Multi-Objective Optimization in Power Electronics

Presentation

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Multi-Objective Optimization in Power Electronics

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Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Outline

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

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Global Megatrends

Climate Change
Digitalization
Sustainable Mobility
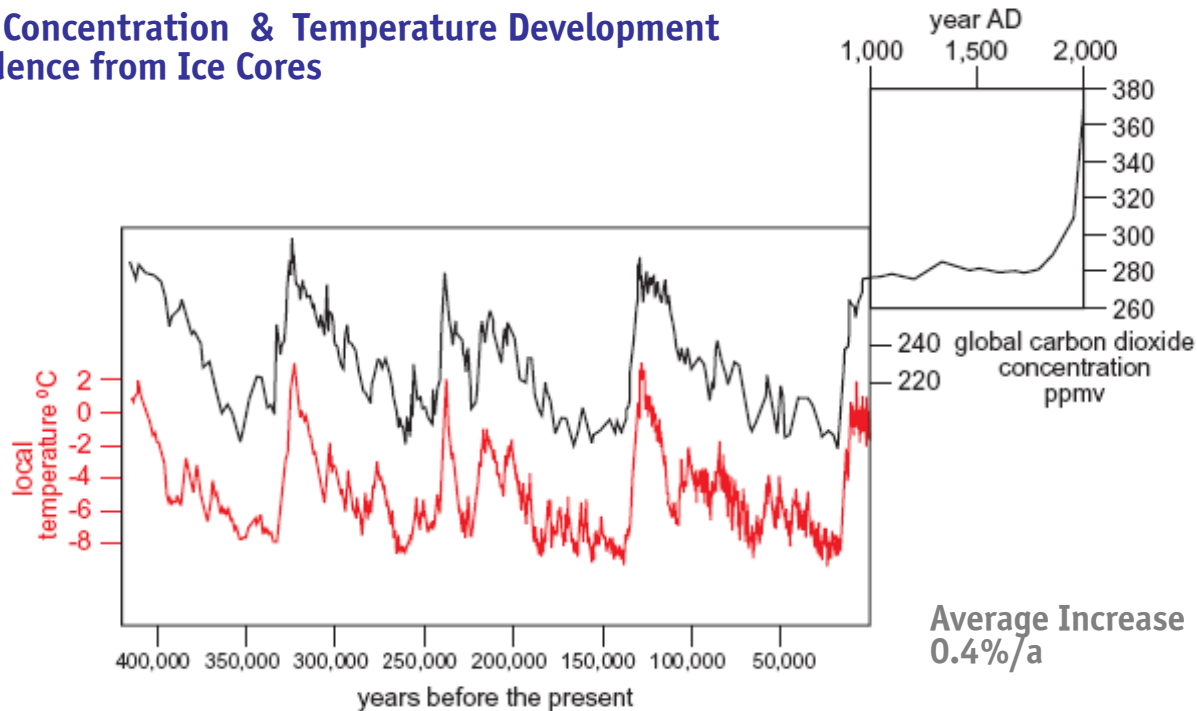*Urbanization*
Etc.

Global Megatrends

Climate Change →
Digitalization
Sustainable Mobility
Urbanization
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

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► 1/3 in 2050 → less than 1/10 in 2100 (AIST, Japan @ IEA Workshop 2007)

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→ *Utilize Renewable Energy* (1)

■ **Enabled by Power Electronics**

— **Higher Reliability (!)**
— **Lower Costs**

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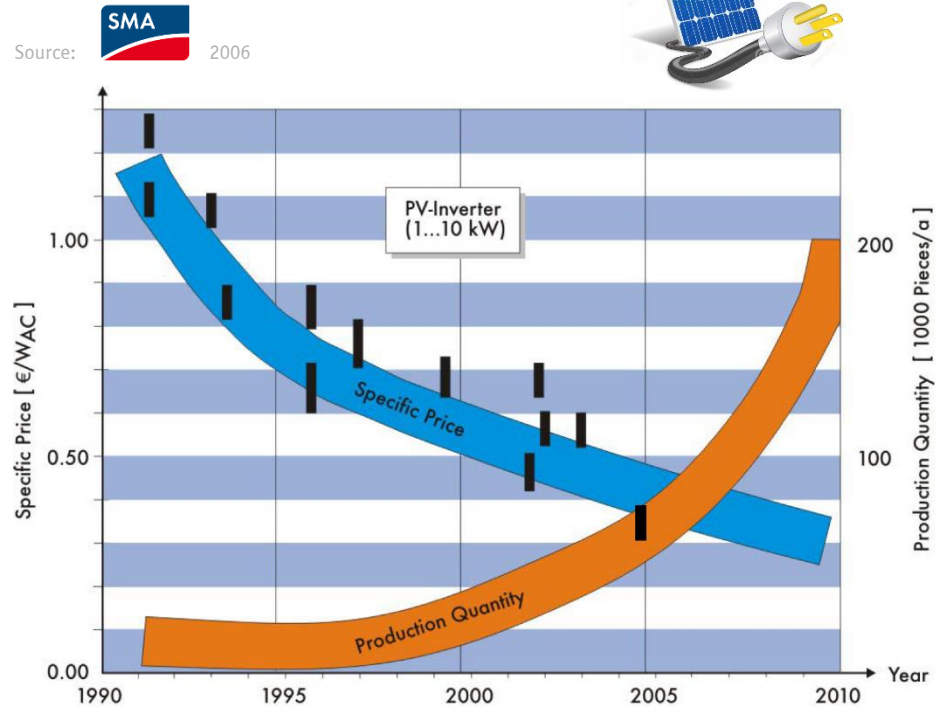to On-Shore Grid

Source: M. Prahm / Flickr

▶ **Off-Shore Wind Farms**
▶ **Medium Voltage Systems**

→ *Utilize Renewable Energy* (2)

■ **Enabled by Power Electronics**

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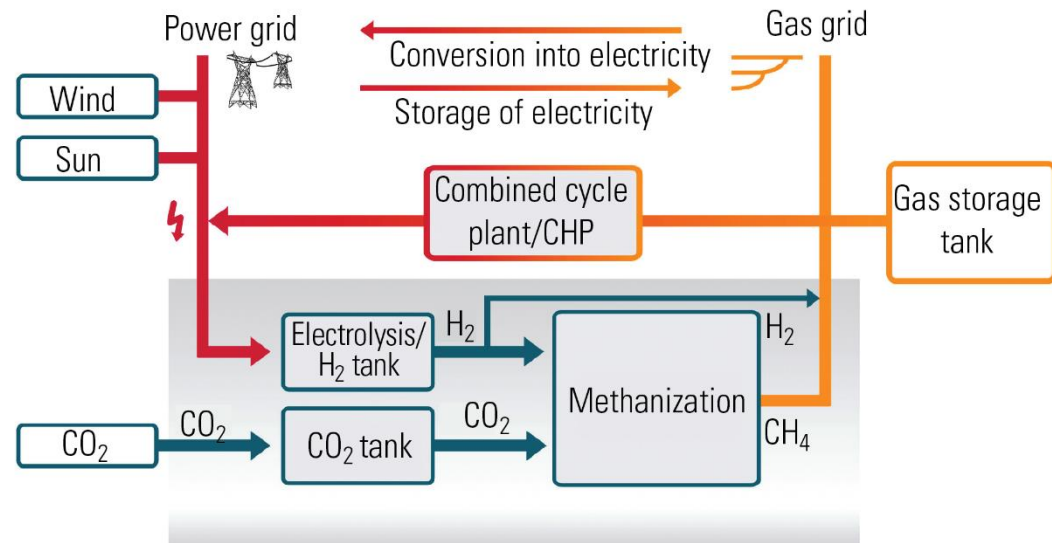— **Higher Efficiency**
— **Higher Power Density**

Source: SMA 2006

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

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→ *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

Power grid

Gas grid

Wind

Sun

Conversion into electricity

Storage of electricity

Combined cycle plant/CHP

Gas storage tank

Electrolysis/ H_2 tank

H_2

H_2

CO_2

CO_2

CO_2 tank

CO_2

Methanization

CH_4

Source: www.r-e-a.net

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Global Megatrends

Climate Change
Digitalization →
Sustainable Mobility
Urbanization
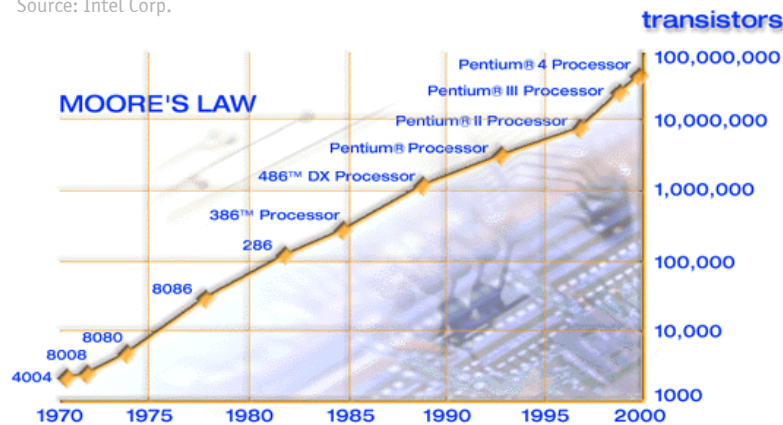Etc.

► Digitalization

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

— **Ubiquitous Computing / BIG DATA**
— **Fully Automated Manufacturing / Industry 4.0**
— **Autonomous Cars**
— **Etc.**
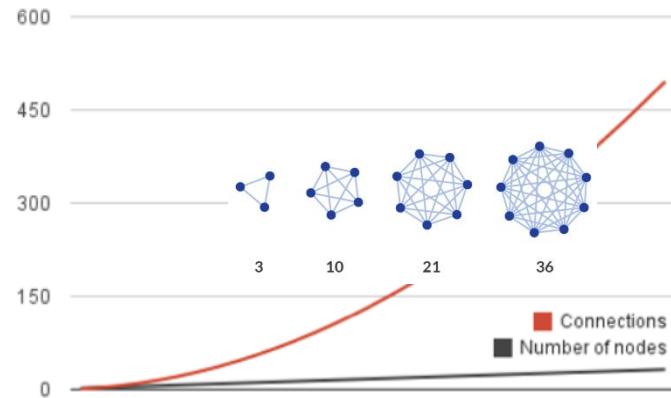
– Moving form Hub-Based to Community Concept Increases Potential Network Value Exponentially (~n(n-1) or ~n log(n))
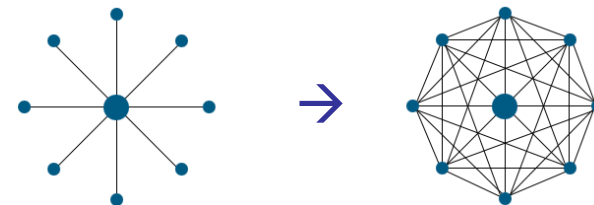
Source: Intel Corp.

► **Moore's Law**

► **Metcalfe's Law**

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→ *Green / Zero* CARBON *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**

Source: REUTERS/Sigtryggur Ari

33 Watts   60 Watts

→

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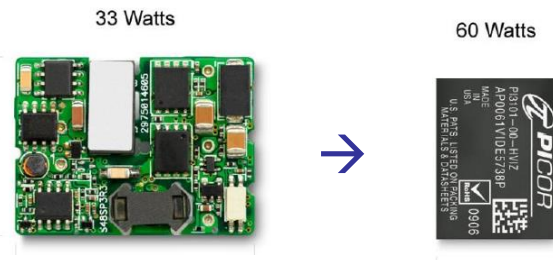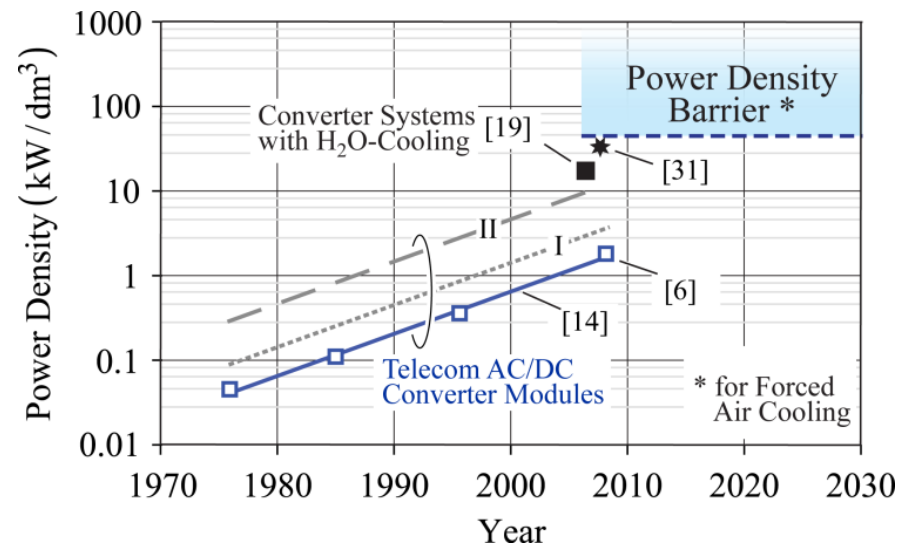# → *Green / Zero* CARBON *Datacenters* (2)

■ 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.**
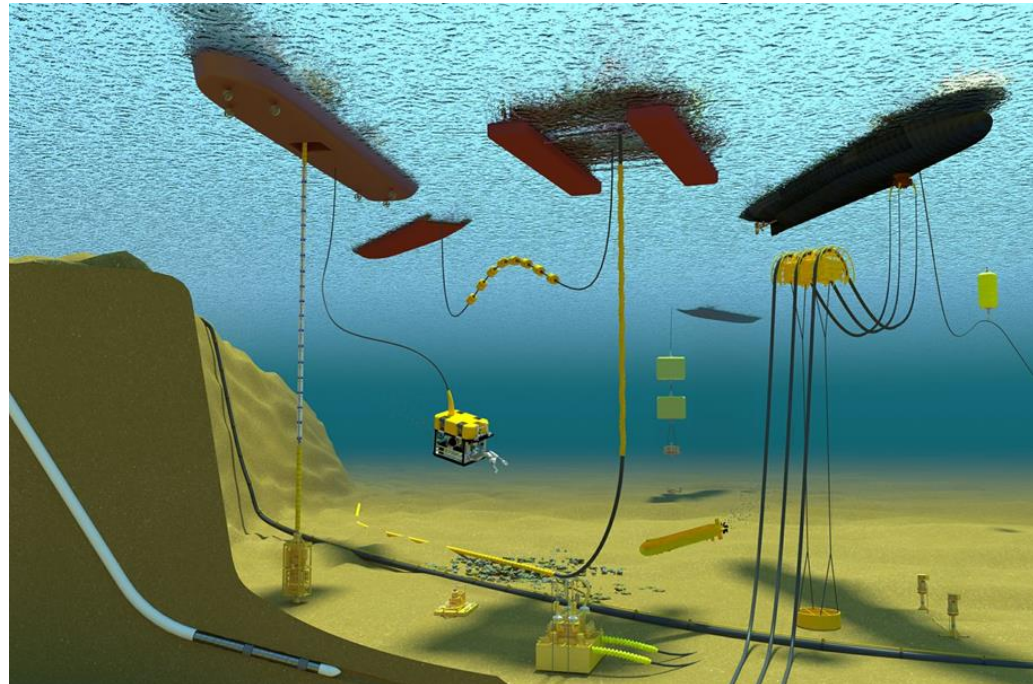
Source: TESLA MOTORS

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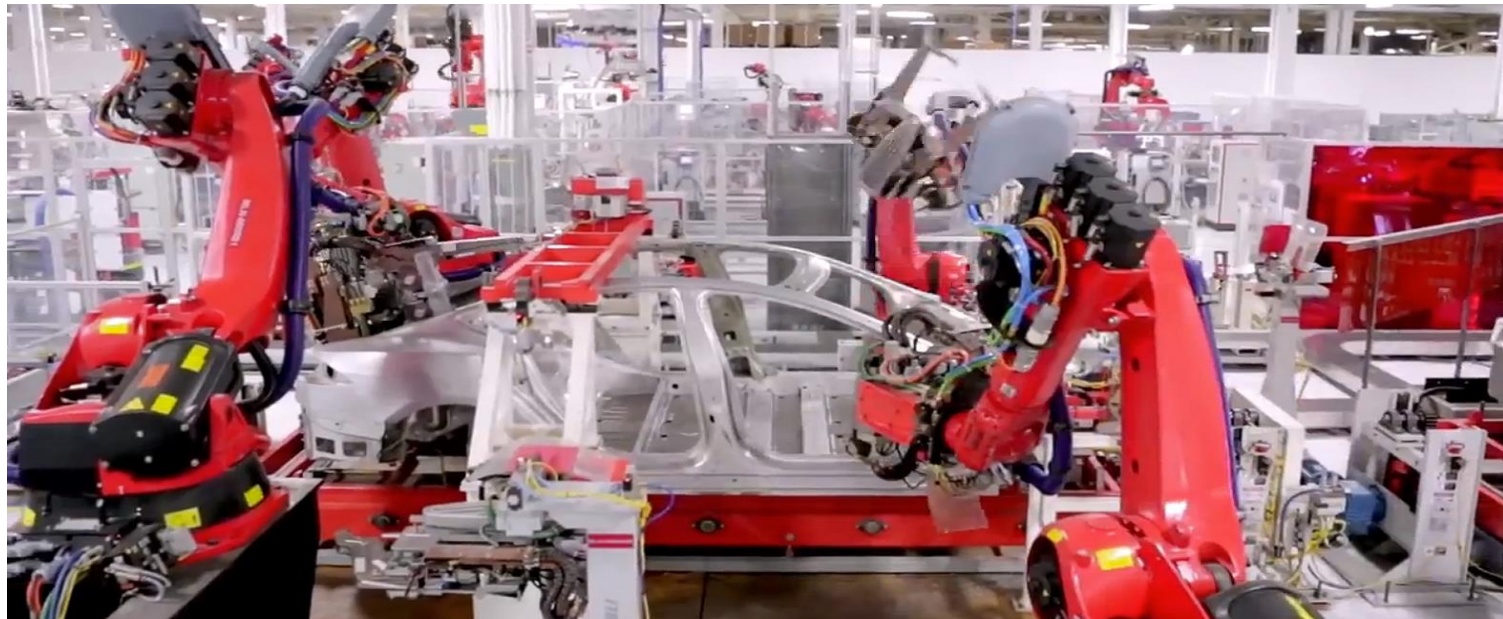
→ *Fully Automated Raw Material Extraction*

■ **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
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**

icct
THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION
www.theicct.org
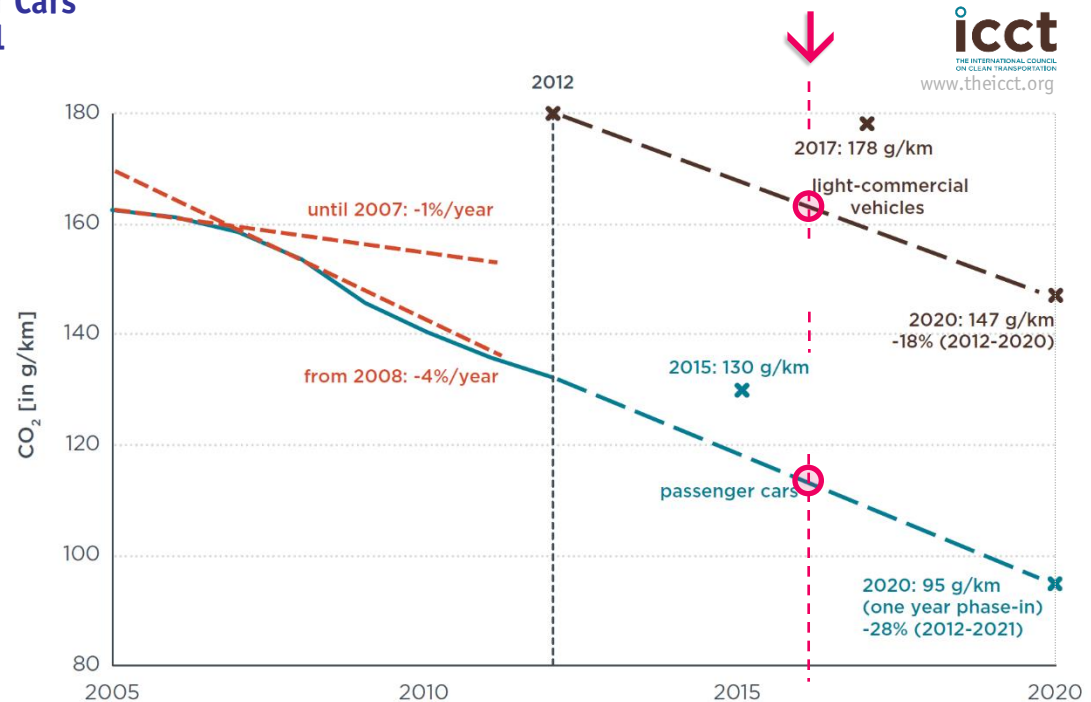
▶ **Hybrid Vehicles**
▶ **Electric Vehicles**

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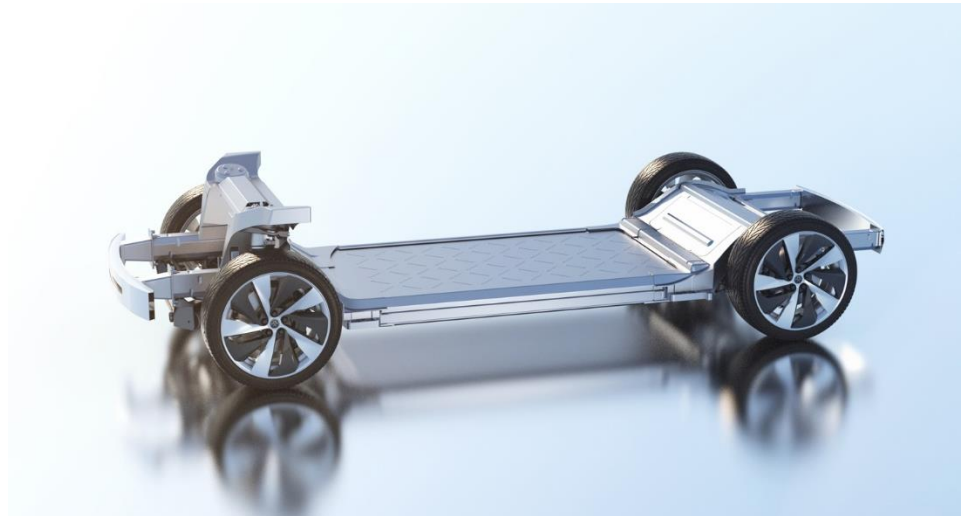
→ *Electric Vehicles* (1)

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

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

Faraday Future

FF-ZERO1
750kW / 322km/h
1 Motor per Wheel
Lithium-Ion Batteries along the Floor

Global

Share in PEV Sales

- Plug-In Hybrids
- Electric Vehicles

Power Electronic Systems
Laboratory
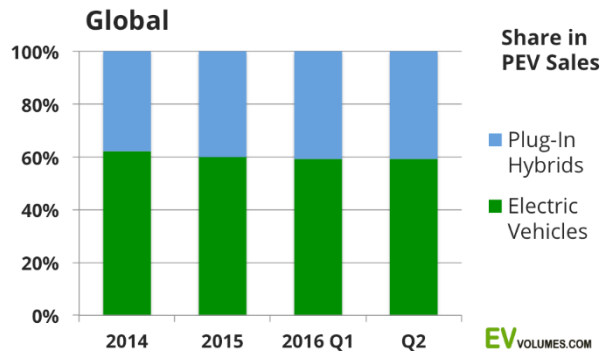
→ *Electric Vehicles* (2)

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

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

Source: PCIM 2013
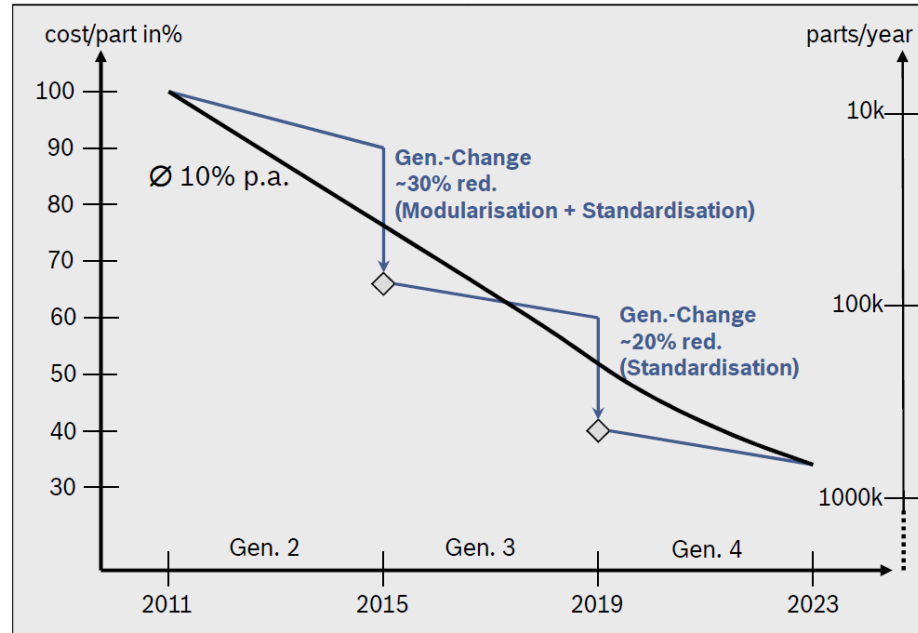
▶ **Typ. 10% / a Cost Reduction**
▶ **Economy of Scale !**

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→ *Futuristic Mobility Concepts* (1)

■ Enabled by Power Electronics

— **Hyperloop**
— **San Francisco → Los Angeles in 35min**

www.spacex.com/hyperloop
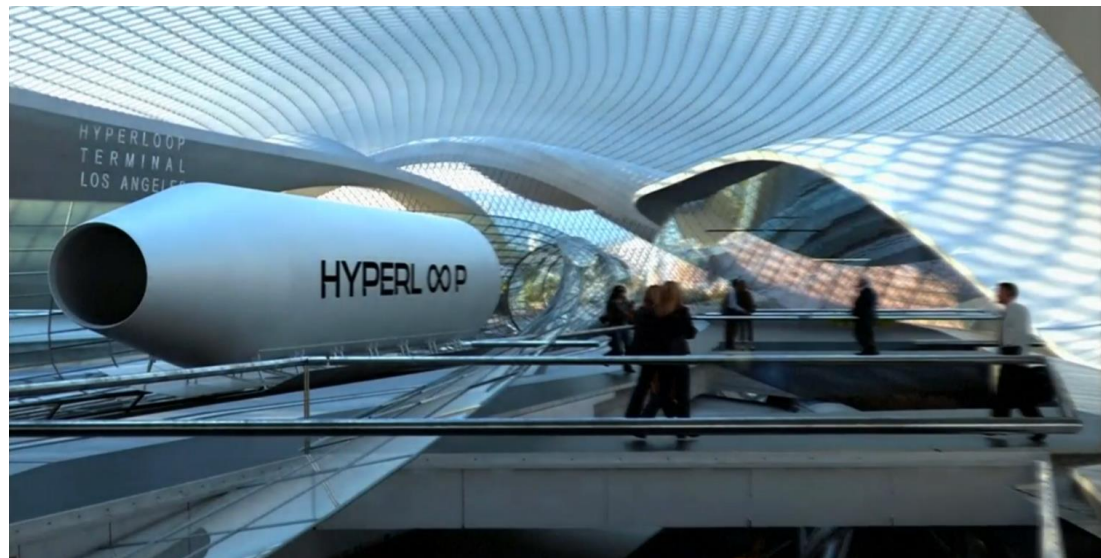
► **Low Pressure Tube**
► **Magnetic Levitation**
► **Linear Ind. Motor**
► **Air Compressor in Nose**

→ *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.**

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→ *Futuristic Mobility Concepts* (3)

■ **Enabled by Power Electronics**

Superconducting-motor-driven fans in a continuous nacelle

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

Wing-tip mounted superconducting turbogenerators

High-speed generator

HTS electrical bus

Fan-speed motors

Distributed fans

Power converter

Turboshaft engine

Cryo cooler(s)

Cryo cooling

Other applications

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

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**Global
Megatrends**

Climate Change
Digitalization
Sustainable Mobility
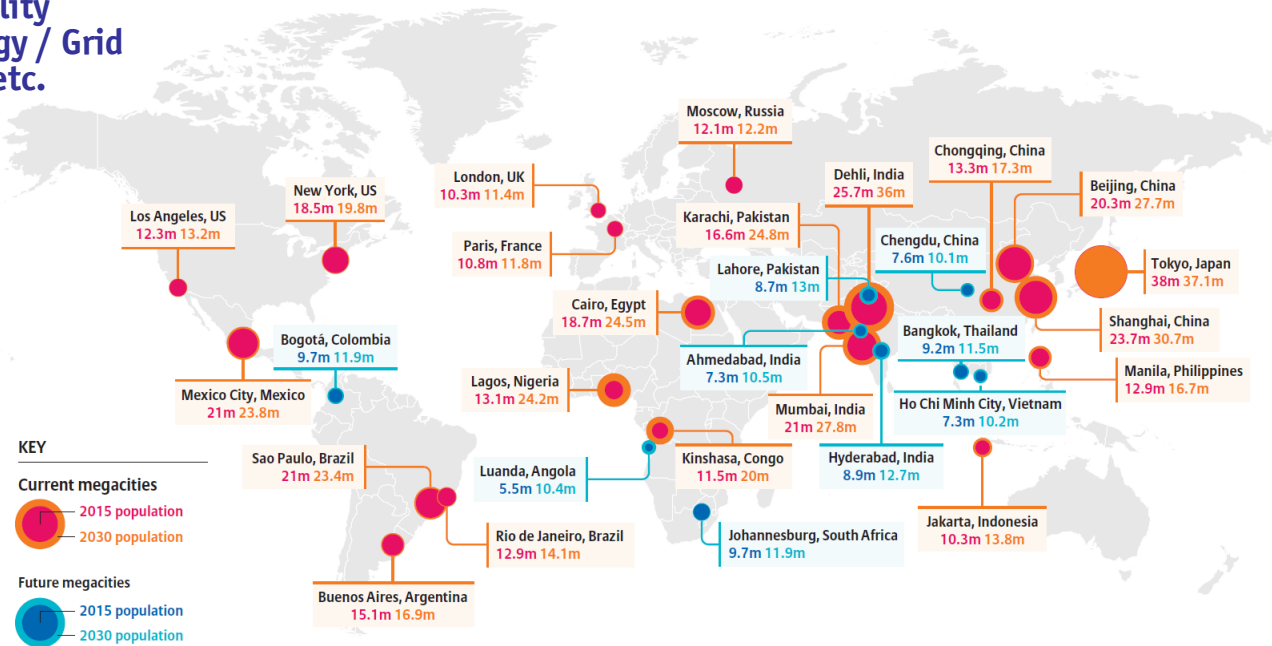**Urbanization** ⟶
Etc.

▶ 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

Moscow, Russia
12.1m 12.2m

New York, US
18.5m 19.8m

London, UK
10.3m 11.4m

Chongqing, China
13.3m 17.3m

Dehli, India
25.7m 36m

Beijing, China
20.3m 27.7m

Los Angeles, US
12.3m 13.2m

Paris, France
10.8m 11.8m

Karachi, Pakistan
16.6m 24.8m

Chengdu, China
7.6m 10.1m

Tokyo, Japan
38m 37.1m

Lahore, Pakistan
8.7m 13m

Cairo, Egypt
18.7m 24.5m

Bangkok, Thailand
9.2m 11.5m

Shanghai, China
23.7m 30.7m

Bogotá, Colombia
9.7m 11.9m

Ahmedabad, India
7.3m 10.5m

Manila, Philippines
12.9m 16.7m

Mexico City, Mexico
21m 23.8m

Lagos, Nigeria
13.1m 24.2m

Mumbai, India
21m 27.8m

Ho Chi Minh City, Vietnam
7.3m 10.2m

Hyderabad, India
8.9m 12.7m

KEY

Sao Paulo, Brazil
21m 23.4m

Luanda, Angola
5.5m 10.4m

Kinshasa, Congo
11.5m 20m

Jakarta, Indonesia
10.3m 13.8m

Current megacities

2015 population
2030 population

Rio de Janeiro, Brazil
12.9m 14.1m

Johannesburg, South Africa
9.7m 11.9m

Future megacities

2015 population
2030 population

Buenos Aires, Argentina
15.1m 16.9m

▶ **Selected Current & Future MEGA Cities 2015 → 2030**
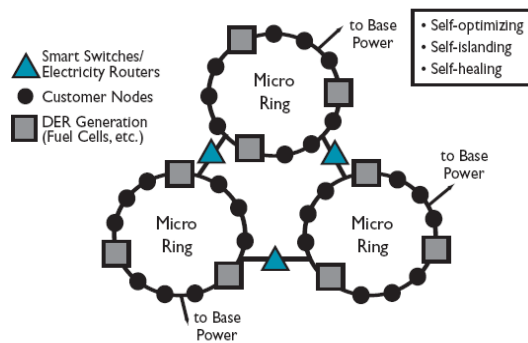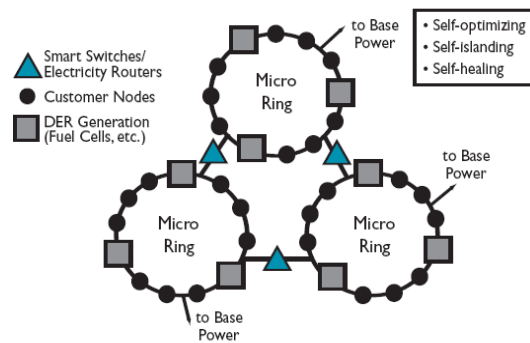
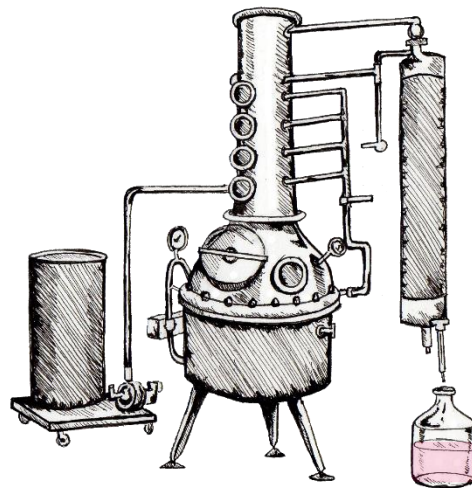ETH zürich

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→ *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 Switches/Electricity Routers
● Customer Nodes
■ DER Generation (Fuel Cells, etc.)

Micro Ring

Micro Ring

Micro Ring

to Base Power

to Base Power

to Base Power

• Self-optimizing
• Self-islanding
• Self-healing

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→ *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

▲ Smart Switches/
  Electricity Routers
● Customer Nodes
▢ DER Generation
  (Fuel Cells, etc.)

to Base Power
• Self-optimizing
• Self-islanding
• Self-healing

Micro Ring

Micro Ring   Micro Ring

to Base Power

to Base Power

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Source: whiskeybehavior.info

... in **Summary**

Power Electronic Systems
Laboratory

► Current / New Application Areas (2)

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

MV / MF Power Electronics

Smart Microgrids, DC Distribution

100 kW

Standard / Integrated Solutions

10 W

System Applications

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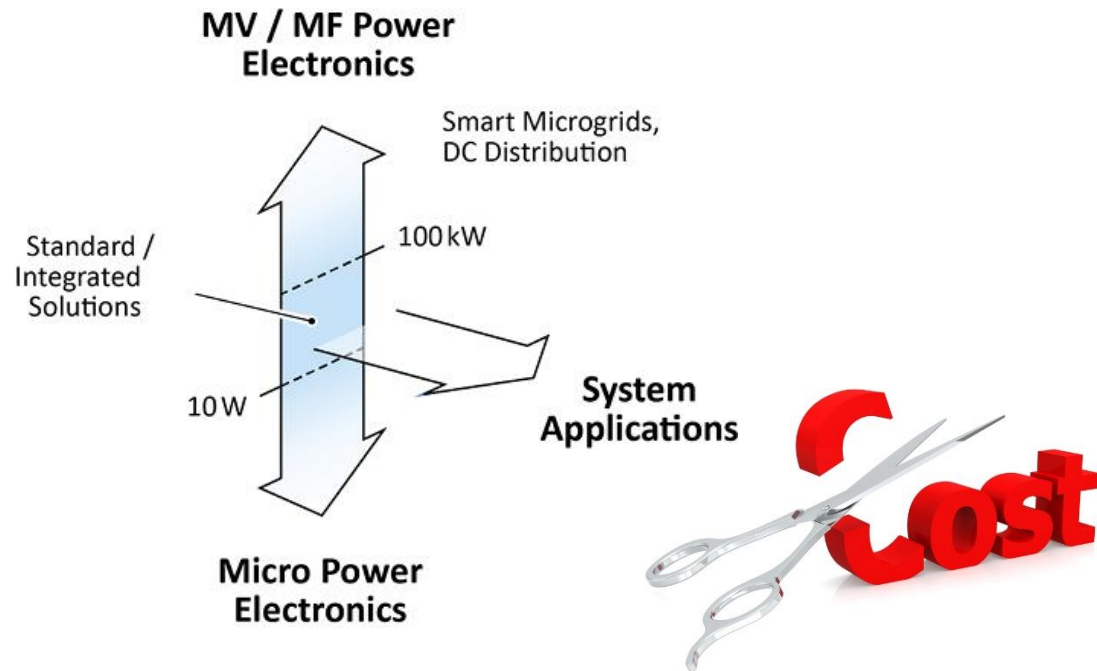
► **Cost Pressure as Common Denominator of All Applications (!)**
► **Key Importance of Technology Partnerships of Academia & Industry**

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► Future "Big-Bang" Disruptions

- ■ **"Catastrophic" Success of Disruptive New (Digital) Technologies**
- ■ **No Bell-Curve Technology Adoption / Technology S-Curve**
- ■ **"Shark Fin"-Model**
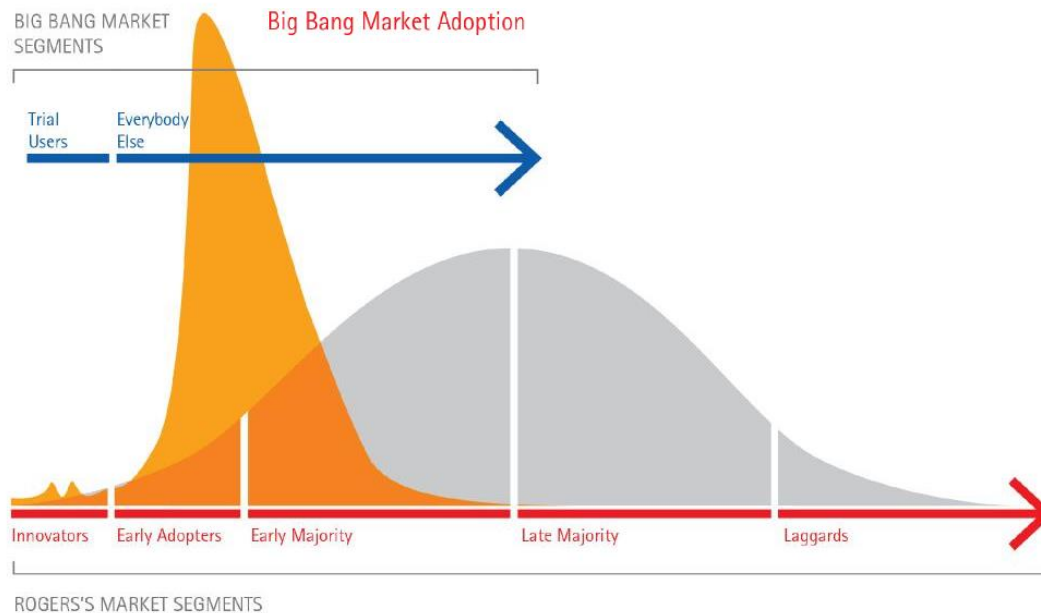
Source: www.verschuerent.wordpress.com
February 2015

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

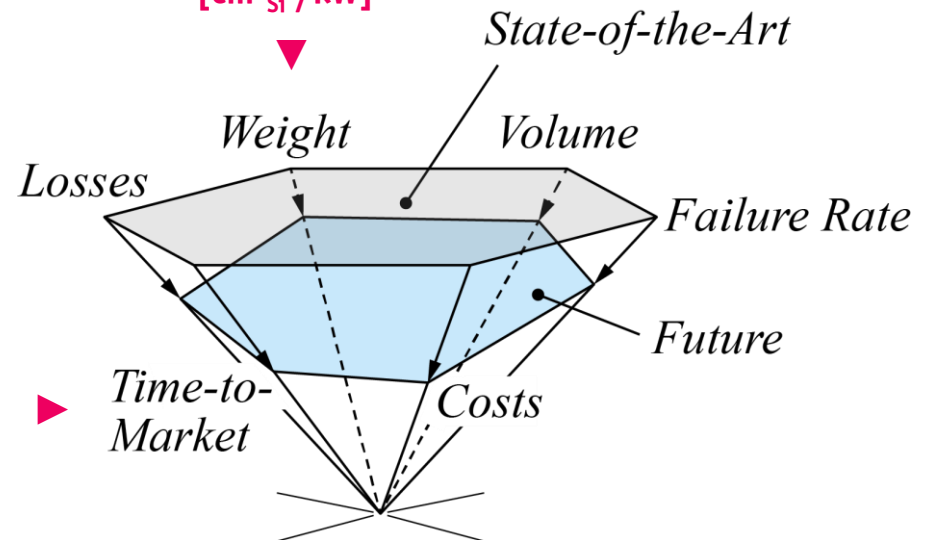► **Consequence: Market Immediately & Be Ready to Scale Up — and Exit — Swiftly (!)**

► **Required Power Electronics Performance Improvements**

Environmental Impact... [kg_{Fe} /kW]
[kg_{Cu} /kW]
[kg_{Al} /kW]
[cm²_{Si} /kW]

■ **Performance Indices**

— **Power Density** [kW/dm³]
— **Power per Unit Weight** [kW/kg]
— **Relative Costs** [kW/$]
— **Relative Losses** [%]
— **Failure Rate** [h⁻¹]

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► **Multi-Objective Design Challenge**

■ **Counteracting Effects of Key Design Parameters**
■ **Mutual Coupling of Performance Indices → Trade-Offs**
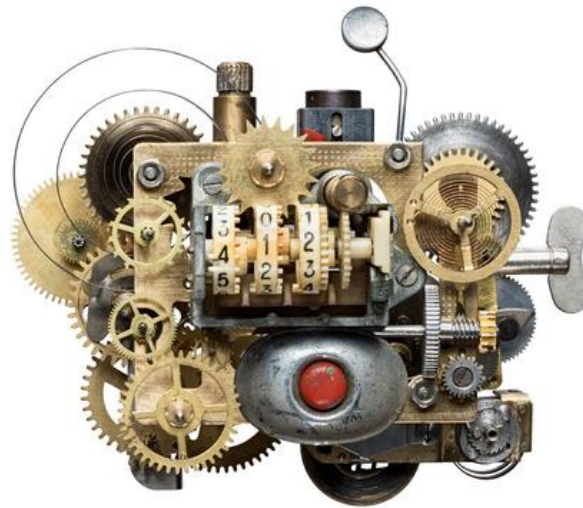
→ **Large Number of Degrees of Freedom / Multi-Dimensional Design Space**
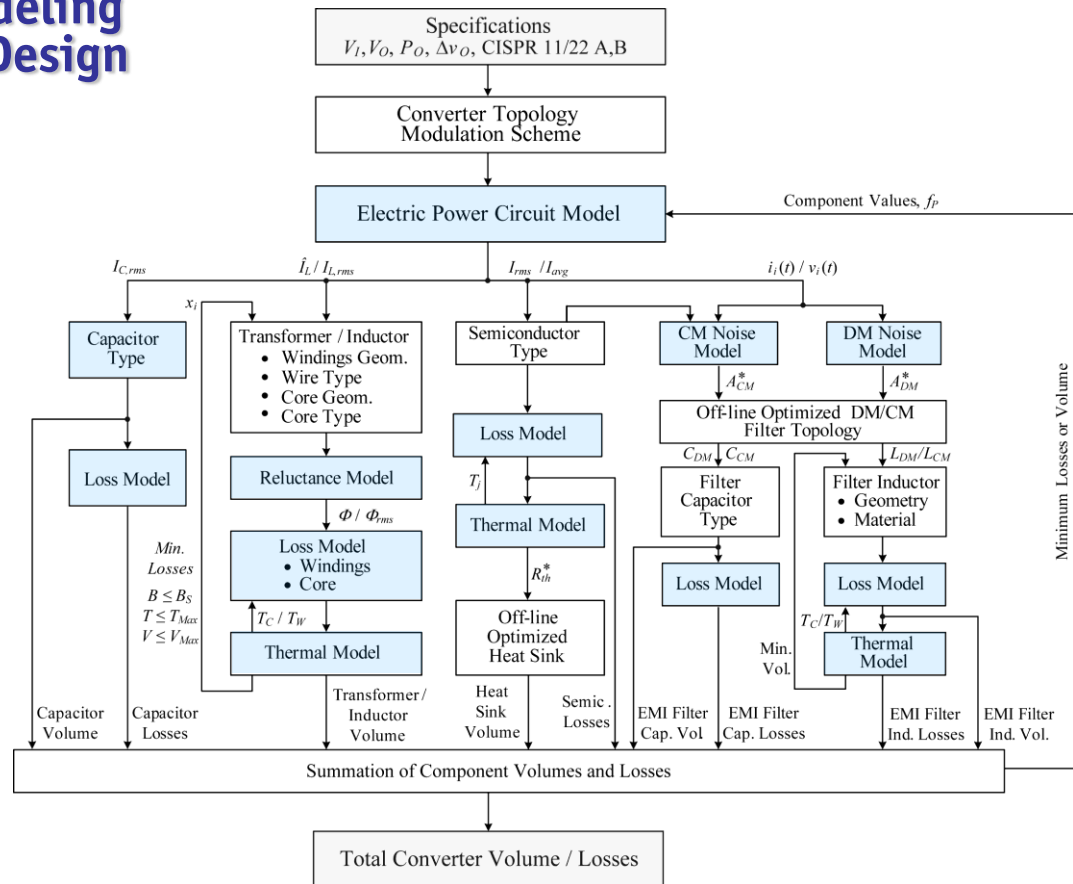→ **Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization**

Power Electronic Systems Laboratory

Multi-Objective Optimization

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

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▶ Abstraction of Power Converter Design

Performance Space
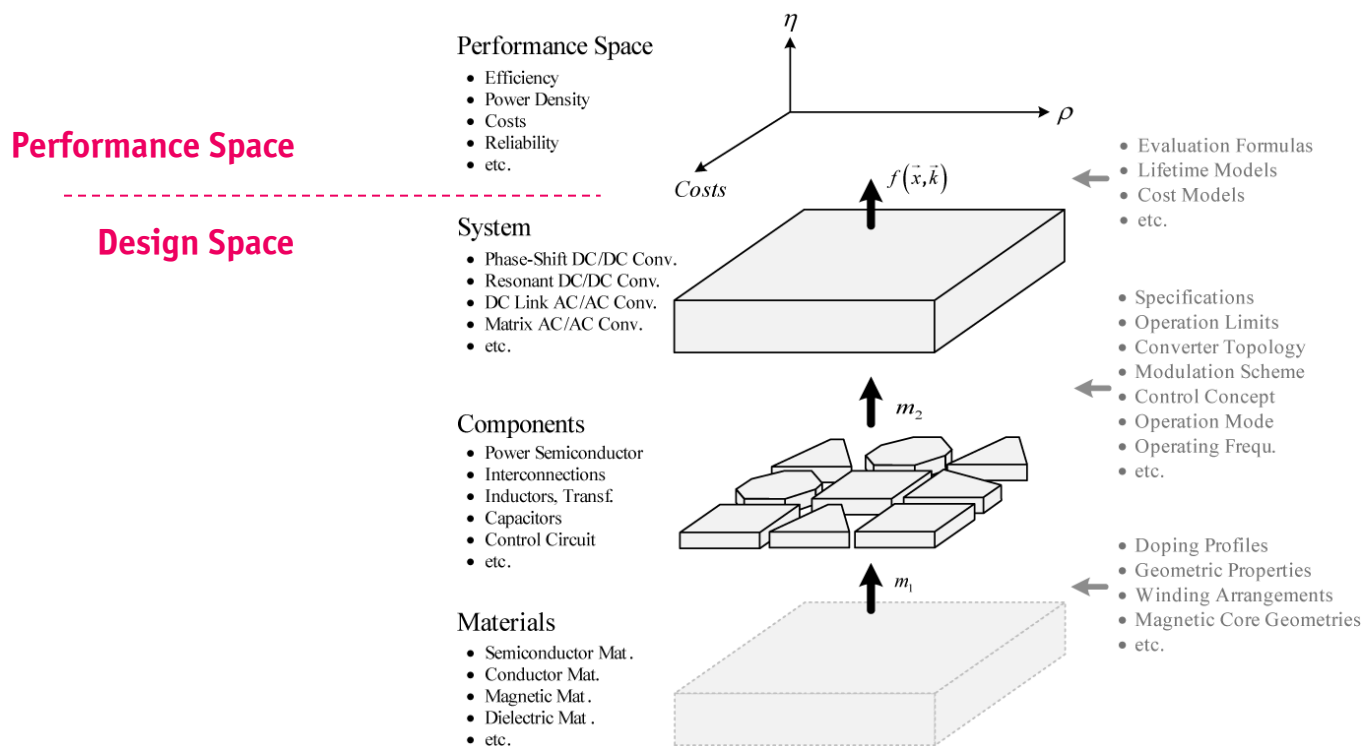
Design Space

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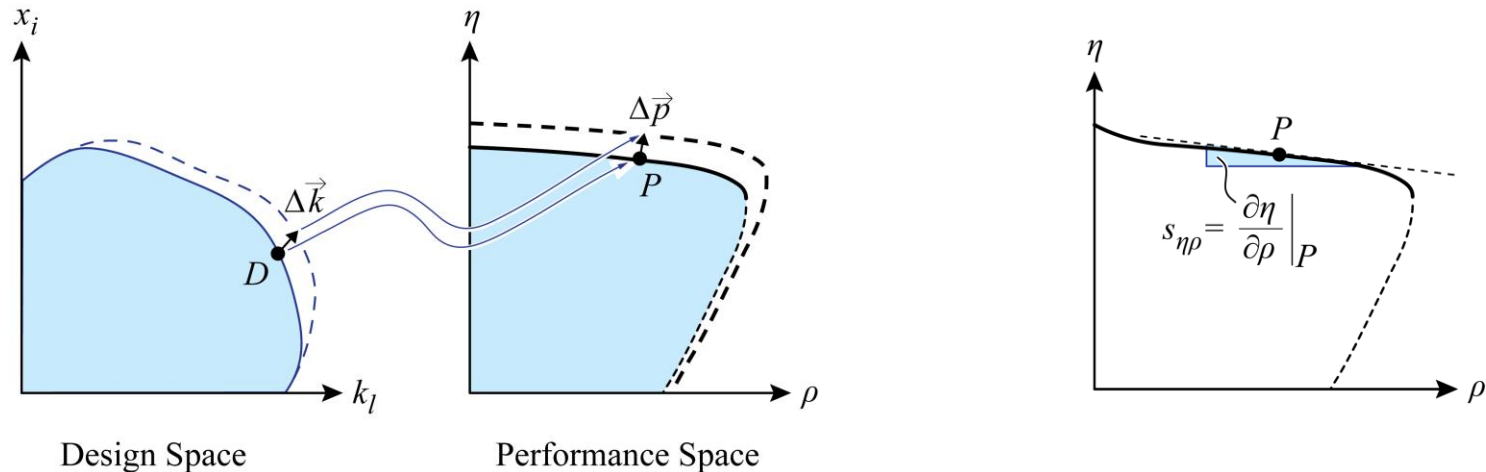
→ Clarifies Sensitivity $\Delta\vec{p} / \Delta\vec{k}$ to Improvements of Technologies
→ Trade-off Analysis

▶ Determination of the η-ρ-Pareto Front (a)
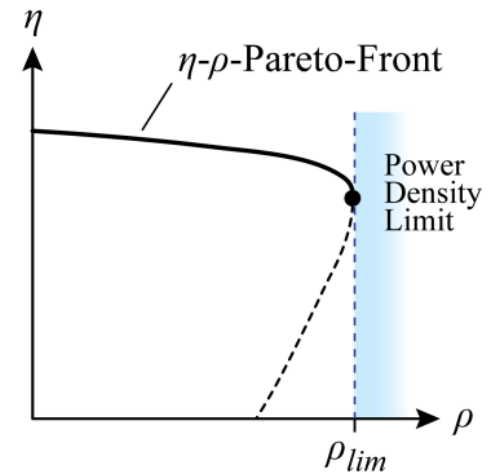
■ **Comp.-Level Degrees of Freedom of the Design**

— **Core Geometry / Material**
— **Single / Multiple Airgaps**
— **Solid / Litz Wire, Foils**
— **Winding Topology**
— **Natural / Forced Conv. Cooling**
— **Hard-/Soft-Switching**
— **Si / SiC**
— **etc.**
— **etc.**
— **etc.**
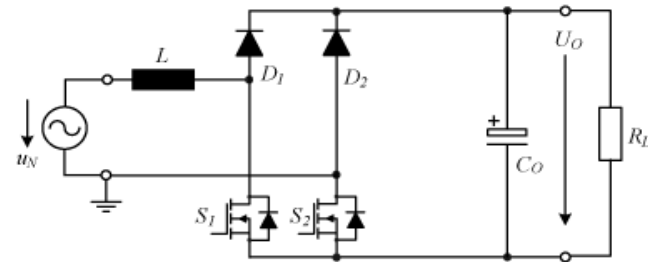
■ **System-Level Degrees of Freedom**

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

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

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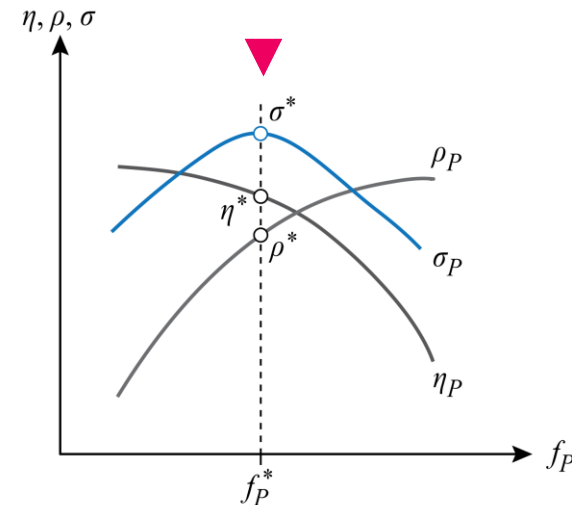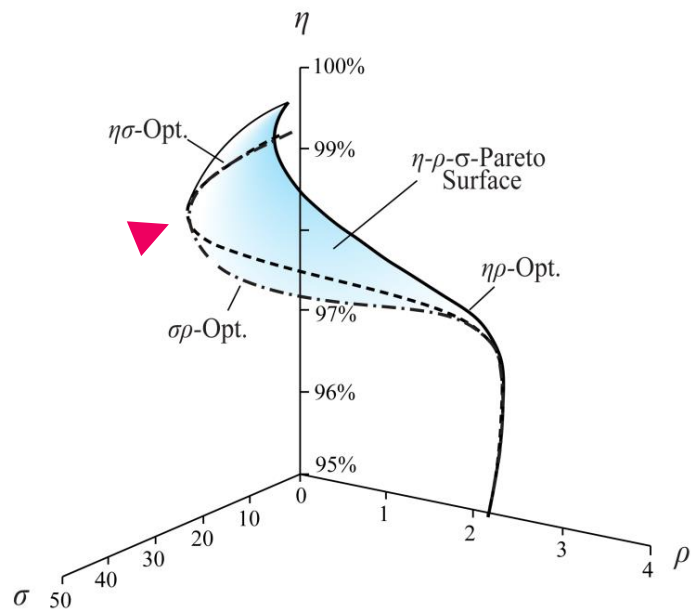# ► Determination of the η-ρ-Pareto Front (b)

■ **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

► Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface
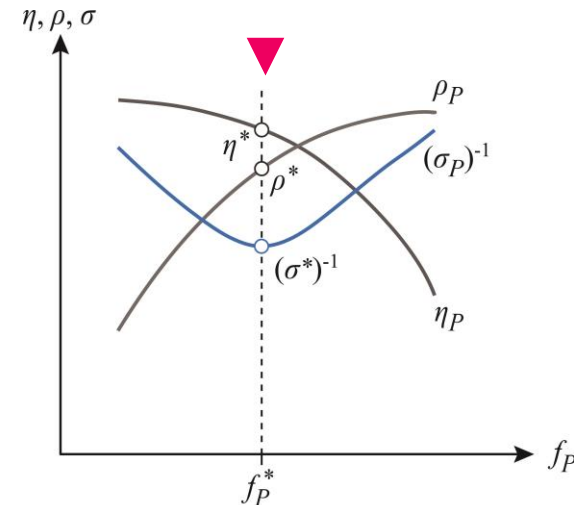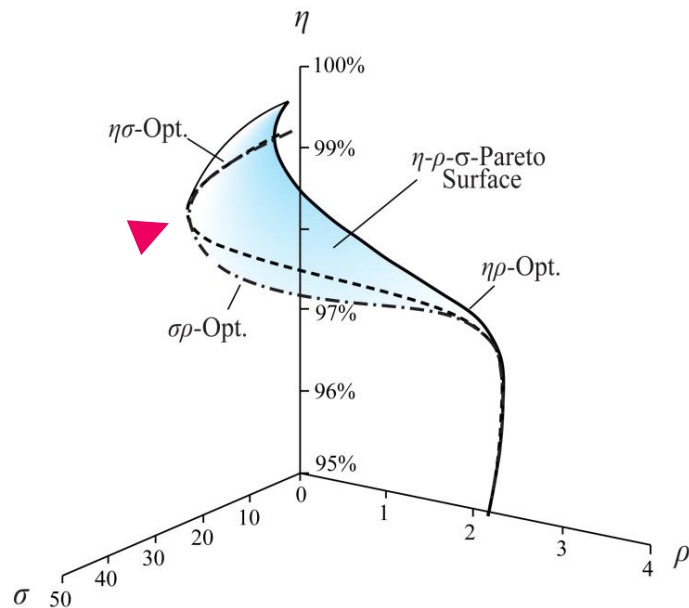
- **Definition of a Power Electronics *"Technology Node"* → ($\eta^*,\rho^*,\sigma^*,f_P^*$)**
- **Maximum σ [kW/\$], Related Efficiency & Power Density**

→ **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)**

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▶ 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 (!)**
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► 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**

>2015: Smaller Transistors but Not any more Cheaper
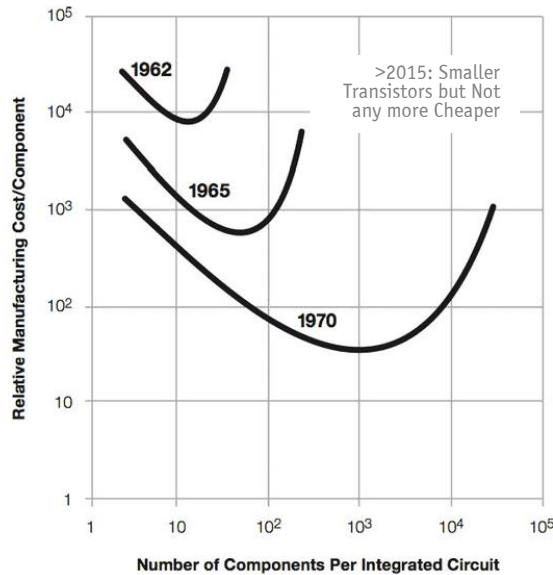
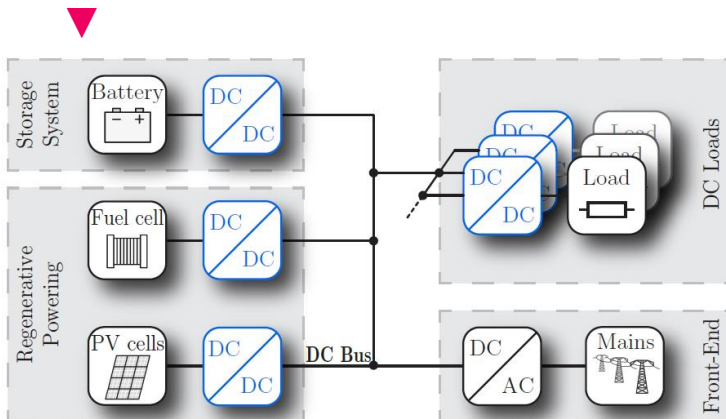Gordon Moore: The Future of Integrated Electronics, 1965 (Consideration of Three Consecutive Technology Nodes)
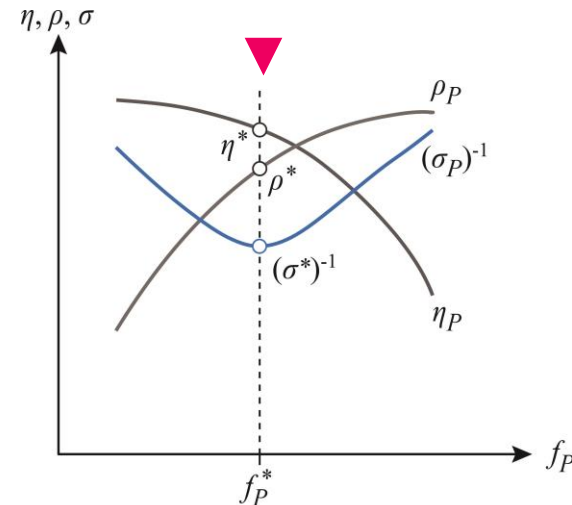
→ Definition of "$\eta^*,\rho^*,\sigma^*,f_P^*$–Node" Must Consider Conv. Type / Operating Range etc. (!)

Multi-Objective Optimization Application Example
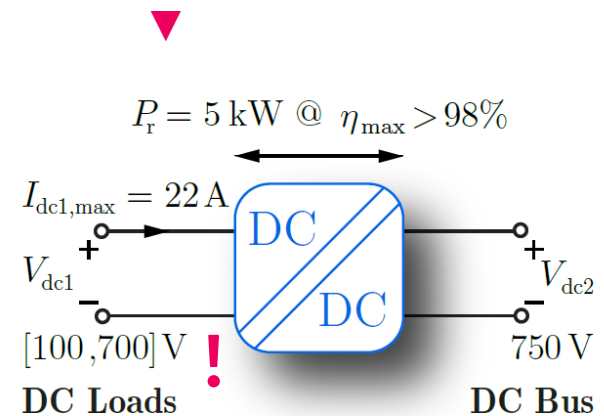
Comparative Converter Evaluation

▶ Wide Input Voltage Range Isolated DC/DC Converter

Structure of "Smart Home" DC Microgrid
▼

Universal DC/DC Converter
▼

$$P_r = 5\,\text{kW} \ @ \ \eta_{\text{max}} > 98\%$$

$$I_{\text{dc1,max}} = 22\,\text{A}$$

V_{dc1} V_{dc2}

$[100,700]\,\text{V}$ $750\,\text{V}$

DC Loads   **DC Bus**

■ **Universal Isolated DC/DC Converter**

— **Bidirectional Power Flow**
— **Galvanic Isolation**
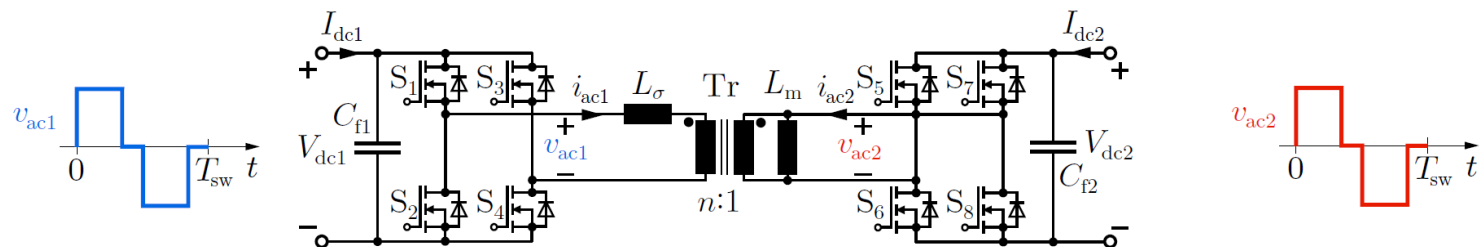— **Wide Voltage Range**
— **High Partial Load Efficiency**

■ **Advantages**

— **Reduced System Complexity**
— **Lower Overall Development Costs**
— **Economy of Scale**

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pels

▶ Comparative Evaluation of Converter Topologies

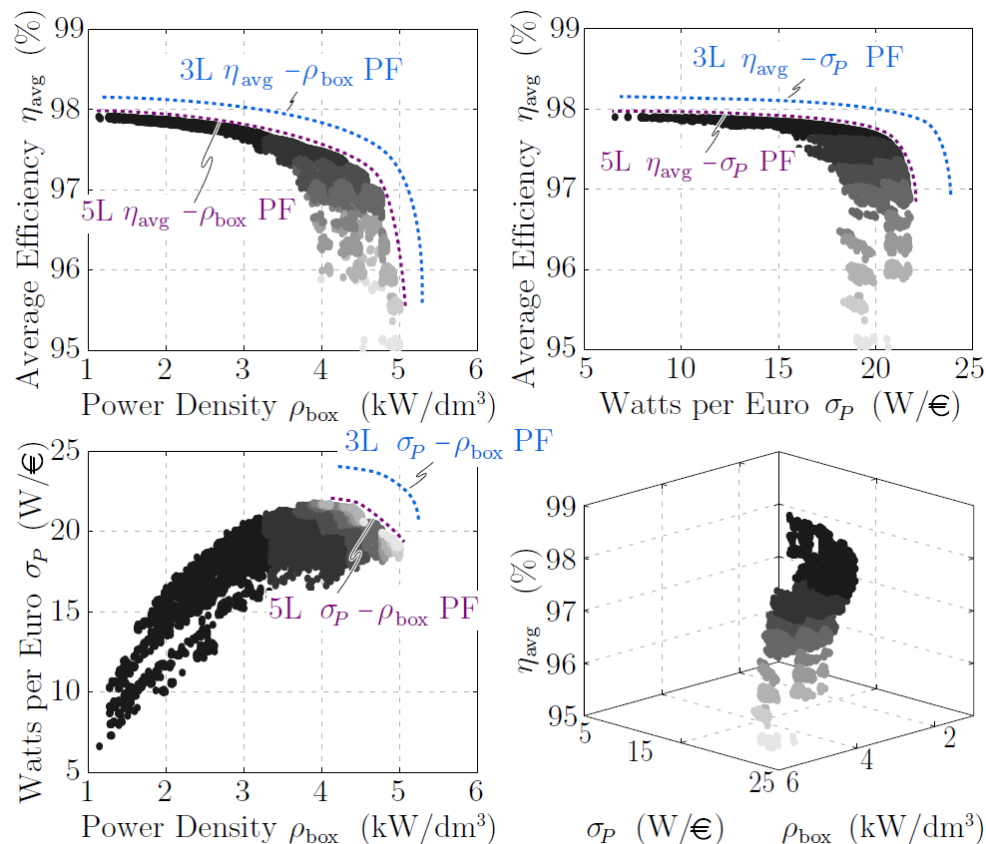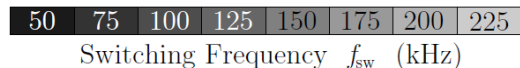■ **Conv. 3-Level Dual Active Bridge (3L-DAB)**

■ **Advanced 5-Level Dual Active Bridge (5L-DAB)**
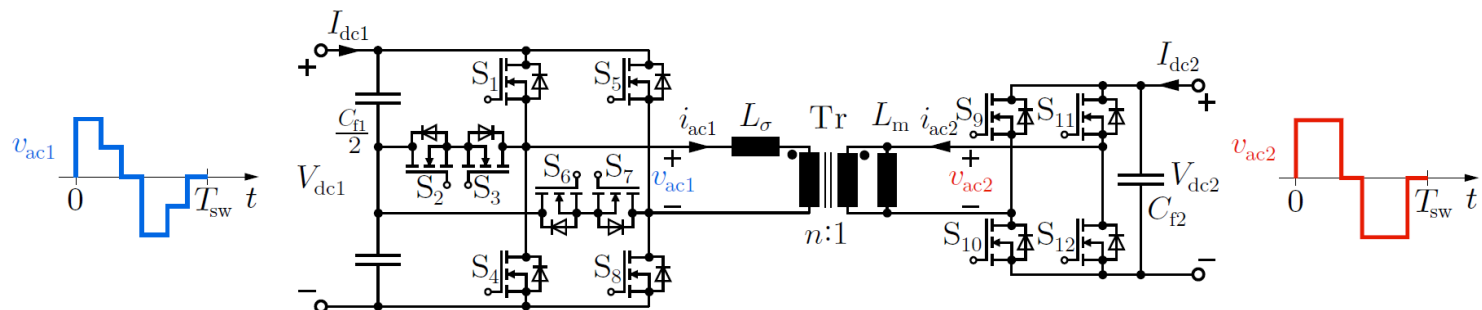
► Optimization Results - Pareto Surfaces
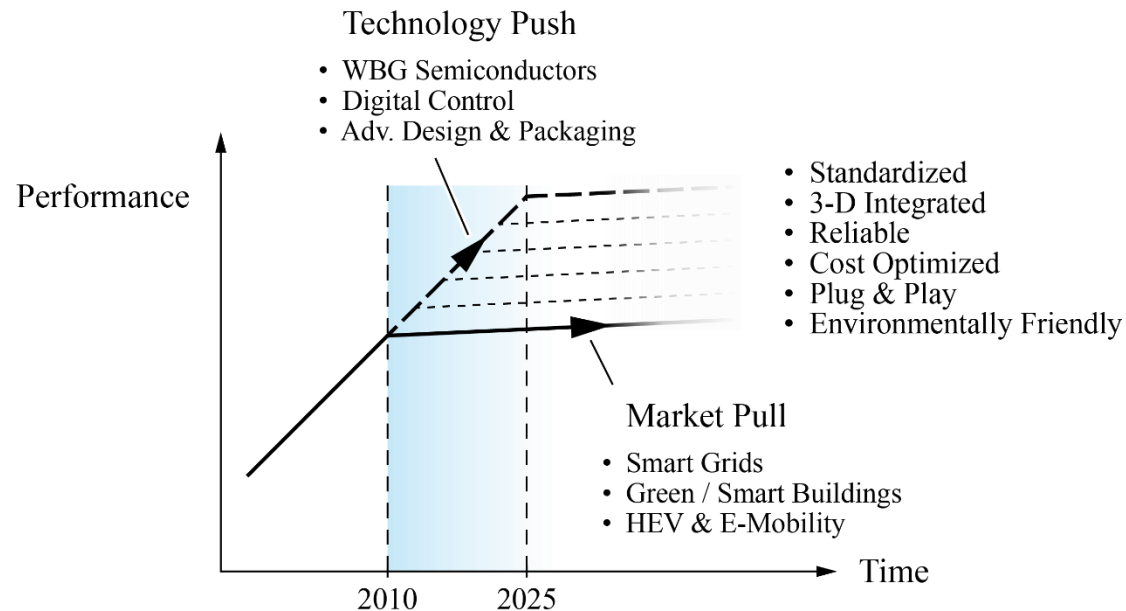
- 3-Level Dual Active Bridge
- 5-Level Dual Active Bridge

| 50 | 75 | 100 | 125 | 150 | 175 | 200 | 225 |

Switching Frequency f_{sw} (kHz)

Conclusions

Future Power Electronics Development
"Stairway to Heaven"

▶ Future Development

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

Technology Push
• WBG Semiconductors
• Digital Control
• Adv. Design & Packaging

Performance

• Standardized
• 3-D Integrated
• Reliable
• Cost Optimized
• Plug & Play
• Environmentally Friendly

Market Pull
• Smart Grids
• Green / Smart Buildings
• HEV & E-Mobility

Time

2010   2025

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

► **Extrapolation of Technology S-Curve**

■ **"Stairway to Heaven"**

"Passives"
Adv. Packaging
η-ρ-σ-Design of Converters & "Systems"
Interdisciplinarity

!

► **Super-Junct. Techn. / WBG**
► **Digital Power**
Modeling & Simulation

► **Power MOSFETs & IGBTs**
► **Microelectronics**
Circuit Topologies
Modulation Concepts
Control Concepts

SCRs / Diodes
Solid-State Devices

Performance

Replacement
(Disruptive)
Technology

Emerging

Established

Mature

I

II

III

Existing
Technology

Effort / Time

★
2015

2025

ETH *zürich*

■ **Thank You!**