Power Electronic Systems Laboratory

ETH zürich

Efficiency is Not Enough!

Environmental Impacts as New Dimensions in Multi-Objective Optimization of Power Electronic Systems

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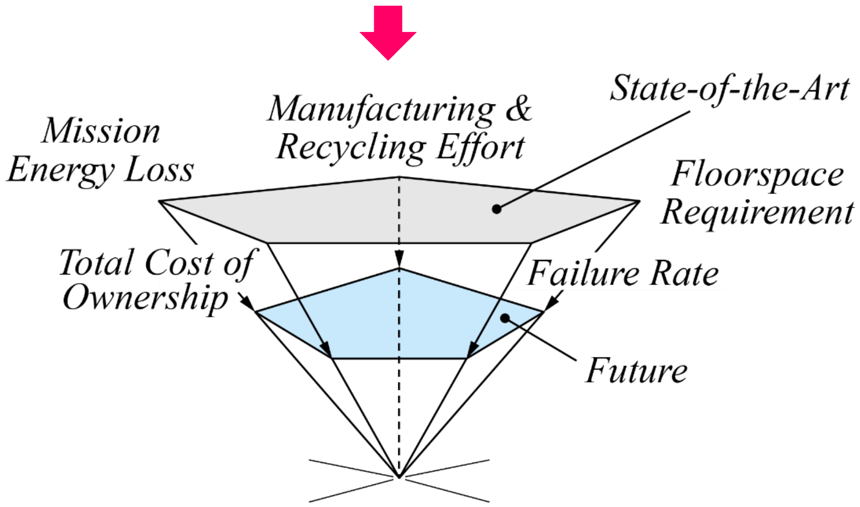
Expert Discussion
Sustainability in Power Electronics

The Future

- Assuming 20+ Years Lifetime → Systems Installed Today Reach End-of-Life in 2050 (!)
- Life-Cycle Analysis (LCA) Mandatory for All Future System Designs

- Complete Set of New Performance Indicators
  - Environmental Impact [kg CO_{2eq}/kW], [species.yr/kW], …
  - Human Health [DALY/kW]
  - Resource Efficiency [kg_{xx}/kW]
  - Resource Scarcity [$/kW]
  - Embodied Energy [kWh/kW]
  - TCO [$/kW]
  - Power Density [kW/dm^3]
  - Mission Efficiency [%]
  - Failure Rate [h^{-1}]

Environmental Impact *et al.*



Outline

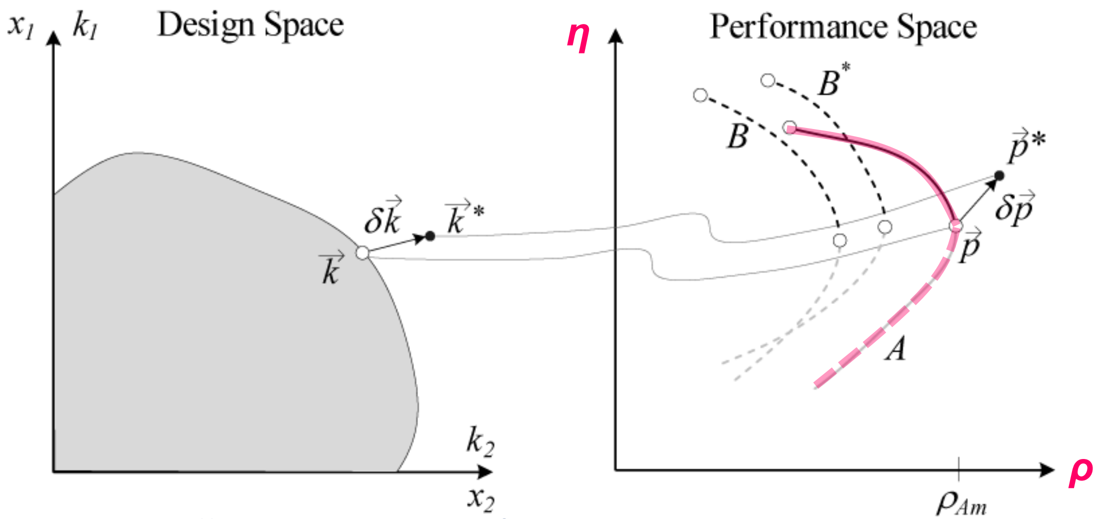
- **The Future**
- **The Opportunity**
  Design Space Diversity
- **The Tool**
  Multi-Objective Optimization with Environmental Impacts as New Dimensions
- **The Roadmap**

The Opportunity

Design Space Diversity

Multi-Objective Optimization (1)

- Converter Design: Mapping of Multi-Dimensional Design Space into a Multi-Dimensional Performance Space
- Pareto Front: Boundary of the Feasible Performance Space



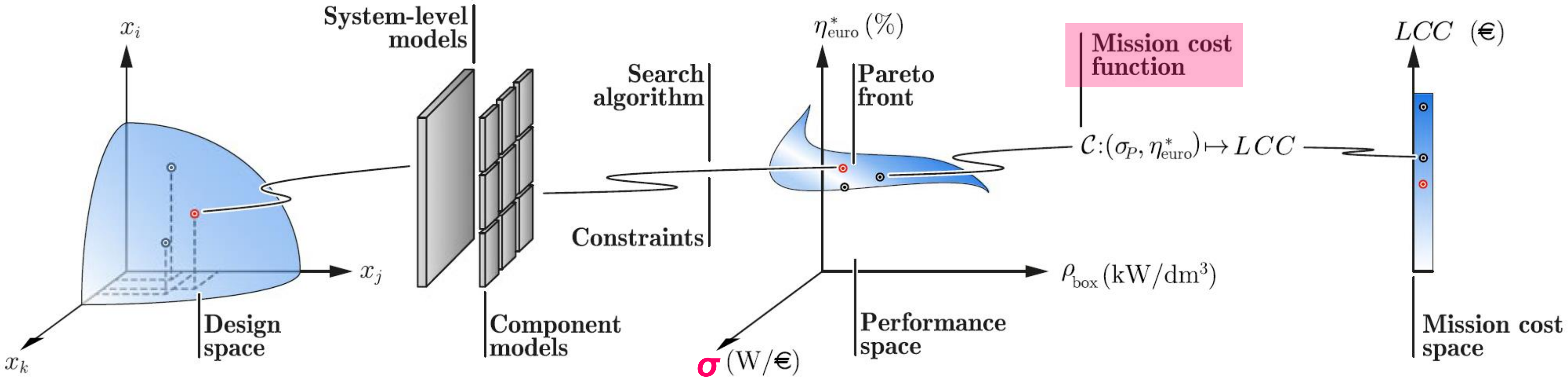
- Typically Considered Performance Indices
  - η Efficiency in %
  - ρ Volumetric Power Density in kW/dm^3
  - γ Gravimetric Power Density in kW/kg

- Comparison of Performance Limits of Different Converter Topologies, Component Technologies

J. W. Kolar, J. Biela, and J. Miniböck, "Exploring the Pareto front of multi-objective single-phase PFC rectifier design optimization - 99.2% efficiency vs. 7kW/dm^3 power density," in *Proc. Int. Power Electron. Motion Control. Conf (IPEMC),* Wuhan, China, May 2009.

Multi-Objective Optimization (2)

■ **Mission Profiles: Power Loss → Energy Loss / Life-Cycle *Cost* (!)**



■ **Typically Considered Performance Indices**

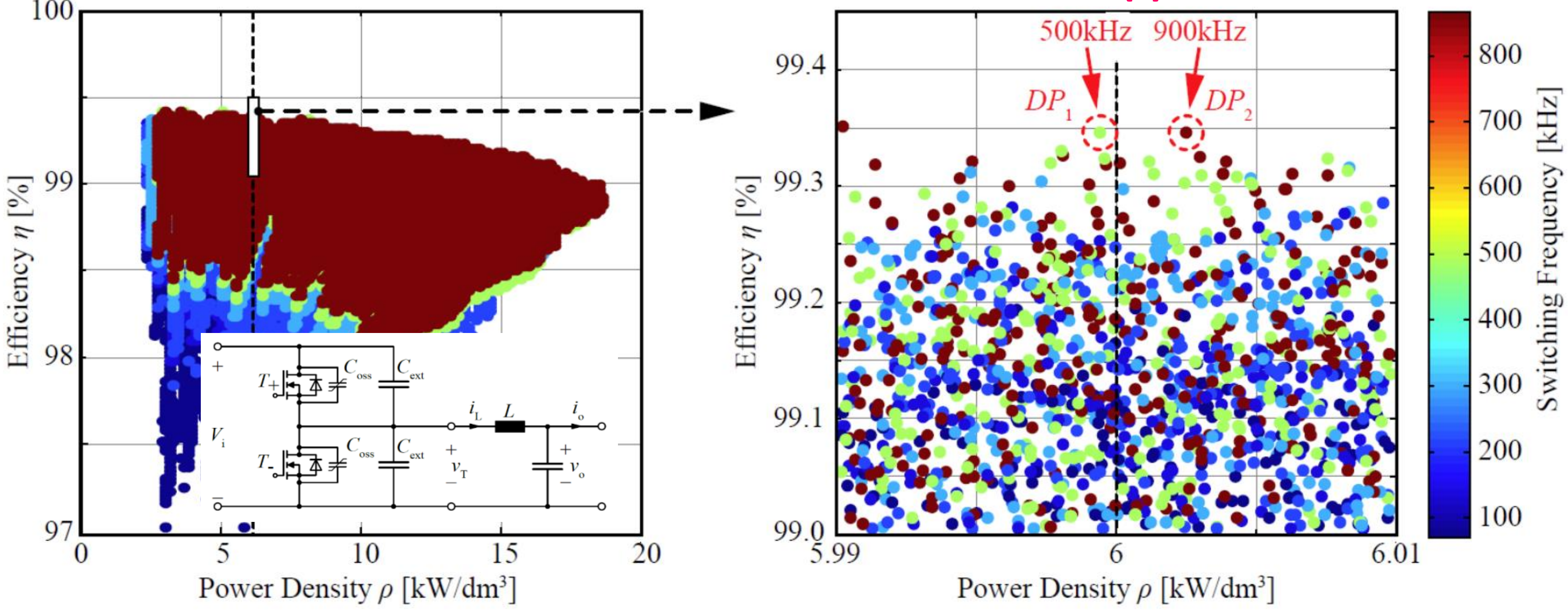
- ***η*** Efficiency in %
- ***ρ*** Volumetric Power Density in kW/dm^3
- ***γ*** Gravimetric Power Density in kW/kg
- ***σ*** **Cost Density in kW/€**

R. M. Burkart and J. W. Kolar, “Comparative life cycle cost analysis of Si and SiC PV converter systems based on advanced η-ρ-σ multiobjective optimization techniques,” *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4344–4358, Jun. 2017.

Design Space Diversity (1)

■ Very Different Design Space Coordinates Map to Very Similar Performance Space Coordinates

(!)

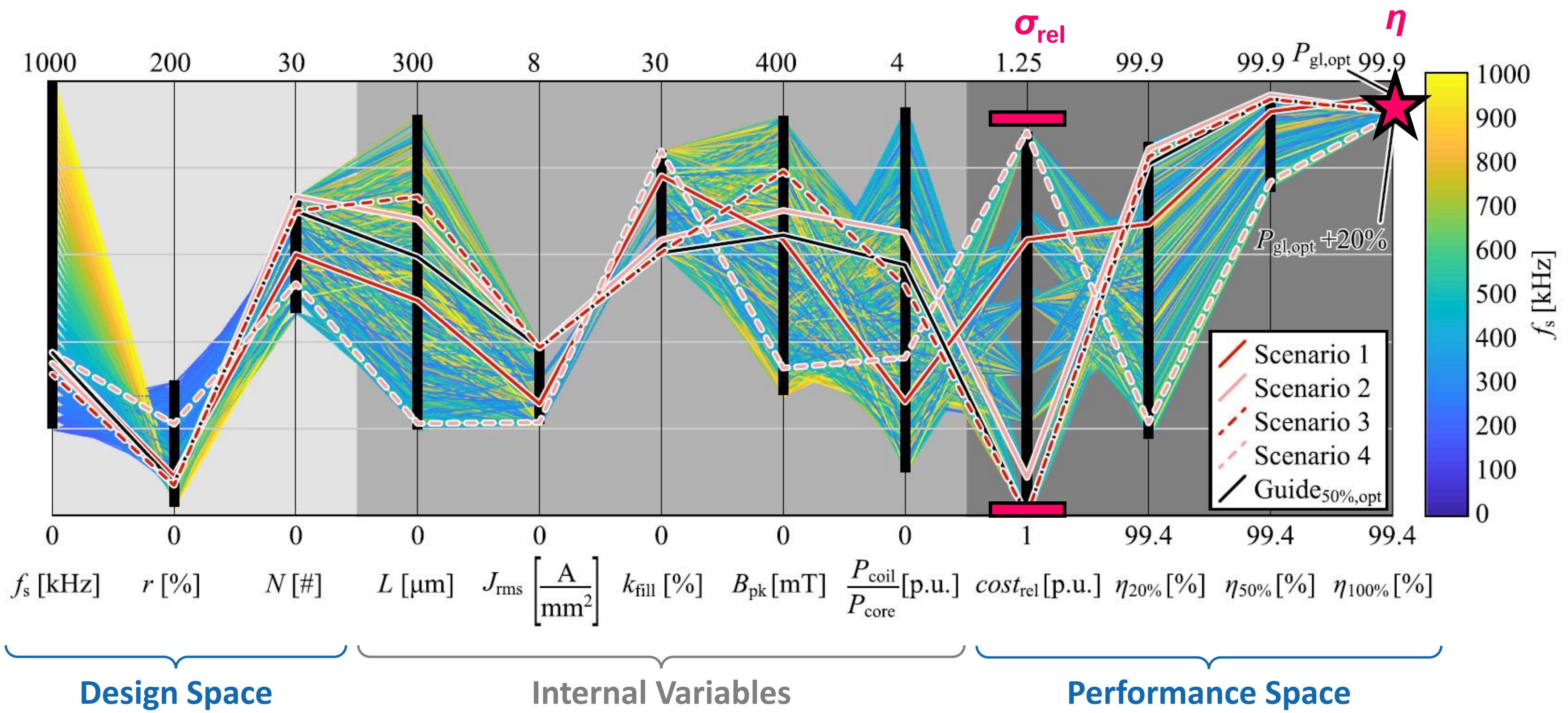


● Example: Google Littlebox Design Optimization w. PWM Operation / Mutual Comp. of HF and LF Loss Contrib.

J. W. Kolar, D. Neumayr, D. Bortis, M. Guacci, and J. Azurza Anderson, "Google Little-Box Reloaded,"
Keynote at the 10th Int. Conf. Integr. Power Electron. (CIPS), Stuttgart, Germany, Mar. 2018.

Design Space Diversity (2)

■ **Opportunity for Adjusting Further Performance Metrics at Unchanged Efficiency (Power Density, …)**



- Example: Inductor Optimization for 2-kW, 400-V DC-DC Converter / Parallel-Coordinate Plot
- Designs with Same (Full-Load) Efficiency Differ Widely in the Cost and Part-Load Eff. Dimensions

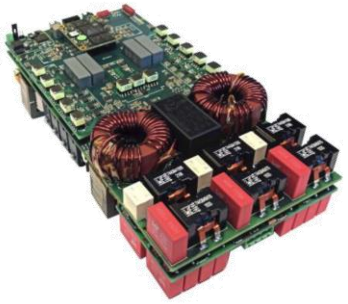
P. Papamanolis, T. Guillod, F. Krismer, and J. W. Kolar, "Minimum loss operation and optimal design of high-frequency inductors for defined core and litz wire," *IEEE Open J. Power Electron.*, vol. 1, pp. 469–487, Sep. 2020.

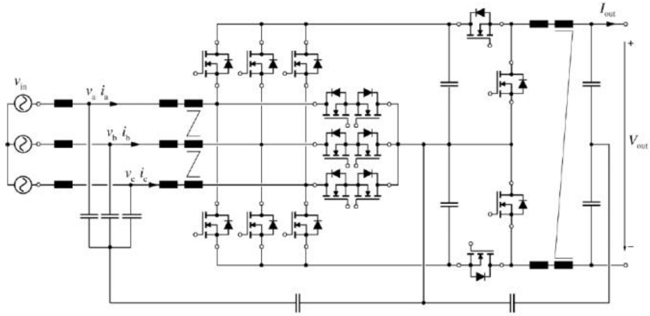
Design Space Diversity / Topologies (1)

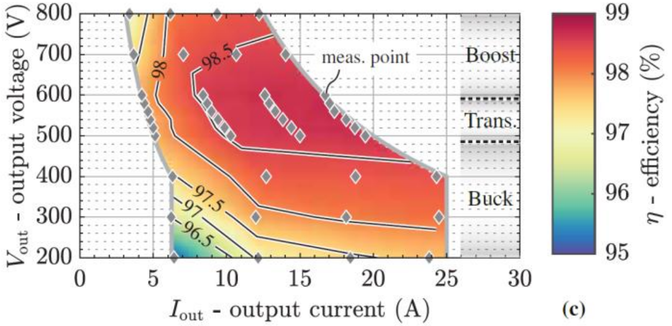
- Two Concepts / Similar Spec.: 10 kW, 400…800/1000 V DC, CISPR 11 Class A / Similar Performance (η, ρ)

Boost-Buck Voltage DC-Link EV Charger

98.8%, 5.4 kW/dm³

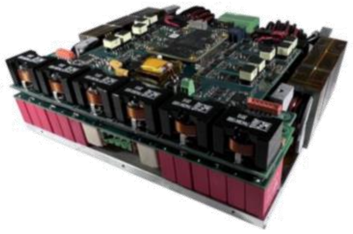


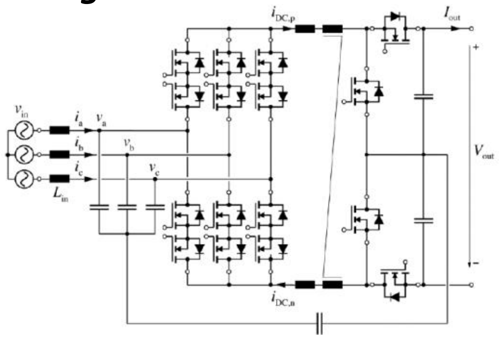


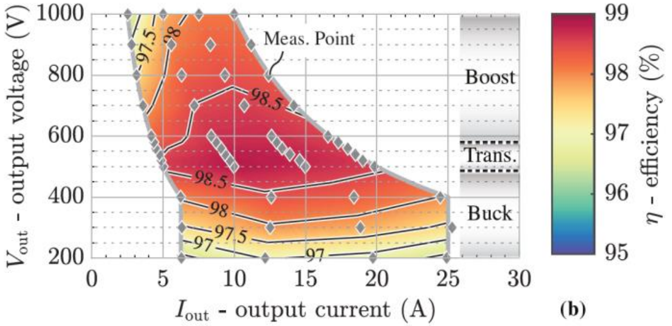


Buck-Boost Current DC-Link EV Charger

98.6%, 6.4 kW/dm³







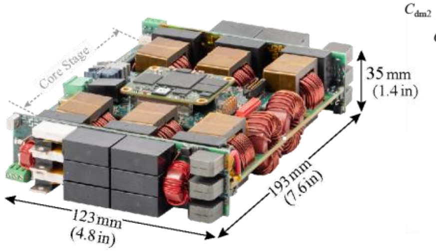
D. Zhang, J. Huber, and J. W. Kolar, "A Three-Phase Synergetically Controlled Buck-Boost Current DC-Link EV Charger," *under review,* 2023.

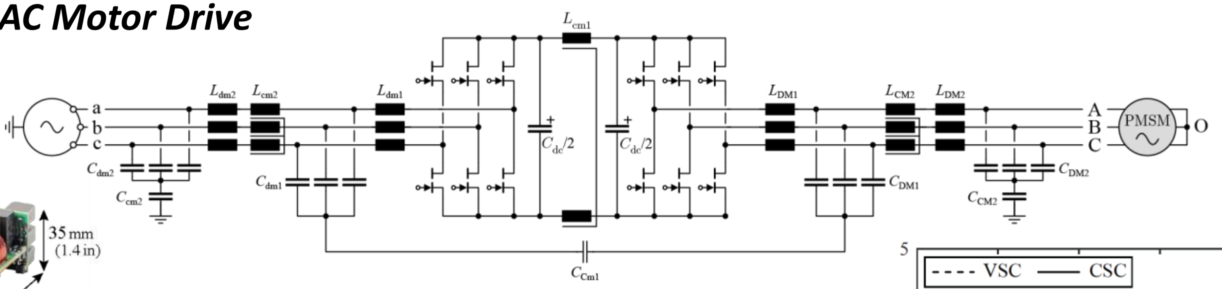
D. Zhang, C. Leontaris, J. Huber, and J. W. Kolar, "Optimal synergetic control of high-efficiency three-phase/level boost-buck voltage DC-link very wide output voltage range EV charger." *TechRxiv,* Mar. 14, 2023.

Design Space Diversity / Topologies (2)

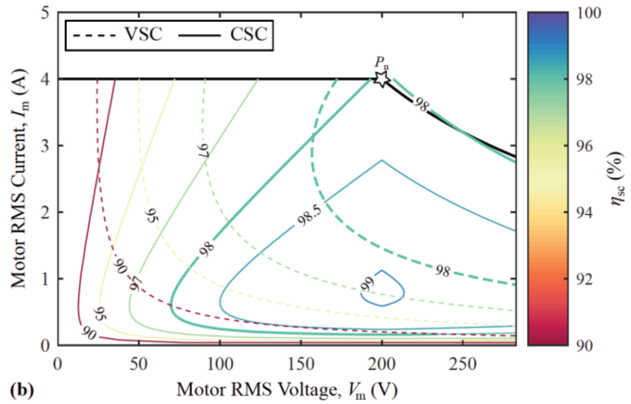
- Two Concepts / Similar Spec.: 1.4 kW, 97% Nominal Efficiency / Similar Performance (η, ρ)

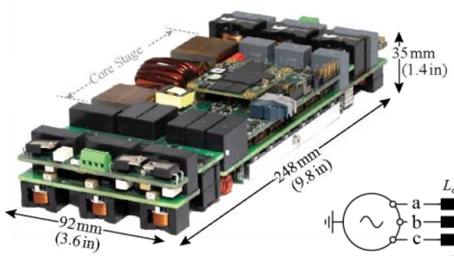
***Voltage-Source* AC-AC Motor Drive**
97%, 1.7 kW/dm^3

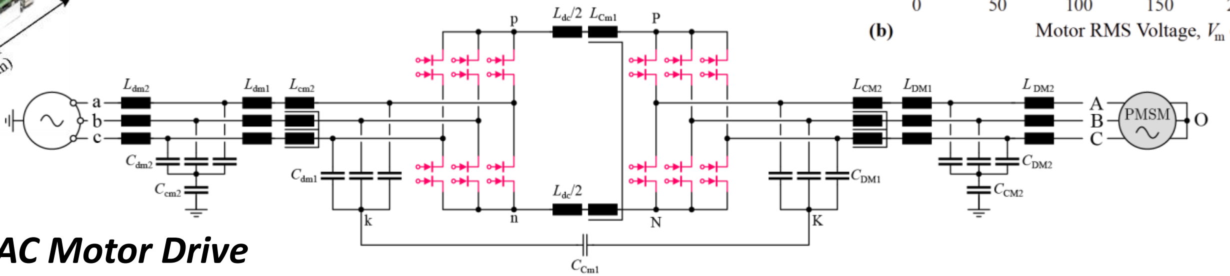




Different Part-Load Semic. Efficiency Characteristics (!)







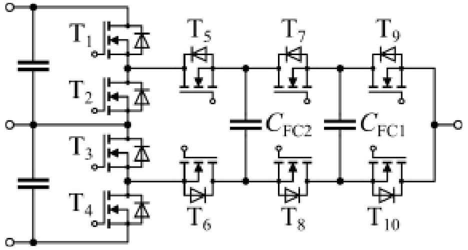
97%, 1.8 kW/dm^3
***Current-Source* AC-AC Motor Drive**

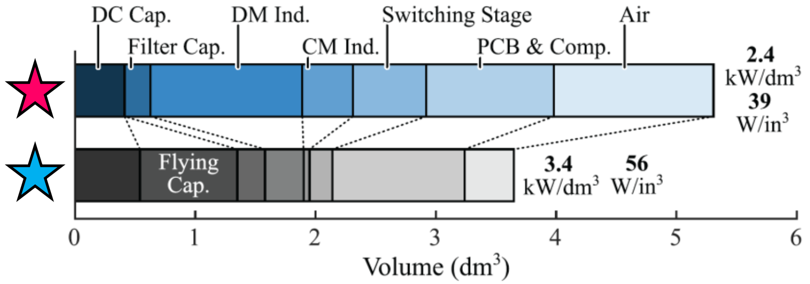
N. Nain, J. Huber, and J. W. Kolar, "Comparative evaluation of three-phase AC-AC voltage/current-source converter systems employing latest GaN power transistor technology," in *Int. Power Electron. Conf. (IPEC/ECCE Asia)*, Himeji, Japan, May 2022, pp. 1726–1733.

Design Space Diversity / Topologies (3)

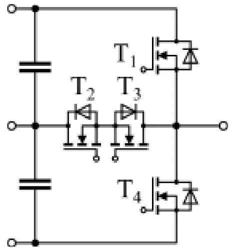
- Two Concepts / Similar Spec.: 12.5 kW, 650…720 V DC, CISPR 11 Class A / Similar Performance (η_{CEC} = 99.1%)

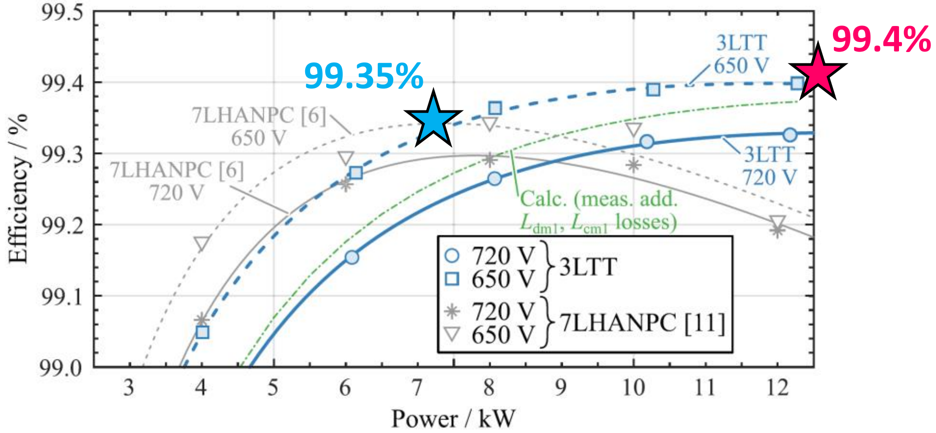
7-Level All-Si HANPC ***PV Inverter***
99.35%, 3.4 kW/dm³





3-Level All-SiC ***T-Type PV Inverter***
99.4%, 2.4 kW/dm³



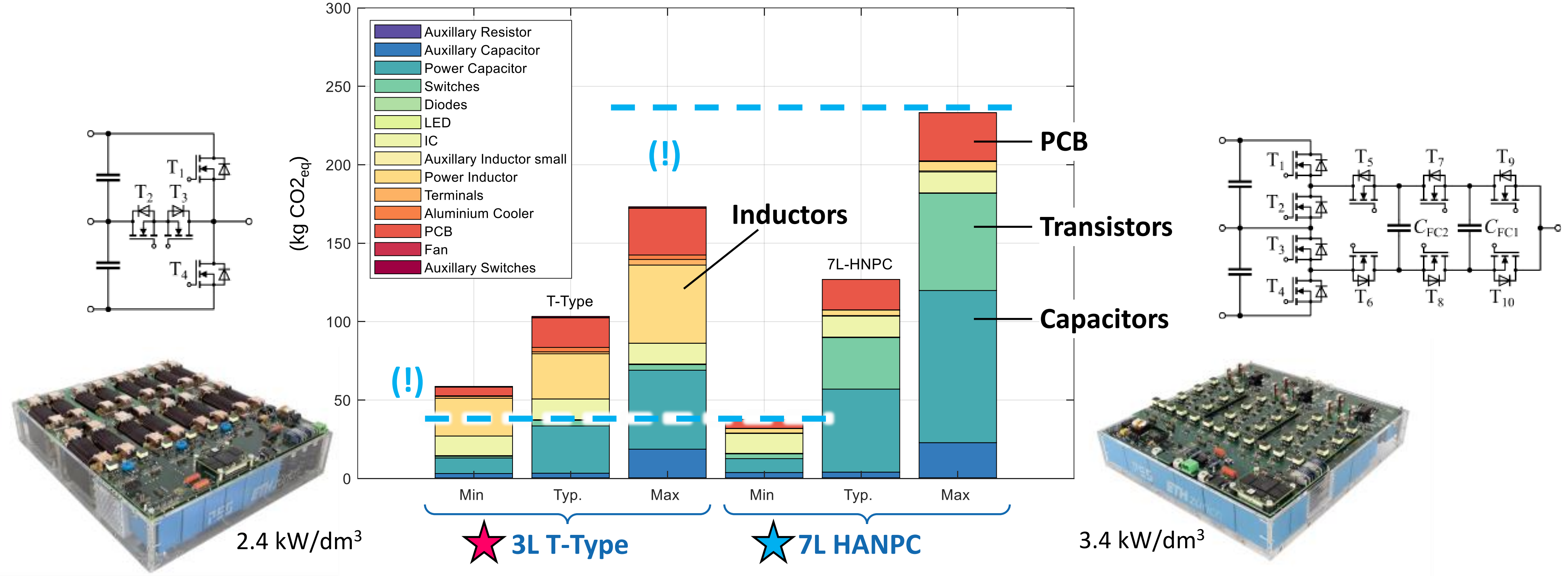


- **Differences in Environmental Impact?**

J. A. Anderson, D. Marciano, J. Huber, G. Deboy, G. Busatto, and J. W. Kolar, "All-SiC 99.4%-efficient three-phase T-type inverter with DC-side common-mode filter," *Electron. Lett.*, vol. 59, no. 12, p. e12821, 2023.

A-Posteriori LCA of the two PV Inverters

- Two Concepts / Similar Spec.: 12.5 kW, 650…720 V DC, CISPR 11 Class A / Similar Performance (η_{CEC} = 99.1%)



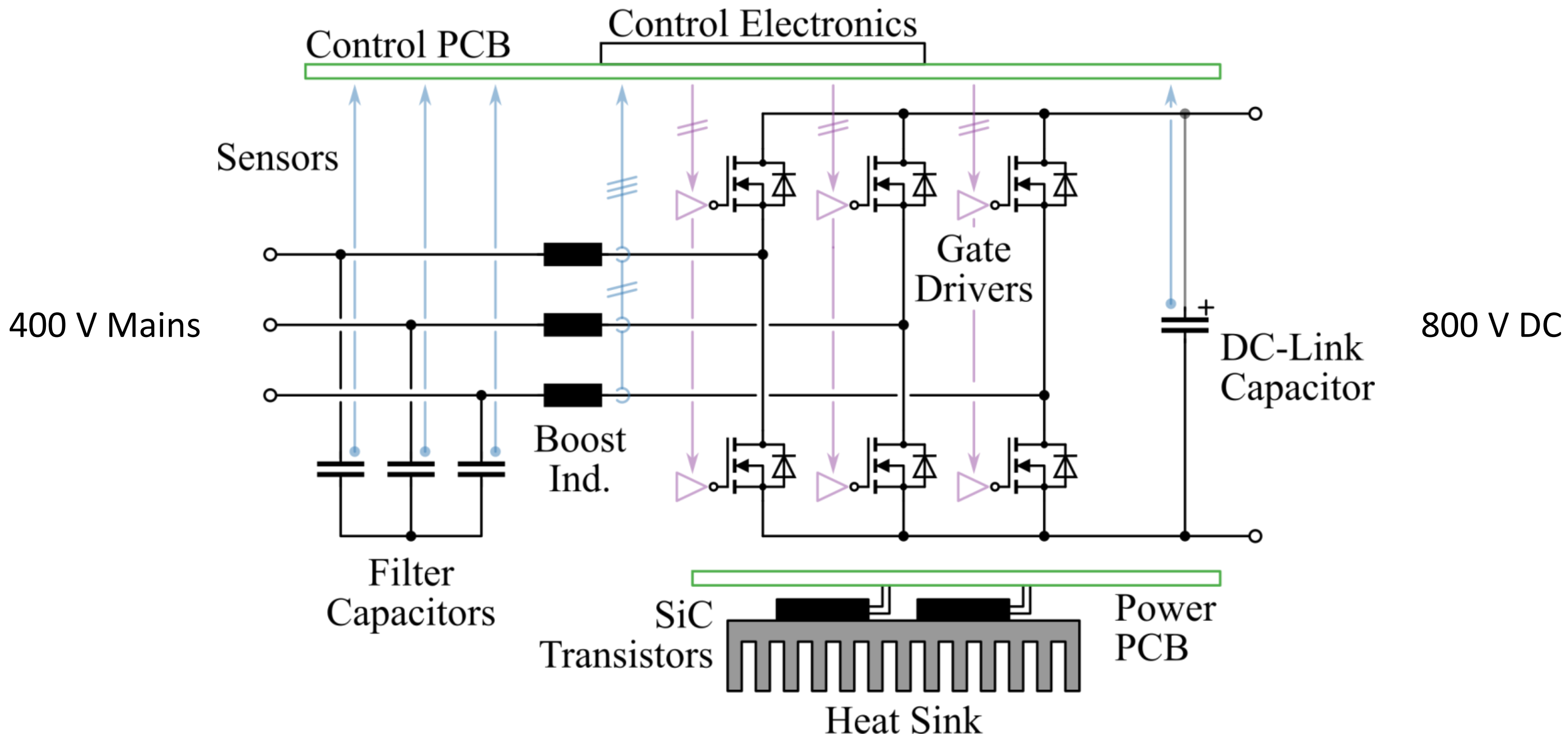
- Generic Models / Data Source: ecoinvent & Literature => Wide Range of Parameter Values / CO_{2eq} Results
- Challenge for Multi-Objective Optimization: Even Further Abstraction Necessary!

The Tool

Multi-Objective Optimization with Environmental Impacts as New Dimensions

Example: 3-Phase Power Electronic Building Block (PEBB)

- **Key Building Block for Three-Phase Rectifiers & Inverters / 400 V Mains, 800 V DC, 10 kW, 1200 V SiC**

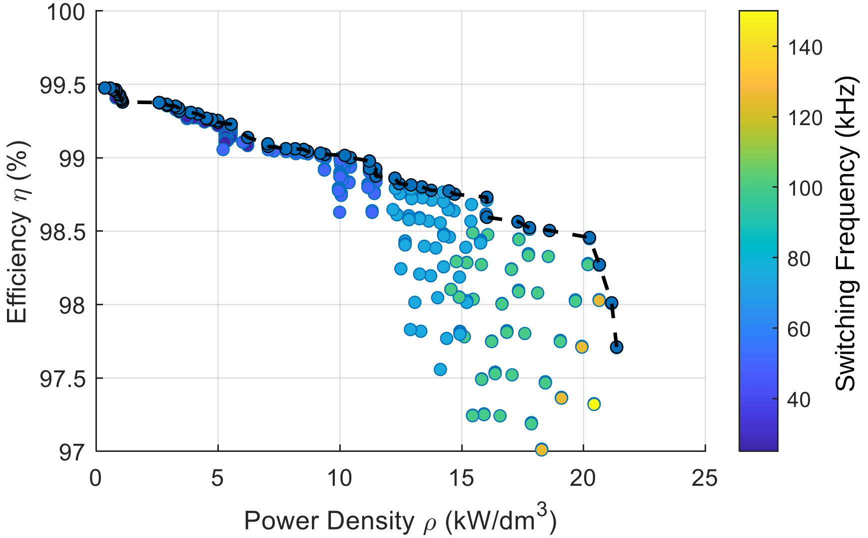


- **Main Components Considered (Losses, Volume, CO_{2eq})**
  Power Transistors, Heat Sink, Boost Inductors, DC-Link Capacitor, Filter Capacitors, Gate Drivers, Sensors, Control Electronics, PCBs

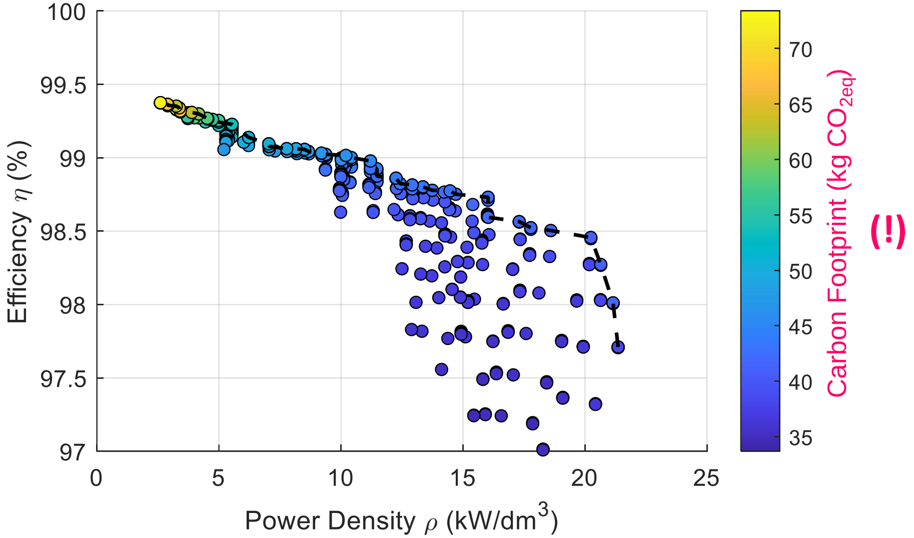
Efficiency vs. Power Density Pareto Front

- **Three-Phase Two-Level AC-DC PEBB with LC Input Filter: 400 V Mains, 800 V DC, 10 kW, 1200 V SiC**

Color: Switching Frequency



Color: Carbon Footprint



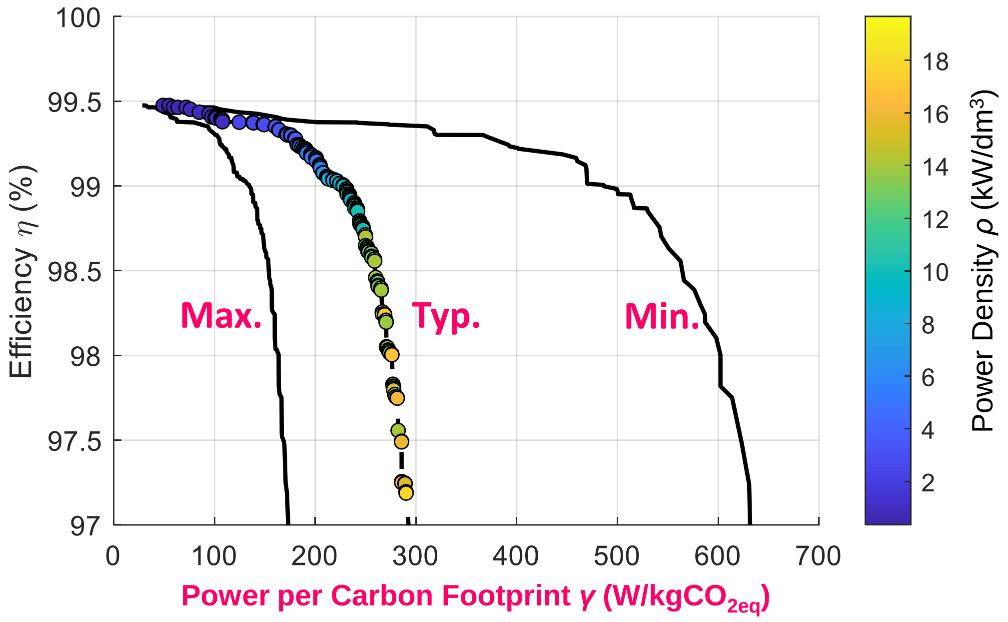
Degrees of Freedom
- Switching Frequency [25…200 kHz]
- Rel. Inductor Peak Current Ripple [0.25…1]
- Variable Transistor Chip Area
- Variable Inductor Size (N87; Solid/Litz Wire)

Assumptions
- Junction Temperature at 120 °C
- Necessary Heat Sink Volume via CSPI = 25 kW/(kg dm^3)

CO_{2eq} Data: ecoinvent, Literature => Typ. Val. (!)

Efficiency vs. Carbon Footprint Pareto Front

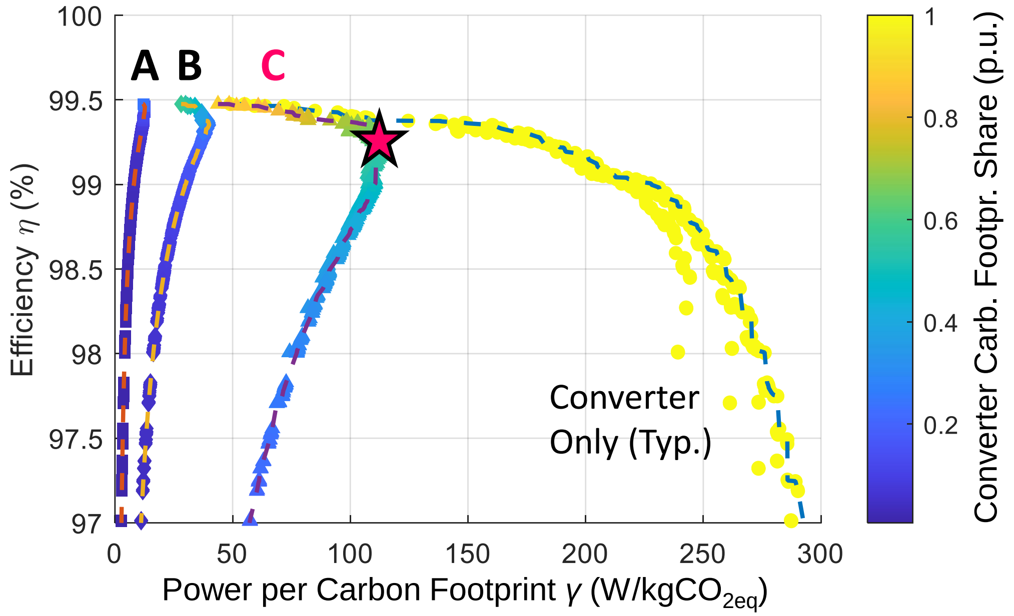
- **Data Quality** is a Major Challenge – Large Spread Between Max. / Typ. / Min. Values!
- **Pareto Front => Pareto Area** w. Probability Density (Not Shown)



- Power Density / Size Related to Carbon Footprint / **Not** a Direct Predictor

Efficiency vs. Lifetime Carbon Footprint Pareto Front

- Converter Losses Covered with **Electricity with Non-Zero Carbon Intensity**
- **Mission Matters:** Example 8 Hours Full Load per Day, 10 Years Lifetime



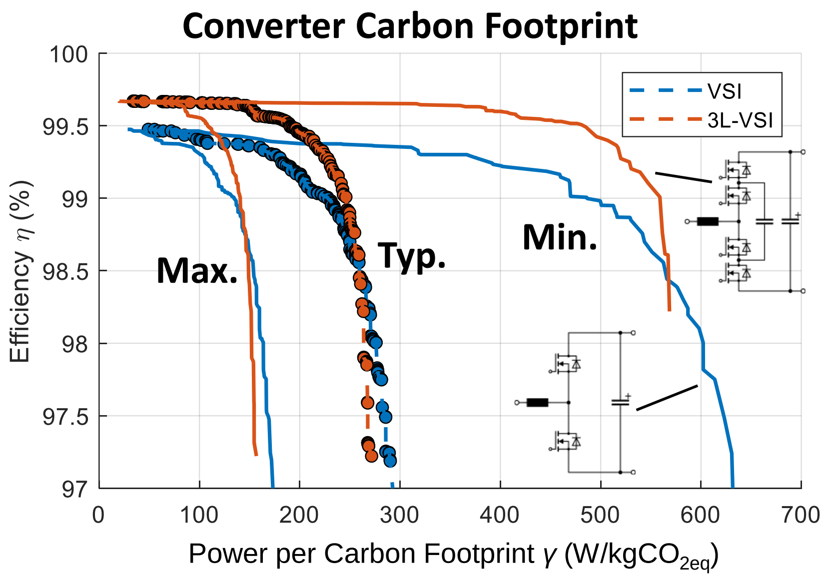
- **Electricity Mix Matters: Carbon Intensity**

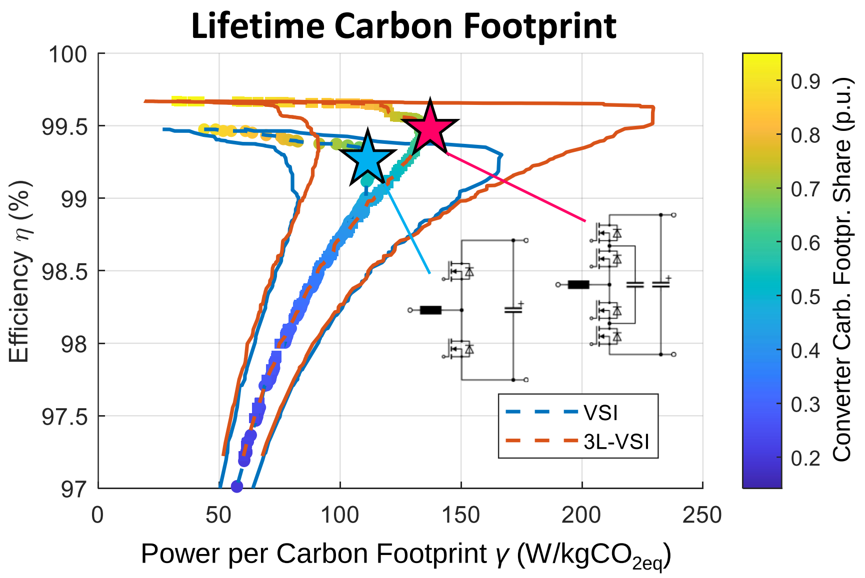
A	Consumption Mix Germany	411 g CO_{2eq} / kWh
B	Consumption Mix Switzerland	99 g CO_{2eq} / kWh
C	**Renewable Production Mix Switzerland**	**16 g CO_{2eq} / kWh**

Source: www.bafu.admin.ch

Topology Evaluation Example: 2-Level vs. 3-Level PEBB

- 3-Level Flying-Capacitor Bridge Legs w. 650 V SiC MOSFETS / 2-Level Bridge Legs w. 1200 V SiC MOSFETs
- 400 V Mains, 800 V DC, 10 kW / LC Filter w. Same Capacitor Voltage Ripple





Scenario: 8 h/d Full Load for 10 Years, Renewable Production Mix Switzerland

- Data Quality / High Uncertainty / Largely Overlapping Performance Spaces
- Environmental Profile with Further Performance Indices?

The Roadmap

Life Cycle Impact Assessment (LCIA)

■ **Example: ReCiPe 2016 – Three Areas of Protection / Endpoint Categories:**

- **Human Health**
  Damage to Human Health
  in Disability-Adjusted Loss of Life Years (DALY)

- **Ecosystem Quality**
  Damage to Ecosystem Quality
  in Time-Integrated Species Loss (Species.yr)

- **Resource Scarcity**
  Damage to Resource Availability
  in Surplus Cost ($)

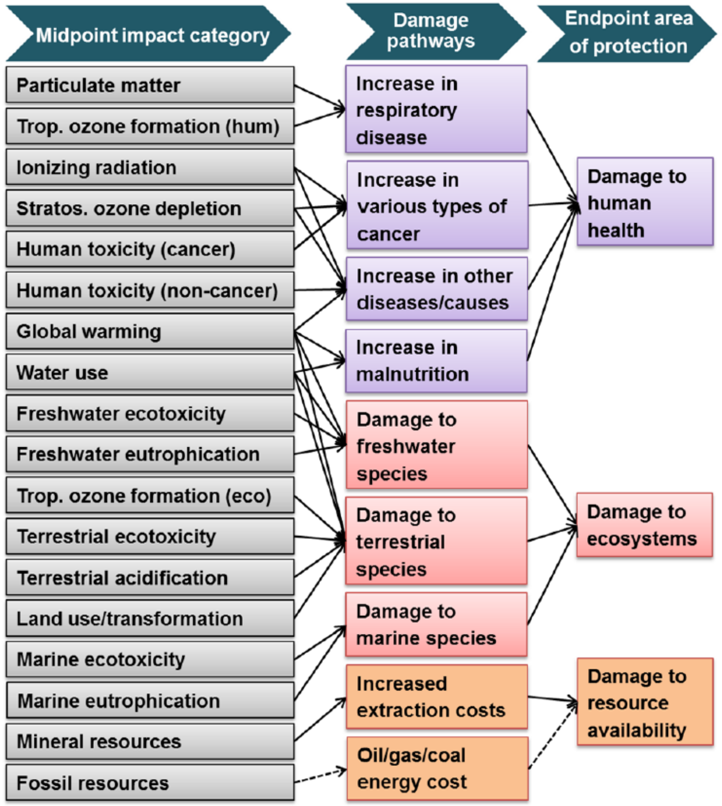


Image: ReCiPe 2016 v1.1 Report

■ **Value Choices (Individualist / Hierarchist / Egalitarian) Affect Time Horizon, Included Effects, etc.**

M. A. J. Huijbregts *et al.*, "ReCiPe 2016 v1.1 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization," RIVM Report 2016-0104a, 2016.

CO_2 is Not Enough: New Performance Space Dimensions

- Life Cycle Impact Assessment (LCIA) Phase of LCA => Environmental Profile w. Wide Range of Perf. Indicators
- Selected Examples (Midpoints / Endpoints):

Land Filling
Bulk waste, Hazardous Waste,
Slag/Ashes in kg waste

Ozone Depletion Potential
in kg $CFC\text{-}11_{eq}$

Global Warming Potential
in kg CO_{2eq}

Cumulative Energy Demand
"Embodied Energy" in MJ_{eq}

Crustal Scarcity Potential
in kg Si_{eq}

Non-Renewable Resources
Aluminum, Coal, Palladium, …
in kg (EDIP 2003)

Human Health
Human Toxicity, Ozone Depletion,
Particulate Matter Formation, …
in DALY (ReCiPe 2016)

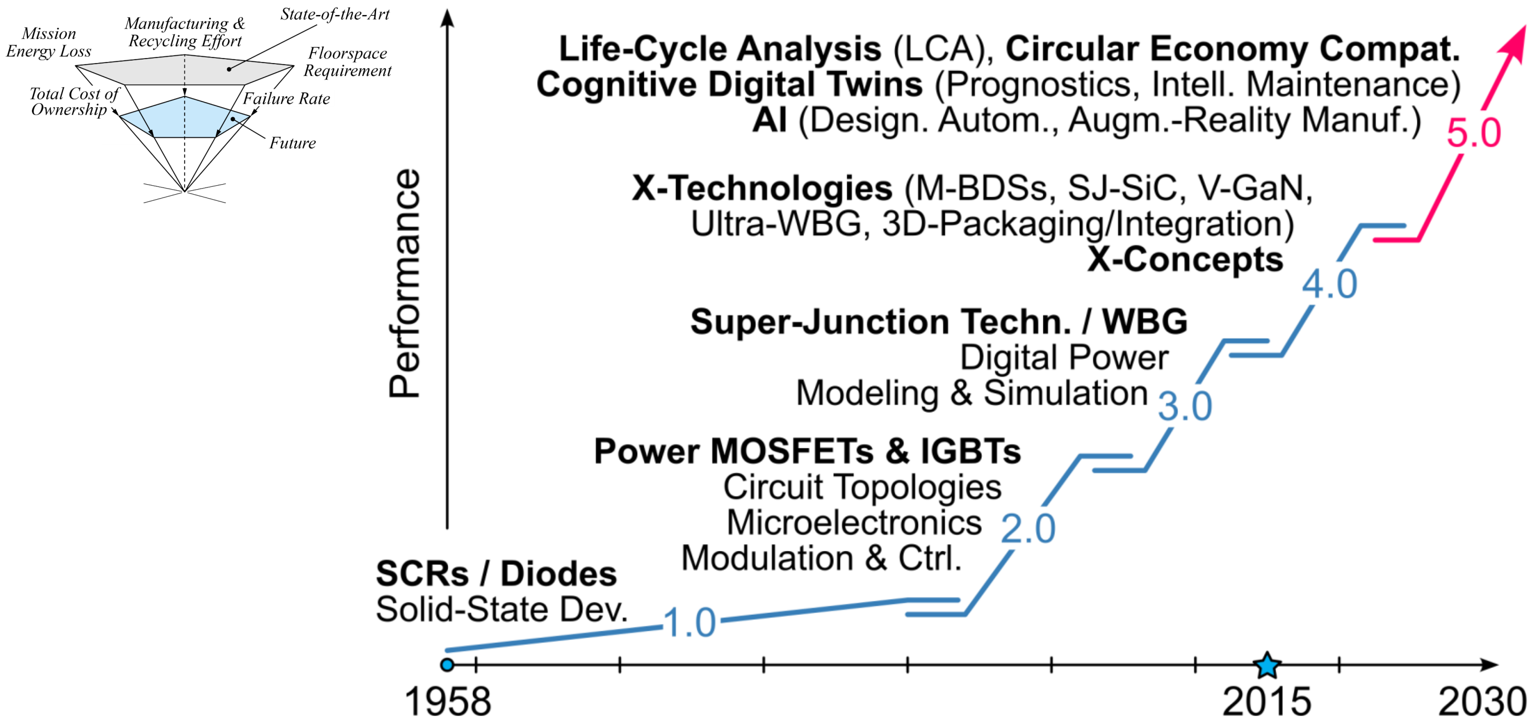
Ecosystem Quality
Acidification, Climate Change,
Land Use, …
in species.yr (ReCiPe 2016)

Resource Scarcity
Energy Resources: Non-Renewable,
Material Resources: Metals/Minerals
in $ (ReCiPe 2016)

Species.yr: Local Species Loss Integrated Over Time; DALY: Disability Adjusted Life Years

Power Electronics Development Cycles

- Technology S-Curves Typ. Triggered by New Power Semiconductor Developments / Disruptive X-Technologies



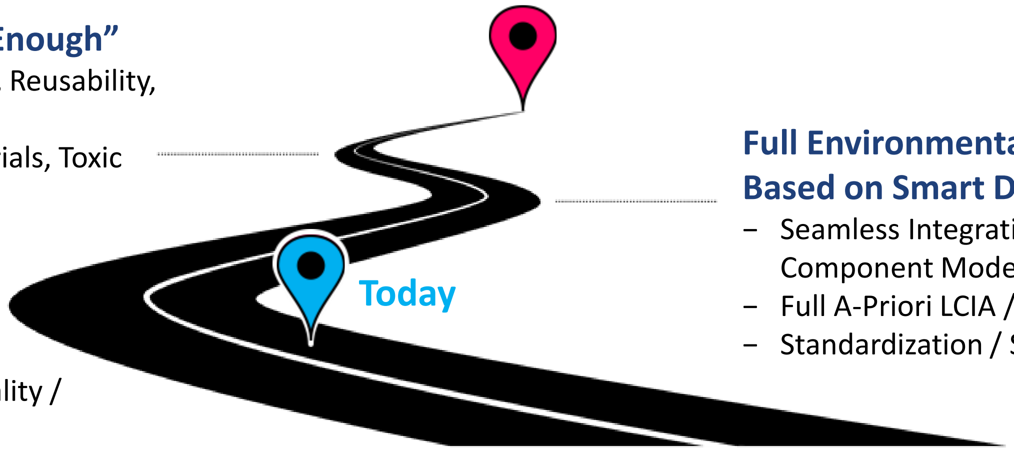
- Life-Cycle Analysis / Circular-Economy-Compatibility are Key for Sustainable Power Electronics 5.0

The Roadmap

- **Environmental Awareness** as Integral Part of the Design Process / Circular-Economy-Compatibility by 2050

Circular-Economy-Compatible Power Electronics

"Net-Zero CO_2 is Not Enough"
- **Maximize** Repairability, Reusability, Recyclability
- **Minimize** Scarce Materials, Toxic Substances, Waste



Full Environmental Footprint Based on Smart Datasheets
- Seamless Integration of Accurate Specific Component Models in Multi-Objective Opt.
- Full A-Priori LCIA / Environmental Footprint
- Standardization / Single Source of Truth

Generic Modeling of LCIA Perf. Ind.
- **New Dimensions in Multi-Obj. Opt.**
- Key Challenges: Data Sources / Data Quality / Abstraction / Generalization

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

- **Up Next: Discussion** ***ECPE Whitepaper and Roadmap Towards Circular-Economy-Compatible Power Electronics***

Thank You!

- **Up Next: Discussion**
  ECPE Whitepaper and Roadmap Towards Circular-Economy-Compatible Power Electronics