

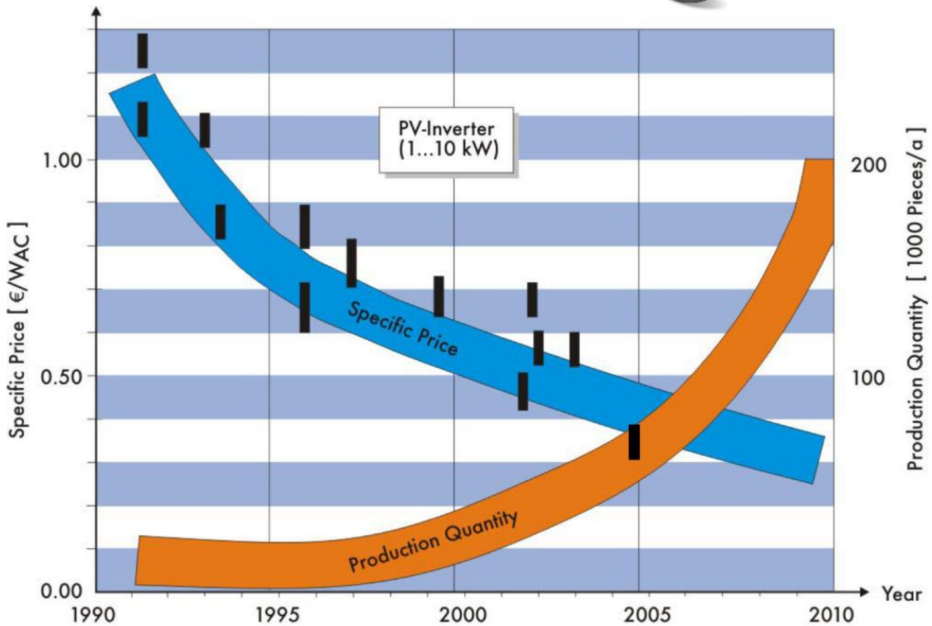
▶ Off-Shore Wind Farms
▶ Medium Voltage Systems

Utilize Renewable Energy (2)

Enabled by Power Electronics

— Extreme Cost Pressure (!)
— Higher Efficiency
— Higher Power Density

Source: SMA 2006



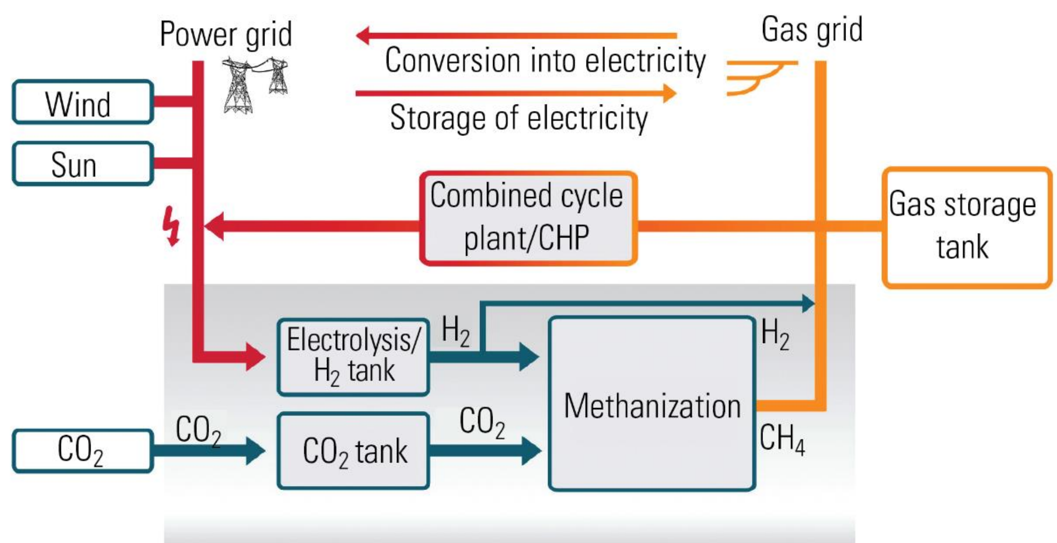
- Photovoltaics Power Plants
- Up to Several MW Power Level
- Future Hybrid PV/Therm. Collectors

→ *Utilize Renewable Energy (3)*

■ Enabled by Power Electronics

— Electrolysis for Conversion of Excess Wind/Solar Electric Energy into Hydrogen
→ Fuel-Cell Powered Cars
→ Heating

Hydrogenics 100 kW H_2-Generator (η=57%), High Power @ Low Voltage



Source: www.r-e-a.net

Global
Megatrends

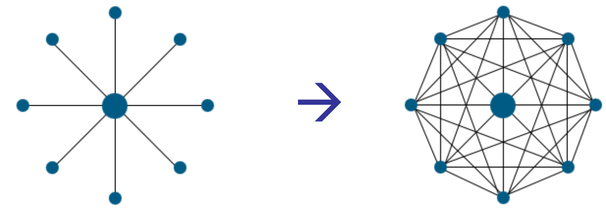
Climate Change
Digitalization
Sustainable Mobility
Urbanization
Alleviate Poverty
Etc.

▶ Digitalization

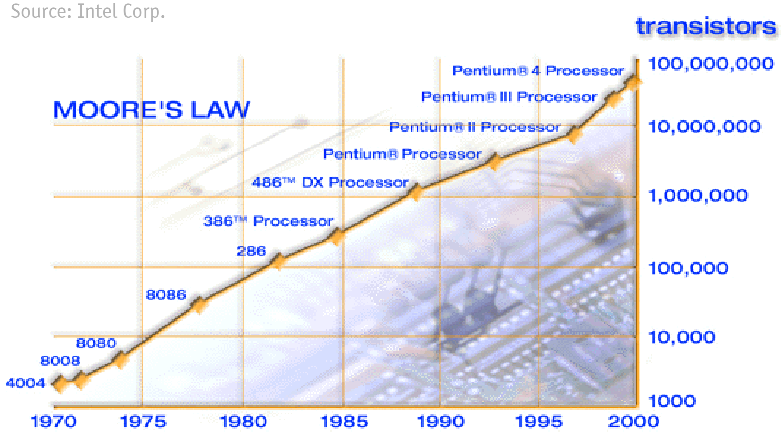
■ **Internet of Things (IoT) / Cognitive Computing**

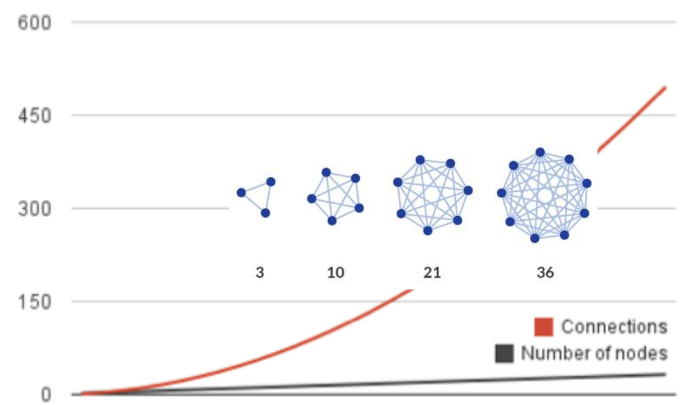
— Ubiquitous Computing / BIG DATA
— Fully Automated Manufacturing / Industry 4.0
— Autonomous Cars
— Etc.

– Moving form Hub-Based to Community Concept Increases Potential Network Value Exponentially (~n(n-1) or ~n log(n))



Source: Intel Corp.





▶ Moore's Law

▶ Metcalfe's Law

→ Green / Zero  Datacenters (1)

■ Enabled by Power Electronics

— Ranging from Medium Voltage to Power-Supplies-on-Chip
— Short Power Supply Innovation Cycles
— Modularity / Scalability

— Higher Power Density (!)
— Higher Efficiency (!)
— Lower Costs

Server-Farms
up to 450 MW
99.9999%/<30s/a
$1.0 Mio./Shutdown

Since 2006
Running Costs >
Initial Costs

Source: REUTERS/Sigtryggur Ari

33 Watts

→

60 Watts

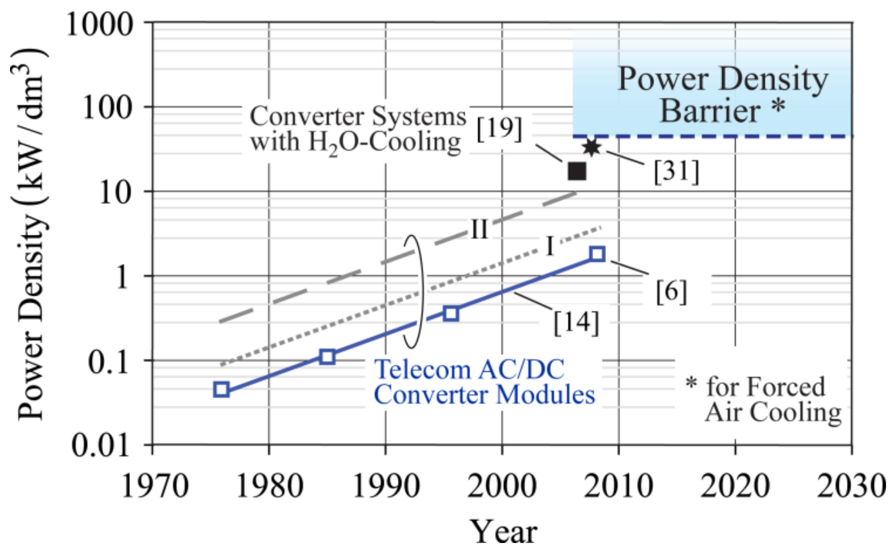
→ Green / Zero CARBON Datacenters (2)

■ Enabled by Power Electronics

— Ranging from Medium Voltage to Power-Supplies-on-Chip
— Short Power Supply Innovation Cycles
— Modularity / Scalability

— Higher Power Density (!)
— Higher Efficiency (!)
— Lower Costs

▶ Power Density Increased by Factor 2 over 10 Years

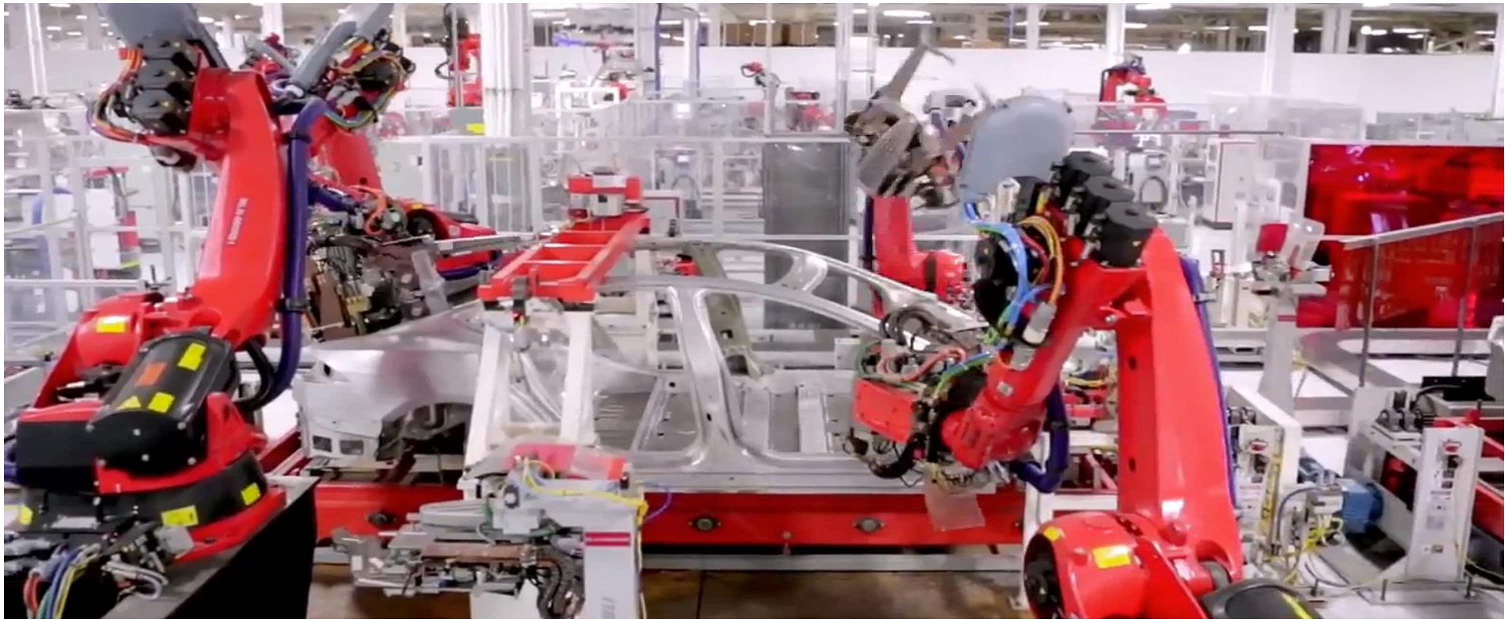


→ Fully Automated Manufacturing – Industry 4.0

■ Enabled by Power Electronics

— Lower Costs (!)
— Higher Power Density
— Self-Sensing etc.

Source: TESLA MOTORS

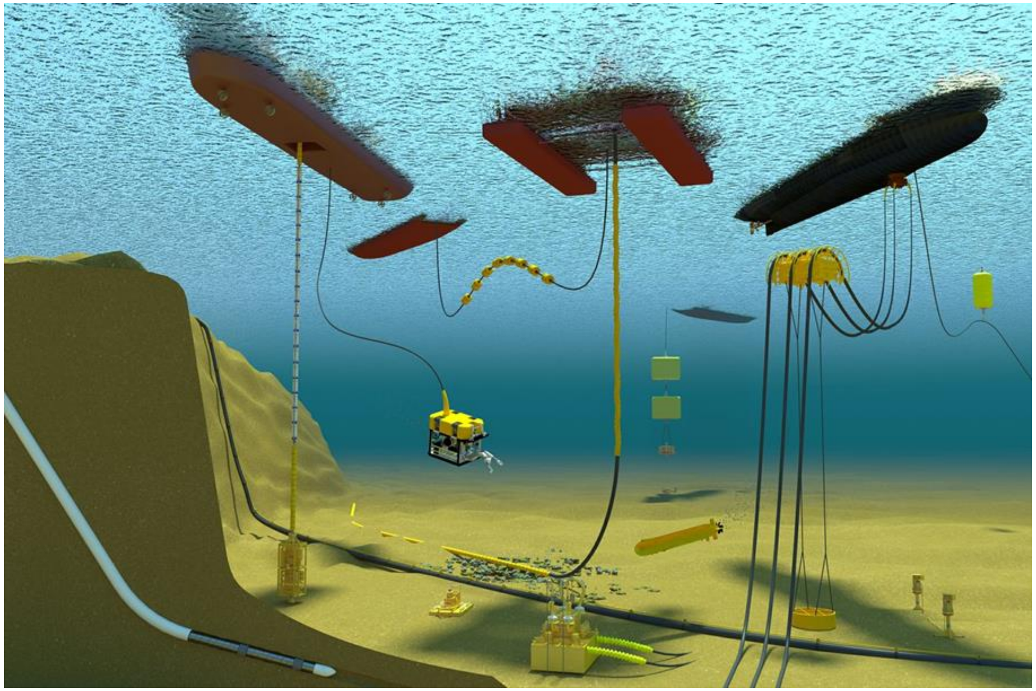


→ Fully Automated Raw Material Extraction

■ **Enabled by Power Electronics**

— High Reliability (!)
— High Power Density (!)

Source: matrixengineered.com



▶ ABB´s Future Subsea Power Grid → "Develop All Elements for a Subsea Factory"

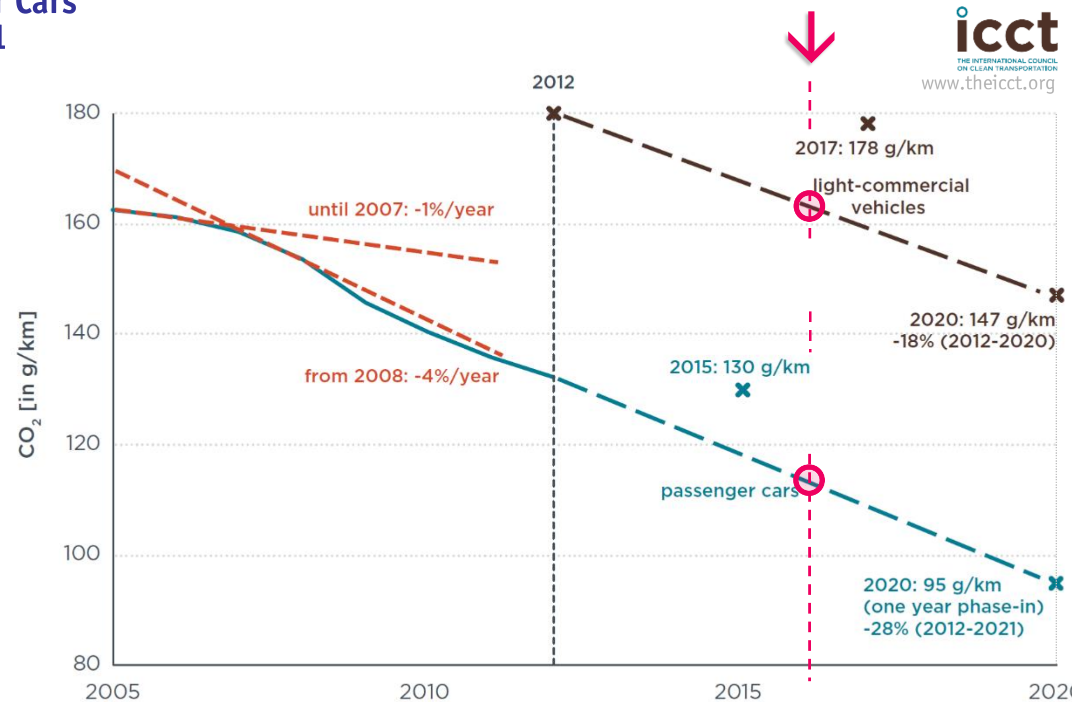
Global Megatrends

Climate Change
Digitalization
Sustainable Mobility →
Urbanization
Alleviate Poverty
Etc.

▶ Sustainable Mobility

■ EU Mandatory 2020 CO_2 Emission Targets for New Cars

— 147g CO_2/km for Light-Commercial Vehicles
— 95g CO_2/km for Passenger Cars
— 100% Compliance in 2021



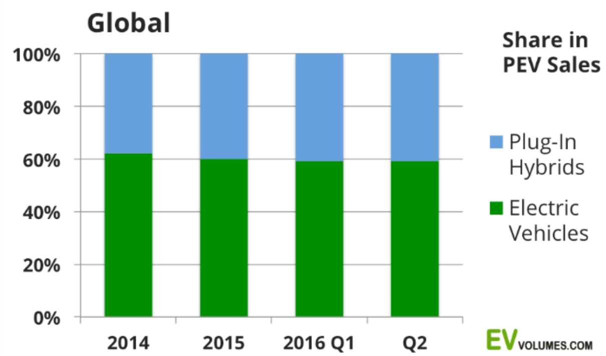
▶ Hybrid Vehicles
▶ Electric Vehicles

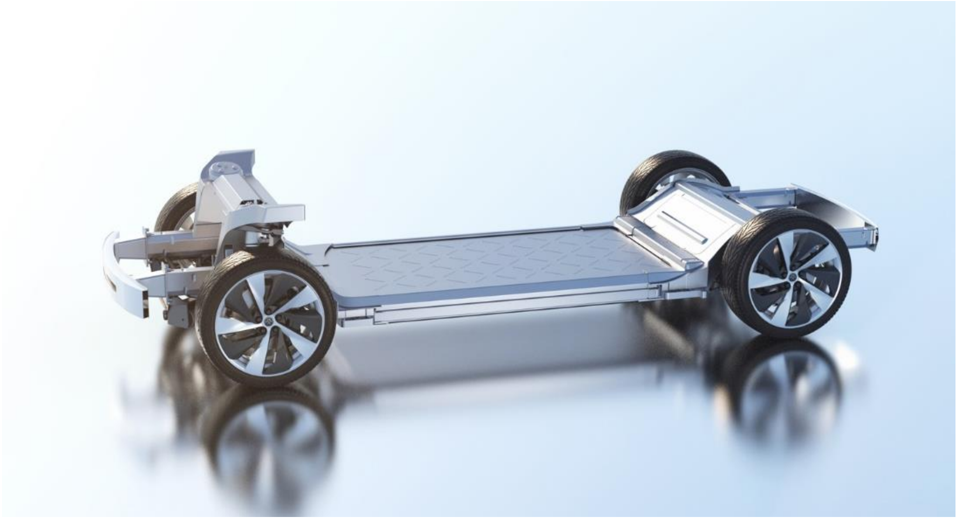
Electric Vehicles (1)

- **Enabled by Power Electronics** - Drivetrain / Aux. / Charger

— Higher Power Density
— Extreme Cost Pressure (!)

Faraday Future
FF-ZERO1
750kW / 322km/h
1 Motor per Wheel
300+ Miles Range
Lithium-Ion Batteries along the Floor



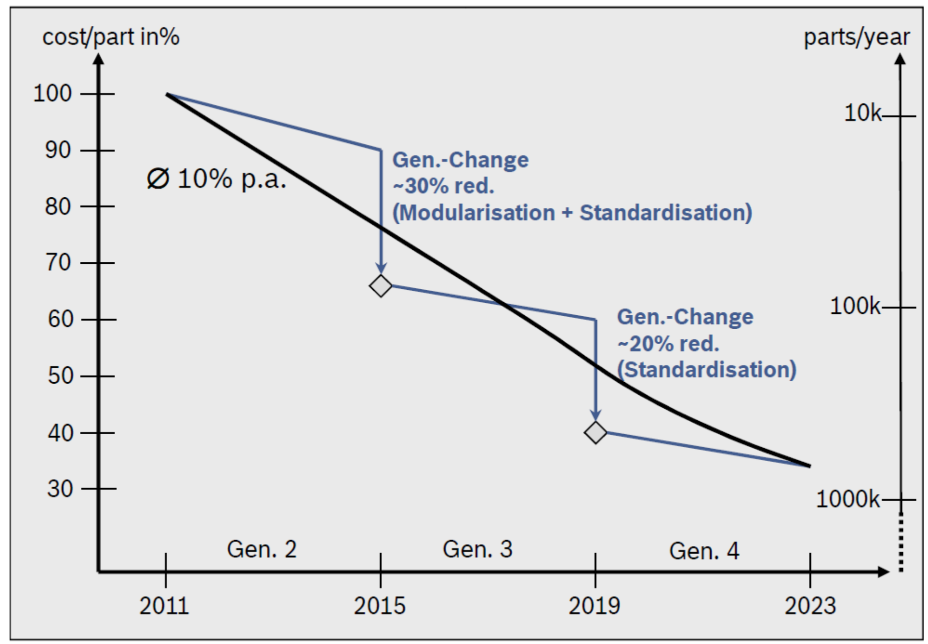


Electric Vehicles (2)

- **Enabled by Power Electronics** - Drivetrain / Aux. / Charger

— Higher Power Density
— Extreme Cost Pressure (!)

Source: PCIM 2013



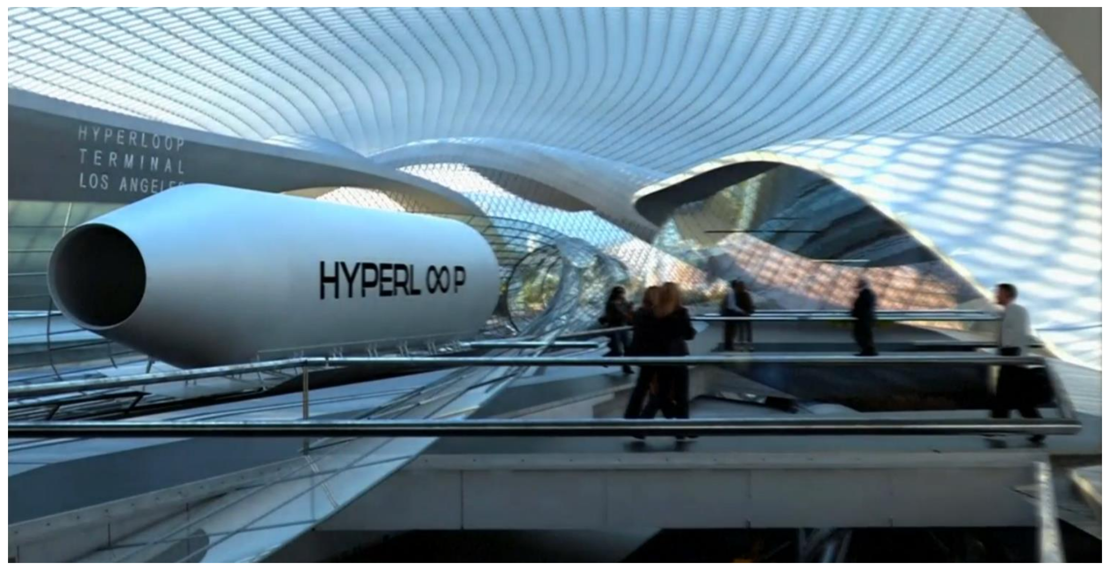
► Typ. 10% / a Cost Reduction
► Economy of Scale !

→ *Futuristic Mobility Concepts* (1)

■ Enabled by Power Electronics

— Hyperloop
— San Francisco → Los Angeles in 35min

HYPERLOOP
POD COMPETITION
www.spacex.com/hyperloop



▶ Low Pressure Tube
▶ Magnetic Levitation
▶ Linear Ind. Motor
▶ Air Compressor in Nose

Futuristic Mobility Concepts (2)

■ Enabled by Power Electronics

— Cut Emissions Until 2050
* CO_2 by 75%,
* NO_x by 90%,
* Noise Level by 65%

Source: EADS

Future Hybrid
Distributed Propulsion Aircraft

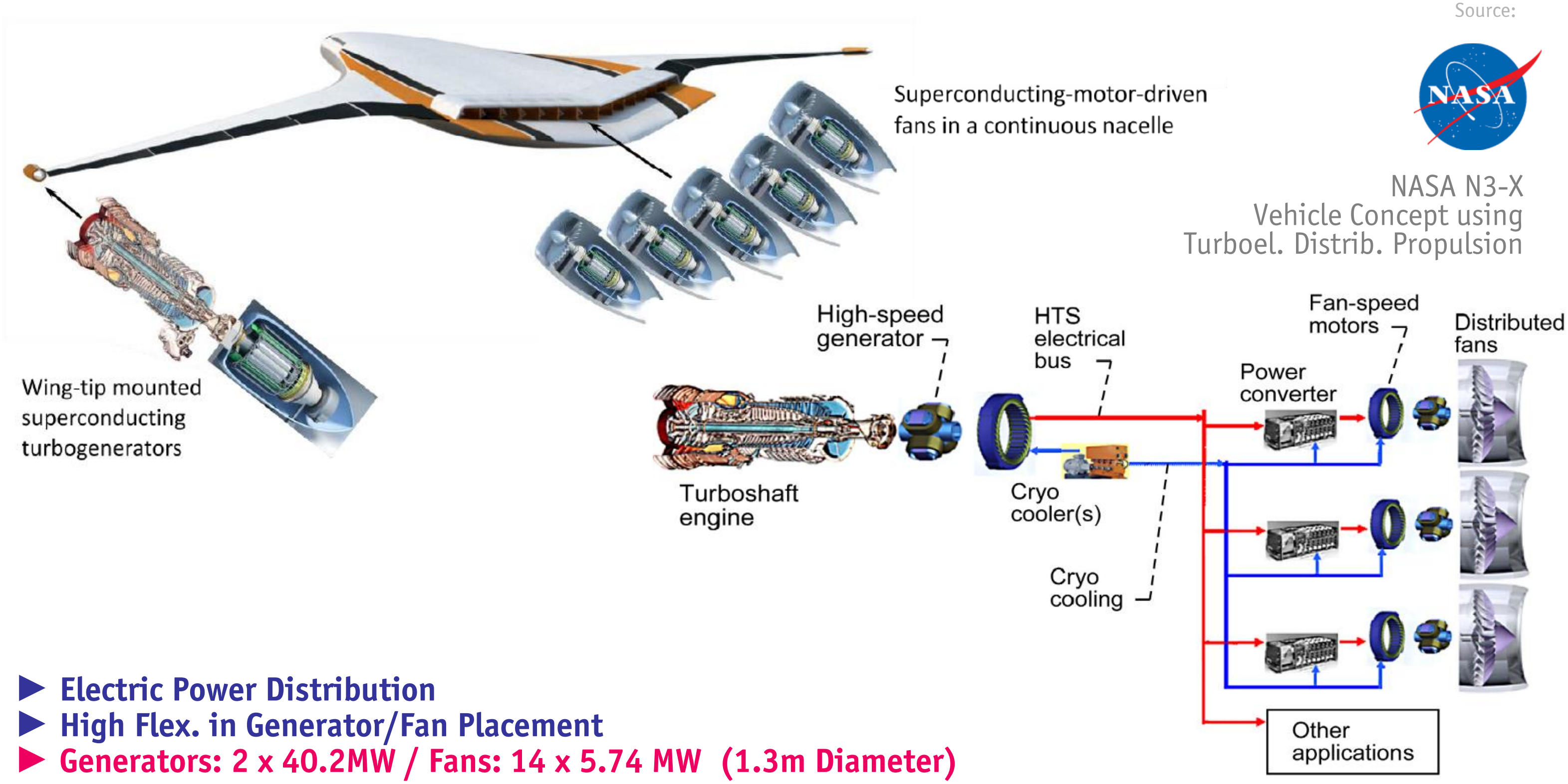
▶ Eff. Optim. Gas Turbine
▶ 1000Wh/kg Batteries
▶ Distrib. Fans (E-Thrust)
▶ Supercond. Motors
▶ Med. Volt. Power Distrib.

Futuristic Mobility Concepts (3)

Enabled by Power Electronics

Source:

NASA N3-X
Vehicle Concept using
Turboel. Distrib. Propulsion



- Electric Power Distribution
- High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

Global Megatrends

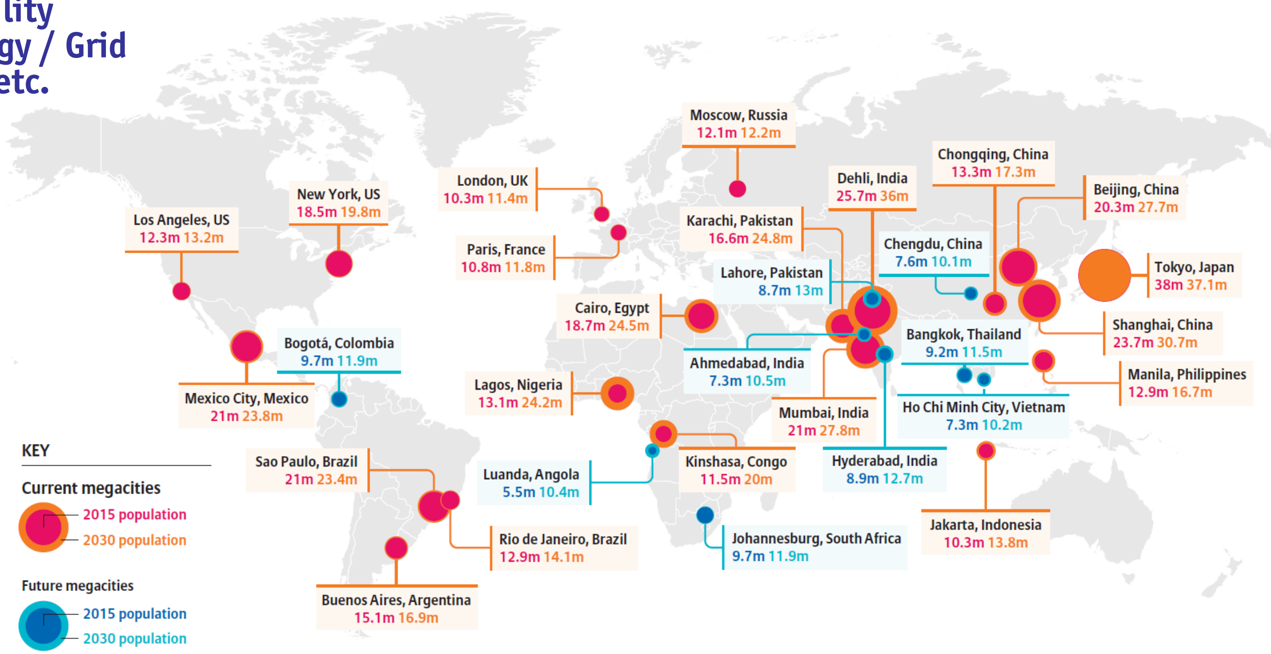
- Climate Change
- Digitalization
- Sustainable Mobility
- **Urbanization** →
- Alleviate Poverty
- Etc.

▶ Urbanization

- 60% of World Population Exp. to Live in Urban Cities by 2025
- 30 MEGA Cities Globally by 2023

— Smart Buildings
— Smart Mobility
— Smart Energy / Grid
— Smart ICT, etc.

Source: World Urbanization Prospects: The 2014 Revision



▶ Selected Current & Future MEGA Cities 2015 → 2030

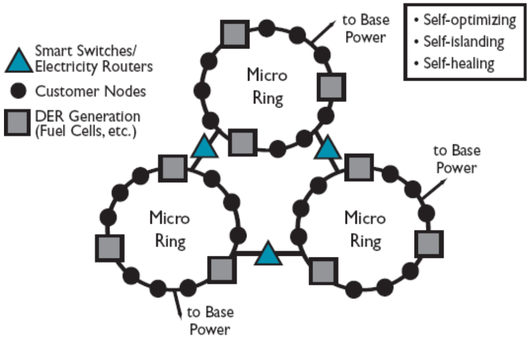
Smart Cities / Grid (1)

■ Enabled by Power Electronics

— *Masdar = "Source"*
— Fully Sustainable Energy Generation
  * Zero CO_2
  * Zero Waste
— EV Transport / IPT Charging
— to be finished 2025

Masdar CITY
www.masdar.ae

Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE



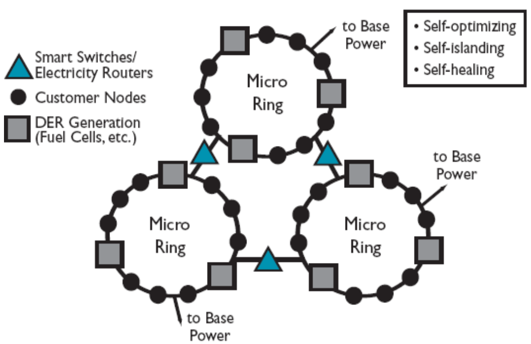
Smart Cities / Grid (2)

■ Enabled by Power Electronics

— *Masdar = "Source"*
— Fully Sustainable Energy Generation
  * Zero CO_2
  * Zero Waste
— EV Transport / IPT Charging
— to be finished 2025

Masdar CITY
www.masdar.ae

Source: EPRI Electric Power Research Institute

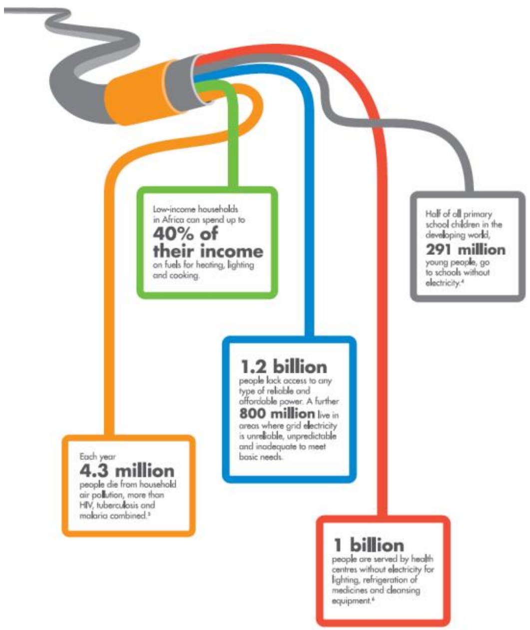


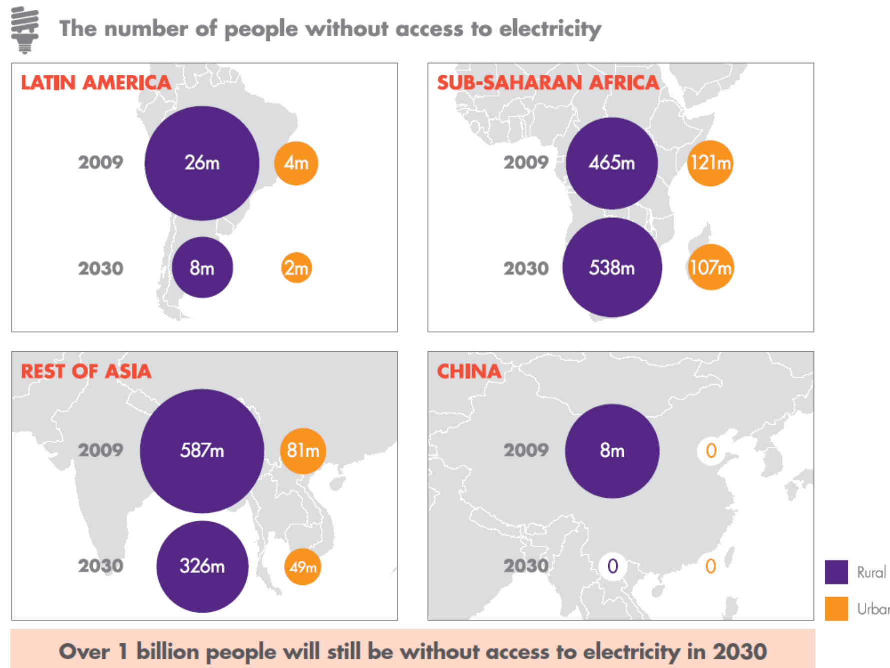
Global Megatrends

- *Climate Change*
- *Digitalization*
- *Sustainable Mobility*
- *Urbanization*
- ***Alleviate Poverty*** →
- *Etc.*

▶ Alleviate Poverty

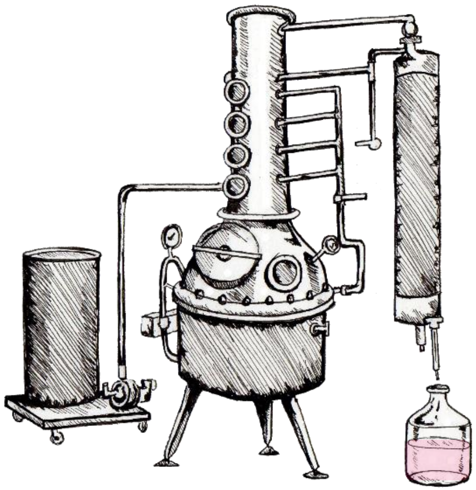
- 2 Billion "Bottom-of-the-Pyramid People" are Lacking Access to Clean Energy
- Rural Electrification in the Developing World





Source: IEA, Dalberg Analysis, IFC

▶ Urgent Need for Village-Scale Solar DC Microgrids etc.
▶ 2 US$ for 2 LED Lights + Mobile-Phone Charging / Household / Month (!)



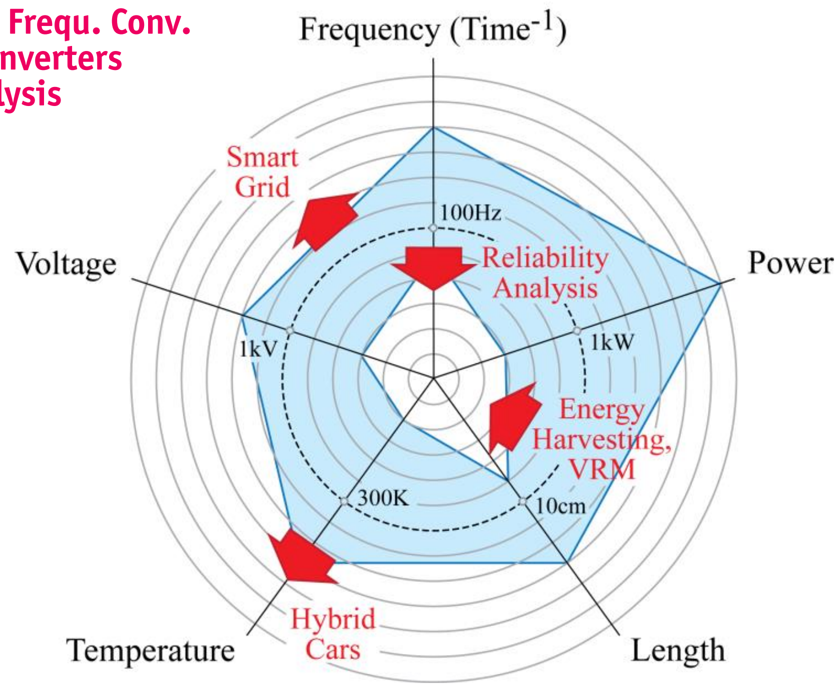
Source: whiskeybehavior.info

... in Summary

► Current / New Application Areas (1)

- **Power Electronics Covers an Extremely Wide Power / Voltage / Frequency Range**
- **Extensions for *SMART xxx* / Mobility Trends / Availability Requirements**

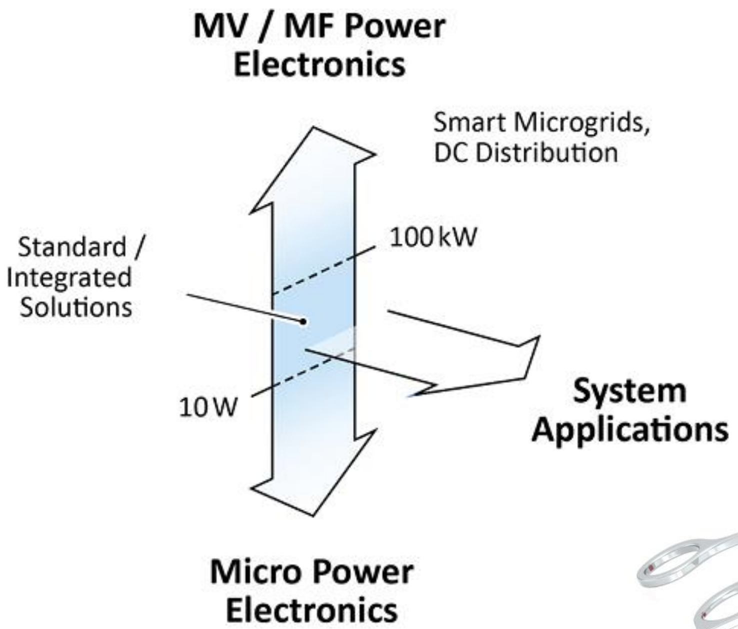
— Medium-Voltage / Medium. Frequ. Conv.
— 3D-Integr. of Low Power Converters
— Life-Cycle & Reliability Analysis



► Future Extensions of Power Electronics Application Areas

► Current / New Application Areas (2)

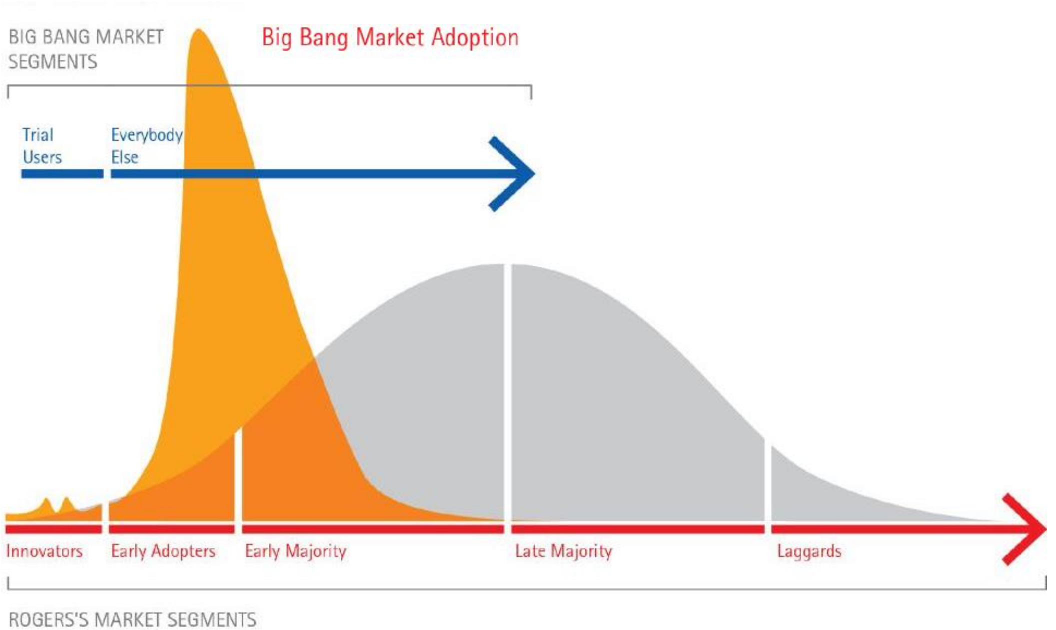
- Commoditization / Standardization for High Volume Applications
- Extension to Microelectronics-Technology (Power Supply on Chip)
- Extensions to MV/MF



► Cost Pressure as Common Denominator of All Applications (!)
► Key Importance of Technology Partnerships of Academia & Industry

► Future "Big-Bang" Disruptions

- "Catastrophic" Success of Disruptive New (Digital) Technologies
- No Bell-Curve Technology Adoption / Technology S-Curve
- "Shark Fin"-Model



Source: www.verschuerent.wordpress.com
February 2015

See also:
Big Bang Disruption –
Strategy in the Age of
Devastating Innovation,
L. Downes and P. Nunes

► Consequence: Market Immediately & Be Ready to Scale Up — and Exit — Swiftly (!)

Power Converter Design Challenges

Mutual Coupling of Performances
New Integration Technologies

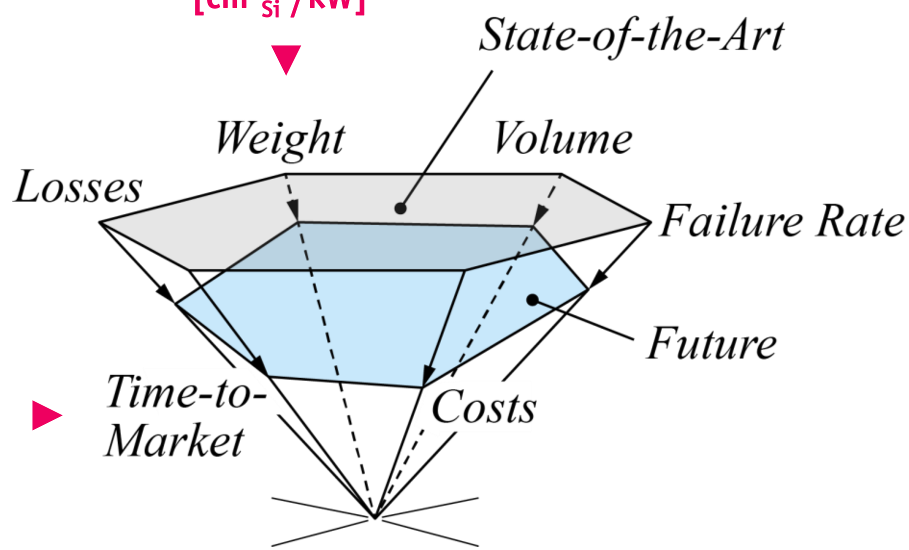
Power Converter Design Challenges

Mutual Coupling of Performances

New Integration Technologies

Required Power Electronics Performance Improvements

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

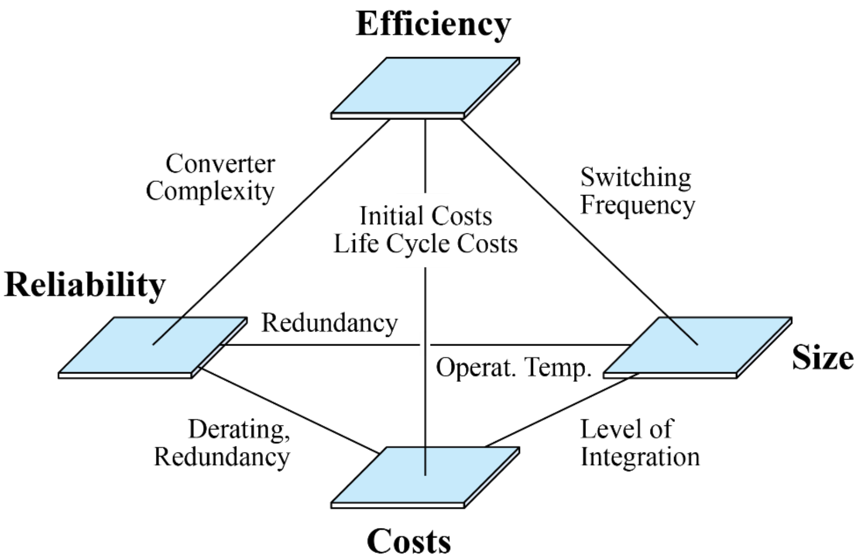


Performance Indices

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

Multi-Objective Design Challenge (1)

- Counteracting Effects of Key Design Parameters
- Mutual Coupling of Performance Indices → Trade-Offs



→ Large Number of Degrees of Freedom / Multi-Dimensional Design Space
→ Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization

Multi-Objective Design Challenge (1)

- Counteracting Effects of Key Design Parameters
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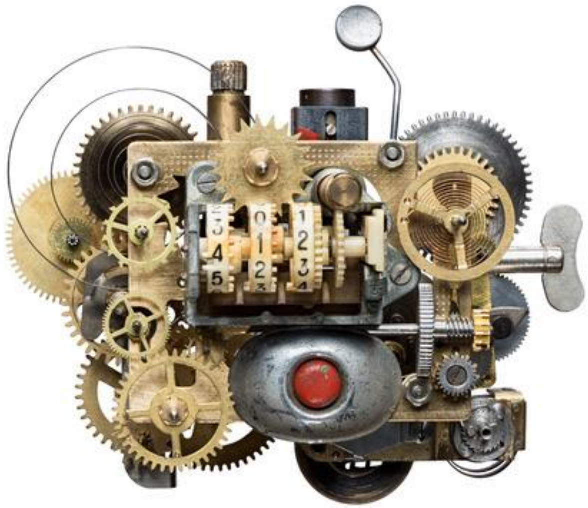
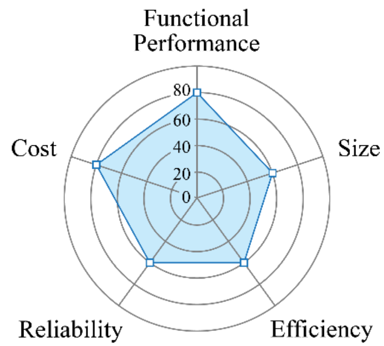


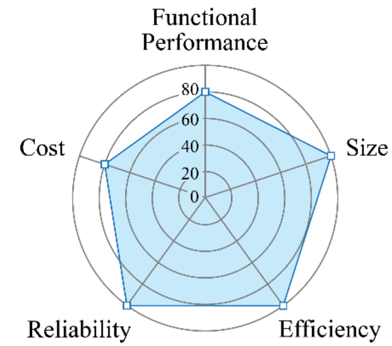
→ Large Number of Degrees of Freedom / Multi-Dimensional Design Space
→ Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization

Multi-Objective Design Challenge (2)

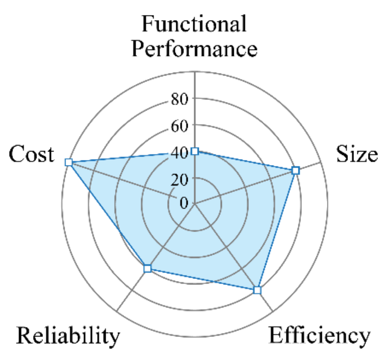
- Specific Performance Profiles / Trade-Offs Dependent on Application



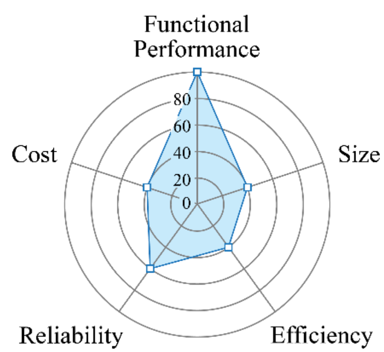
Industry Applications



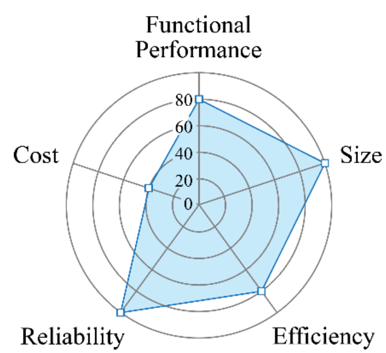
Information & Communication Industry



Domestic Applications



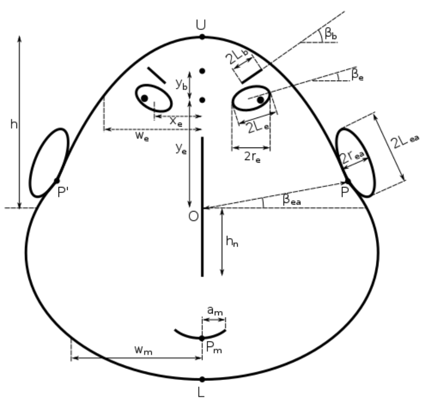
Laboratory Applications

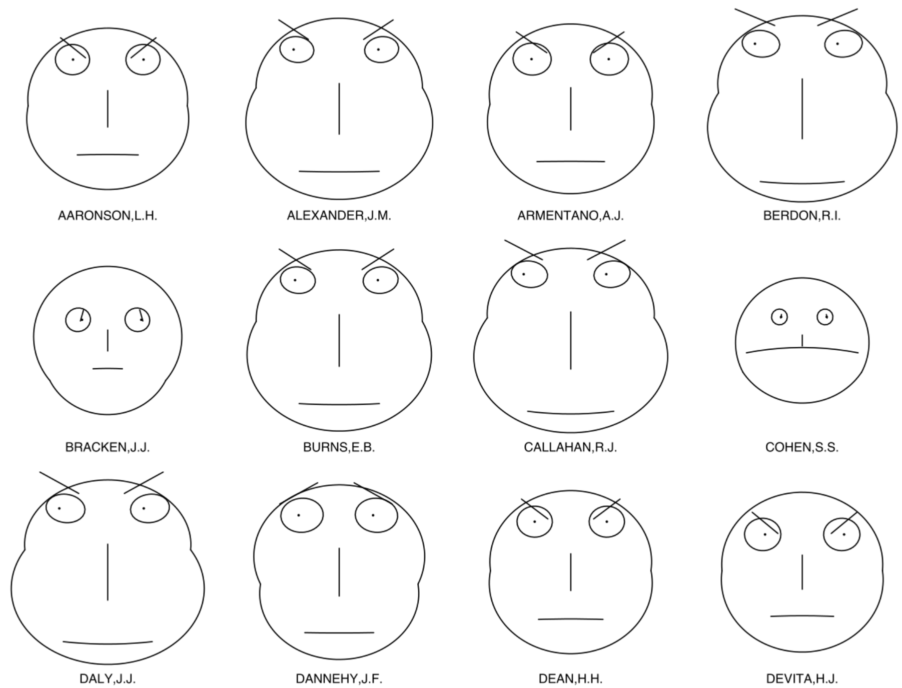


Aerospace Applications

▶ Remark: Visualization of Multiple Performances ;-)

- Spider Charts, etc.
- Chernoff-Faces





▶ H. Chernoff (Stanford): "The Use of Faces to Represent Points in K-Dimensional Space Graphically"

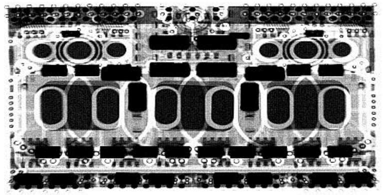
Power Converter
Design Challenges

Mutual Coupling of Performances
New Integration Technologies

▶ Advanced Technologies / Extreme Integration

■ **Industry Is Leading the Field (!)**

- **Cutting Edge Converters (up to 1.5kW) 3D-Integrated (!)**
- **PCB Based Demonstrators Do NOT (any more) Provide Much Information (!)**



■ **Future Role of Universities in Question (!)**

- **Not Any More Many *"Low Hanging"* Fruits**
- ***Solution of Non-Problems vs. Non-Solution of Problems*** ← Citation: L.H. Fink
- **Industry Technology Partnership for Technology Access**
- ***"Fab-Less"* Research @ Universities?**

▶ **Research on Multi-Objective Design / Virtual Prototyping as Natural Consequence (!)**

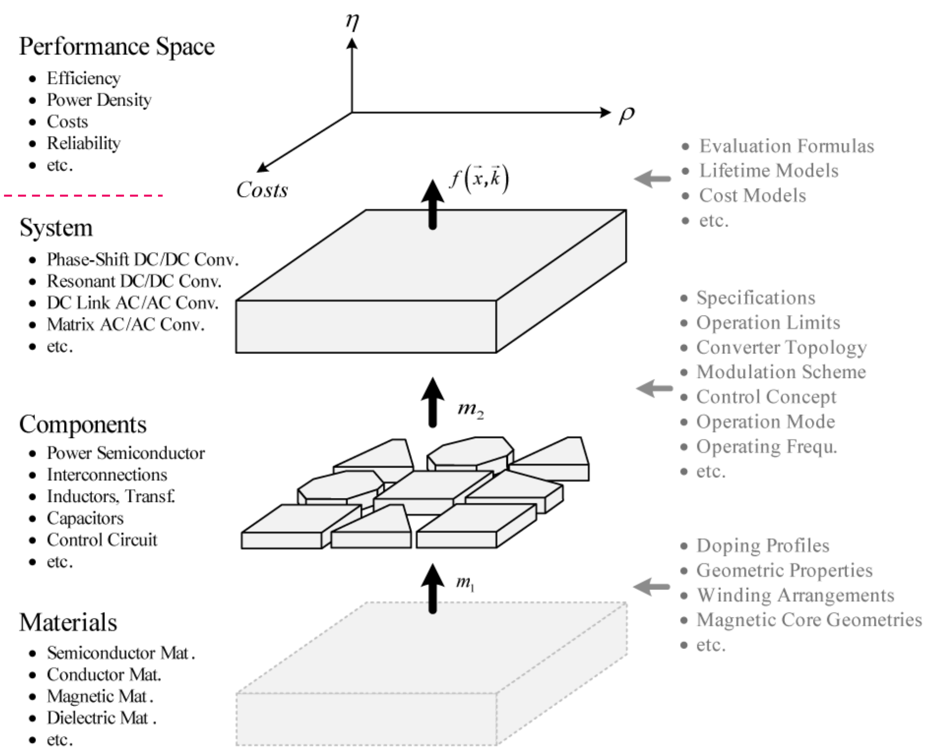
Multi-Objective Optimization

Abstraction of Converter Design
Design Space / Performance Space
Pareto Front
Sensitivities / Trade-Offs

▶ Abstraction of Power Converter Design

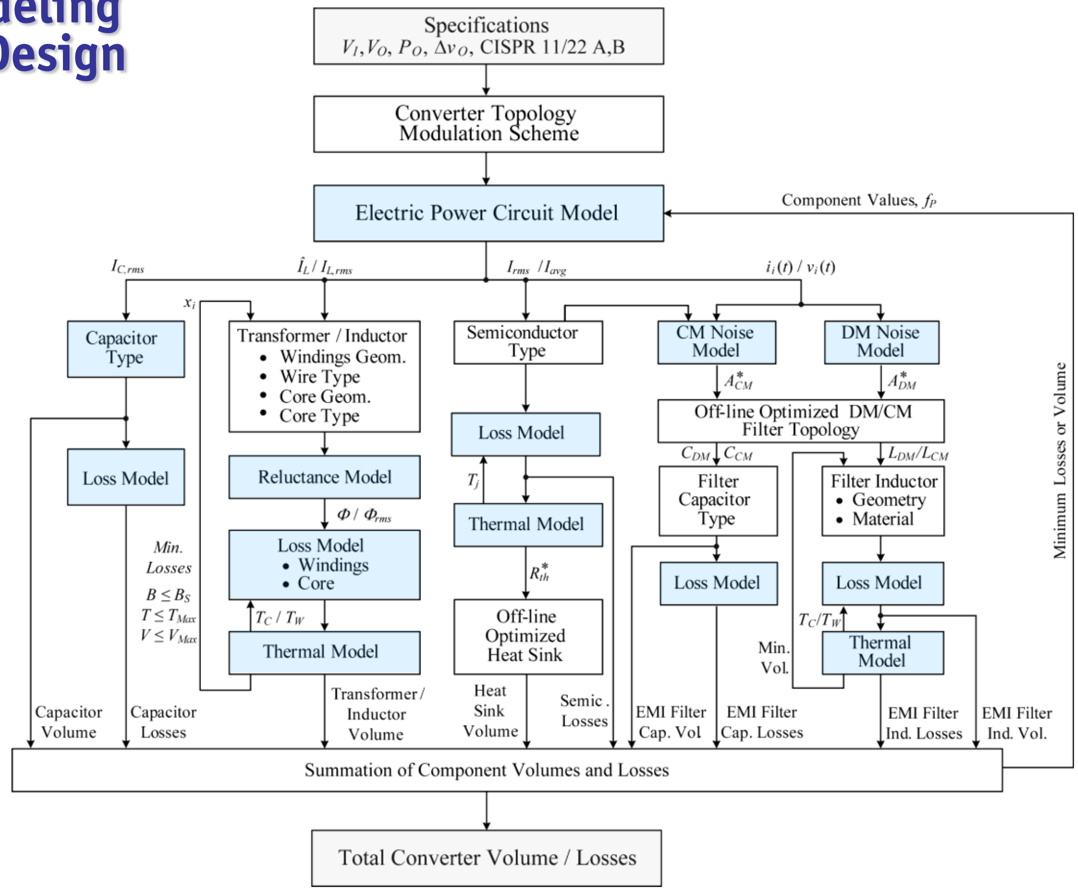
Performance Space

Design Space



→ *Mapping* of "*Design Space*" into System "*Performance Space*"

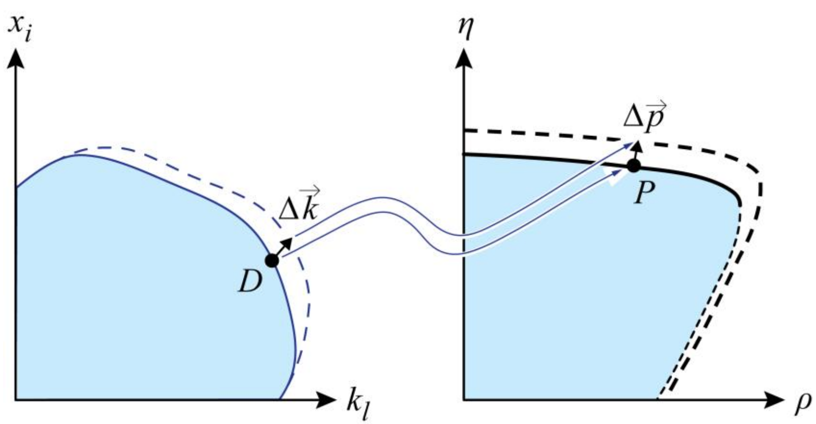
► Mathematical Modeling of the Converter Design



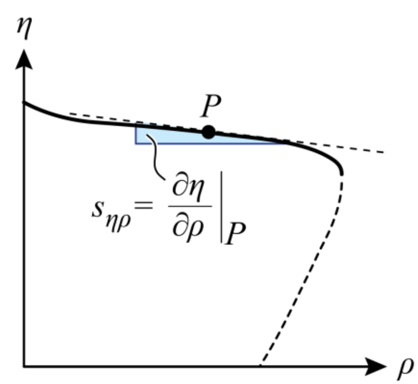
→ **Multi-Objective Optimization** – ***Guarantees Best Utilization of All Degrees of Freedom*** **(!)**

▶ Multi-Objective Optimization (1)

- Ensures Optimal Mapping of the "Design Space" into the "Performance Space"
- Identifies Absolute Performance Limits → Pareto Front / Surface



Design Space   Performance Space

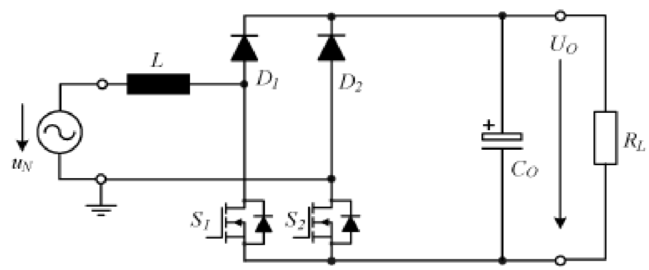


→ Clarifies Sensitivity $\Delta\vec{p}\,/\,\Delta\vec{k}$ to Improvements of Technologies
→ Trade-off Analysis

▶ Determination of the η-ρ-Pareto Front (a)

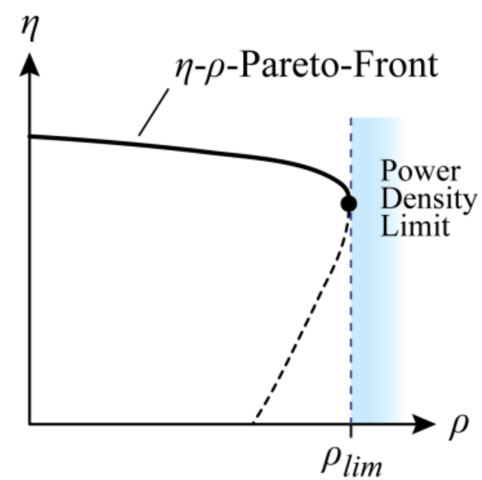
■ **Comp.-Level Degrees of Freedom of the Design**

— Core Geometry / Material
— Single / Multiple Airgaps
— Solid / Litz Wire, Foils
— Winding Topology
— Natural / Forced Conv. Cooling
— Hard-/Soft-Switching
— Si / SiC
— etc.
— etc.
— etc.



■ **System-Level Degrees of Freedom**

— Circuit Topology
— Modulation Scheme
— Switching Frequ.
— etc.
— etc.



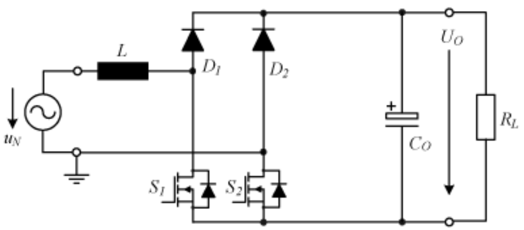
■ **Only η-ρ-Pareto Front Allows Comprehensive Comparison of Converter Concepts (!)**

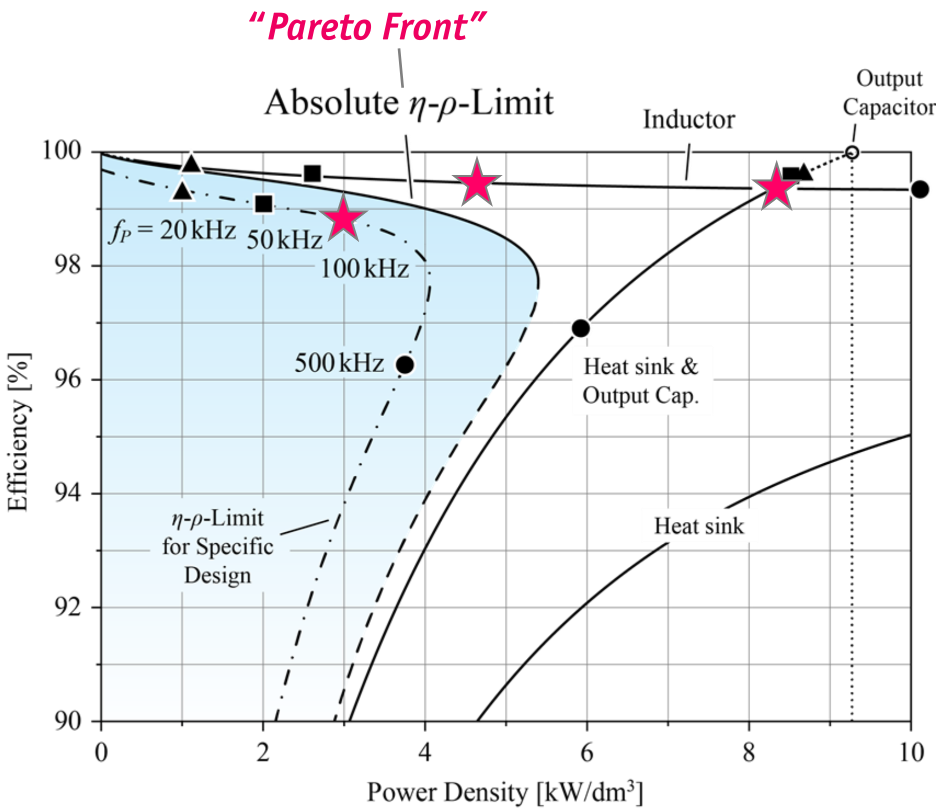
▶ Determination of the η-ρ-Pareto Front (b)

- **Example: Consider Only f_P as Design Parameter**

- **Only the Consideration of All Possible Designs / Degrees of Freedom Clarifies the Absolute η-ρ-Performance Limit**

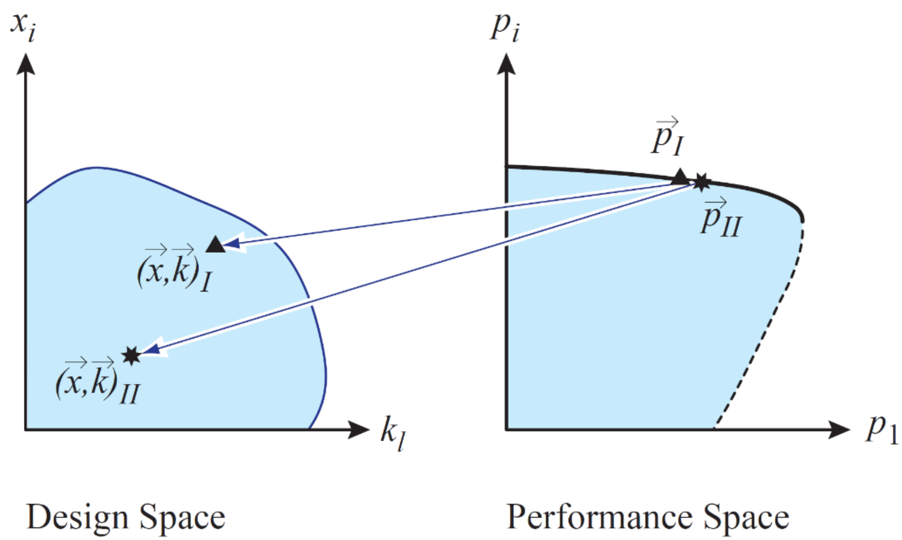
★ f_P =100kHz





Multi-Objective Optimization (2)

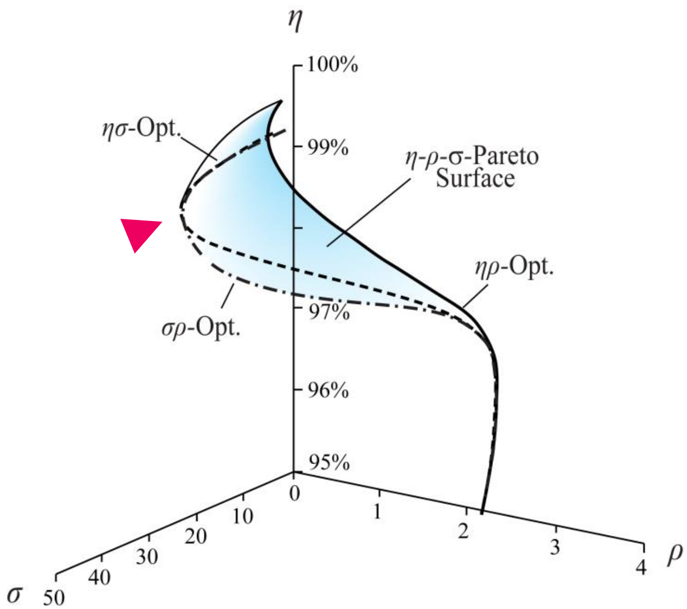
- Design Space Diversity
- Equal Performance for Largely Different Sets of Design Parameters

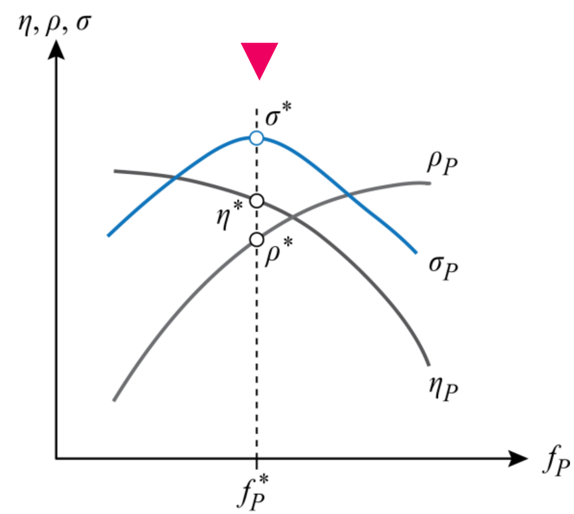


→ E.g. Mutual Compensation of Volume and Loss Contributions (e.g. Cond. & Sw. Losses)
→ Allows Optimization for Further Performance Index (e.g. Costs)

▶ Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface

- Definition of a Power Electronics *"Technology Node"* → ($\eta^*,\rho^*,\sigma^*,f_P^*$)
- Maximum σ [kW/$], Related Efficiency & Power Density





→ Specifying Only a Single Performance Index is of No Value (!)
→ Achievable Perform. Depends on Conv. Type / Specs (e.g. Volt. Range) / Side Cond. (e.g. Cooling)

▶ Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface

- Definition of a Power Electronics *"Technology Node"* → $(\eta^*,\rho^*,\sigma^*,f_P^*)$
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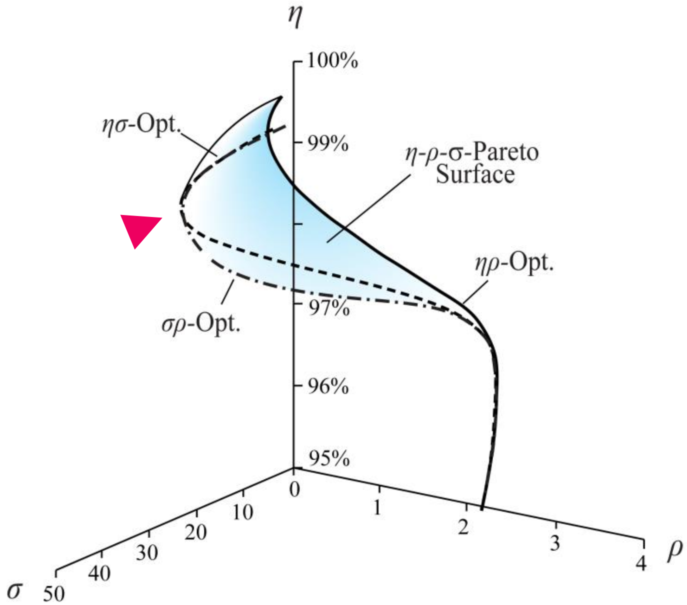
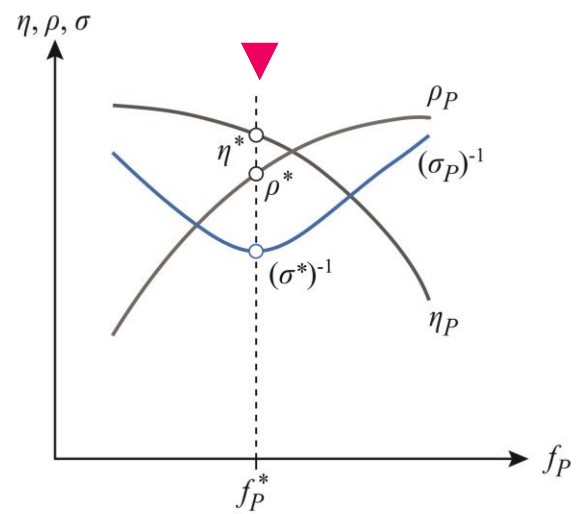


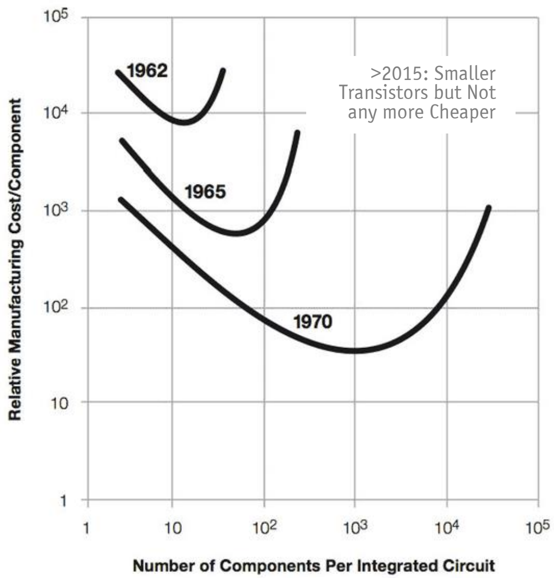


→ Specifying Only a Single Performance Index is of No Value (!)
→ Achievable Perform. Depends on Conv. Type / Specs (e.g. Volt. Range) / Side Cond. (e.g. Cooling)

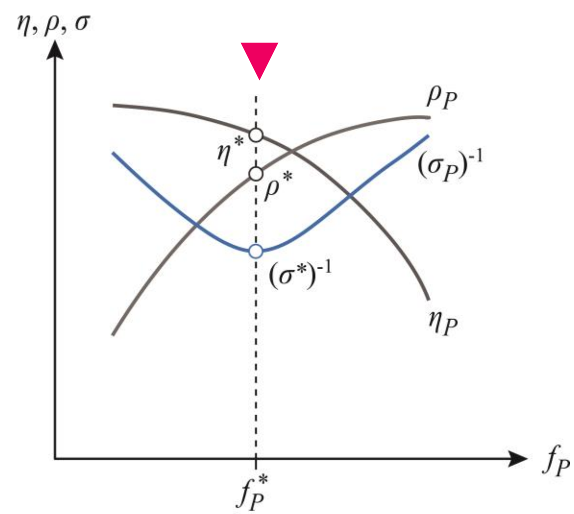
Remark: Comparison to "Moores Law"

- "Moores Law" Defines Consecutive Techn. Nodes Based on Min. Costs per Integr. Circuit (!)
- Complexity for Min. Comp. Costs Increases approx. by Factor of 2 / Year

Economy of Scale → ← Lower Yield



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



→ Definition of "$\eta^*, \rho^*, \sigma^*, f_P^*$–Node" Must Consider Conv. Type / Operating Range etc. (!)

Multi-Objective Optimization Application Examples

Comparative Converter Evaluation
Impact of Technology Progress
Design Space Diversity

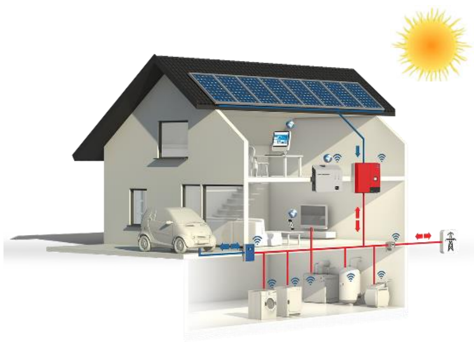
Multi-Objective
Optimization
Application Examples

Comparative Converter Evaluation
Impact of Technology Progress
Design Space Diversity

Example #1

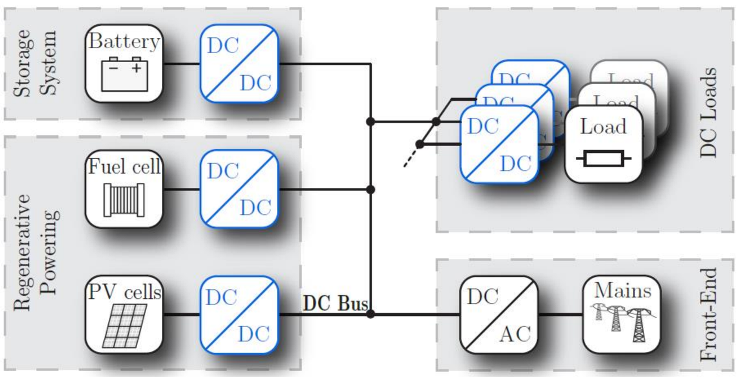
Two-Level vs. Three-Level
Dual Active Bridge

Source: SMA

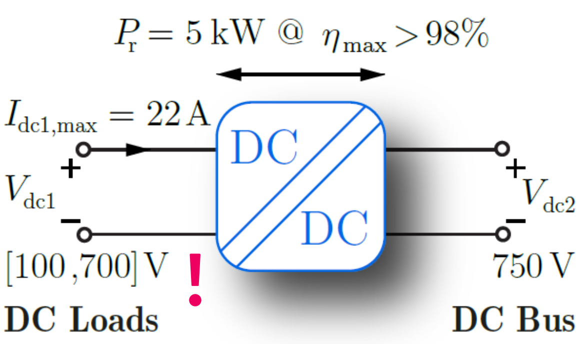


Wide Input Voltage Range Isolated DC/DC Converter

Structure of "Smart Home" DC Microgrid



Universal DC/DC Converter

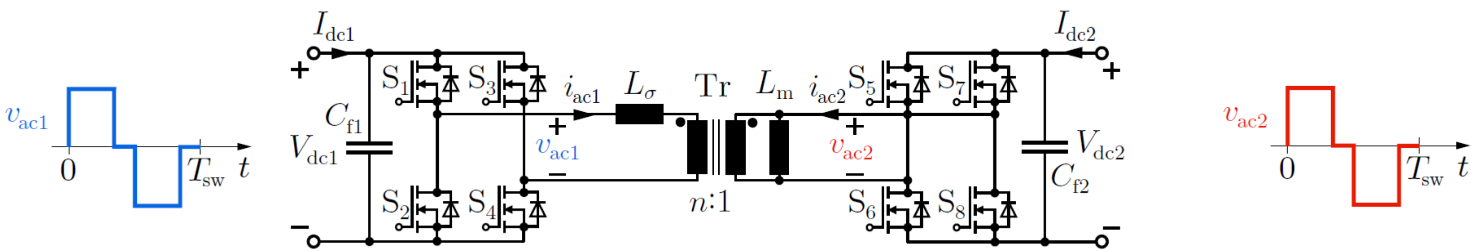


- Universal Isolated DC/DC Converter
  - Bidirectional Power Flow
  - Galvanic Isolation
  - Wide Voltage Range
  - High Partial Load Efficiency

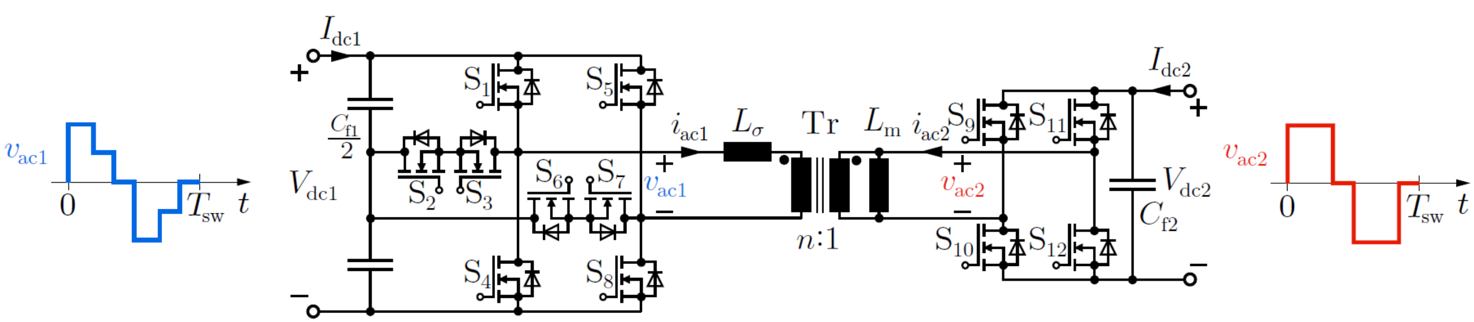
- Advantages
  - Reduced System Complexity
  - Lower Overall Development Costs
  - Economy of Scale

▶ Comparative Evaluation of Converter Topologies

■ Conv. 3-Level Dual Active Bridge (3L-DAB)

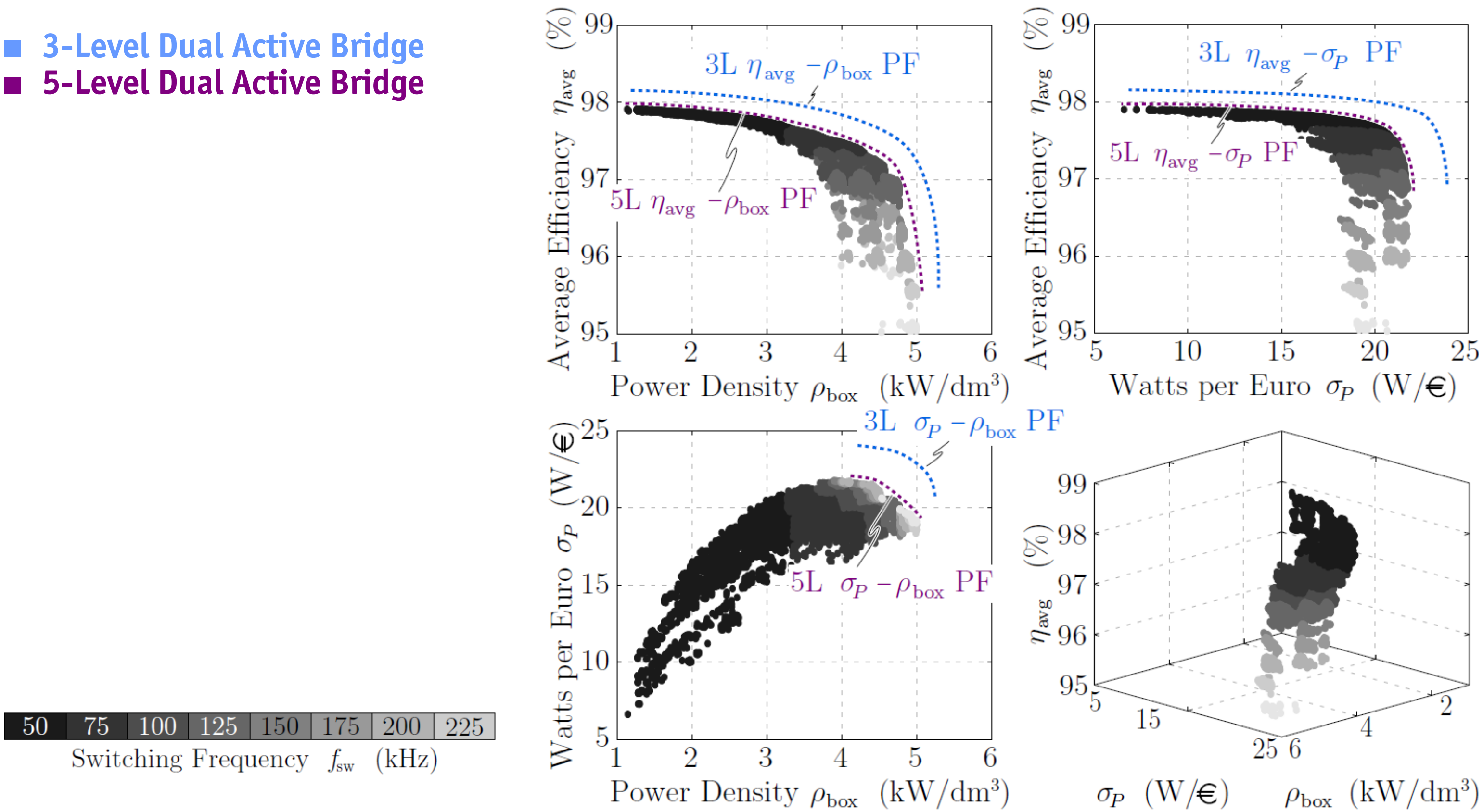


■ Advanced 5-Level Dual Active Bridge (5L-DAB)



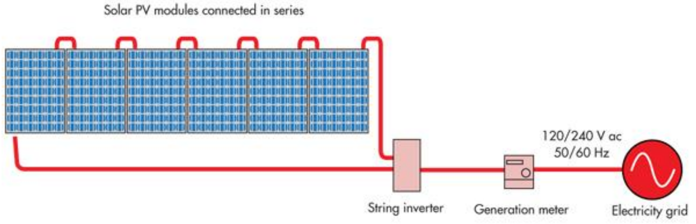
▶ Optimization Results - Pareto Surfaces

- 3-Level Dual Active Bridge
- 5-Level Dual Active Bridge



Example #2

Performance & Life-Cycle-Costs of Si vs. SiC

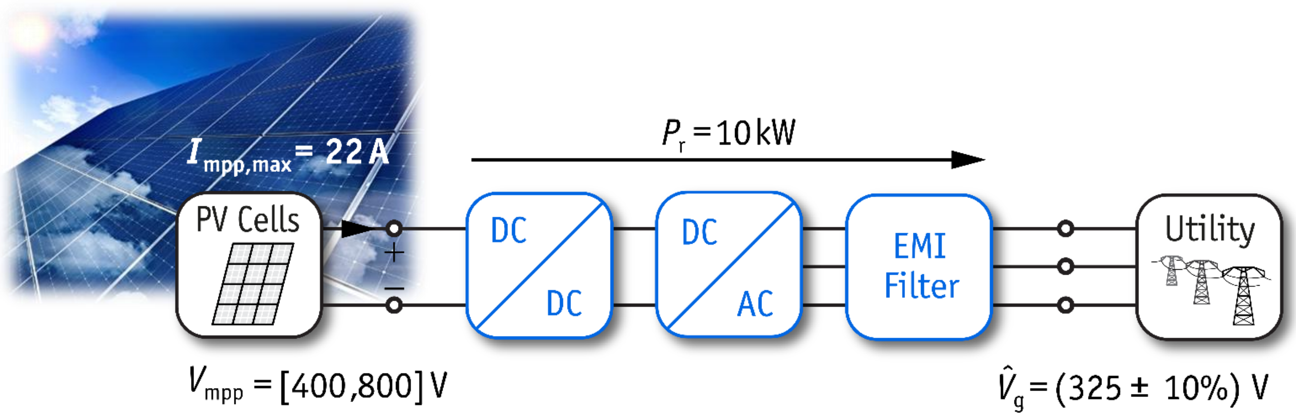


Source: L. Lalonde / electronicdesign.com

▶ Multi-Objective η-ρ-σ-Comparison of *Si vs. SiC*

■ Three-Phase PV Inverter System

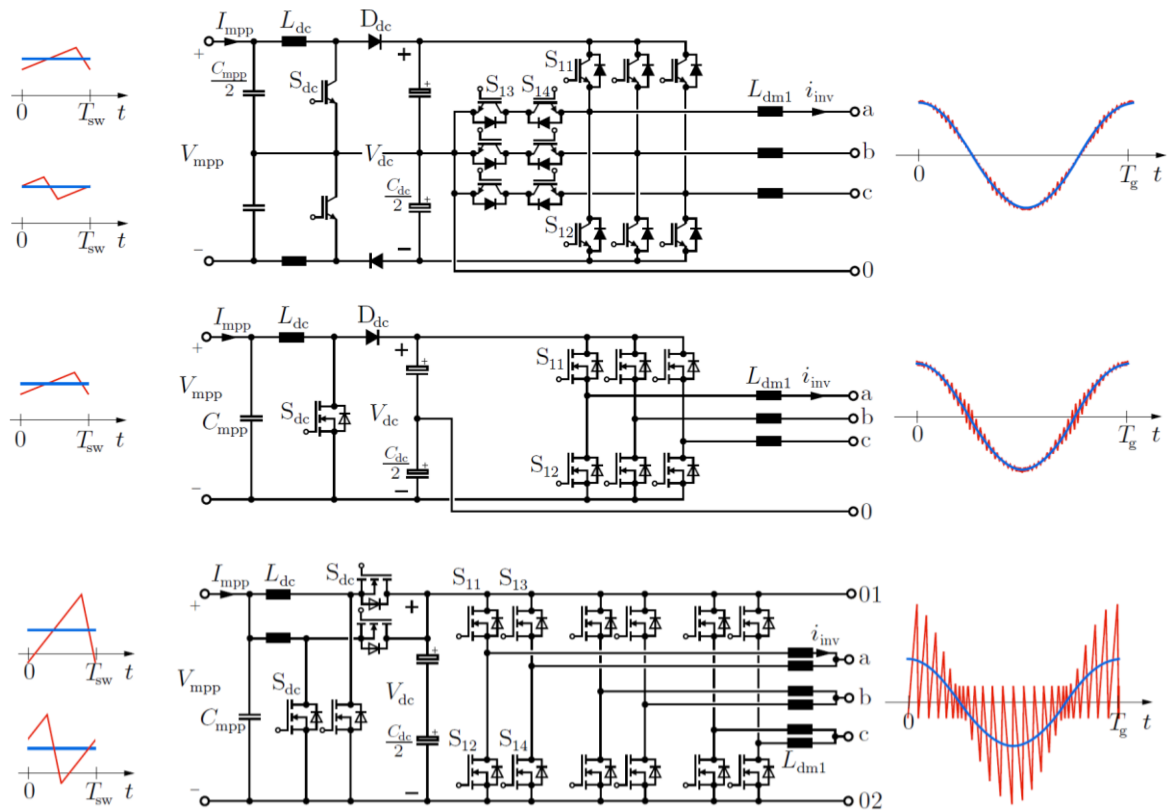
— Typical Residential Application
— Single-Input/Single-MPP-Tracker Multi-String PV Inverter
— DC/DC Boost Converter for Wide MPP Voltage Range
— Output EMI Filter



→ Exploit Excellent Hard- AND Soft-Switching Capabilities of SiC
→ Find Useful Sw. Frequency and Current Ripple Ranges
→ Find Appropriate Core Material

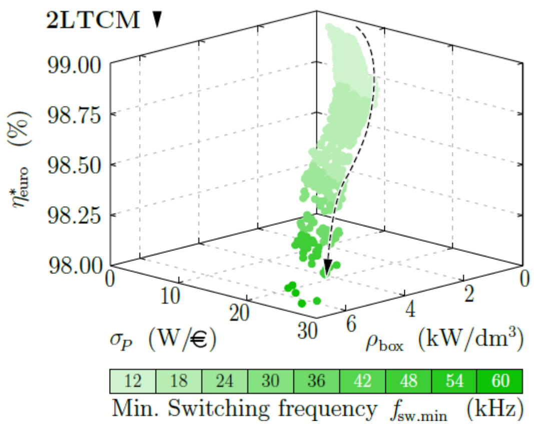
▶ Topologies - Converter Stages

- **Si IGBT 3L-PWM Inverter**
- **SiC MOSFET 2L-PWM Inverter**
- **SiC MOSFET Interleaved 2L-TCM Inverter**

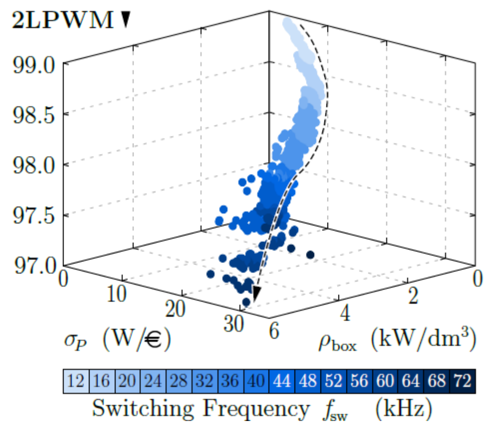


▶ Optimization Results - Pareto Surfaces

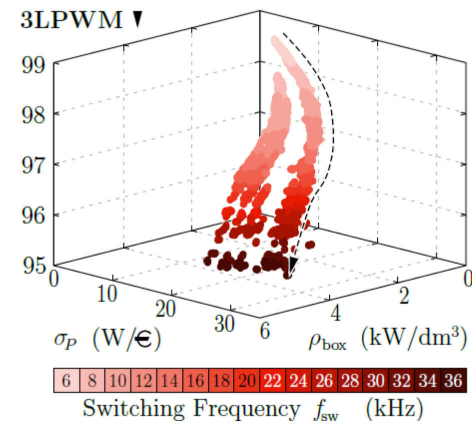
SiC



SiC



Si



- No Pareto-Optimal Designs for $f_{sw,min}$ > 60 kHz
- No METGLAS Amorphous Iron Designs

- Pareto-Optimal Designs for Entire Considered f_{sw} Range
- No METGLAS Amorphous Iron Designs

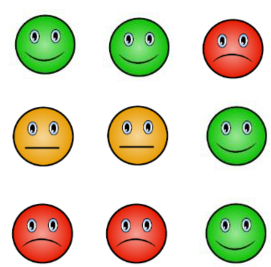
- Pareto-Optimal Designs for Entire Considered f_{sw} Range
- METGLAS Amorphous Iron and Ferrite Designs

▶ Optimization Results – *Investigations Along Pareto Surfaces*

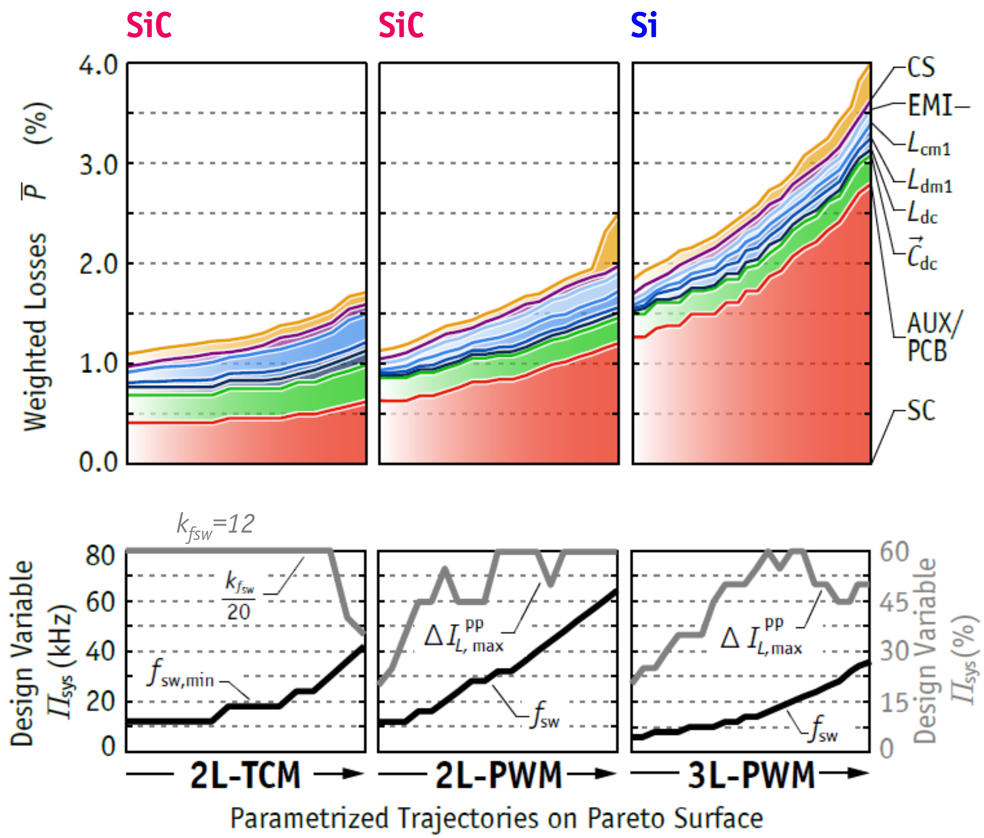
- **Comparison of the Inverter Concepts**

η ρ σ

- 2L-TCM
- 2L-PWM
- 3L-PWM



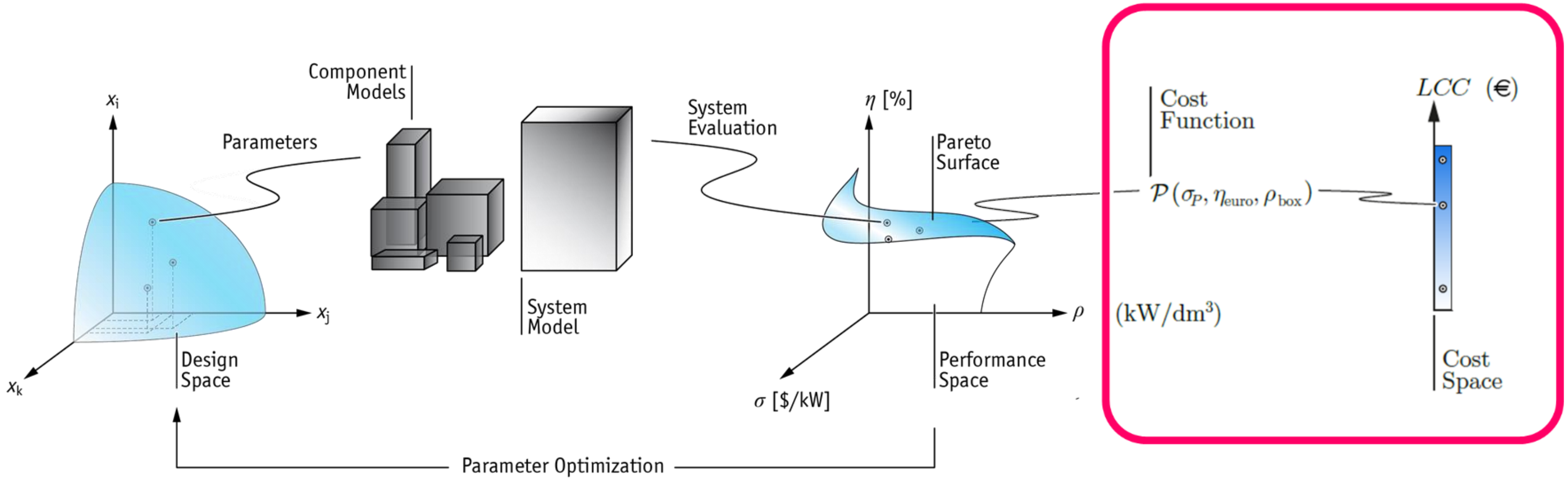
→ **Semiconductor Losses Clearly Dominating (35…70%)**



▶ Extension to *Life-Cycle Cost (LCC) Analysis*

- **Performance Space Analysis**
  - 3 Performance Measures: η, ρ, σ
  - Reveals Absolute Performance Limits / Trade-Offs Between Performances

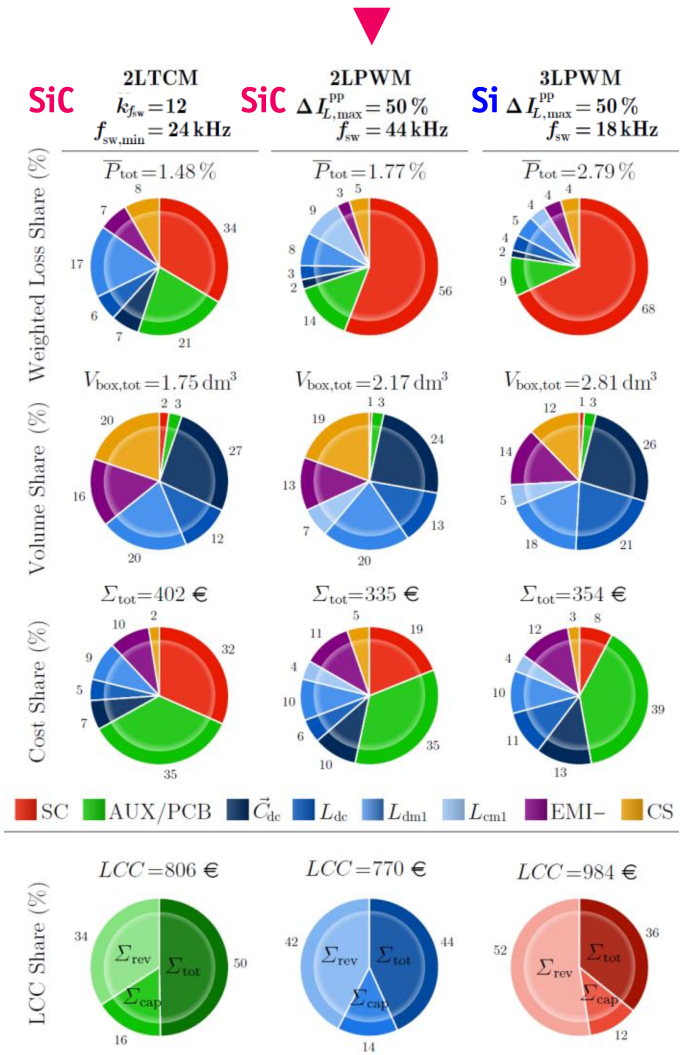
- **Life-Cycle Cost Analysis**
  - Post-Processing of Pareto-Optimal Designs
  - Determination of Min.-LCC Design
  - Arbitrary Cost Function Possible



→ Which is the Best Solution Weighting $\eta, \rho, \sigma,$ e.g. in Form of Life-Cycle Costs (LCC)?
→ How Much Better is the Best Design?
→ Optimal Switching Frequency?

▶ Post-Processing

- **Life-Cycle Cost Analysis (10 years)**

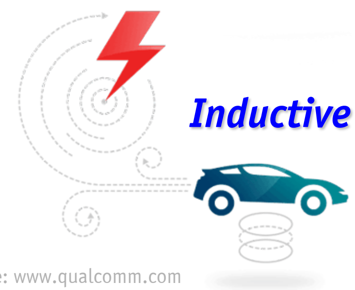


- **Best System - 2L-PWM SiC Converter @ 44kHz & 50% Current Ripple**

  — 22% Lower LCC than 3L-PWM
  — 5% Lower LCC than 2L-TCM
  — Simplest Design
  — Probably Highest Reliability
  — Lower Vol. (Housing) Not Yet Considered!

→ **Application of SiC Justified on "System Level"**

Example #3



Source: www.qualcomm.com

Inductive Power Transfer →

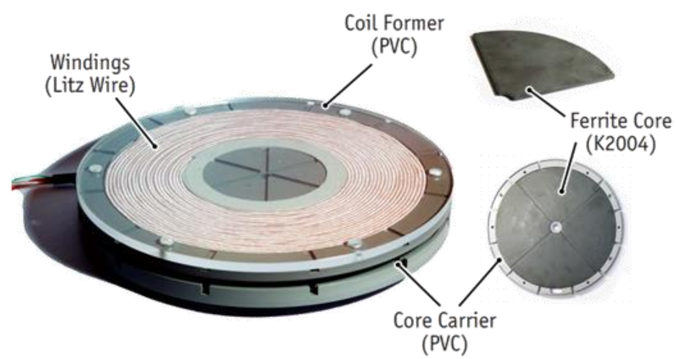
Multi-Objective Optimization of 5kW Prototype

- Design Process Taking All Performance Aspects into Account

- **System Specification**
  - Input Voltage 400V
  - Battery Voltage 350V
  - Output Power 5kW
  - Air Gap 50mm

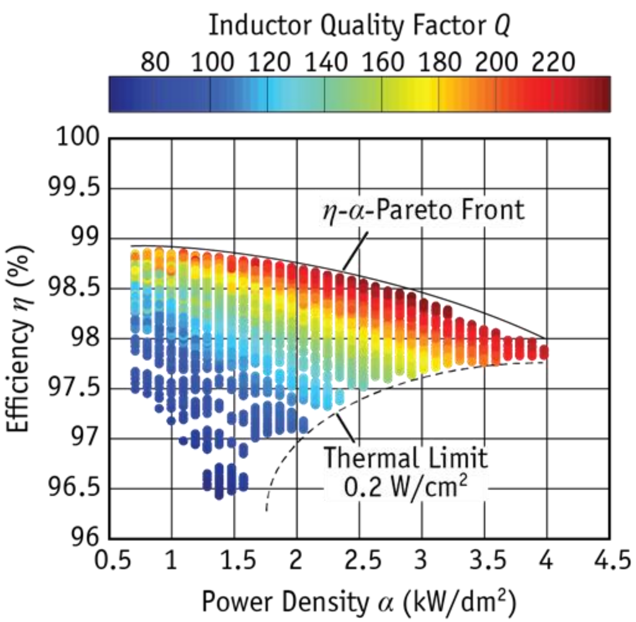
- **Constraints / Side Conditions**
  - Thermal Limitations [°C]
  - Stray Field Limits [μT]
  - Max. Constr. Vol. [m^3]
  - Switching Frequency [kHz]

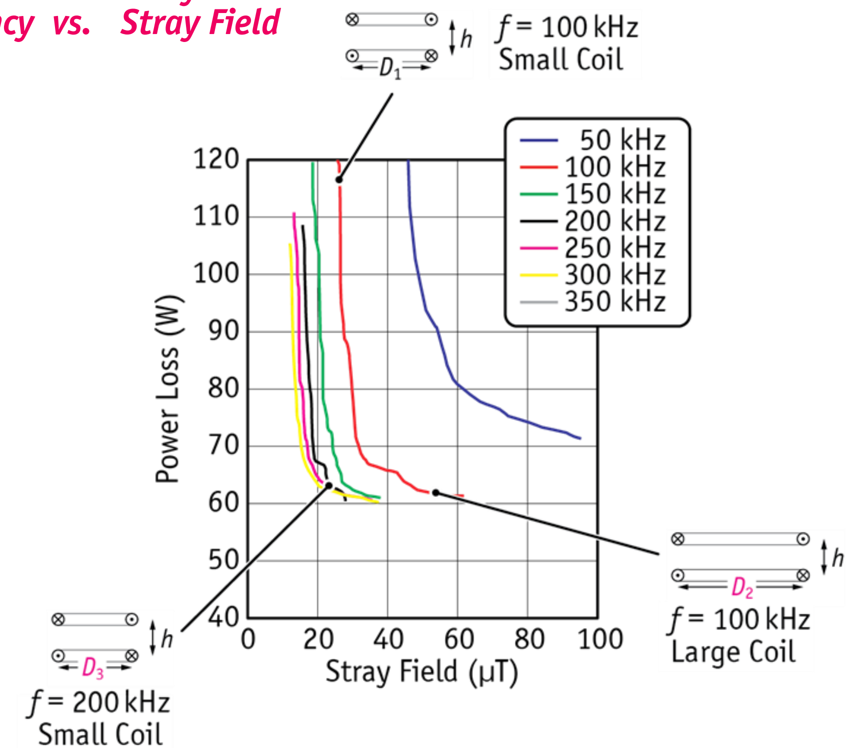
- **System Performance**
  - * Efficiency $\eta = P_{out}/P_{in}$ [%]
  - * Power Density $\alpha = P_{out}/A_{coil}$ [kW/dm^2]
  - * Stray Field $\beta = B_{max}/B_{norm}$ [%]



▶ η-α-β-Pareto Coil Optimization

■ **Encountered Design Trade-Offs** ** Coil Size vs. Efficiency*
** Coil Size vs. Stray Field*
** Frequency vs. Stray Field*



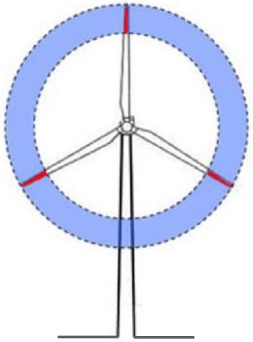


→ **Pareto-Optimization Allows to Study Influence of Key Design Parameters**

Example #4

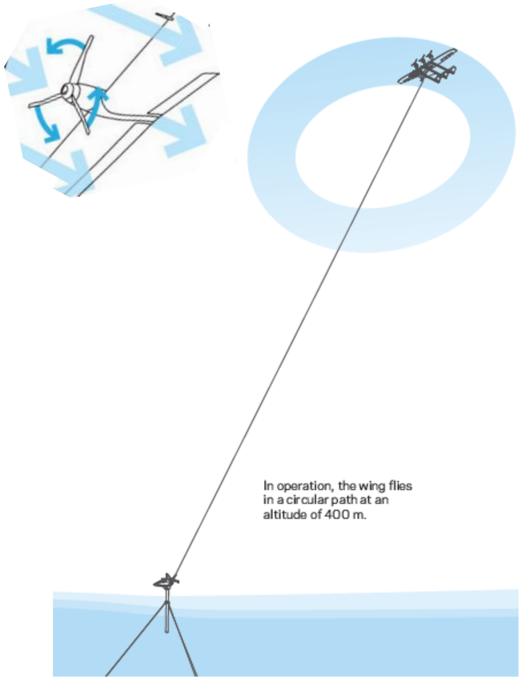
Electrical System of an Airborne Wind Turbine

M. Loyd, 1980



► Airborne Wind Turbine (AWT) - Google X

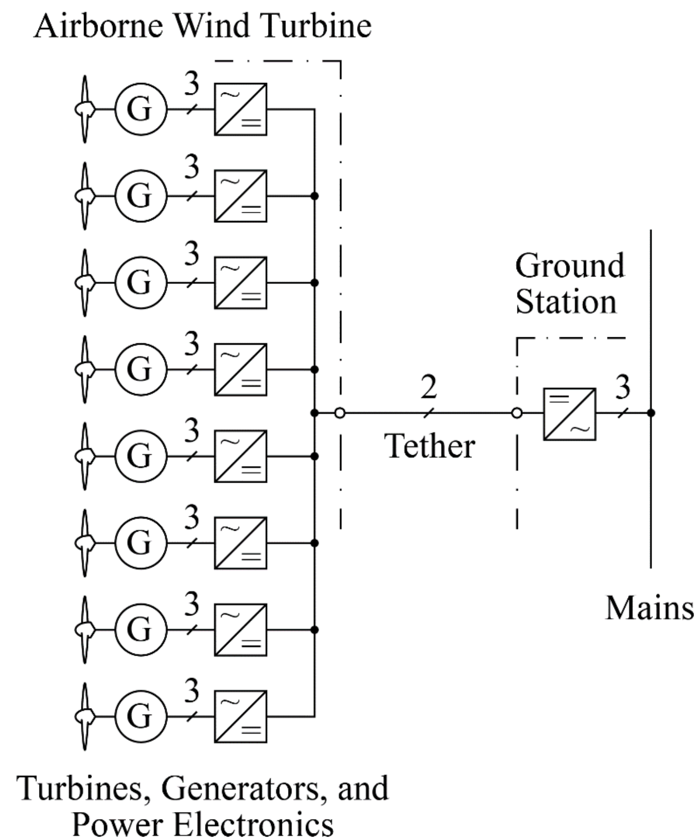
- Power Kite → On-Board Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically
- Minimum of Mechanical Support



MAKANI POWER

► AWT Electrical *System* Structure

■ Rated Power	100kW
■ Operating Height	800...1000m
■ Ambient Temp.	40°C
■ Power Flow	Motor & Generator

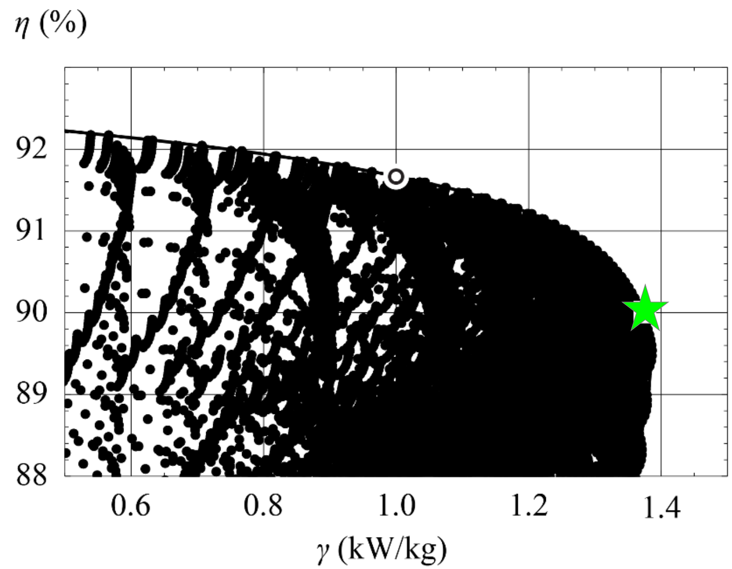


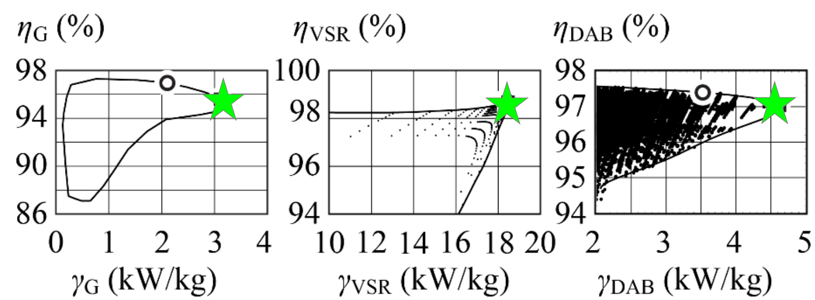
→ El. System Target Weight	100kg
→ Efficiency (incl. Tether)	90%
→ Turbine /Motor	2000/3000rpm

▶ Overall AWT *System* Performance

EFFICIENCIES AND POWER-TO-WEIGHT RATIOS AT THE 2 DESIGN POINTS MARKED IN FIG. 24(A) (CALCULATED FOR NOMINAL OPERATION).

Total system	Generator, VSR, and DAB converter		
$\gamma = 1.37\,\mathrm{kW/kg}$ $\eta = 90.0\%$	Generator:	$\gamma_G = 3.11\,\mathrm{kW/kg}$,	$\eta_G = 95.4\%$
	VSR:	$\gamma_{VSR} = 18.3\,\mathrm{kW/kg}$,	$\eta_{VSR} = 98.6\%$
	DAB:	$\gamma_{DAB} = 4.60\,\mathrm{kW/kg}$,	$\eta_{DAB} = 97.1\%$
$\gamma = 1.00\,\mathrm{kW/kg}$ $\eta = 91.7\%$	Generator:	$\gamma_G = 2.14\,\mathrm{kW/kg}$,	$\eta_G = 96.9\%$
	VSR:	$\gamma_{VSR} = 18.3\,\mathrm{kW/kg}$,	$\eta_{VSR} = 98.6\%$
	DAB:	$\gamma_{DAB} = 3.53\,\mathrm{kW/kg}$,	$\eta_{DAB} = 97.4\%$





- **Final Step: System Control Consideration**

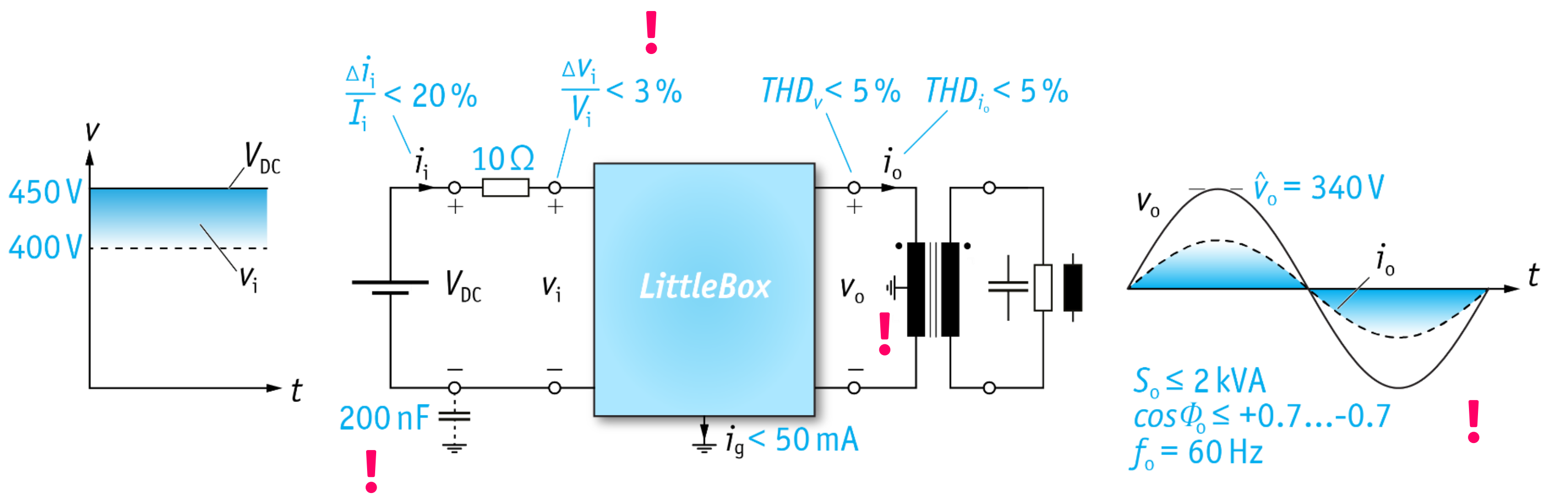
Multi-Objective
Optimization
Application Examples

Comparative Converter Evaluation
Impact of Technology Progress &
Design Space Diversity

LiTTLE BOX CHALLENGE

Google | IEEE

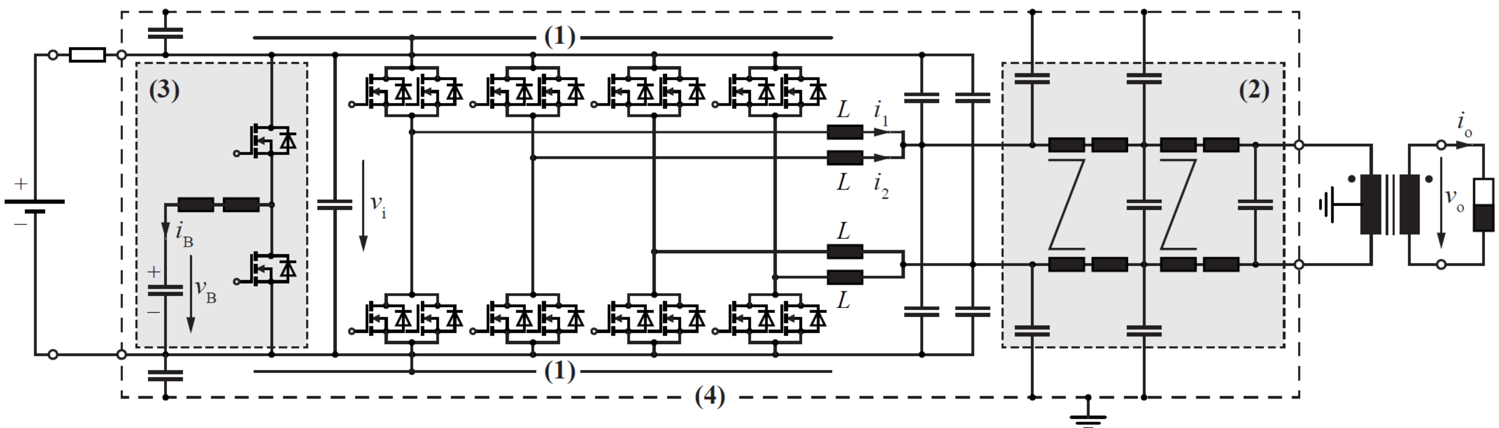
- Design / Build the 2kW 1-Φ Solar Inverter with the Highest Power Density in the World
- Power Density > 3kW/dm³ (50W/in³)
- Efficiency > 95%
- Case Temp. < 60°C
- EMI FCC Part 15 B



→ Push the Forefront of New Technologies in R&D of High Power Density Inverters

Selected Converter Topology

- Interleaving of 2 Bridge Legs per Phase
- Active DC-Side Buck-Type Power Pulsation Buffer
- 2-Stage EMI AC Output Filter



→ ZVS of All Bridge Legs @ Turn-On/Turn-Off in Whole Operating Range (4D-TCM-Interleaving)
→ Heatsinks Connected to DC Bus / Shield to Prevent Cap. Coupling to Grounded Enclosure

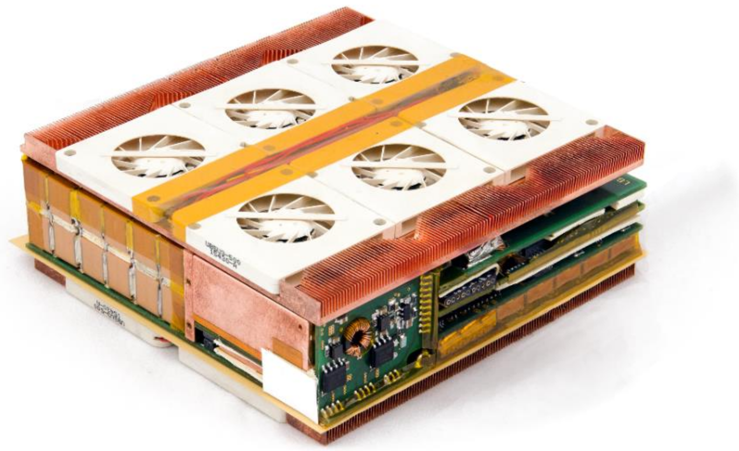
Little-Box 1.0 Prototype

- **Performance**

  - 8.2 kW/dm^3
  - 96,3% Efficiency @ 2kW
  - T_c=58°C @ 2kW

- **Design Details**

  - 600V IFX Normally-Off GaN GIT
  - Antiparallel SiC Schottky Diodes
  - Multi-Airgap Ind. w. Multi-Layer Foil Wdg
  - Triangular Curr. Mode ZVS Operation
  - CeraLink Power Pulsation Buffer



→ Analysis of Potential Performance Improvement for *"Ideal Switches"*

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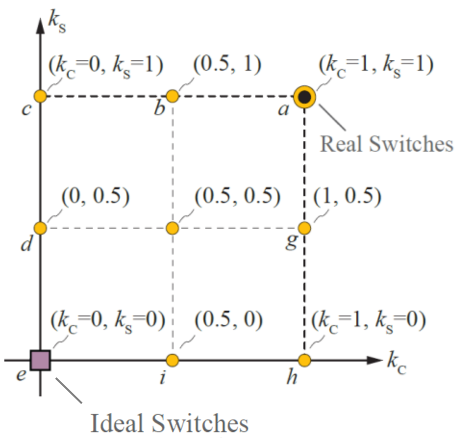
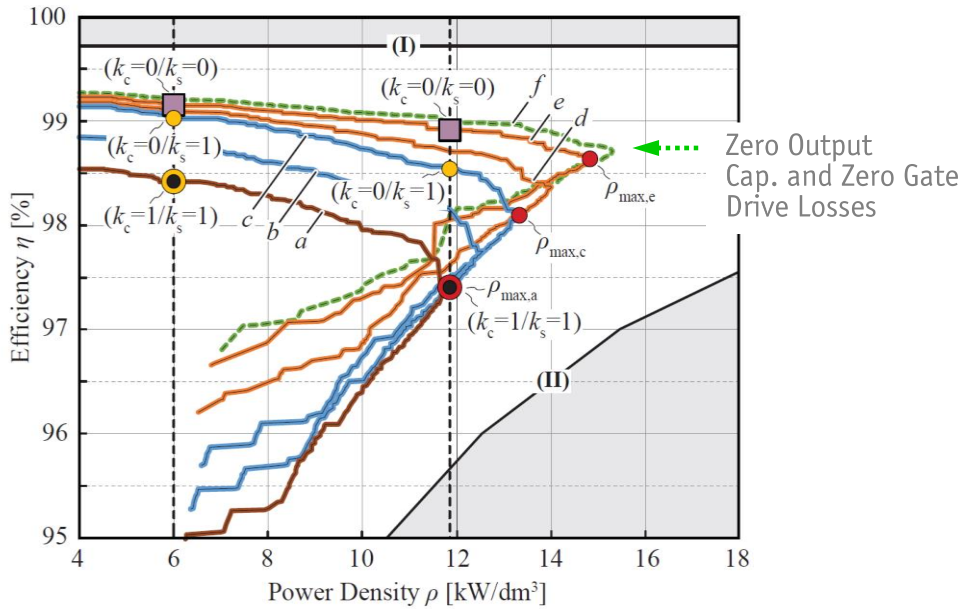
  - CeraLink Power Pulsation Buffer

→ Analysis of Potential Performance Improvement for *"Ideal Switches"*

Little Box 1.0 @ Ideal Switches (TCM)

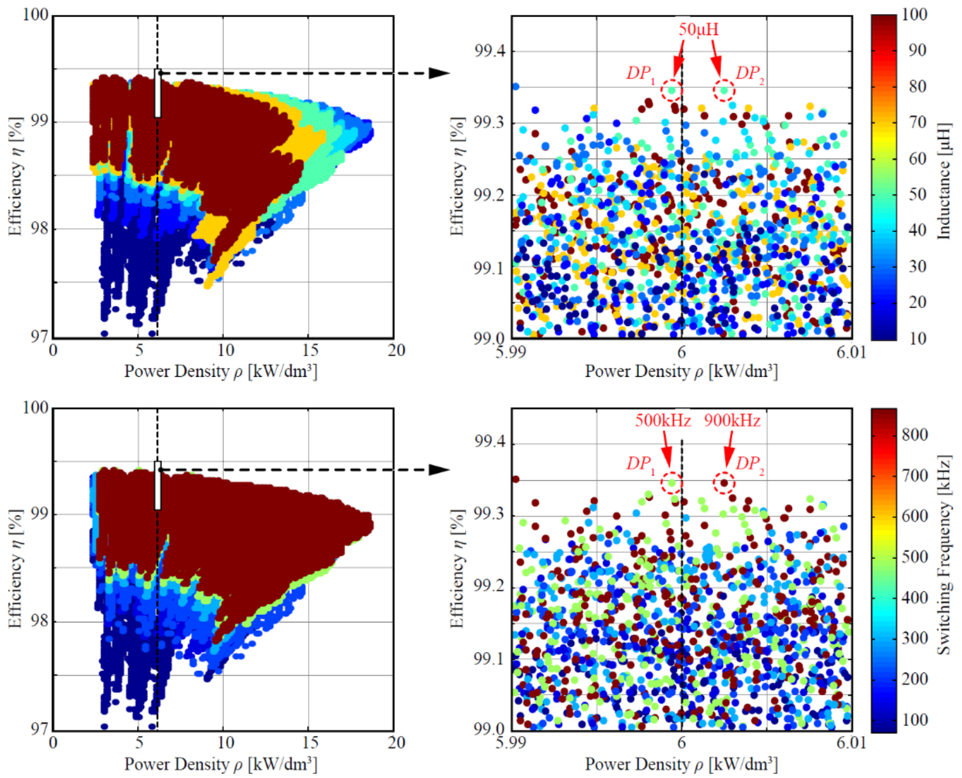
- Multi-Objective Optimization of Little-Box 1.0 (X6S Power Pulsation Buffer)
- Step-by-Step Idealization of the Power Transistors
- Ideal Switches: $k_C = 0$ (Zero Cond. Losses); $k_S = 0$ (Zero Sw. Losses)





→ Analysis of Improvement of Efficiency @ Given Power Density & Maximum Power Density
→ *The Ideal Switch is NOT Enough* (!)

Little Box 1.0 @ Ideal Switches (PWM)



ρ = 6kW/dm^3
η ≈ 99.35%

L = 50uH
f_S = 500kHz or 900kHz

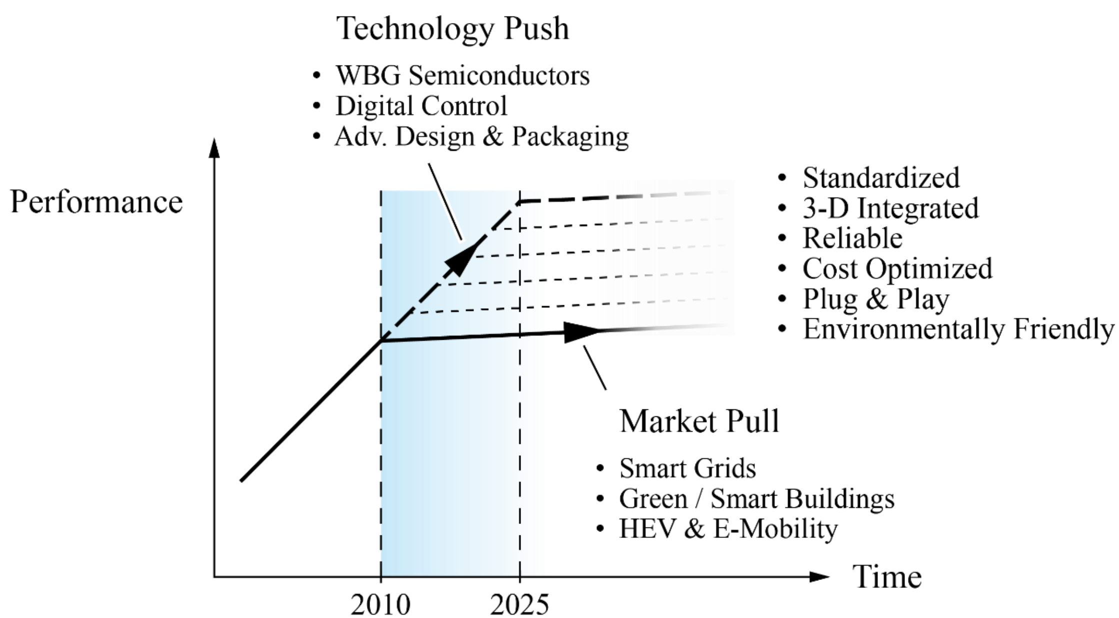
- L & f_S are Independent Degrees of Freedom
- Large Design Space Diversity (Mutual Compensation of HF and LF Loss Contributions)

Conclusions

Future Power Electronics Development
Future Virtual Prototyping
"Stairway to Heaven"

▶ Future Development

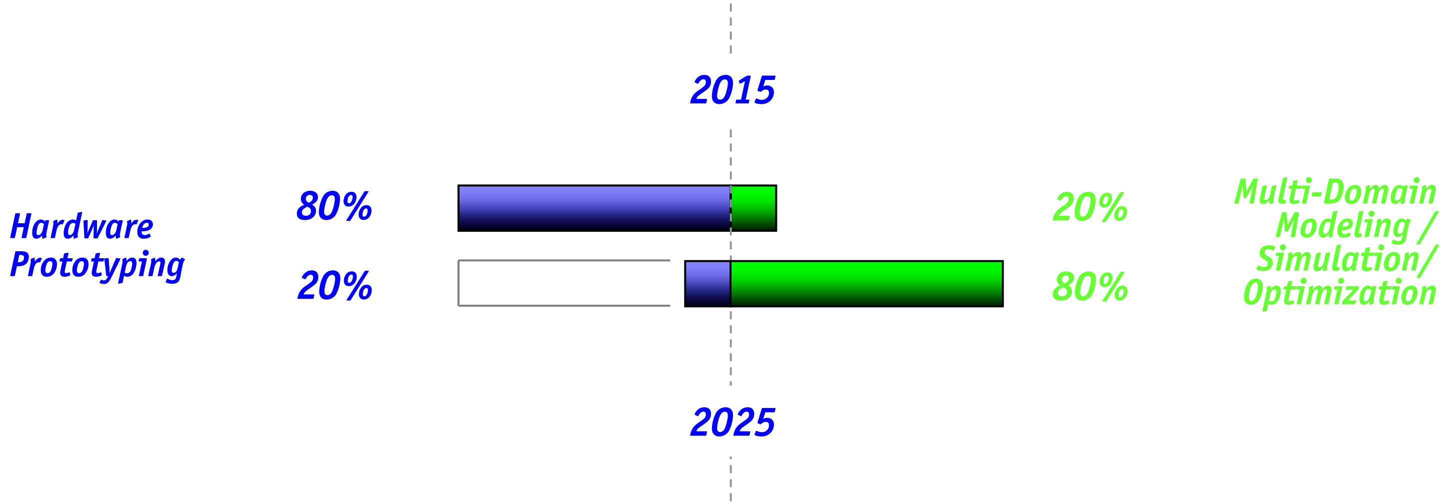
- Megatrends – Renewable Energy / Energy Saving / E-Mobility / "SMART XXX"
- Power Electronics will Massively Spread in Applications



→ More Application Specific Solutions
→ Mature Technology – Cost Optimization @ Given Performance Level
→ Design / Optimize / Verify (All in Simulation) - Faster / Cheaper / Better

▶ Future "Virtual Prototyping"

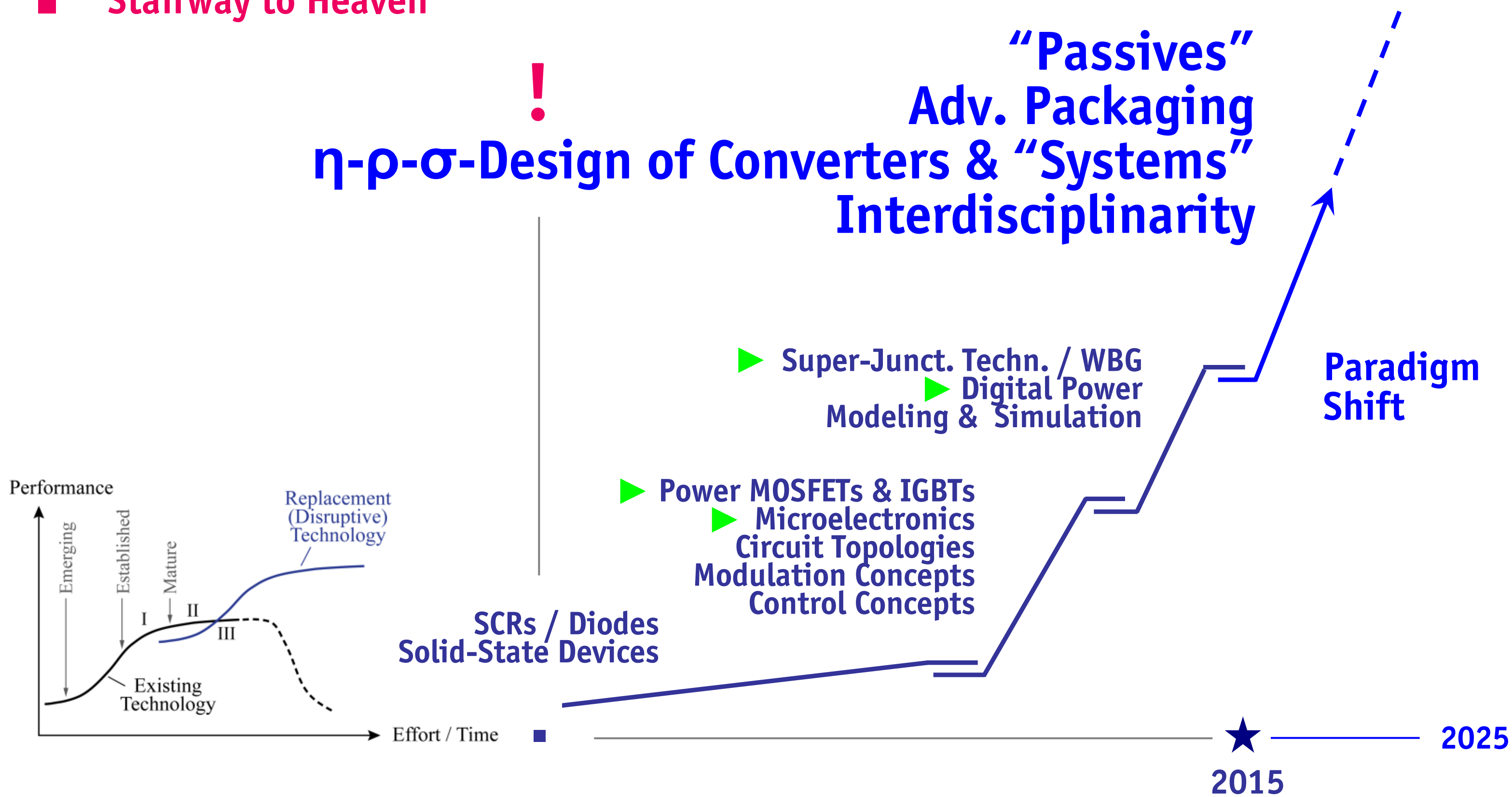
- Offers Incredible Design Insight – Quantifies Trade-Offs / Technology Sensitivities (!)
- Extends Theory of Components – "Theory of Systems"
- Reduces Time-to-Market – Cuts Design Time from Weeks to Hours



→ Main Research Challenges in Modeling (EMI, Reliability, Reduced Order Models etc.)
→ Main Practical Challenge is the Implementation in Industry & Academia ;-)

▶ Extrapolation of Technology S-Curve

- "Stairway to Heaven"



Future Paradigm Shift

▶ Power Electronics 2.0

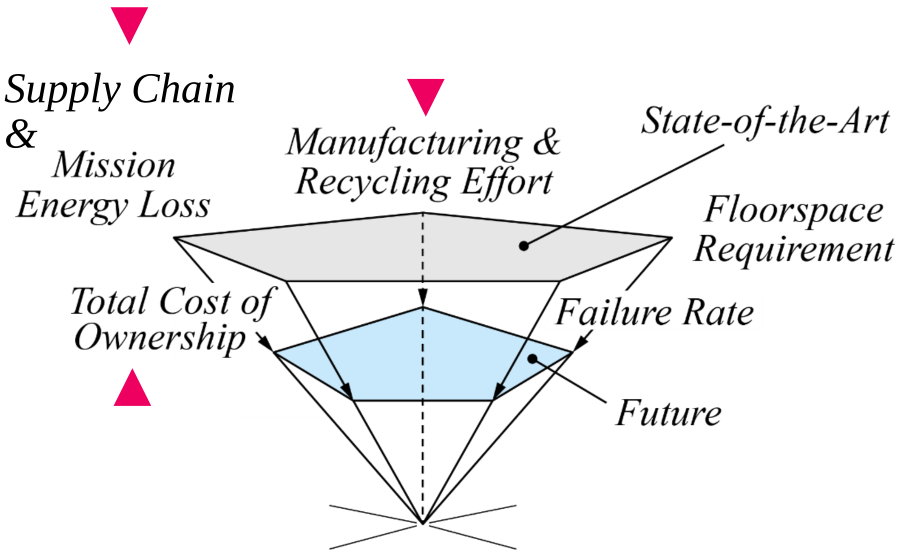
- Design Considering Converters as "Integrated Circuits" (PEBBs)
- Extend Analysis to Converter Clusters / Power Supply Chains / etc.

— "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.

► New Power Electronics Systems Performance Figures/Trends



- **Complete Set of New Performance Indices**

- — **Power Density** [kW/m²]
- — **Environm. Impact** [kWs/kW]
- — **TCO** [$/kW]
- — **Mission Efficiency** [%]
- — **Failure Rate** [h^{-1}]

- End

Thank You !