ETH zürich

IEEE Power Electronics Society
SPEC
SOUTHERN POWER ELECTRONICS CONFERENCE

Multi-Objective Optimization in Power Electronics

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Outline

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

Acknowledgement
D. Bortis
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R. Burkart
F. Krismer

Global Megatrends

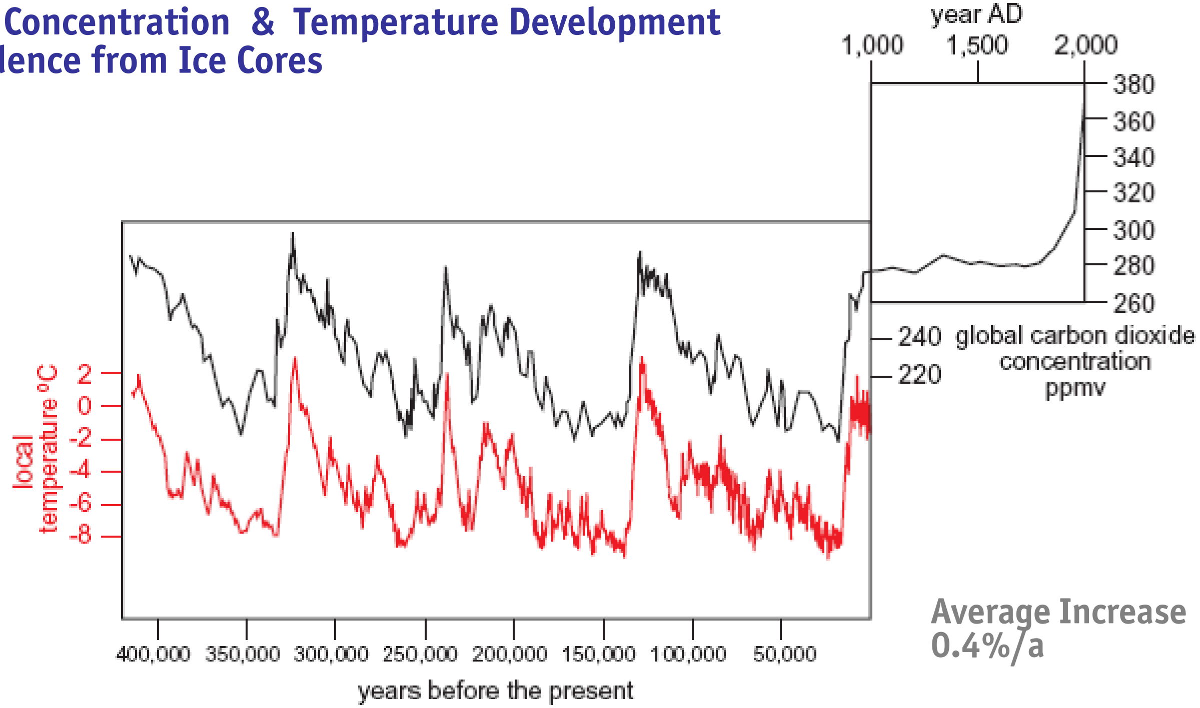
Climate Change
Digitalization
Sustainable Mobility
Urbanization
Alleviate Poverty
Etc.

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

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▶ 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

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

Source: M. Prahm / Flickr

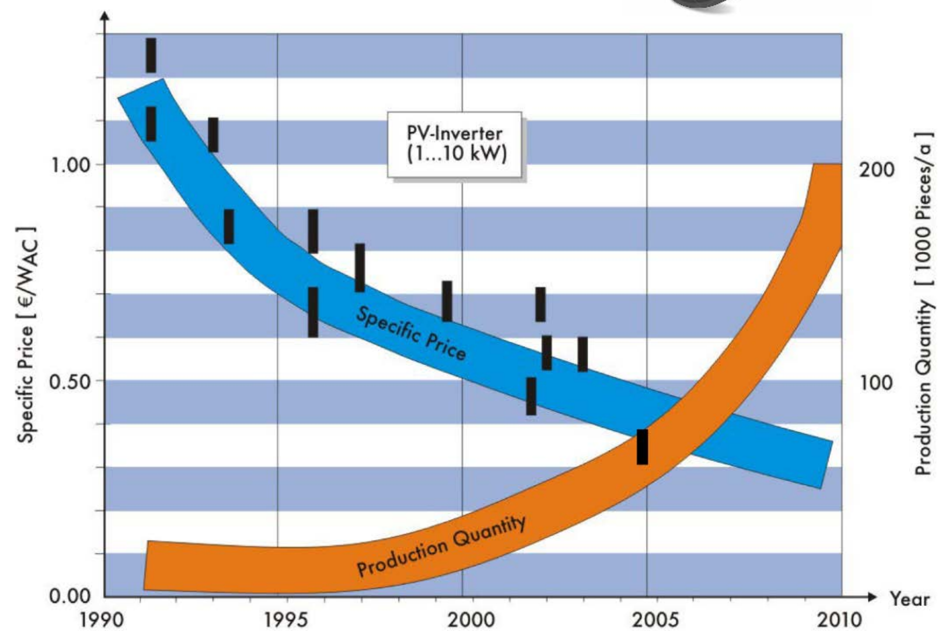
▶ Off-Shore Wind Farms
▶ Medium Voltage Systems

→ *Utilize Renewable Energy (2)*

■ Enabled by Power Electronics

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

Source: SMA 2006



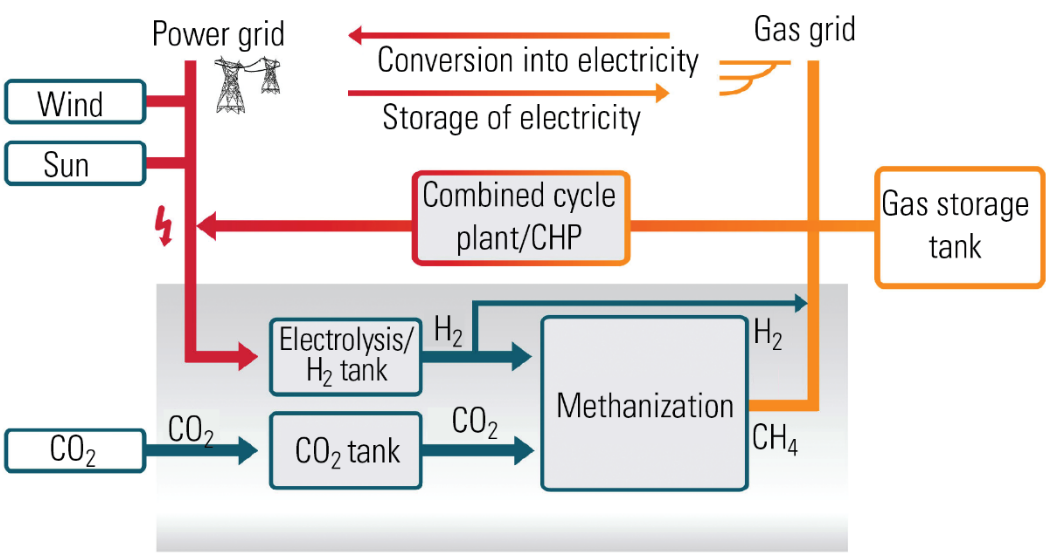
▶ Photovoltaics Power Plants
▶ Up to Several MW Power Level
▶ Future Hybrid PV/Therm. Collectors

→ *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 →
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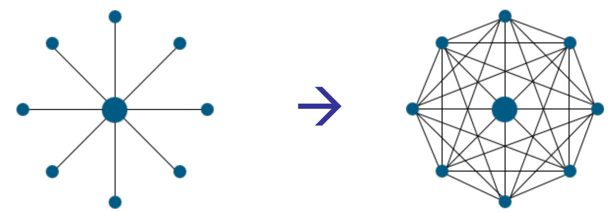
Etc.

▶ Digitalization

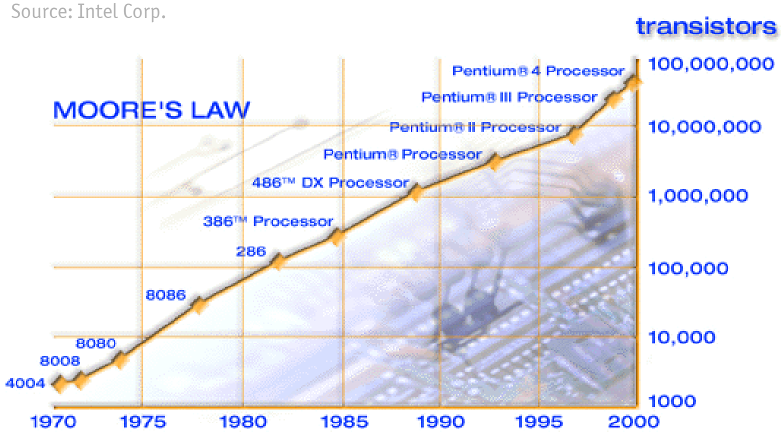
■ Internet of Things (IoT) / Cognitive Computing

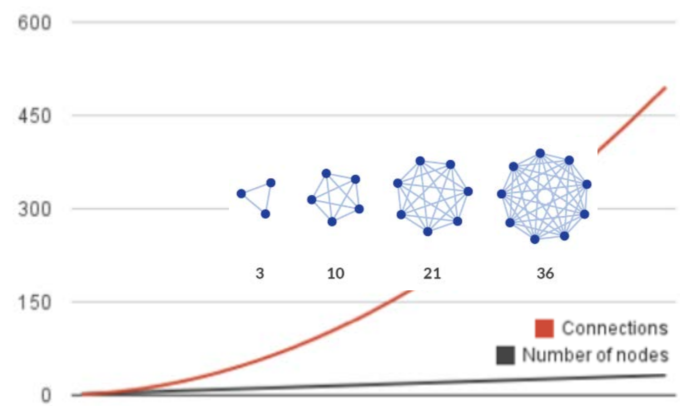
– Ubiquitous Computing / BIG DATA
– Fully Automated Manufacturing / Industry 4.0
– Autonomous Cars
– Etc.

– 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

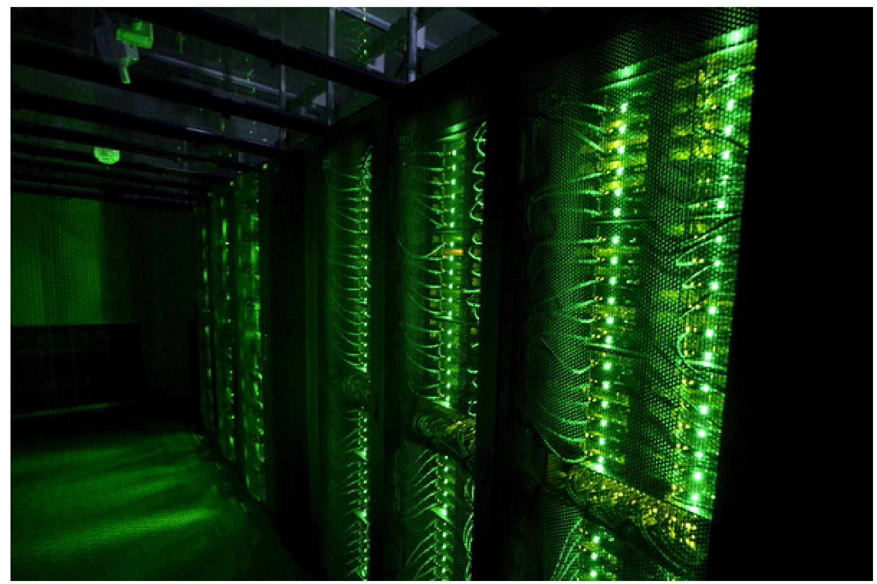
— Ranging from Medium Voltage to Power-Supplies-on-Chip
— Short Power Supply Innovation Cycles
— Modularity / Scalability

— 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

→

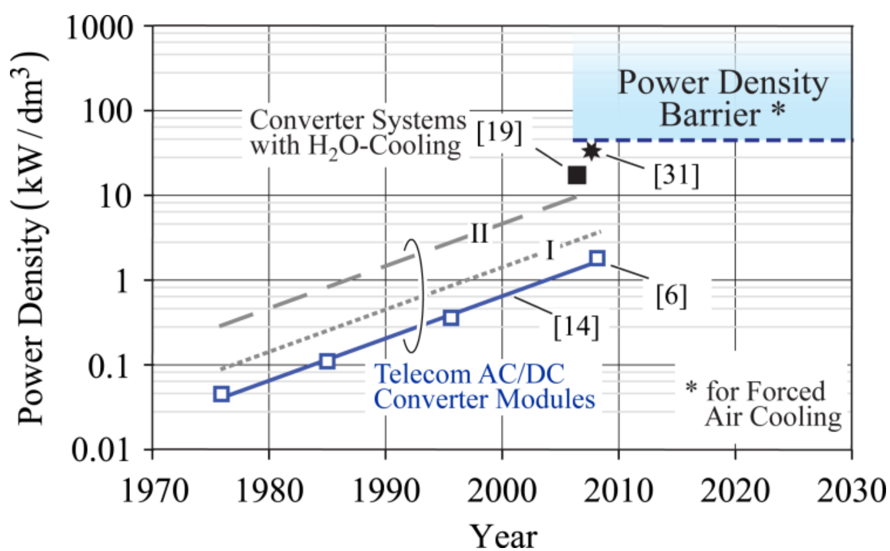
60 Watts

→ 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



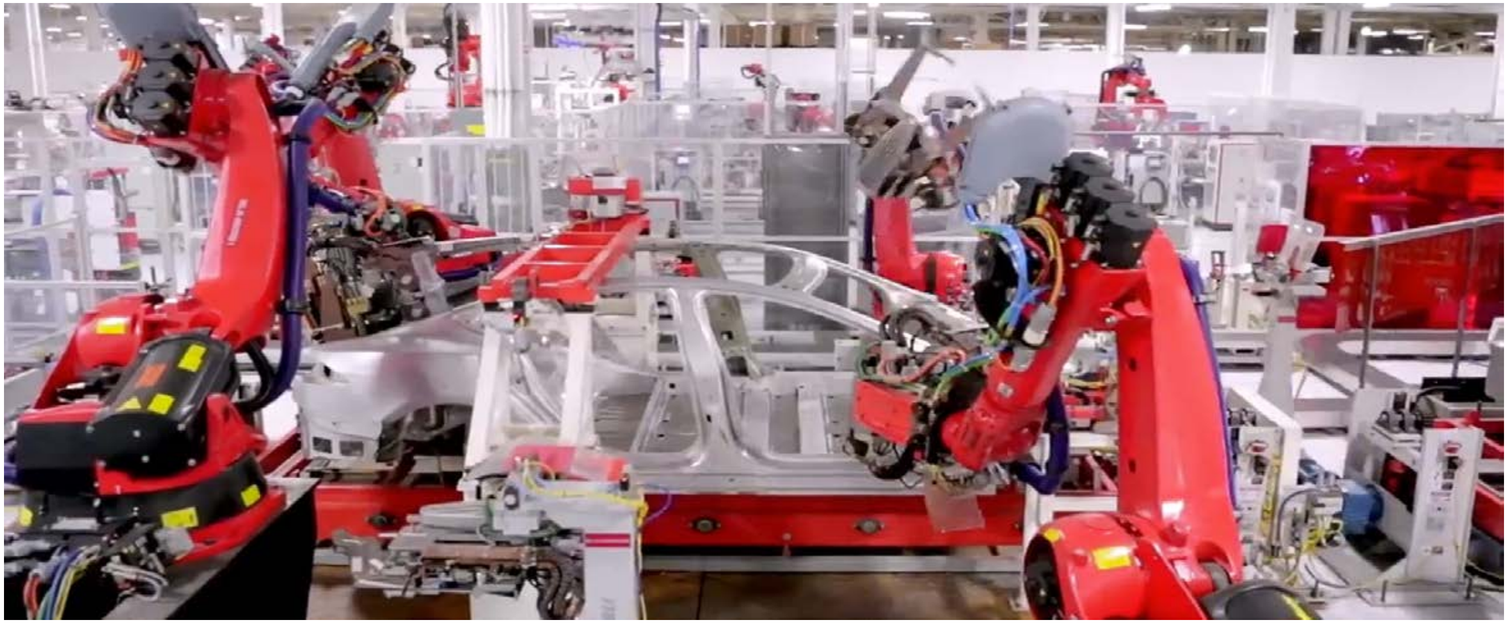
► Power Density Increased by Factor 2 over 10 Years

Fully Automated Manufacturing – Industry 4.0

Enabled by Power Electronics

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

Source: TESLA MOTORS

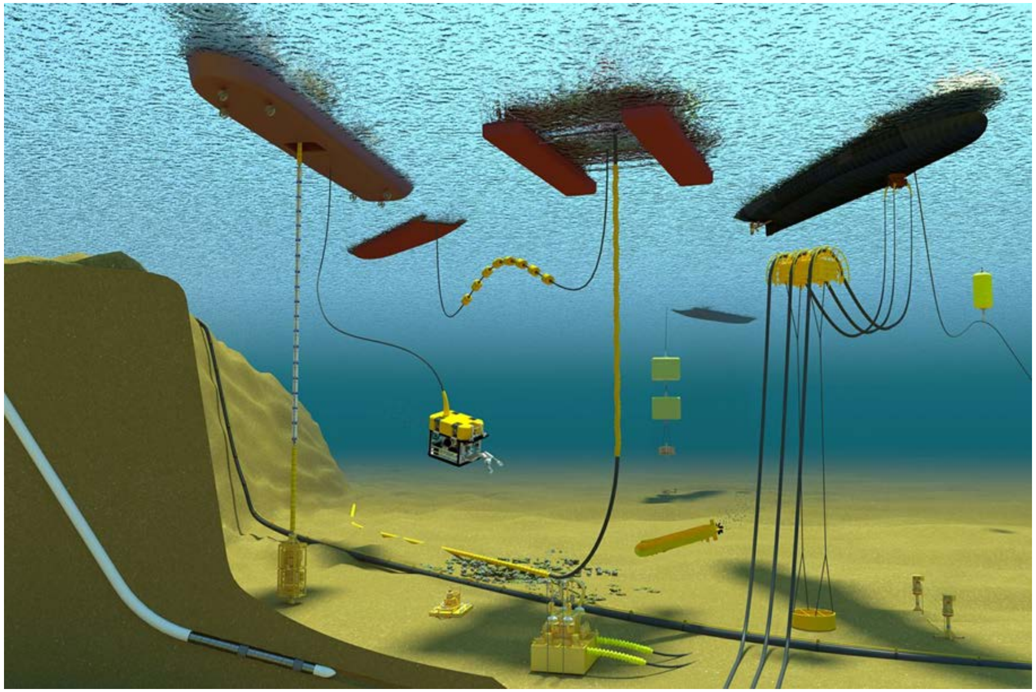


→ *Fully Automated Raw Material Extraction*

- **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"

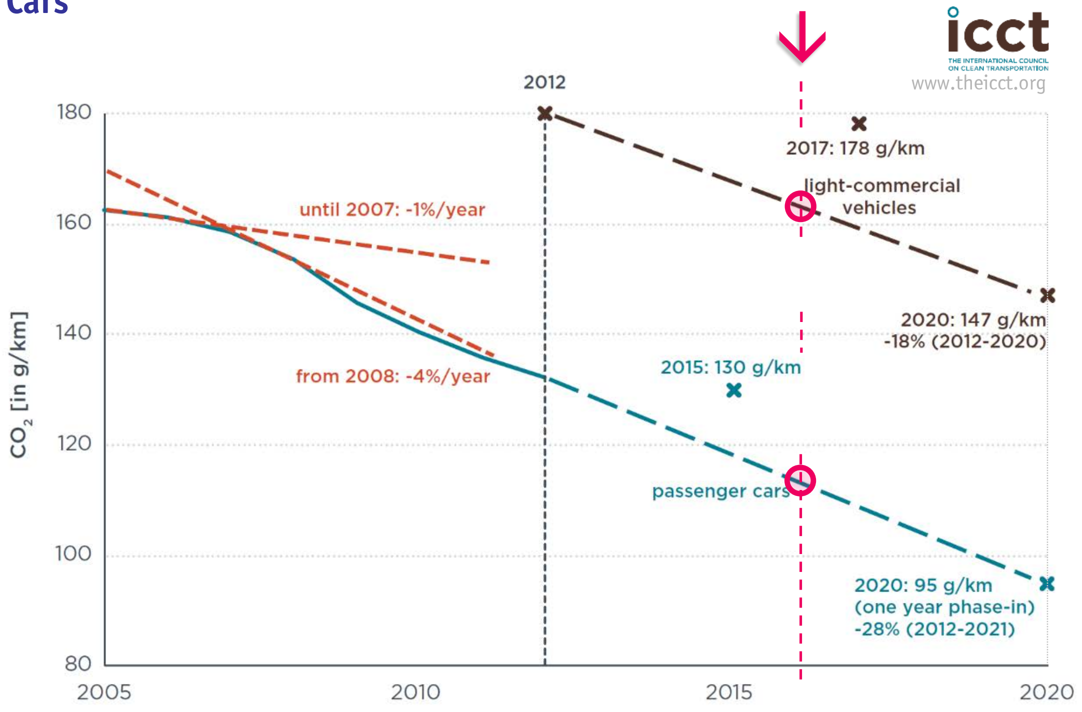
Global Megatrends

- 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

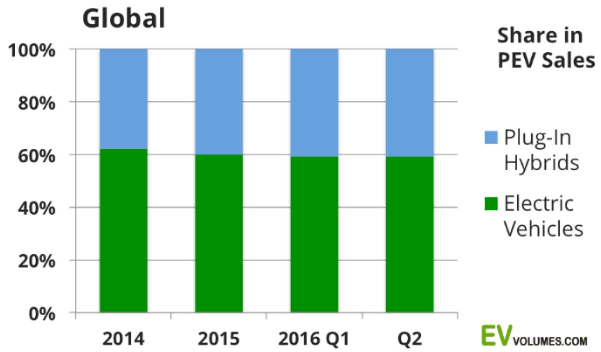
Electric Vehicles (1)

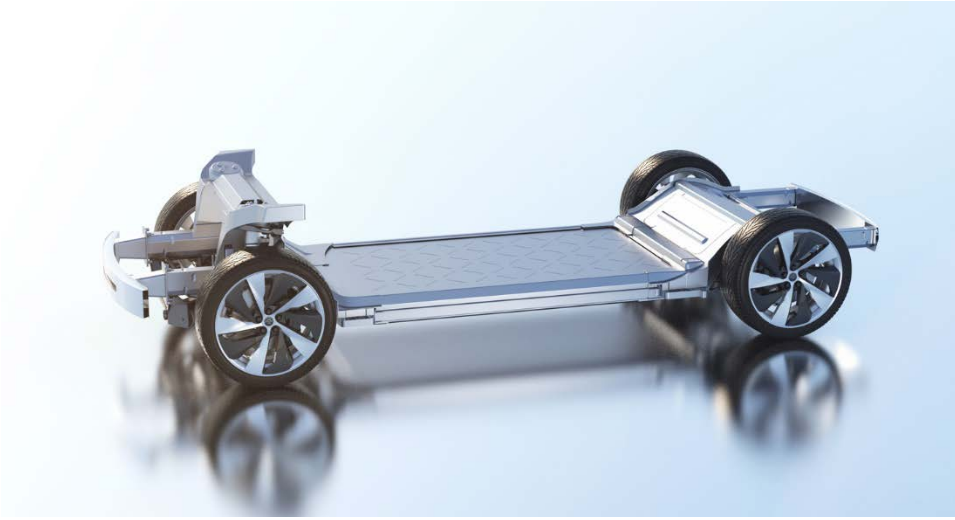
- **Enabled by Power Electronics** - Drivetrain / Aux. / Charger

— 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



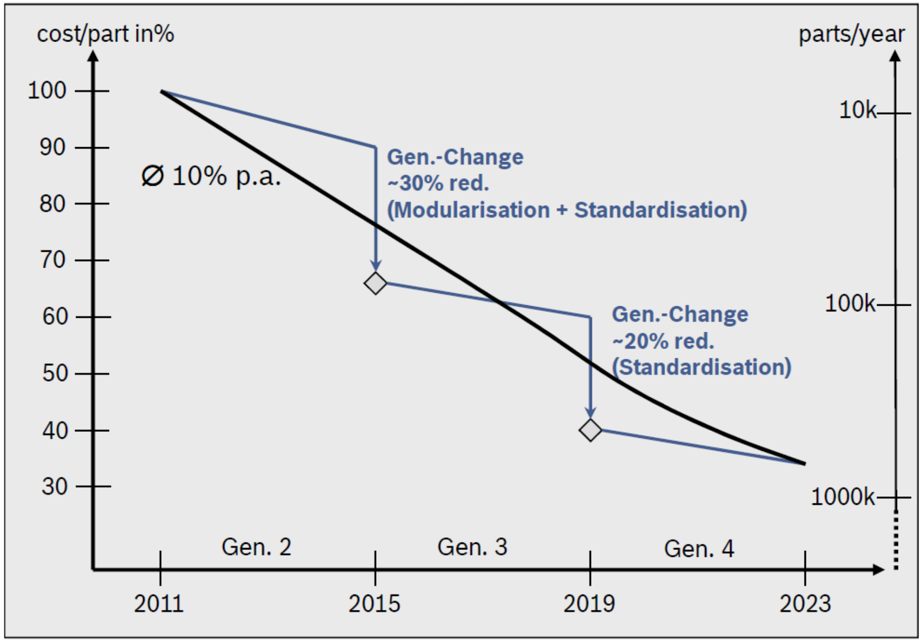


Electric Vehicles (2)

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

— Higher Power Density
— Extreme Cost Pressure (!)

Source: PCIM 2013



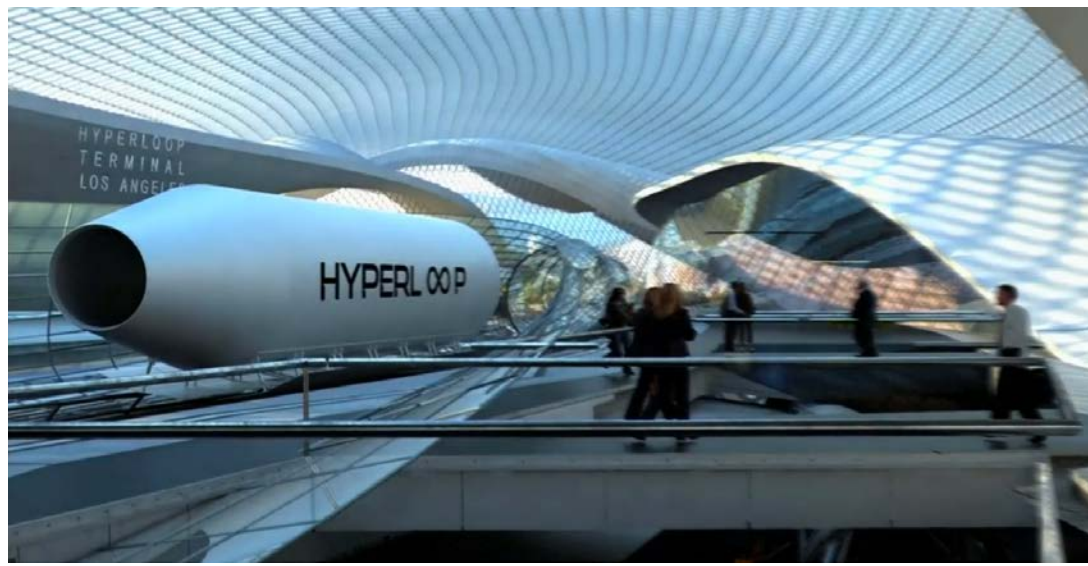
▶ Typ. 10% / a Cost Reduction
▶ Economy of Scale !

→ *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)

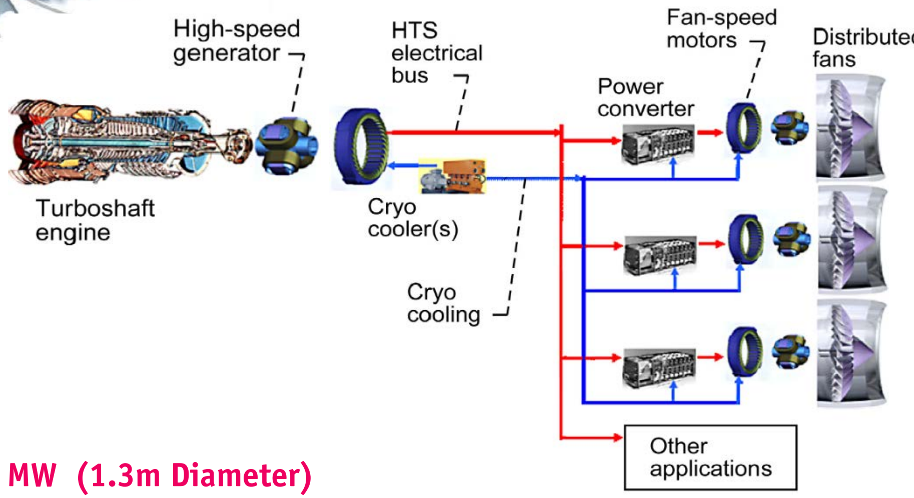
▶ Supercond. Motors
▶ Med. Volt. Power Distrib.

→ *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
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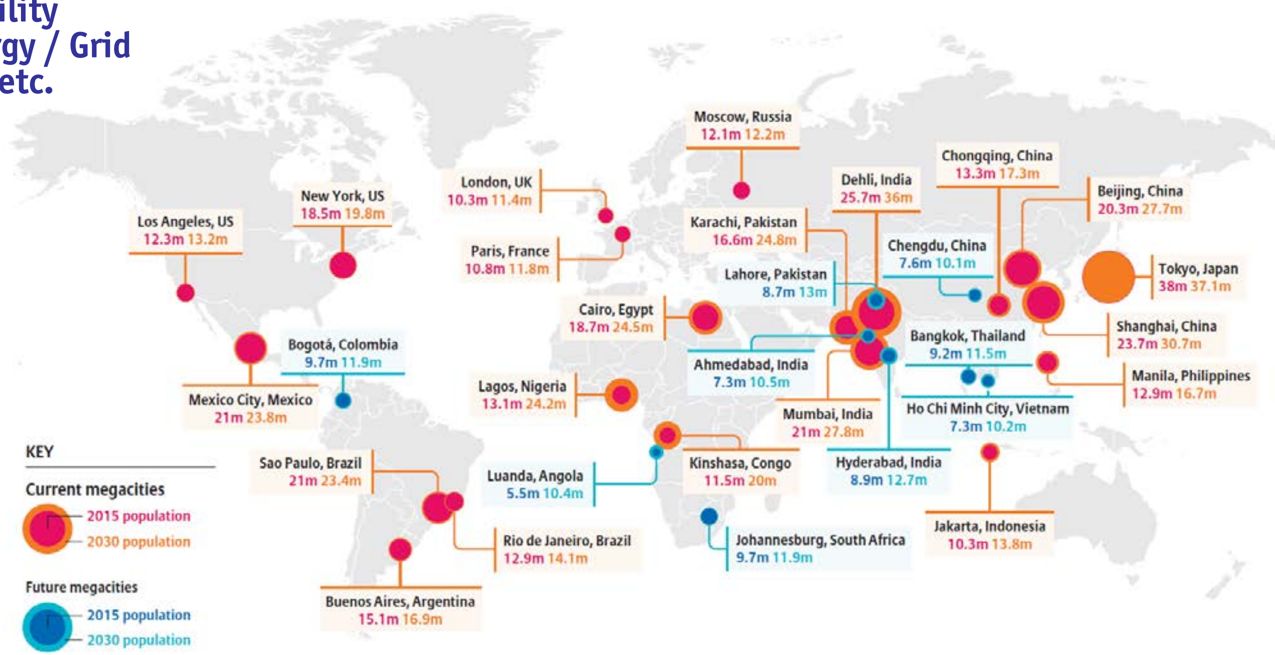
Urbanization →
Alleviate Poverty
Etc.

▶ 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

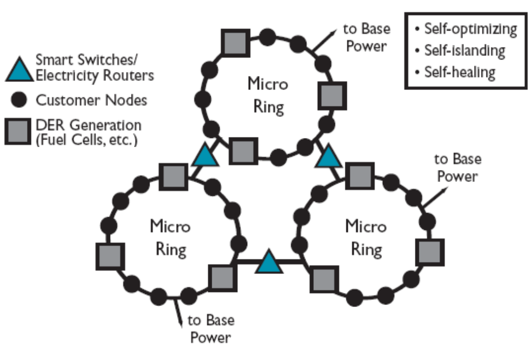
Smart Cities / Grid (1)

■ 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



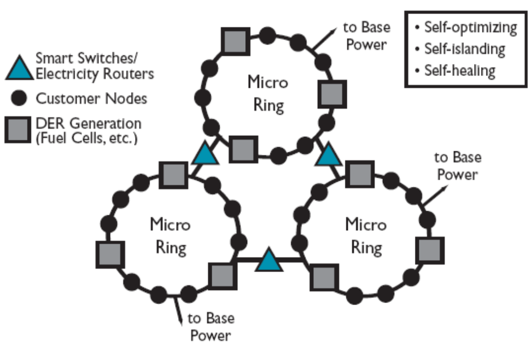
Smart Cities / Grid (2)

■ 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

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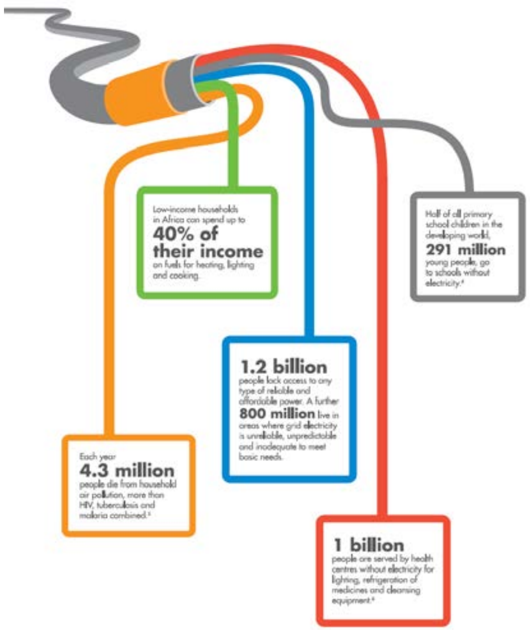
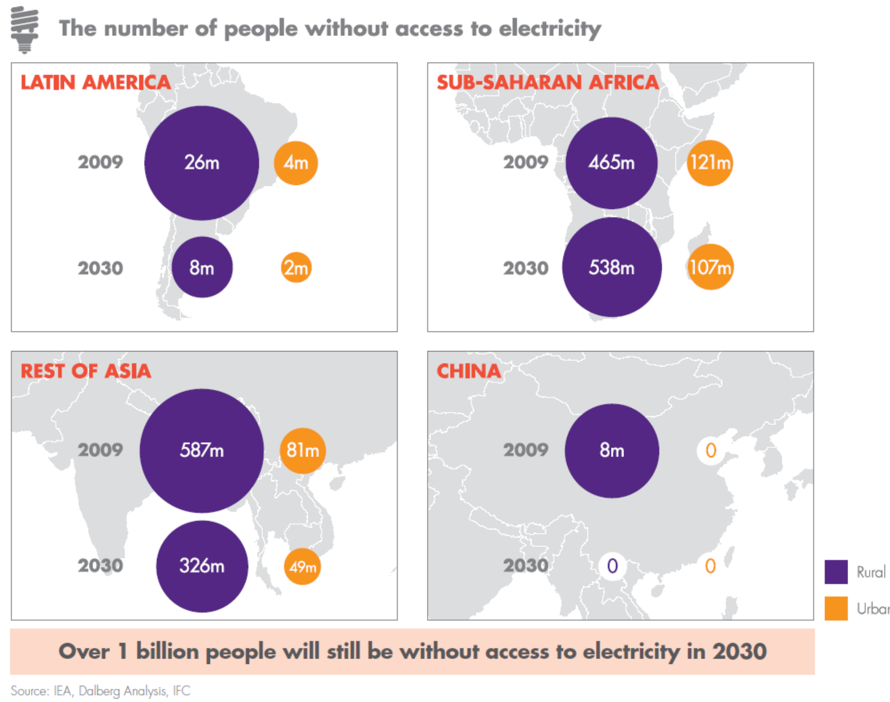
Alleviate Poverty →
Etc.

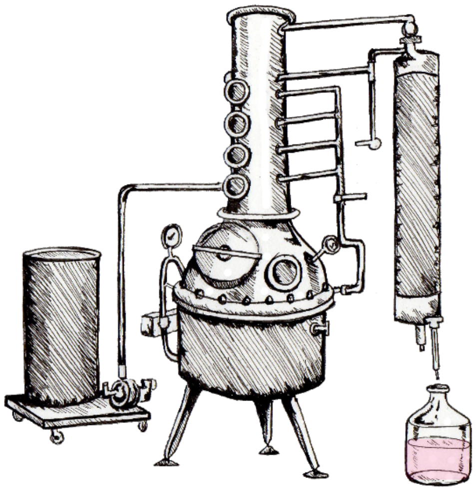
► Alleviate Poverty

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





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



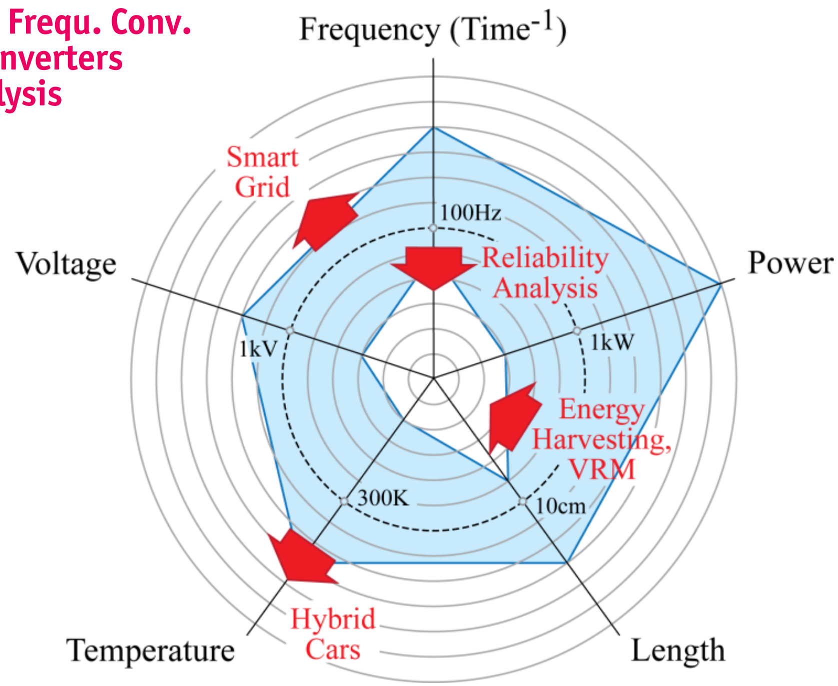
Source: whiskeybehavior.info

... 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

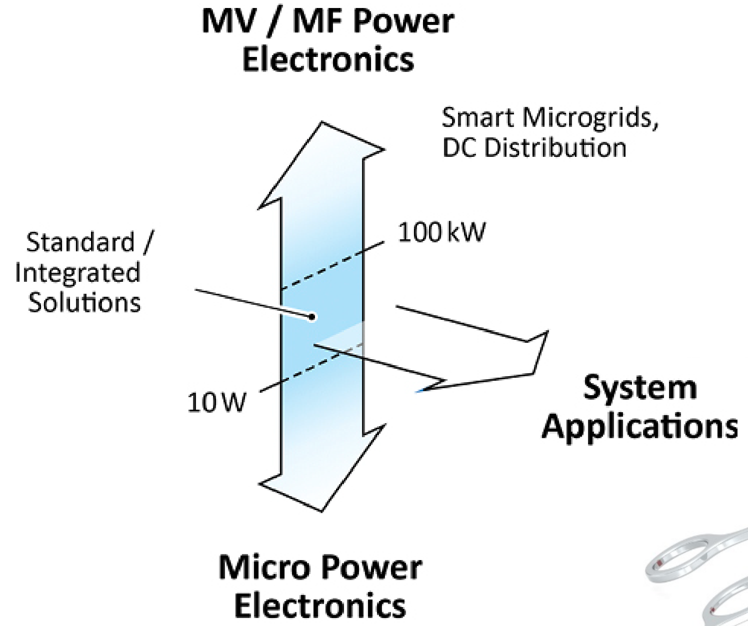
— Medium-Voltage / Medium. Frequ. Conv.
— 3D-Integr. of Low Power Converters
— Life-Cycle & Reliability Analysis



► Future Extensions of Power Electronics Application Areas

► Current / New Application Areas (2)

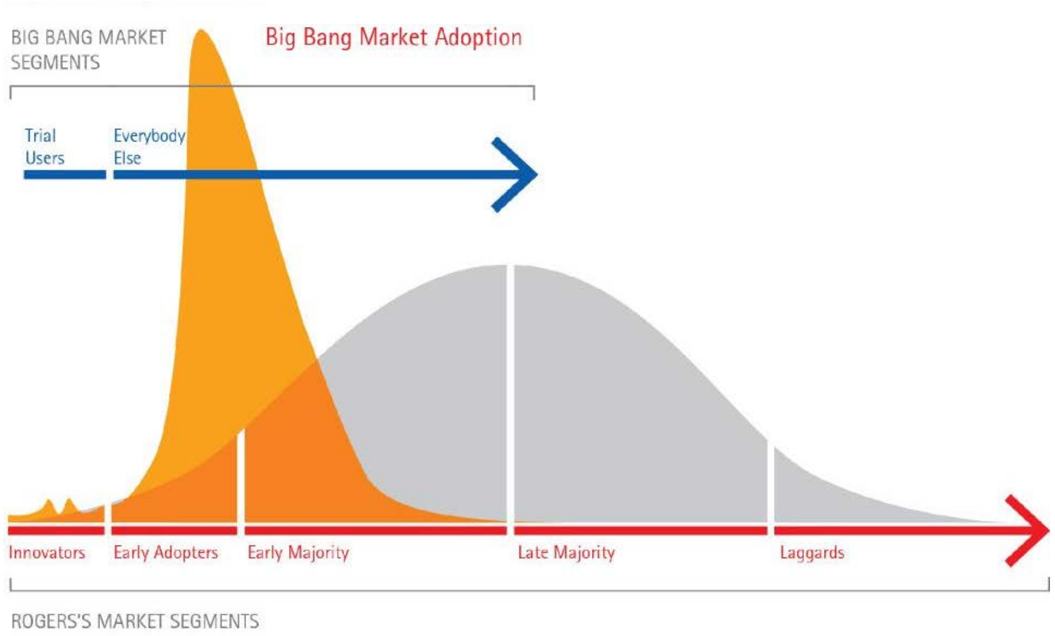
- Commoditization / Standardization for High Volume Applications
- Extension to Microelectronics-Technology (Power Supply on Chip)
- Extensions to MV/MF



► 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

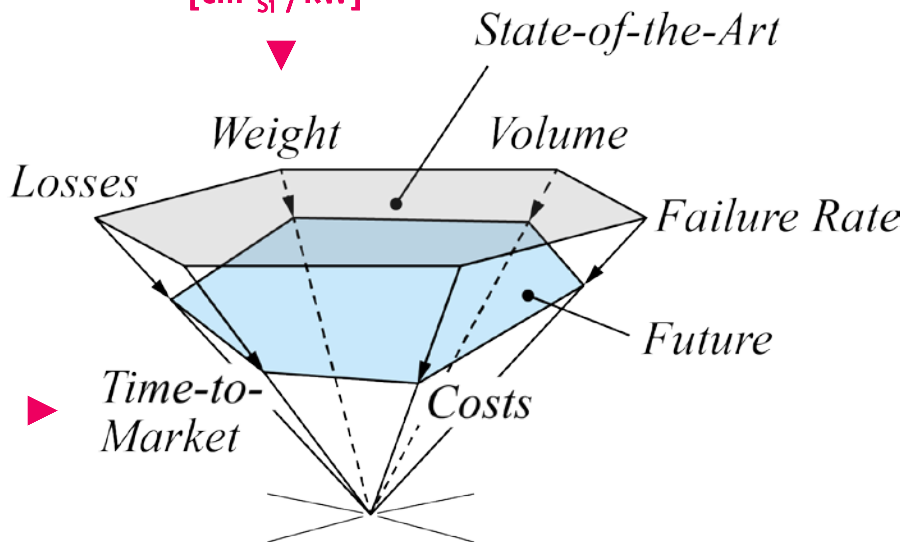
Power Converter
Design Challenges

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]

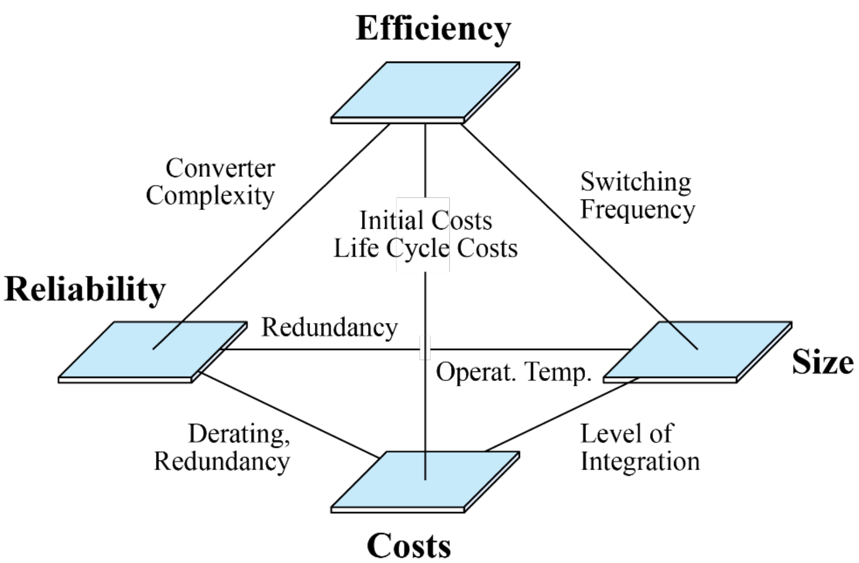


Performance Indices

- 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

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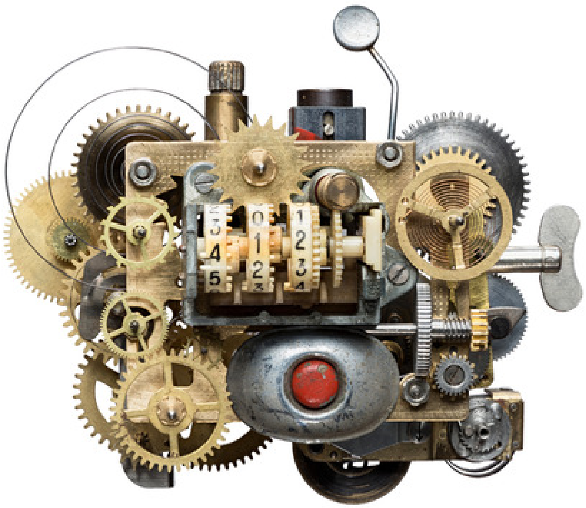
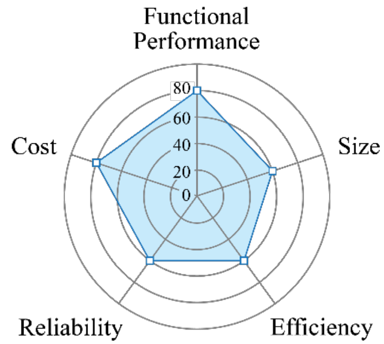


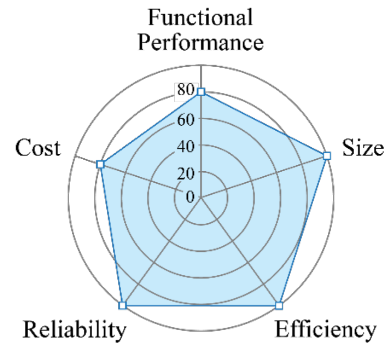
→ Large Number of Degrees of Freedom / Multi-Dimensional Design Space
→ Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization

▶ Multi-Objective Design Challenge (2)

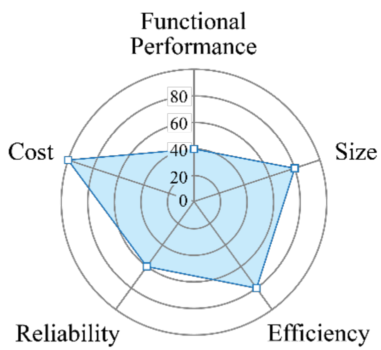
- **Specific Performance Profiles / Trade-Offs Dependent on Application**



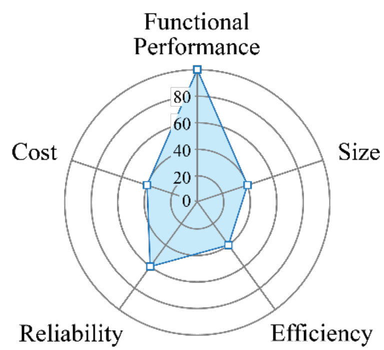
Industry Applications



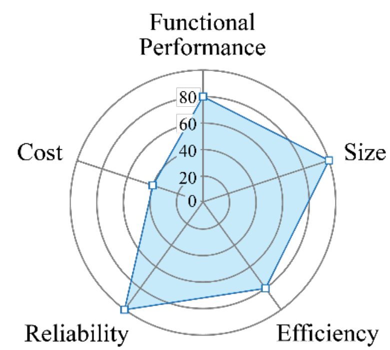
Information & Communication Industry



Domestic Applications



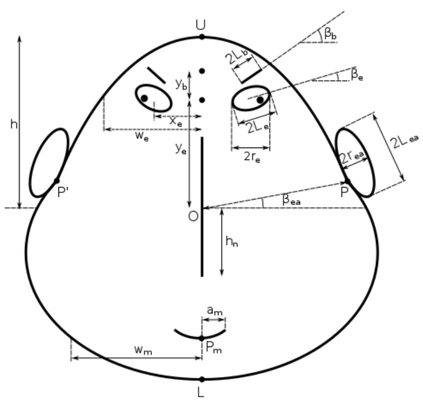
Laboratory Applications

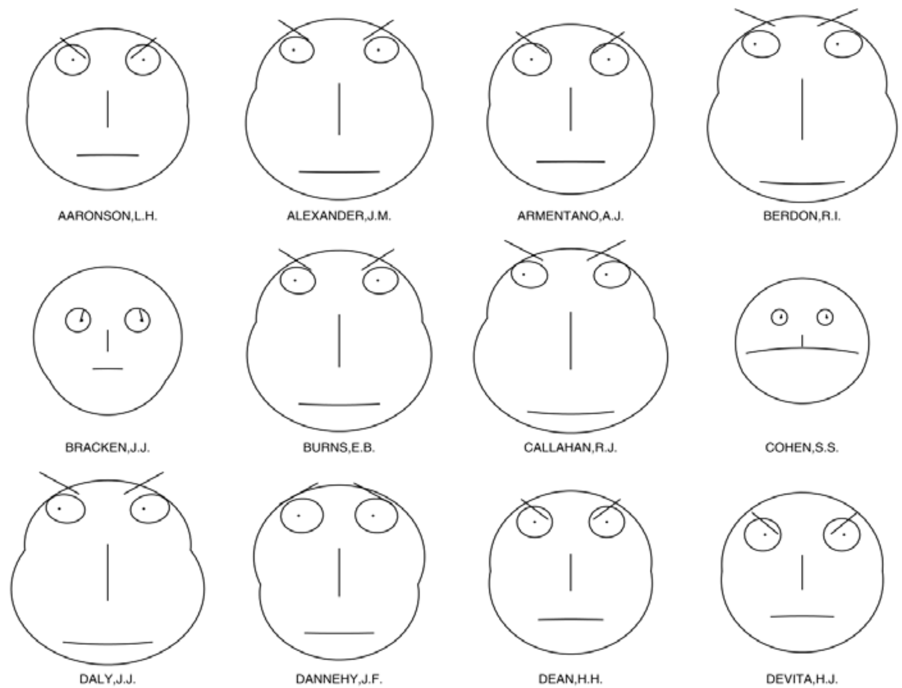


Aerospace Applications

▶ 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

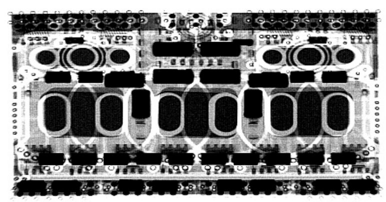
Mutual Coupling of Performances

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 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 (!)**

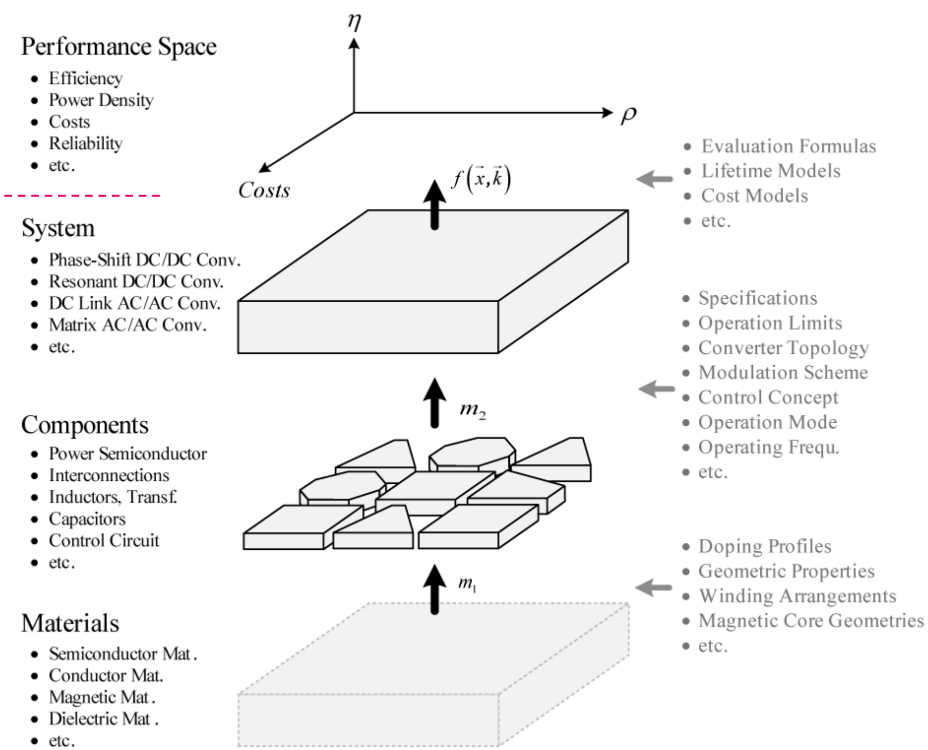
Multi-Objective Optimization

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

► Abstraction of Power Converter Design

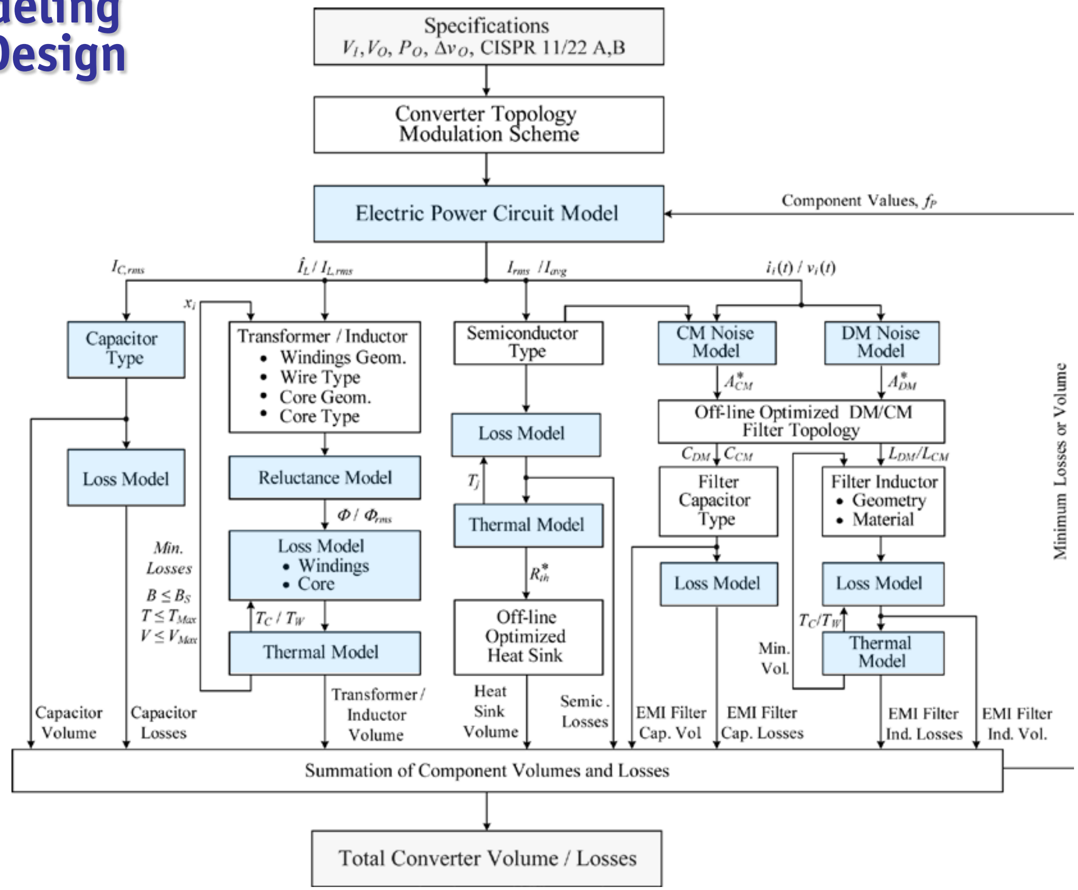
Performance Space

Design Space



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

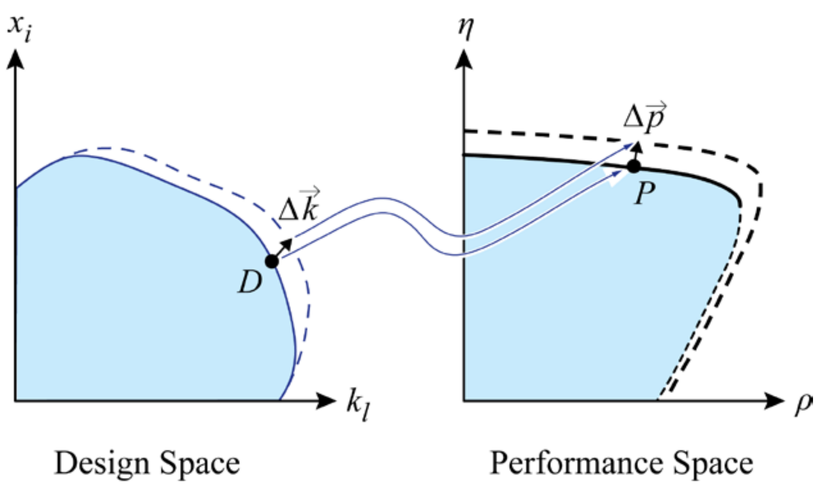
▶ Mathematical Modeling of the Converter Design

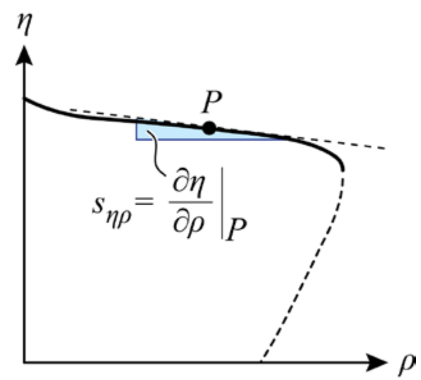


→ **Multi-Objective Optimization** – ***Guarantees Best Utilization of All Degrees of Freedom*** **(!)**

Multi-Objective Optimization (1)

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



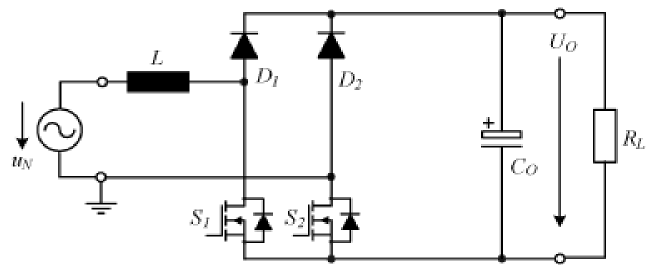


→ Clarifies Sensitivity $\Delta\vec{p}/\Delta\vec{k}$ to Improvements of Technologies
→ Trade-off Analysis

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

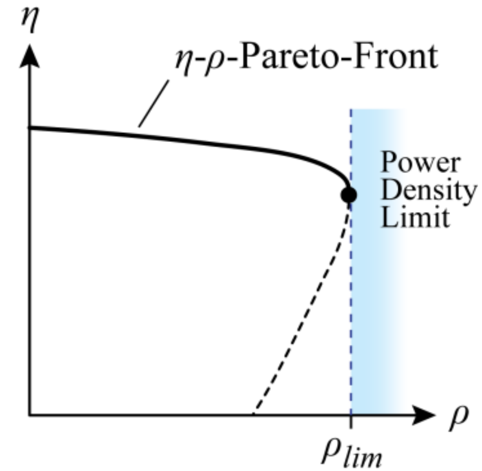
■ **Comp.-Level Degrees of Freedom of the Design**

— 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.



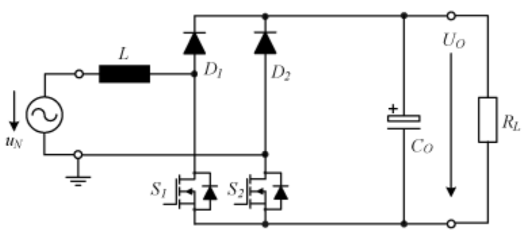
■ **Only η-ρ-Pareto Front Allows Comprehensive Comparison of Converter Concepts (!)**

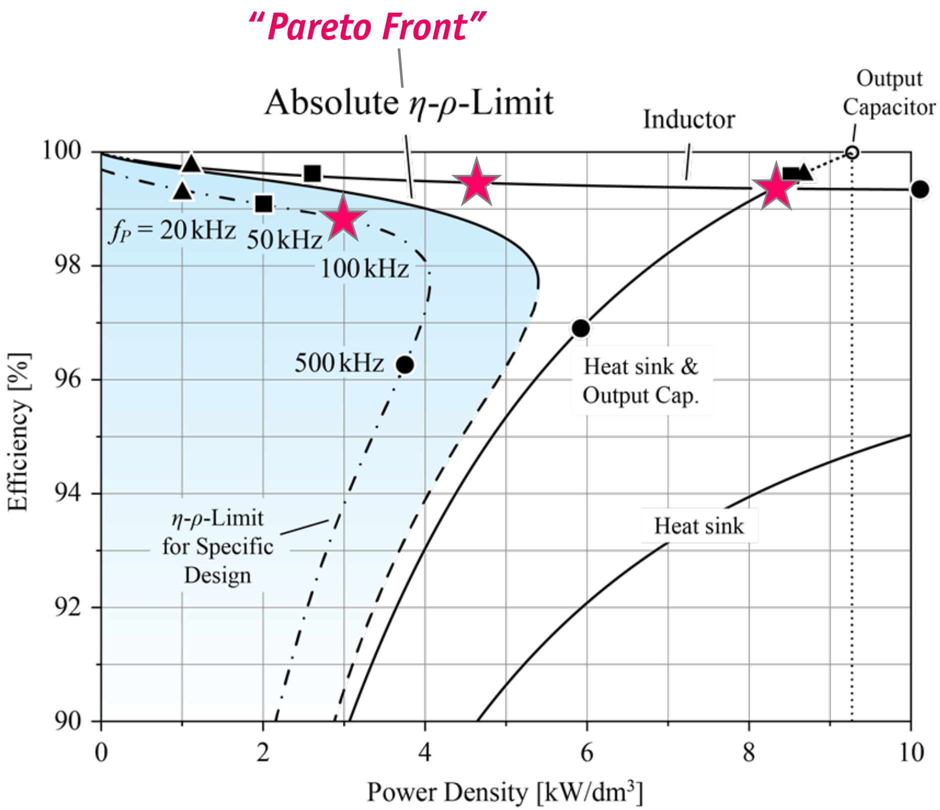
▶ Determination of the η-ρ-Pareto Front (b)

- 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

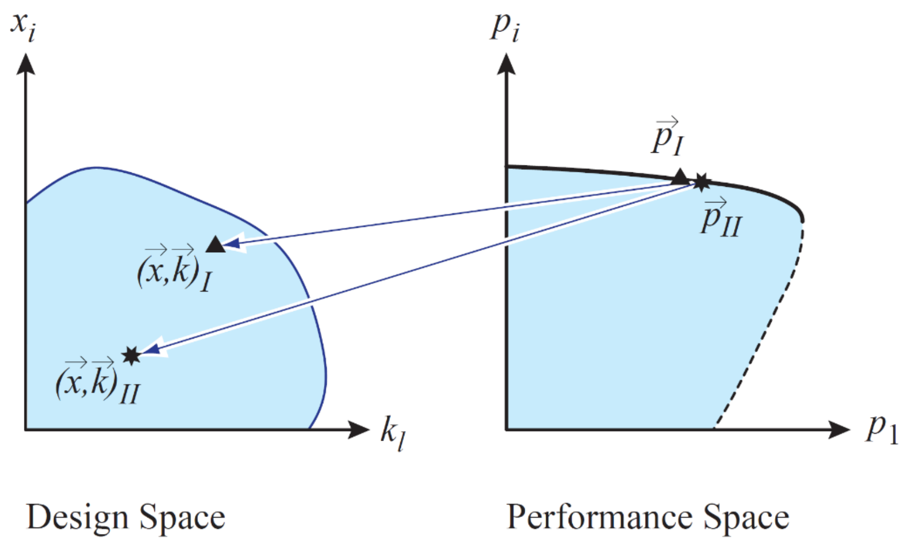
★ f_P =100kHz





Multi-Objective Optimization (2)

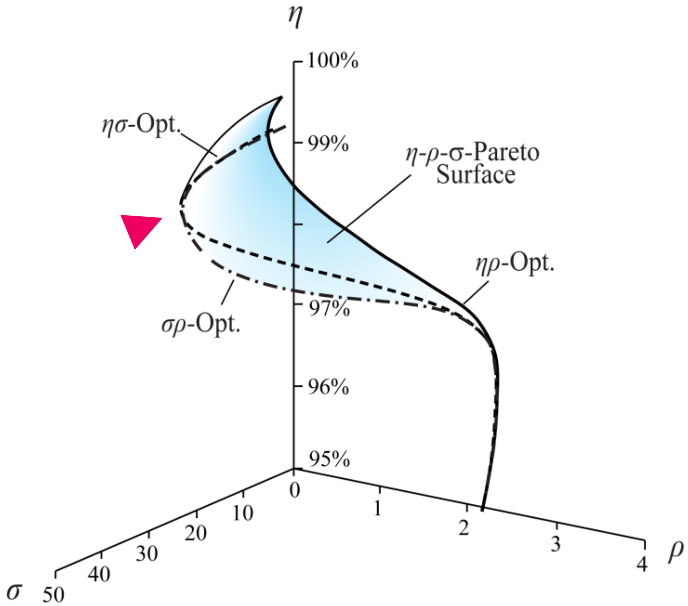
- Design Space Diversity
- Equal Performance for Largely Different Sets of Design Parameters

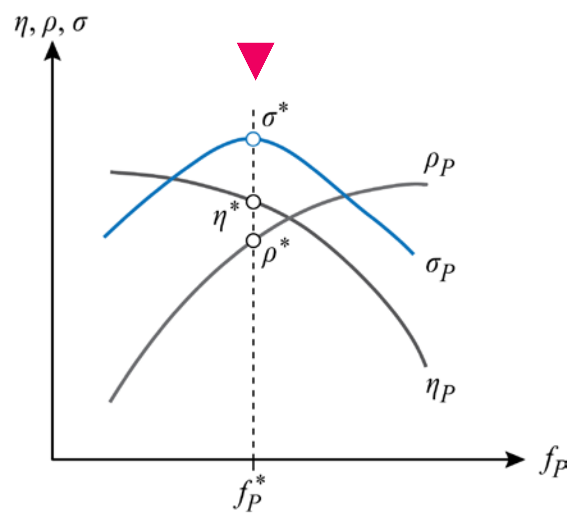


→ E.g. Mutual Compensation of Volume and Loss Contributions (e.g. Cond. & Sw. Losses)
→ Allows Optimization for Further Performance Index (e.g. Costs)

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

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

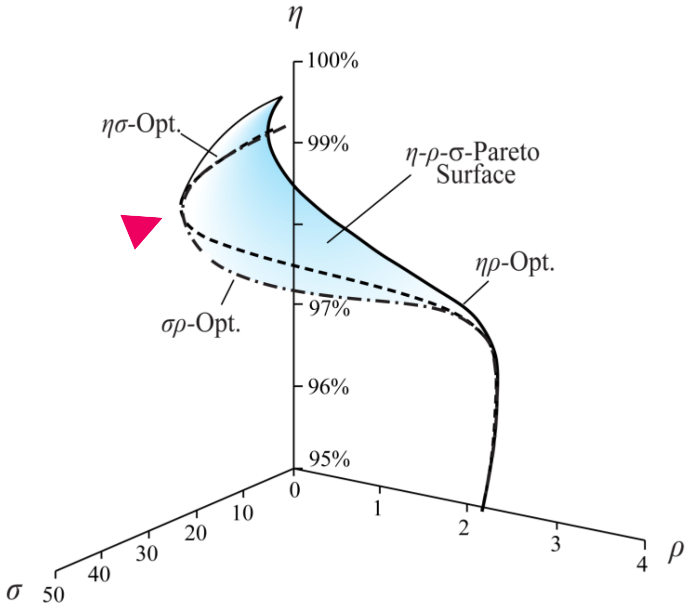


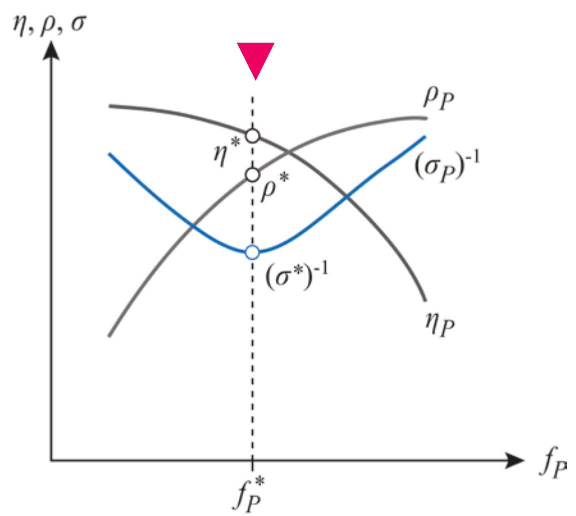


→ Specifying Only a Single Performance Index is of No Value (!)
→ Achievable Perform. Depends on Conv. Type / Specs (e.g. Volt. Range) / Side Cond. (e.g. Cooling)

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

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



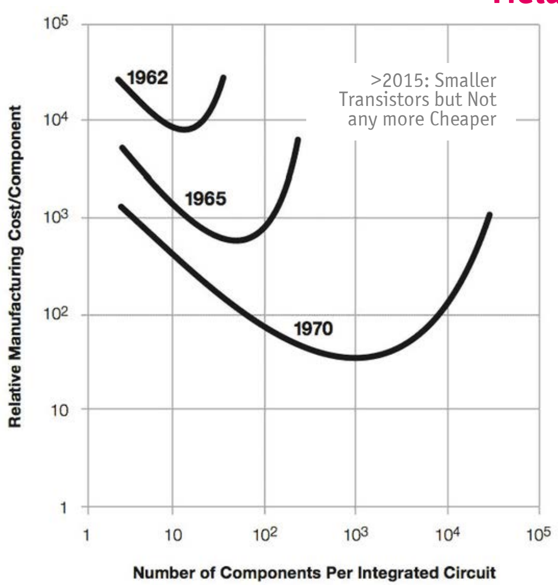


→ Specifying Only a Single Performance Index is of No Value (!)
→ Achievable Perform. Depends on Conv. Type / Specs (e.g. Volt. Range) / Side Cond. (e.g. Cooling)

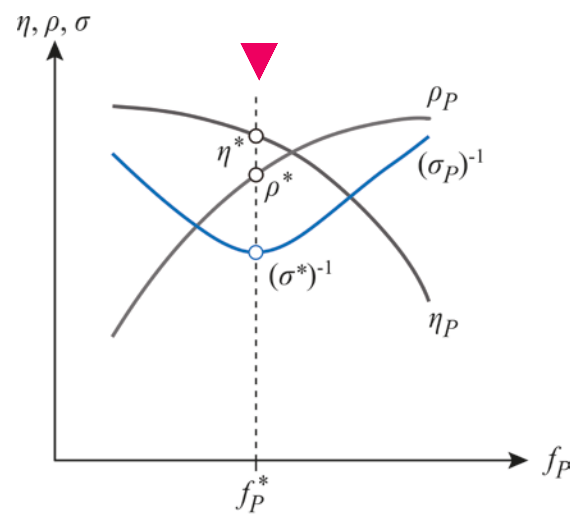
▶ Remark: Comparison to "Moores Law"

- "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

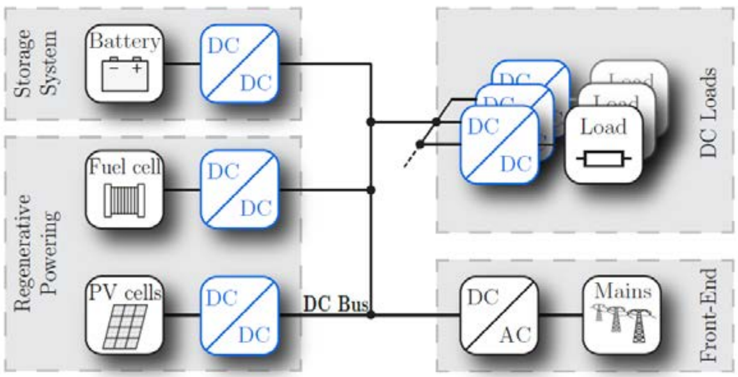
Example #1

Two-Level vs. Three-Level Dual Active Bridge

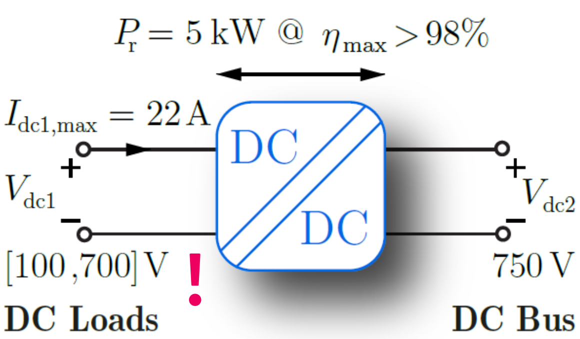
Source: SMA

Wide Input Voltage Range Isolated DC/DC Converter

Structure of “Smart Home“ DC Microgrid



Universal DC/DC Converter

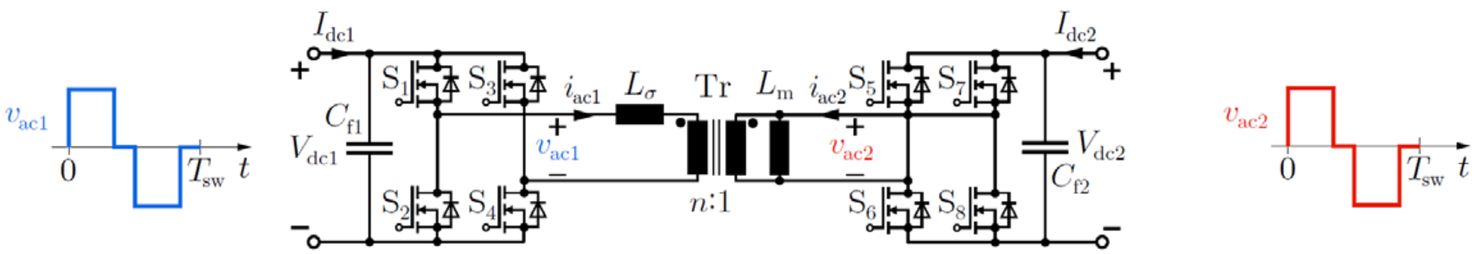


- Universal Isolated DC/DC Converter
  - Bidirectional Power Flow
  - Galvanic Isolation
  - Wide Voltage Range
  - High Partial Load Efficiency

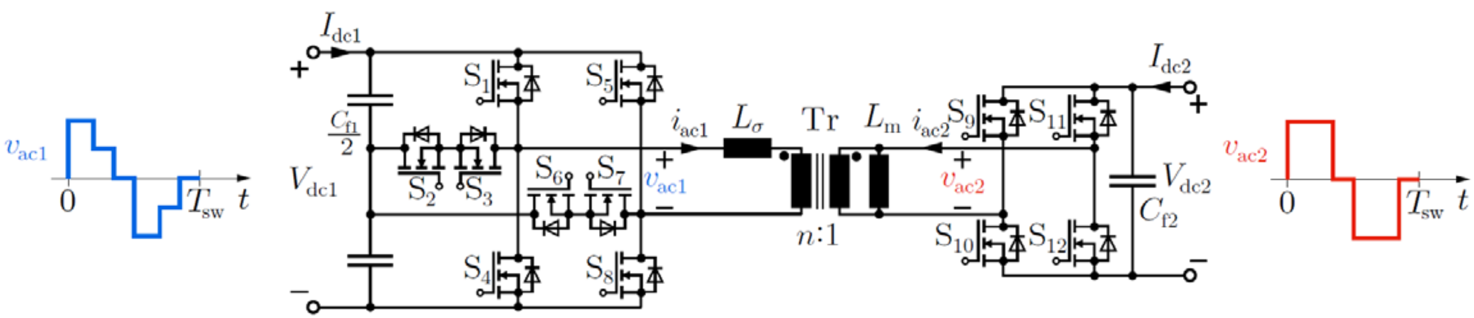
- Advantages
  - Reduced System Complexity
  - Lower Overall Development Costs
  - Economy of Scale

▶ Comparative Evaluation of Converter Topologies

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

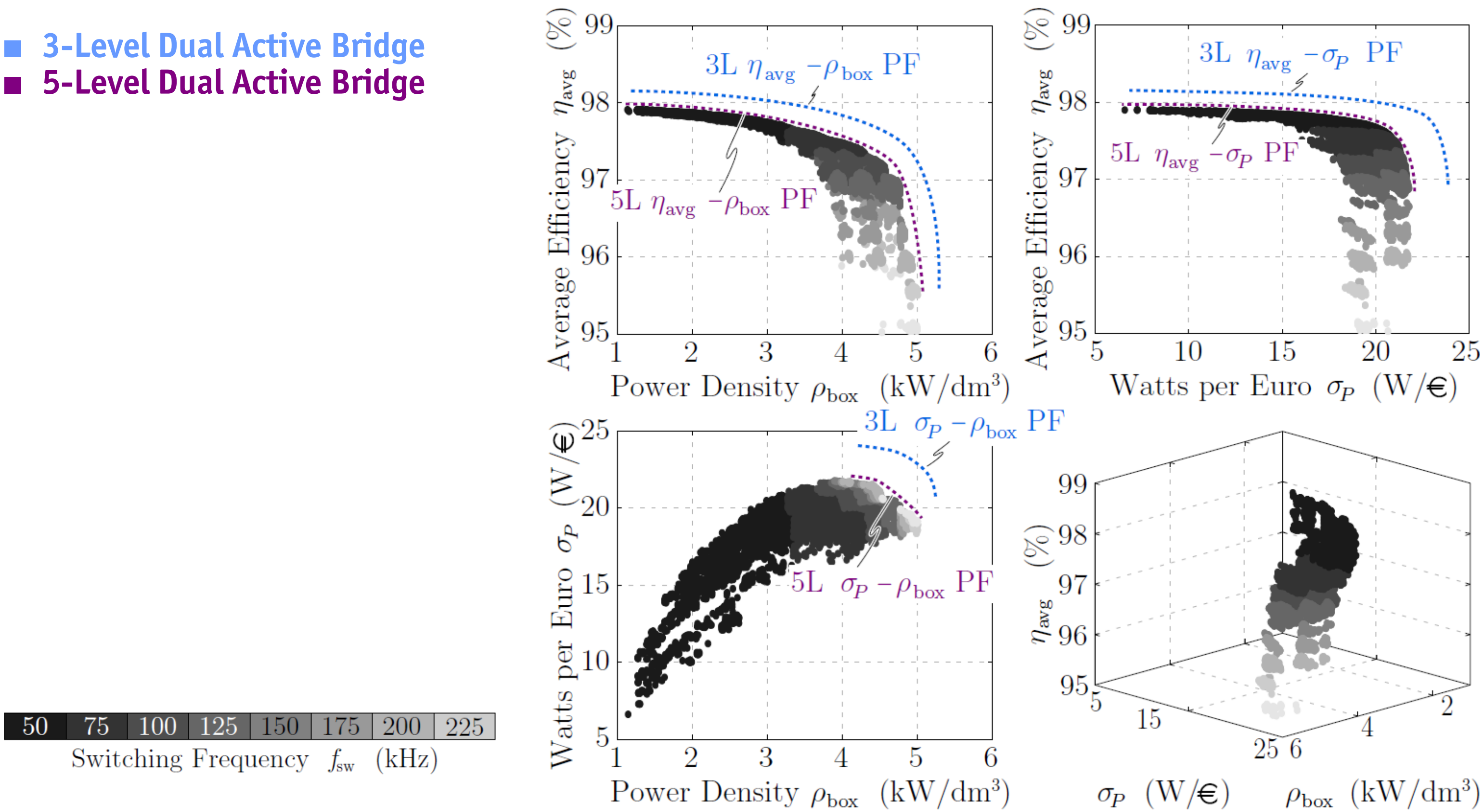


- Advanced 5-Level Dual Active Bridge (5L-DAB)



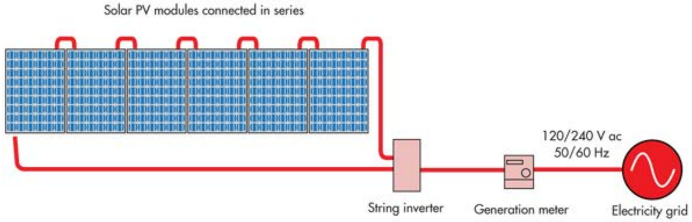
Optimization Results - Pareto Surfaces

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



Example #2

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

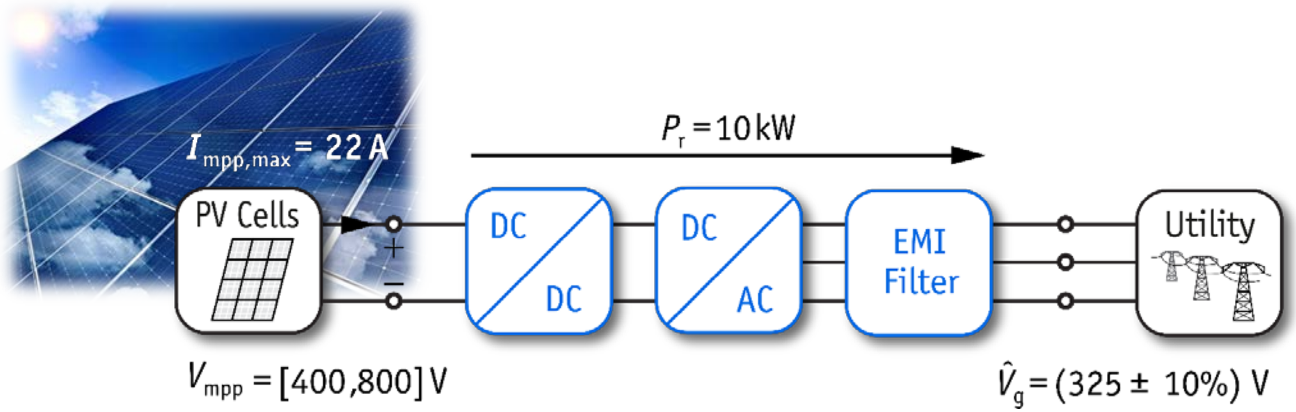


Source: L. Lalonde / electronicdesign.com

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

■ Three-Phase PV Inverter System

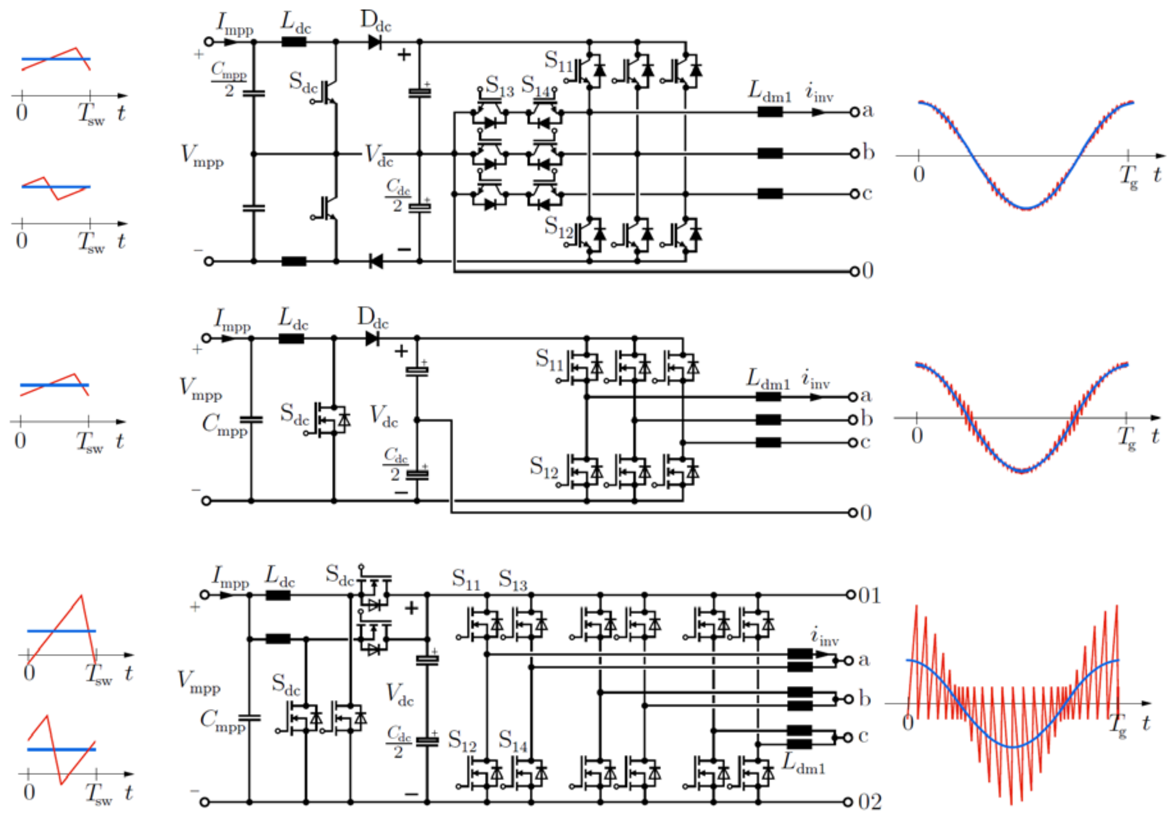
— Typical Residential Application
— Single-Input/Single-MPP-Tracker Multi-String PV Inverter
— DC/DC Boost Converter for Wide MPP Voltage Range
— Output EMI Filter



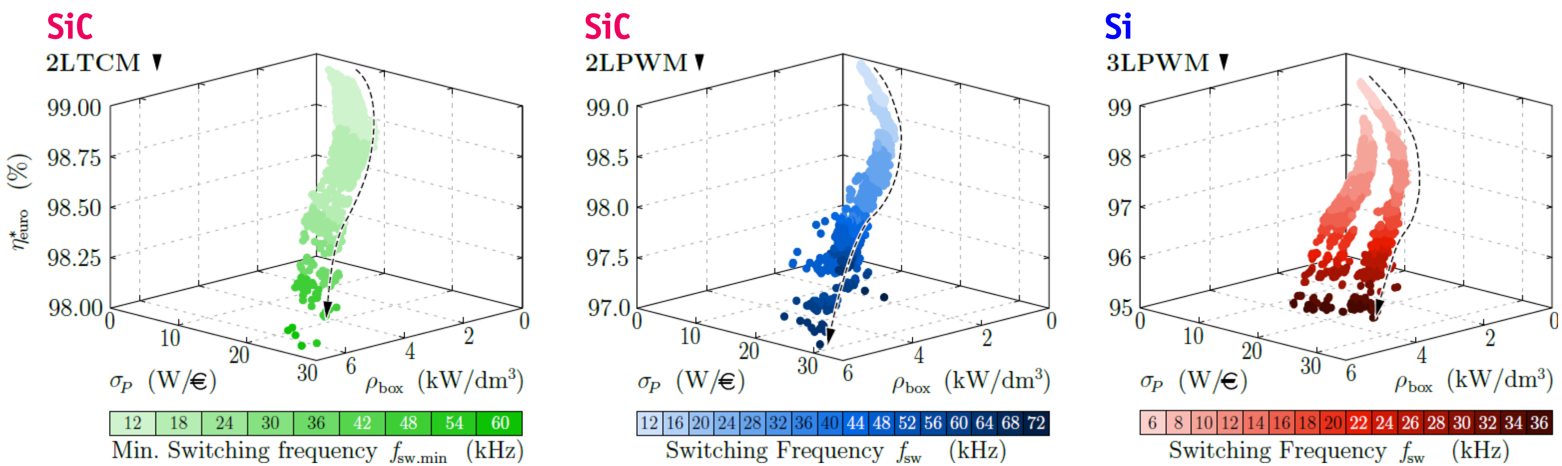
→ Exploit Excellent Hard- AND Soft-Switching Capabilities of SiC
→ Find Useful Sw. Frequency and Current Ripple Ranges
→ Find Appropriate Core Material

▶ Topologies - Converter Stages

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



▶ Optimization Results - Pareto Surfaces



- 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

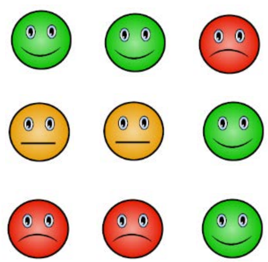
- Pareto-Optimal Designs for Entire Considered f_{sw} Range
- METGLAS Amorphous Iron and Ferrite Designs

▶ Optimization Results – *Investigations Along Pareto Surfaces*

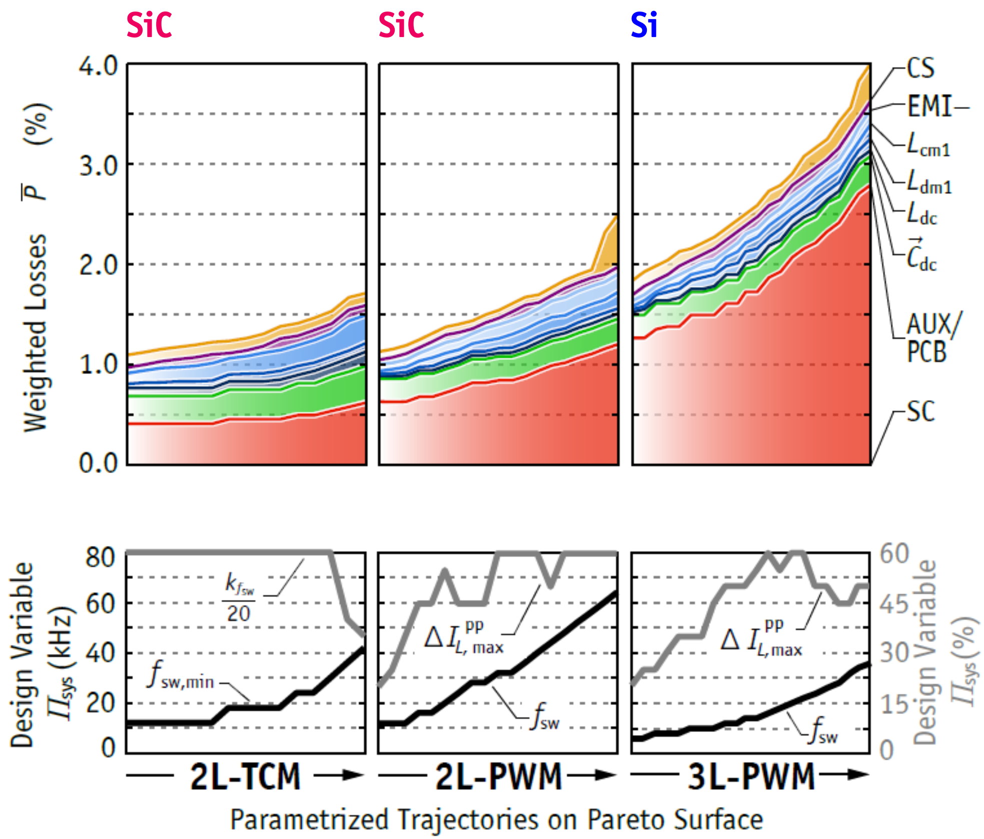
■ **Comparison of the Inverter Concepts**

η ρ σ

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



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



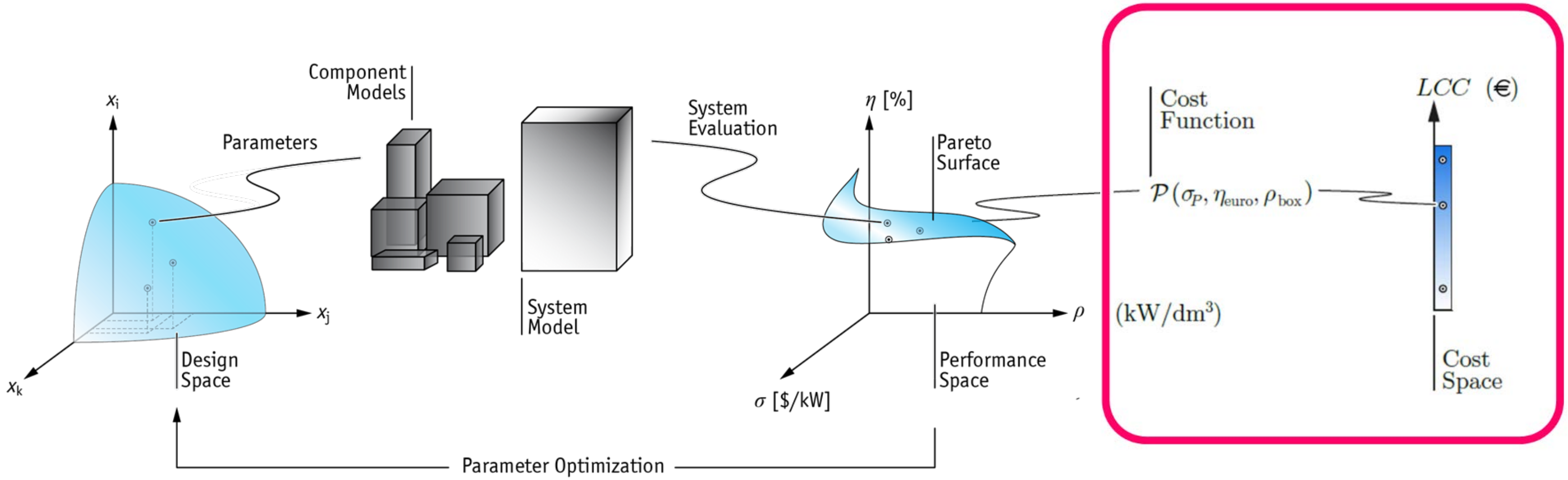
▶ Extension to *Life-Cycle Cost (LCC) Analysis*

■ **Performance Space Analysis**

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

■ **Life-Cycle Cost Analysis**

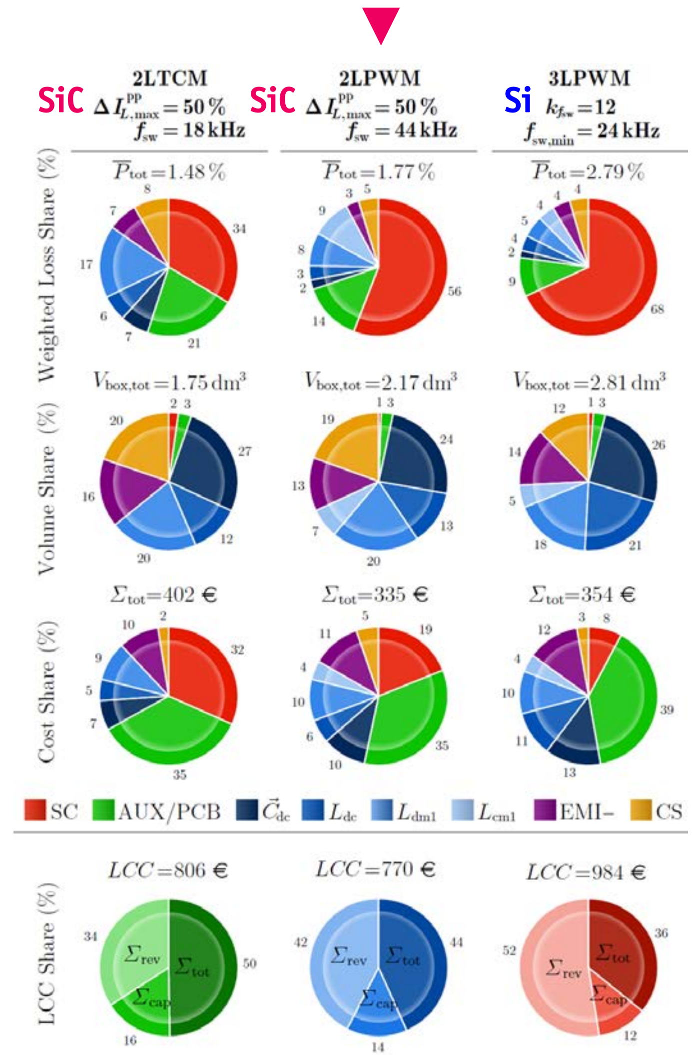
— Post-Processing of Pareto-Optimal Designs
— Determination of Min.-LCC Design
— Arbitrary Cost Function Possible



→ 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**

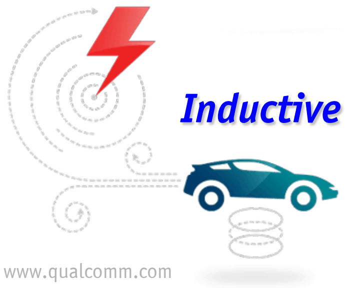


- **Best System - 2L-PWM SiC Converter @ 44kHz & 50% Current Ripple**

  — 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**

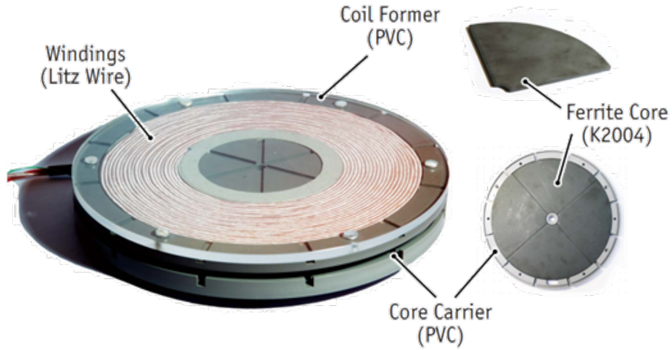
- Input Voltage 400V
- Battery Voltage 350V
- Output Power 5kW
- Air Gap 50mm

■ **Constraints / Side Conditions**

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

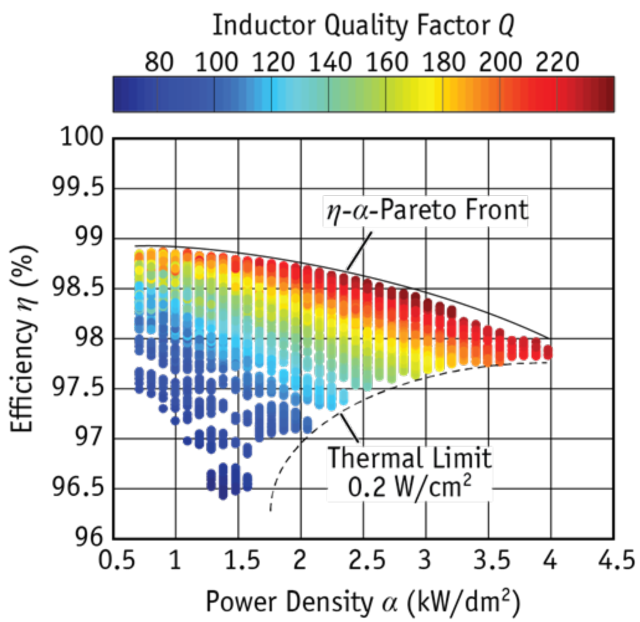
■ **System Performance**

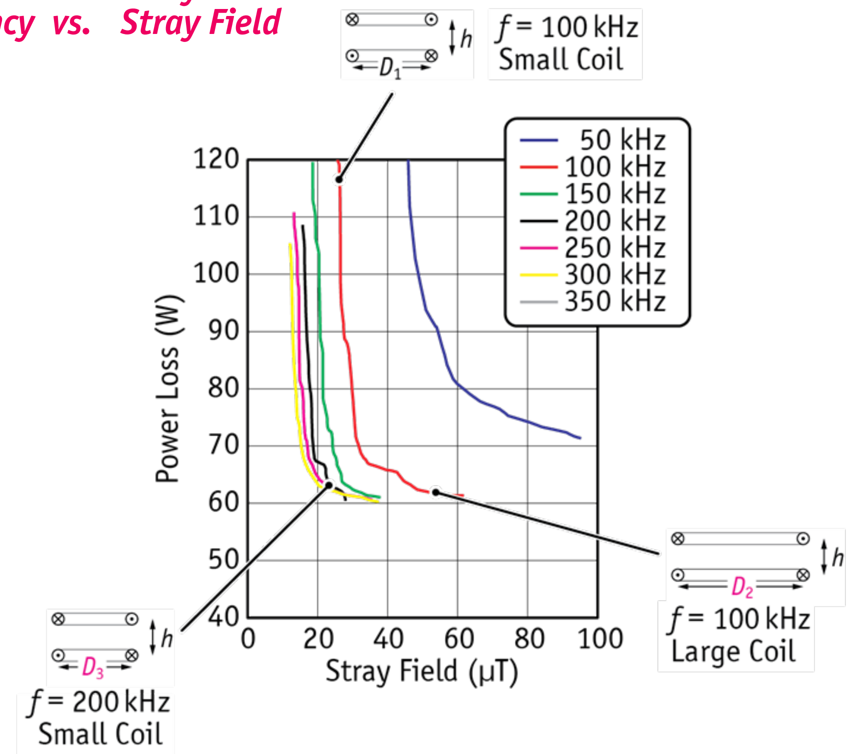
* Efficiency $\eta = P_{out}/P_{in}$ [%]
* Power Density $\alpha = P_{out}/A_{coil}$ [kW/dm^2]
* Stray Field $\beta = B_{max}/B_{norm}$ [%]



▶ η-α-β-Pareto Coil Optimization

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



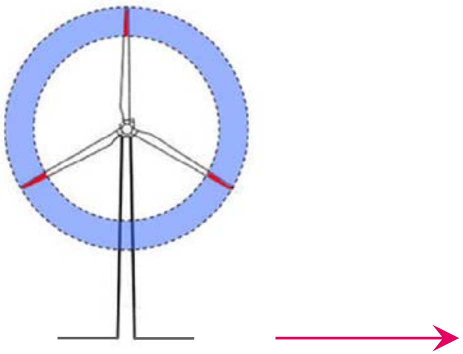


→ **Pareto-Optimization Allows to Study Influence of Key Design Parameters**

Example #4

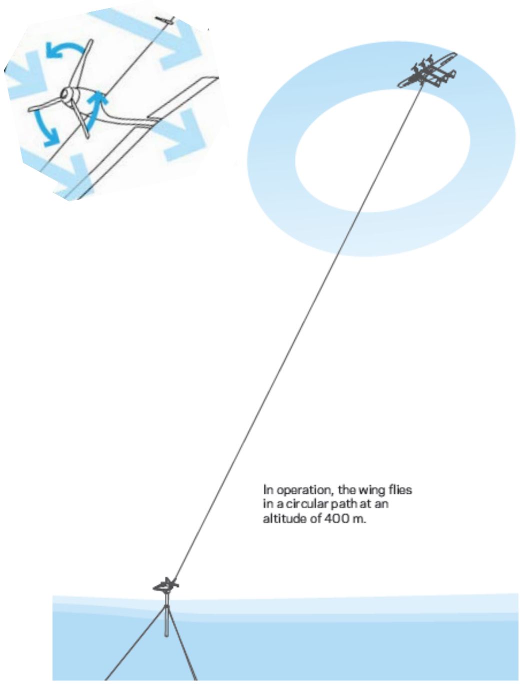
Electrical System of an Airborne Wind Turbine

M. Loyd, 1980



▶ Airborne Wind Turbine (AWT) - Google X

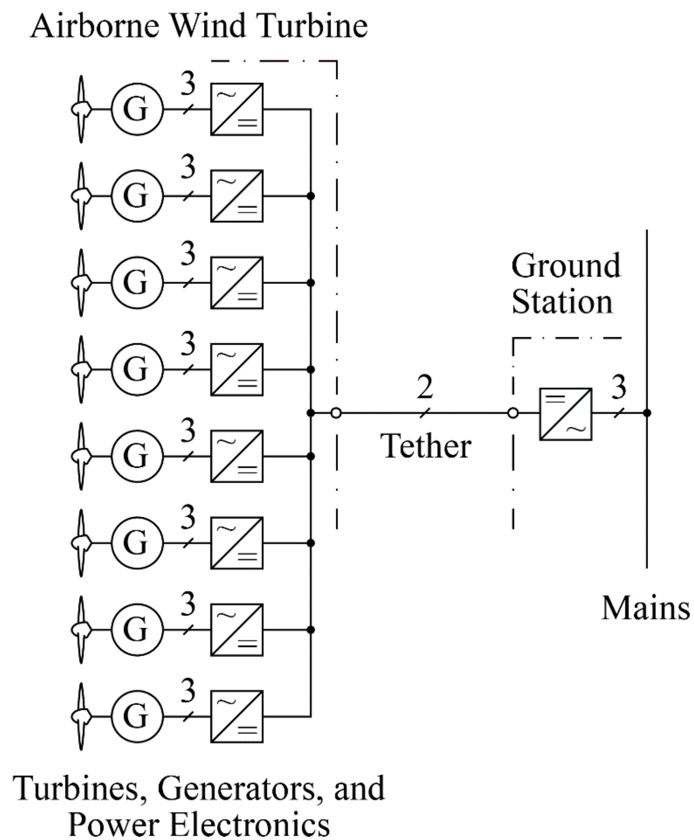
- Power Kite → On-Board Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically
- Minimum of Mechanical Support



MAKANI POWER

► AWT Electrical *System* Structure

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

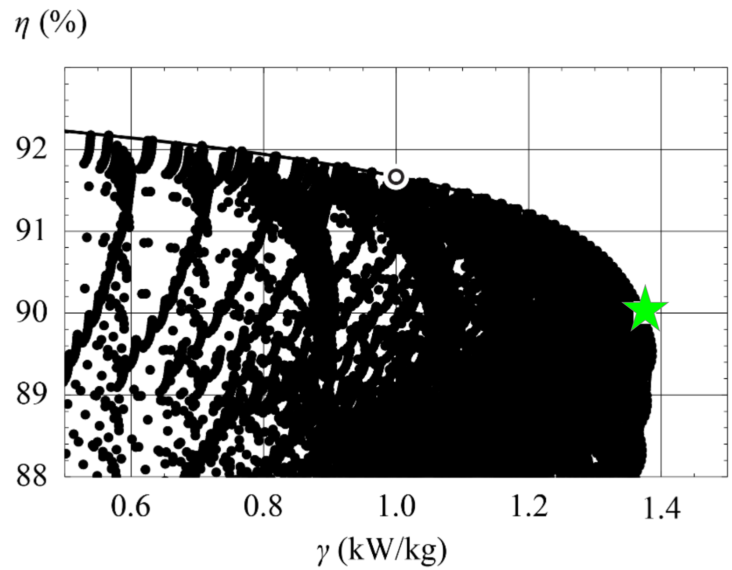


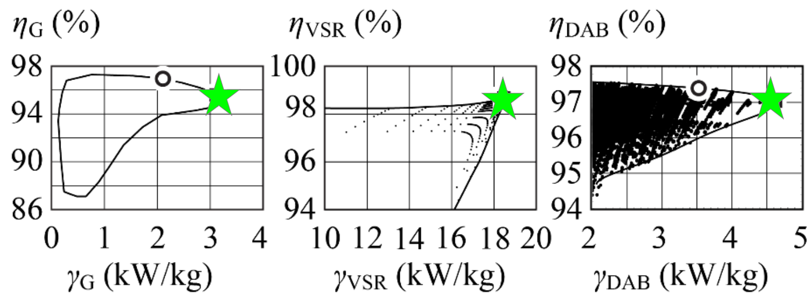
→ El. System Target Weight	100kg
→ Efficiency (incl. Tether)	90%
→ Turbine /Motor	2000/3000rpm

▶ 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

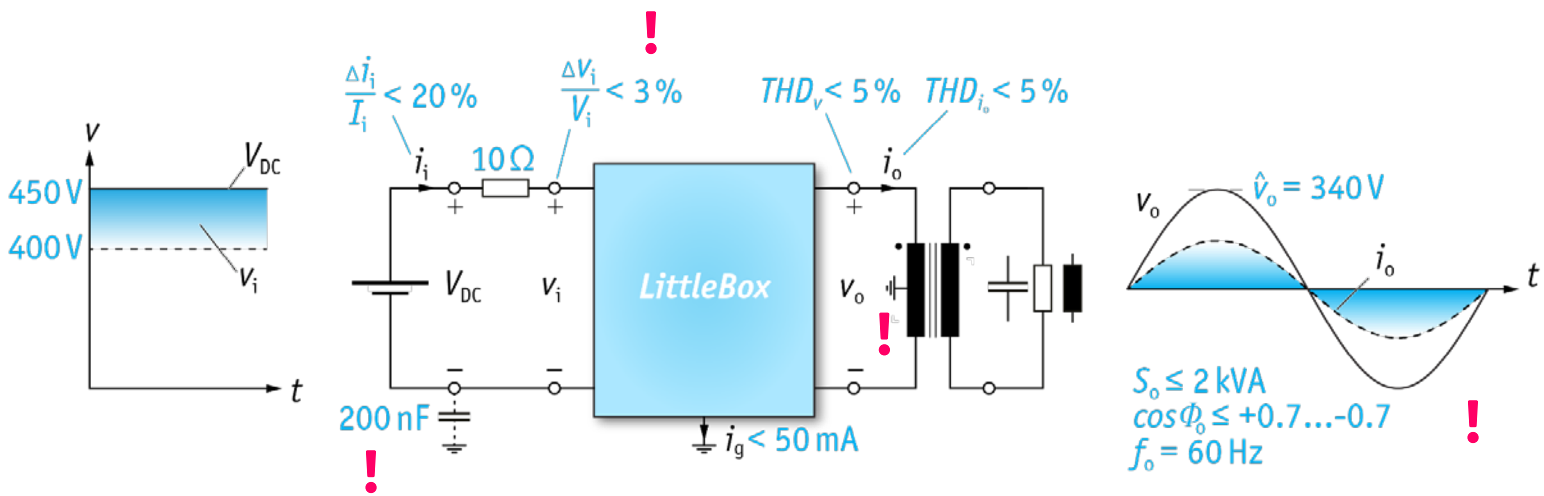
Comparative Converter Evaluation

Impact of Technology Progress & Design Space Diversity

LiTTLE BOX CHALLENGE

Google | IEEE

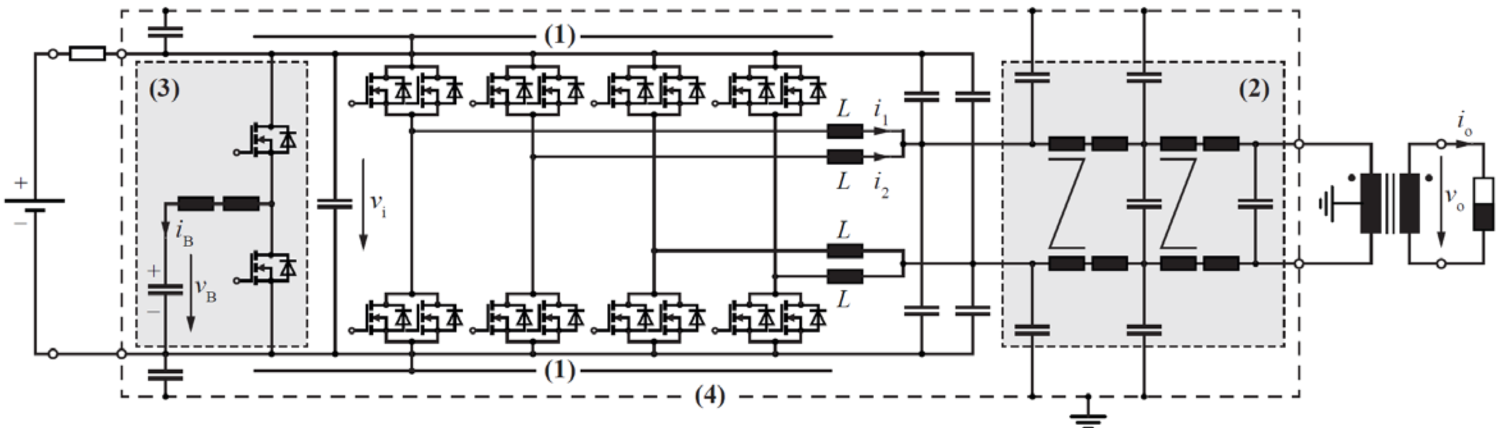
- Design / Build the 2kW 1-Φ Solar Inverter with the Highest Power Density in the World
- Power Density > 3kW/dm³ (50W/in³)
- Efficiency > 95%
- Case Temp. < 60°C
- EMI FCC Part 15 B



→ 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

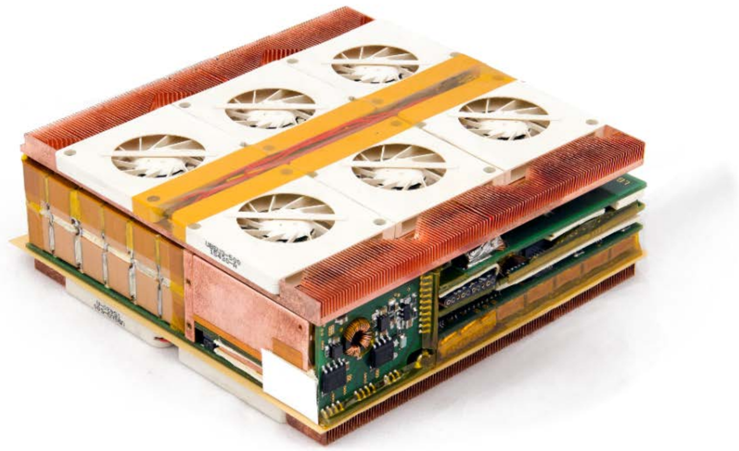


→ ZVS of All Bridge Legs @ Turn-On/Turn-Off in Whole Operating Range (4D-TCM-Interleaving)
→ Heatsinks Connected to DC Bus / Shield to Prevent Cap. Coupling to Grounded Enclosure

Little-Box 1.0 Prototype

- **Performance**
  - 8.2 kW/dm³
  - 96,3% Efficiency @ 2kW
  - T_c=58°C @ 2kW

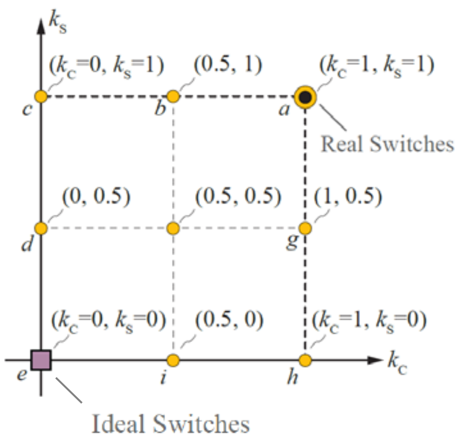
- **Design Details**
  - 600V IFX Normally-Off GaN GIT
  - Antiparallel SiC Schottky Diodes
  - Multi-Airgap Ind. w. Multi-Layer Foil Wdg
  - Triangular Curr. Mode ZVS Operation
  - CeraLink Power Pulsation Buffer

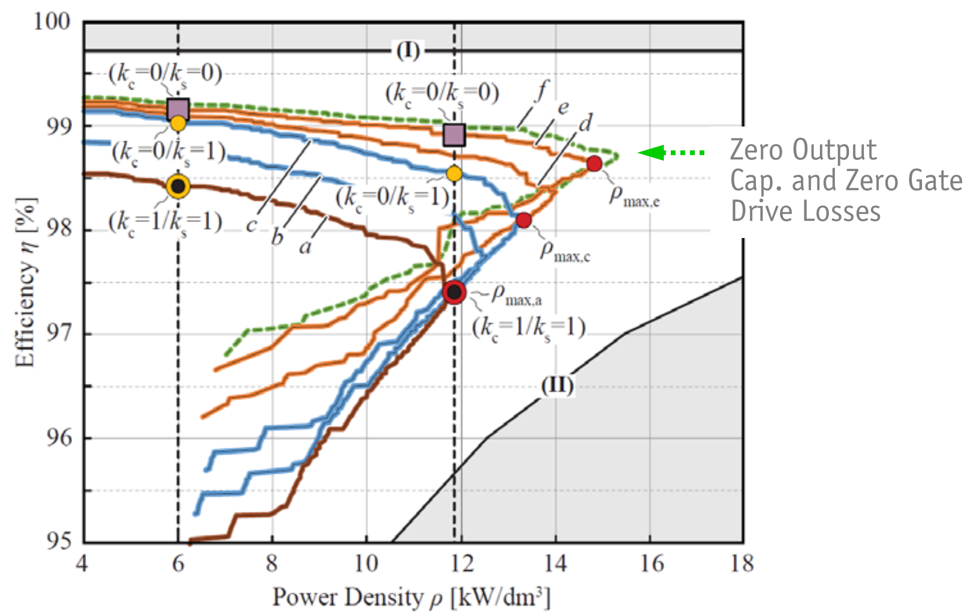


→ Analysis of Potential Performance Improvement for *"Ideal Switches"*

Little Box 1.0 @ Ideal Switches (TCM)

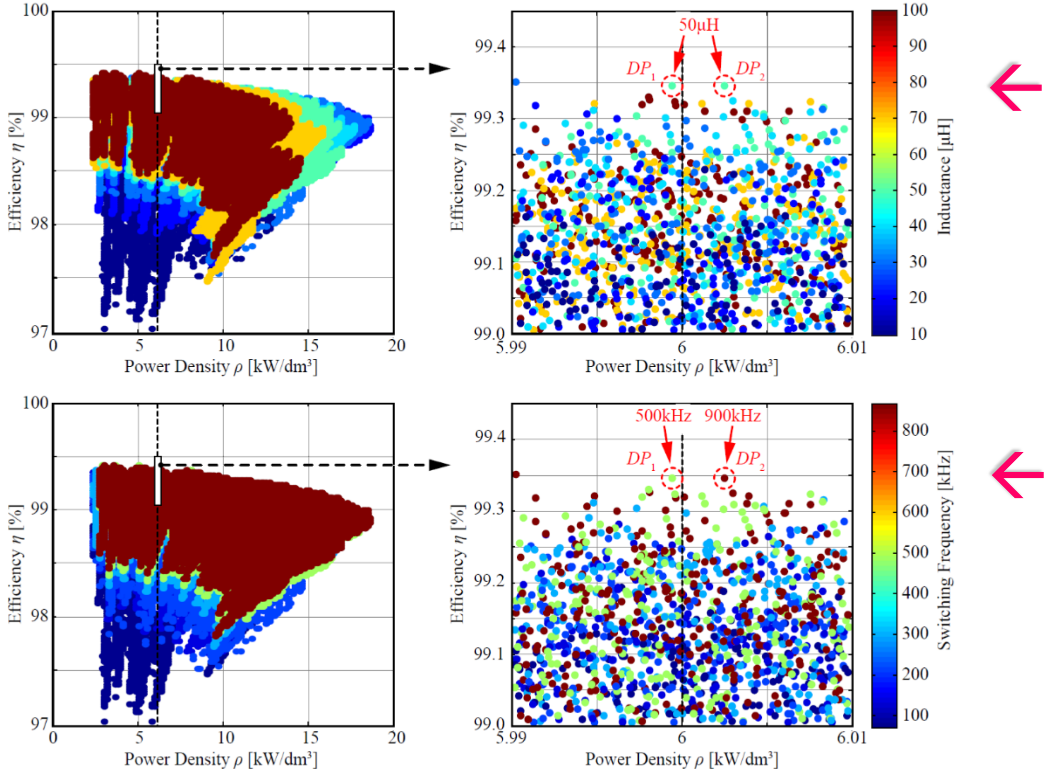
- Multi-Objective Optimization of Little-Box 1.0 (X6S Power Pulsation Buffer)
- Step-by-Step Idealization of the Power Transistors
- Ideal Switches: k_C= 0 (Zero Cond. Losses); k_S= 0 (Zero Sw. Losses)





→ 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/dm³
η ≈ 99.35%

L = 50uH
f_S = 500kHz or 900kHz

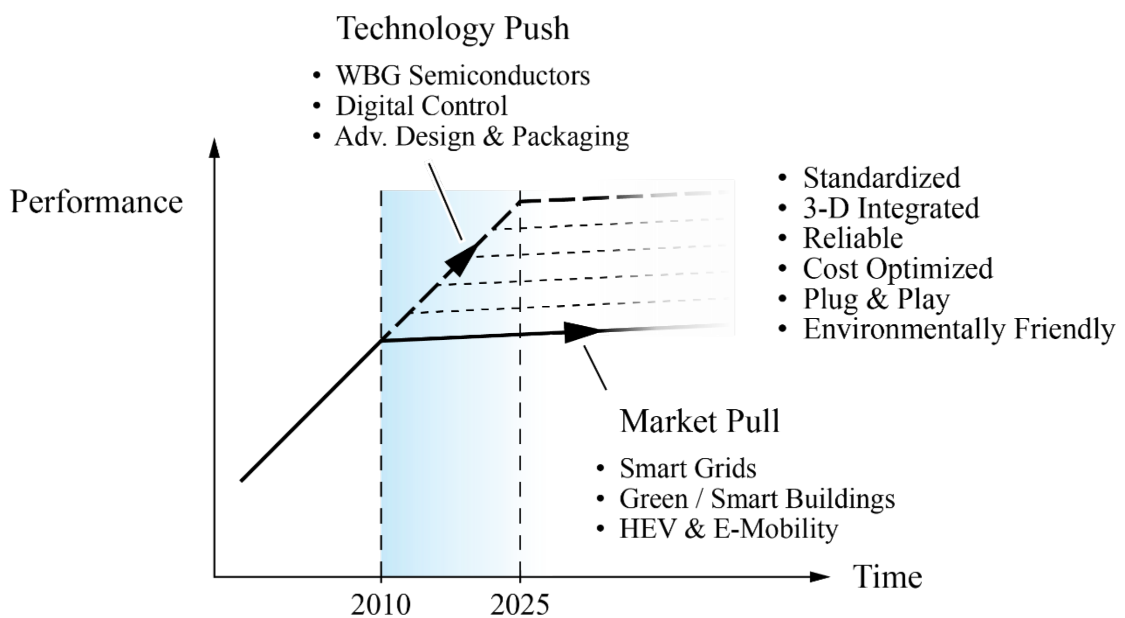
- L & f_S are Independent Degrees of Freedom
- Large Design Space Diversity (Mutual Compensation of HF and LF Loss Contributions)

Conclusions

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

▶ Future Development

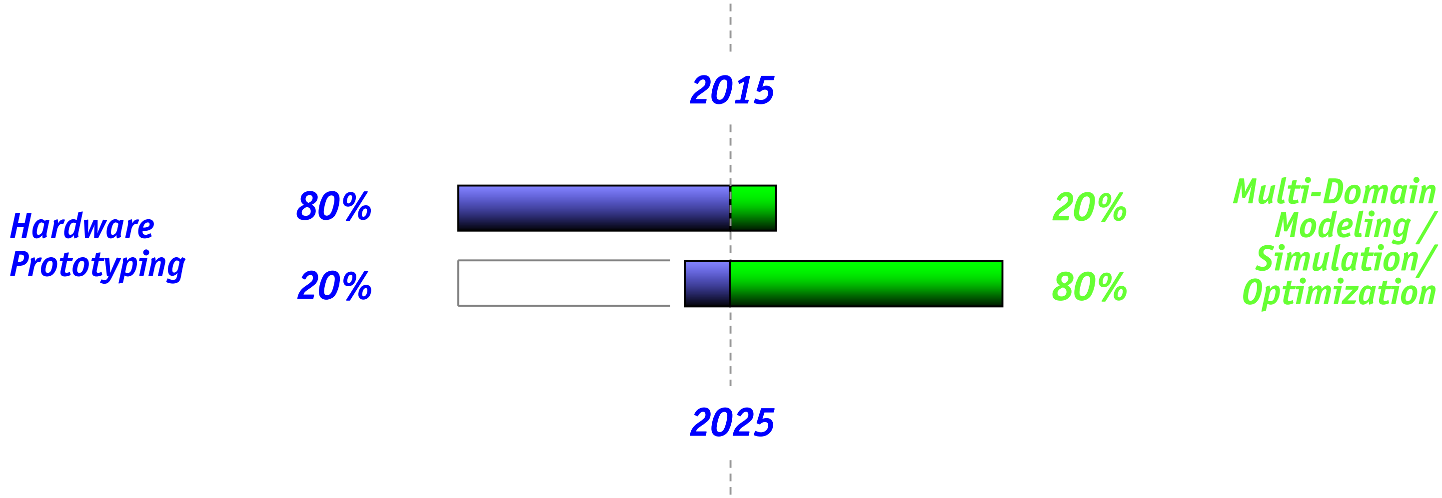
- Megatrends – Renewable Energy / Energy Saving / E-Mobility / "SMART XXX"
- Power Electronics will Massively Spread in Applications



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

Future "Virtual Prototyping"

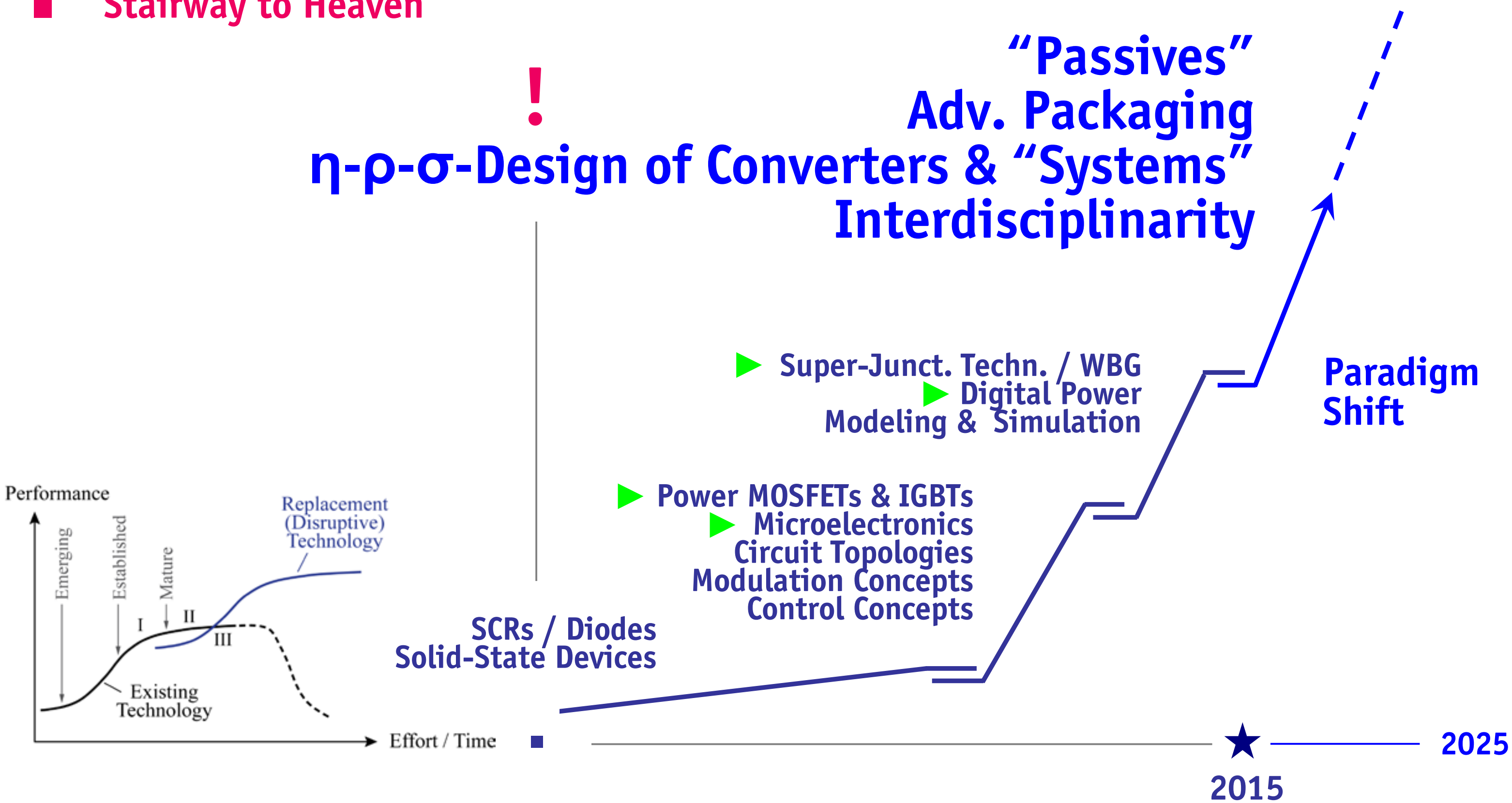
- Offers Incredible Design Insight – Quantifies Trade-Offs / Technology Sensitivities (!)
- Extends Theory of Components – "Theory of Systems"
- Reduces Time-to-Market – Cuts Design Time from Weeks to Hours



→ 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"

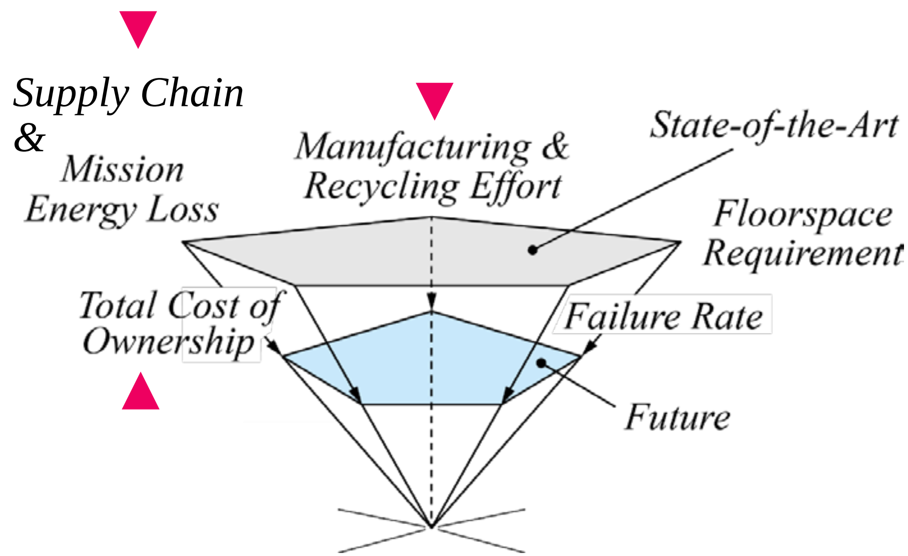
$$p(t) \rightarrow \int_0^t p(t)\,\mathrm{d}t$$

— 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 !