ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Performance Trends and Limitations of Electronic EEnergy Processing Systems

J. W. Kolar

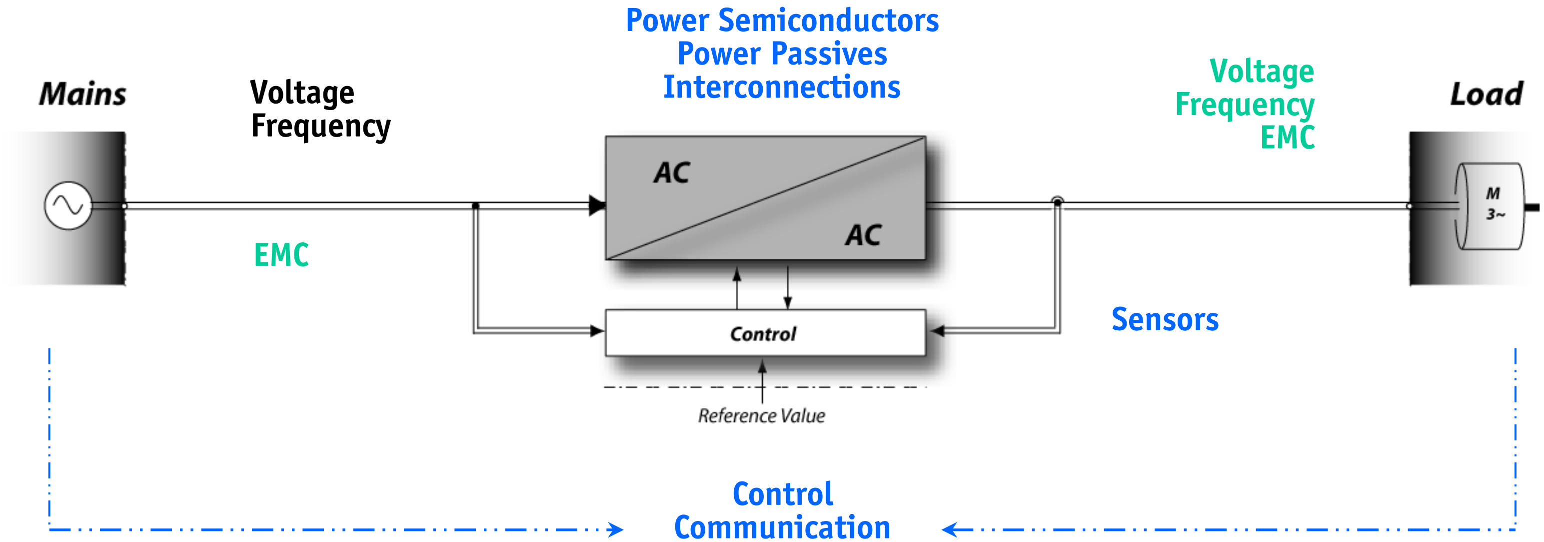
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Basic Structure of Electronic *Power* Processing Systems

Power Electronics Systems

Basic Electronic Power Processing System

Highest Efficiency
Highest Dynamics
Highest Compactness
Highest Compatibility
Highest Reliability



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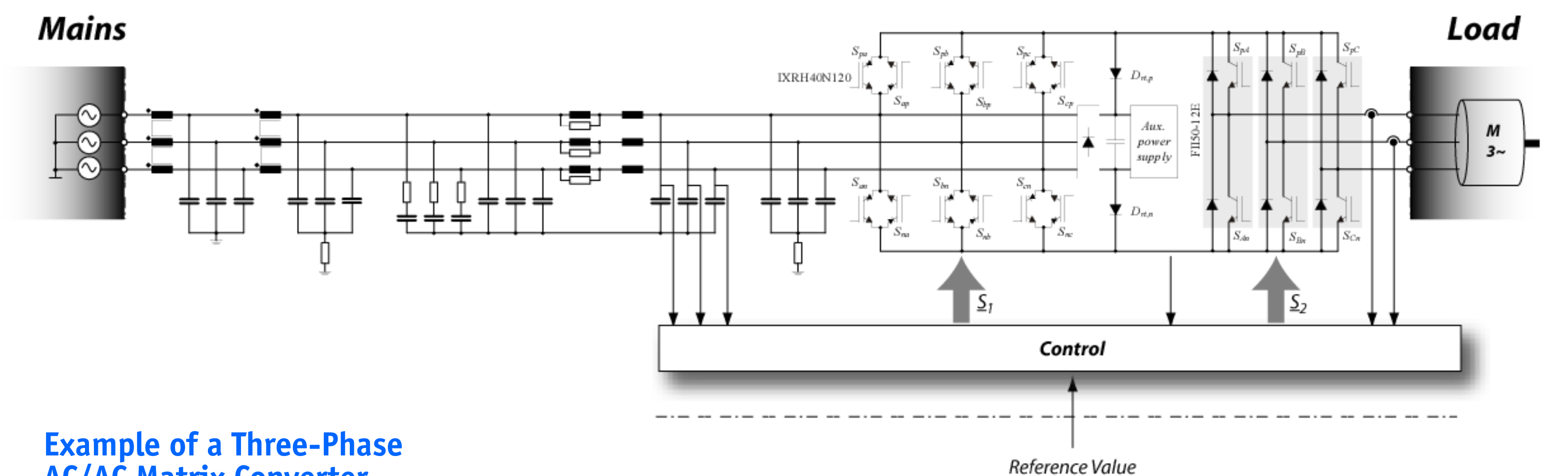


Example of a Three-Phase AC/AC Matrix Converter

Outline

- ETH Zurich
- Power Electronic Systems Laboratory (PES)

- Future Importance of EEnergy / Power Electronics (PE)
- Inspiring Concepts of Future Renewable Energy Systems
- ETH MEGA Cube Project
- General Applications of PE / Efficiency Challenge
- Pareto-Optimal PE Converter Design Approach

- Potential Future Extensions of PE Applications Areas
- Summary

Zurich Profile

ETHZ Zurich	14’500 Students
University of Zurich	20’000 Students
8 Univ. of Appl. Science	7’000 Students

1 Lake
2 Rivers
1’100 Fresh H_2O Fount.
1’946 Rest. & Bars
57 Museums
32 Theaters
2 Soccer Clubs
10 Min. to Airport
100km to Snowy Alps

Zurich 370’000
Aggl. 1’102’000

21	Nobel Prizes
350	Professors
3600	T&R Staff
2	Campuses
136	Labs
21%	Int. Students
90	Nationalities
36	Languages
150th	Anniv. in 2005

Departments of ETH Zurich

AGRL	Agriculture and Food Sciences
ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
INFK	Computer Science
ITET	Information Technology and Electrical Eng.
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
UWIS	Environmental Sciences

Students ETH in total

11'300	Diploma-Students
3'200	Doctoral Students

Power Electronics Systems Laboratory

Organization
Spin-off Network

D-ITET Power Electronic Systems Laboratory

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter
M. Hartmann
Ch. Marxgut

AC-AC Converter
T. Friedli
M. Schweizer

DC-DC Converter
D. Aggeler
U. Badstübner
F. Krismer
G. Ortiz
H. Plesko
St. Waffler
C. Zhao

DC-AC Converter
D. Bortis
Y. Lobsiger
B. Wrzecionko

Pulsed Power
J. Mühlethaler
T. Soeiro

Multi-Domain Modeling
U. Drofenik
F. Giezendanner
I. Kovacevic
A. Müsing
A. Stupar

Mega-Speed Drives
T. Baumgartner
P. Imoberdorf
D. Krähenbühl
A. Looser
A. Tüysüz

Magnetic Levitation
Ph. Karutz
T. Reichert
B. Warberger
F. Zürcher

Secretariat
M. Kohn

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

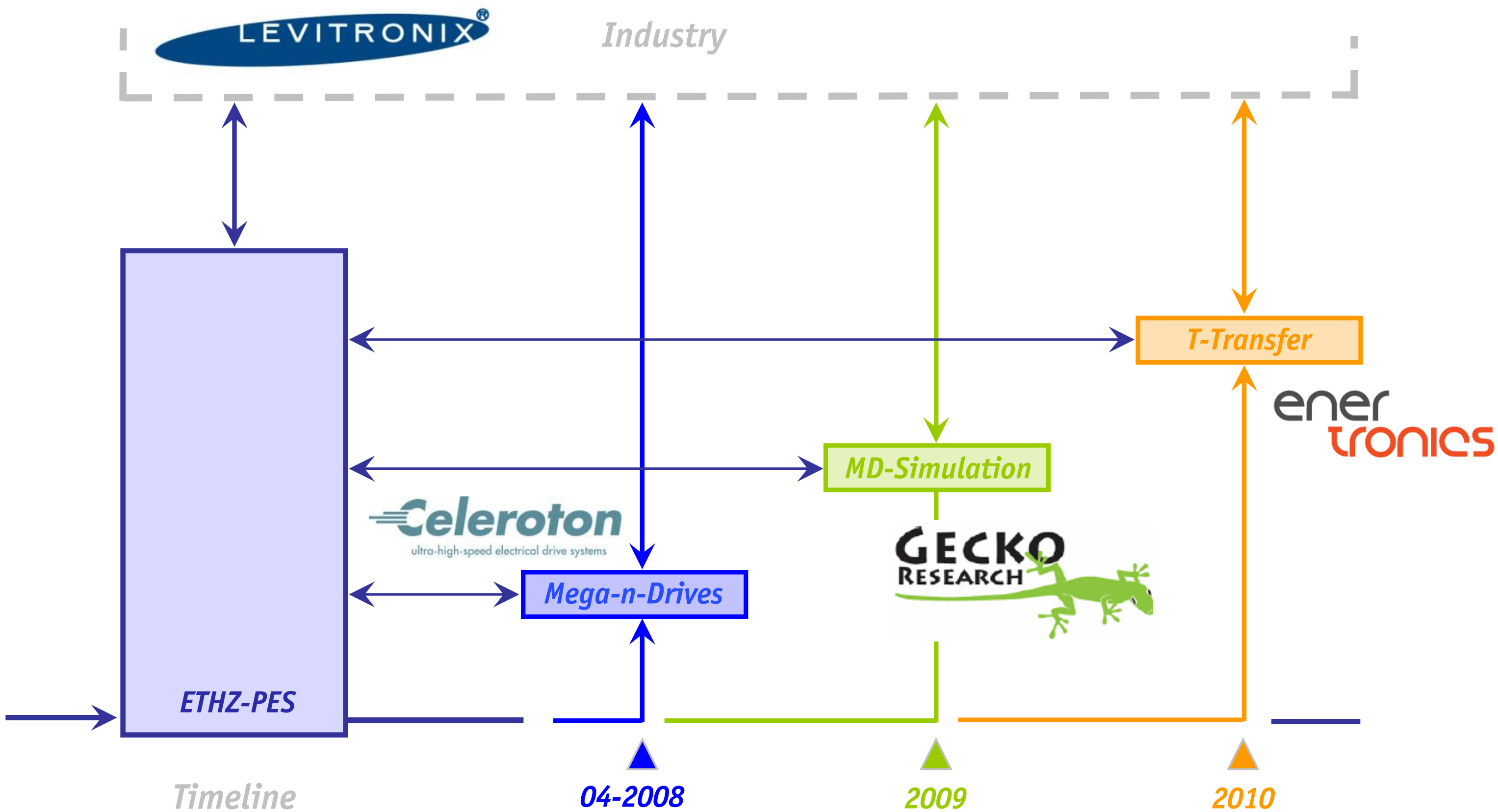
Electronics Laboratory
P. Seitz

28 Ph.D. Students
2 Post Docs

Competence Centre

Leading Univ. in Europe

PES Spin-Off Network



PES Selected Research Results

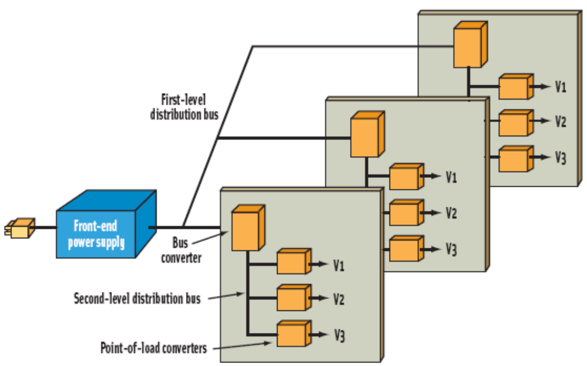
Ultra Compact Systems
Ultra Efficient Systems
Ultra High Speed Systems

Deep Green IT Power Supplies

Supercomputing
Targets 95% Efficiency
from 3-Φ Mains Input to
POL Converter Output

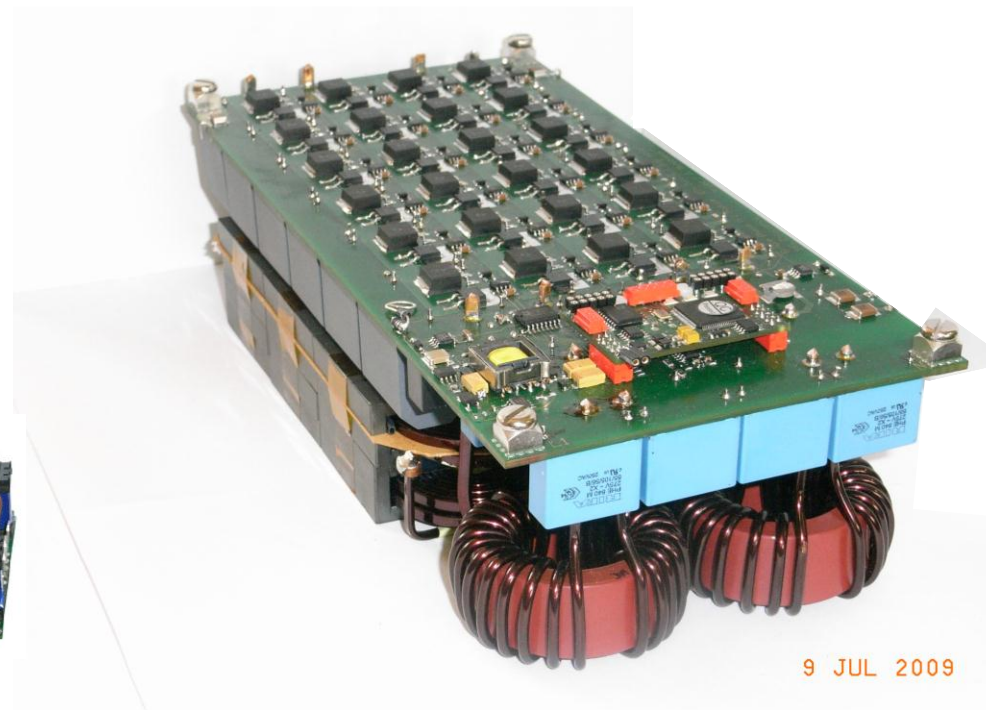
164TWh/year
(110 Mio Tons of CO_2)
Global Telecom
Industry Energy
Consumption

Communications Power Systems 12-V Intermediate Bus Architecture



Single-Phase PFC Rectifier

★ 99.2% @ 1.1 kW/dm^3



★ 5.5 kW/dm^3 @ 95.8%

Solar Impulse

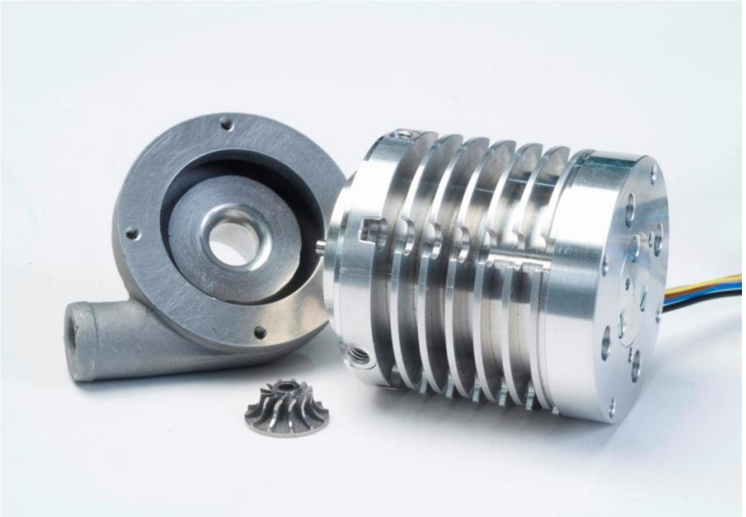
Attempt to Fly a Solar-Powered Airplane Around the World

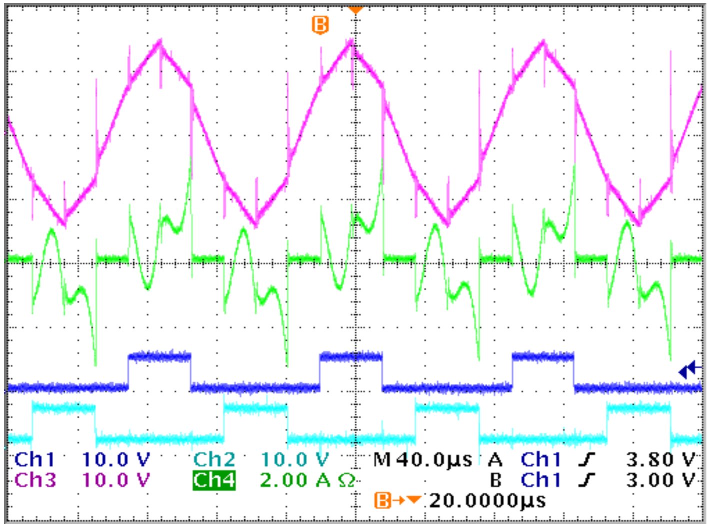
▶ Requires Cabin Air Pressurization

Solar Impulse
European Space Agency /
B. Piccard

Turbocompressor Prototype

- Operated up to 550'000 rpm
- Rotor and Bearing Cooling by Leakage Airflow
- Maximum Winding Temperature 80 °C



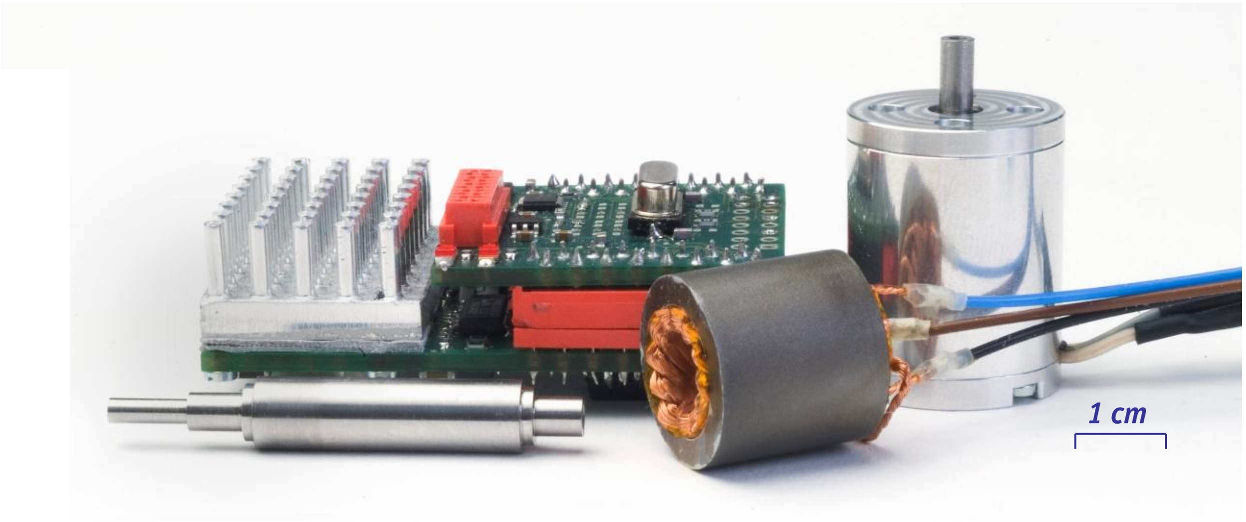


Ultra High Speed Drive Systems

- 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

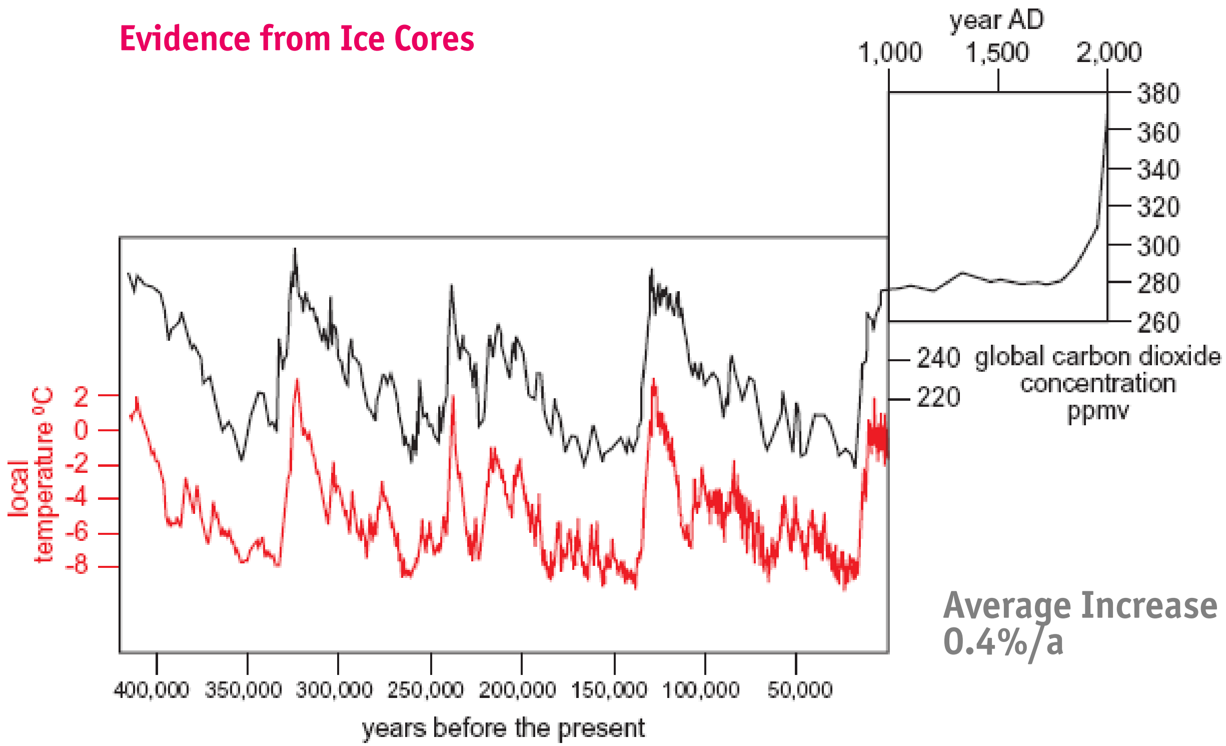


Future Importance of EEnergy / Electronic EEnergy Processing

Energy Technology Roadmaps
Increasing EEnergy Demand

Carbon Dioxide Concentration and Temperature Devlopment

Evidence from Ice Cores



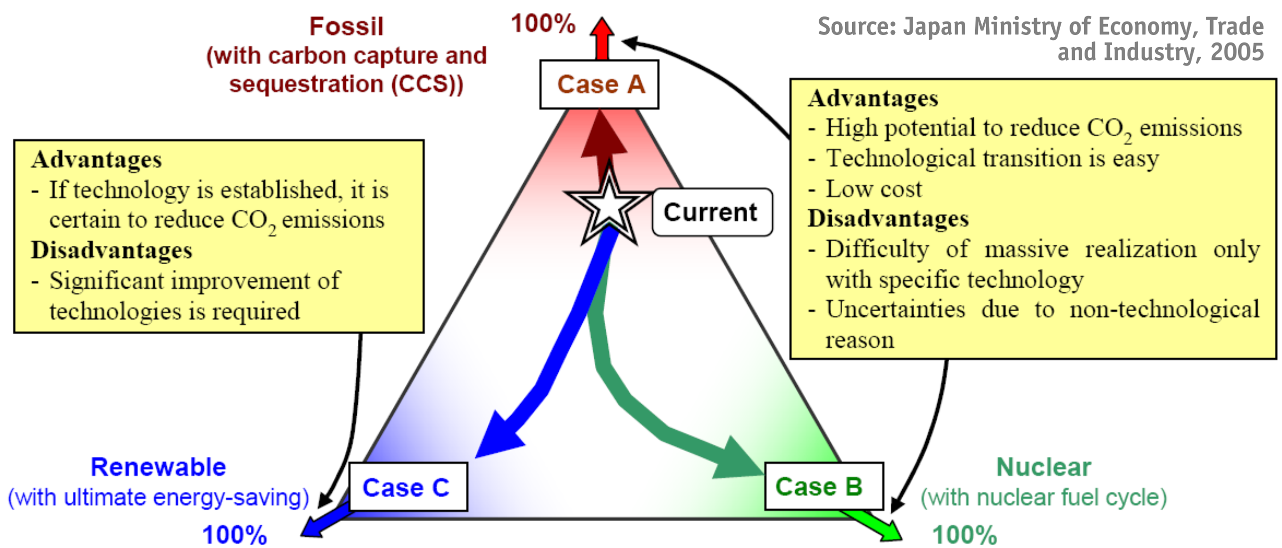
Average Increase 0.4%/a

New Policies - Doing More with *Much* Less !

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)

Japan Energy Technology Vision 2100

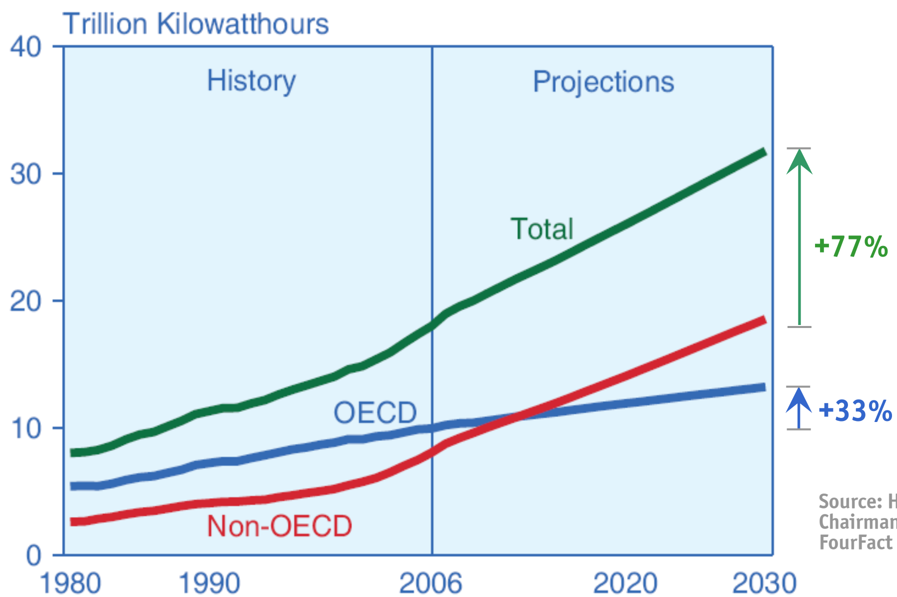


Images of the three cases of primary energy supply structures

100% Share of Electr. and/or Hydrogen in Res./Comm., Transport
70% Reduction of Energy Required in Industry

► Strategic Technology Roadmaps of Energy Sector Developed by Backcasting Starting with Assumed Resource and Environmental Constraints

World Net Electric Power Generation 1980 - 2030

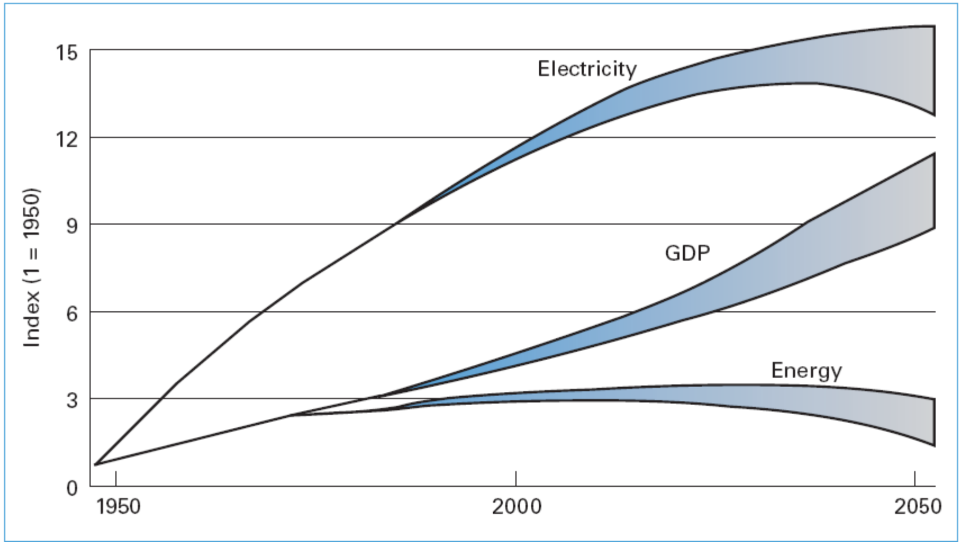


Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2006* (June-December 2008), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2009).

Source: H. Nilsson
Chairman IEA DSM Program
FourFact AB

US EPRI Electricity
Technology Roadmap

Source: EPRI, US, 2003



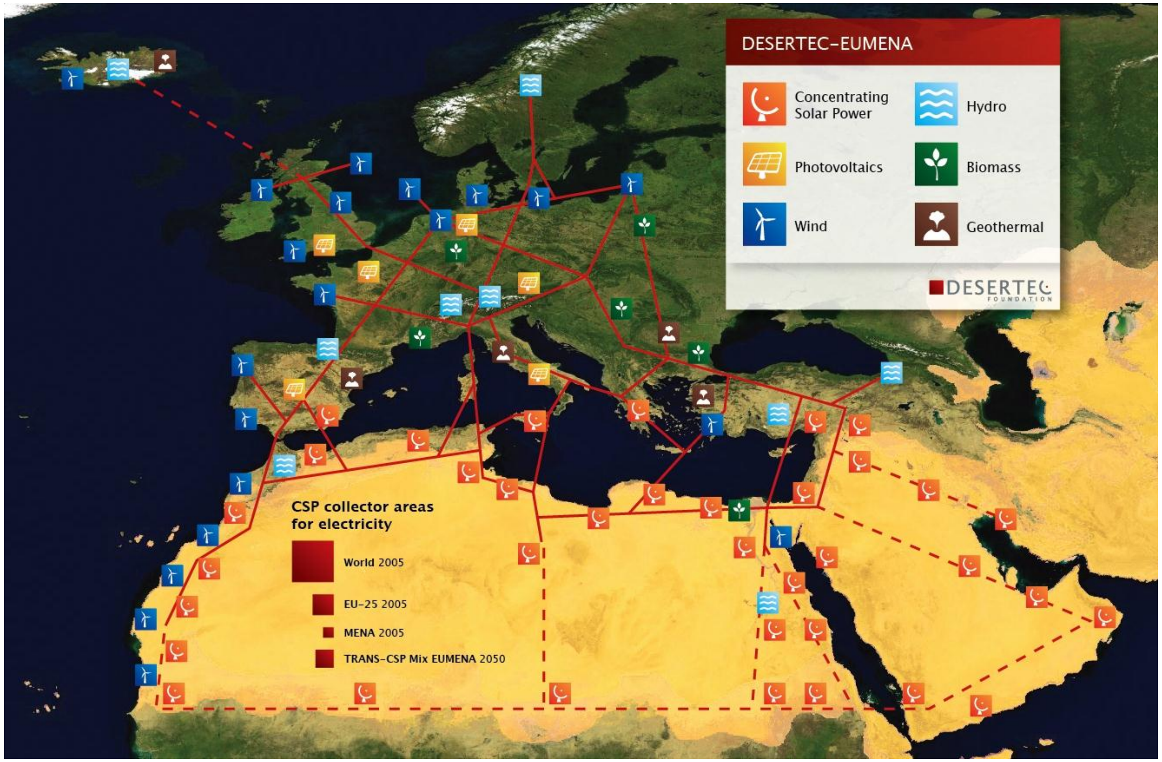
► **Electricity Gains a Progressively Larger Share of Total US Energy**
Digital Technologies – Precision and Efficiency of Electricity

Inspiring Concepts of Future
Renewable Energy Generation Systems

DESERTEC
Airborne Wind Turbines

DESERTEC

Concentrating Solar Thermal Power Plant in the Sahara
Transmission Utilizing HVDC Technology (3% Loss/1000km)
Target 2050 - 100GW HVDC, 700TWh @ 5€ct/kWh



Clean Power from the Desert

Technology Overview

Mirrors Concentrating Solar Radiation / Creating Heat

Heat Storage Tanks
(e.g. Molten Salt Storage) –
Ability to Provide Power for
24h a Day

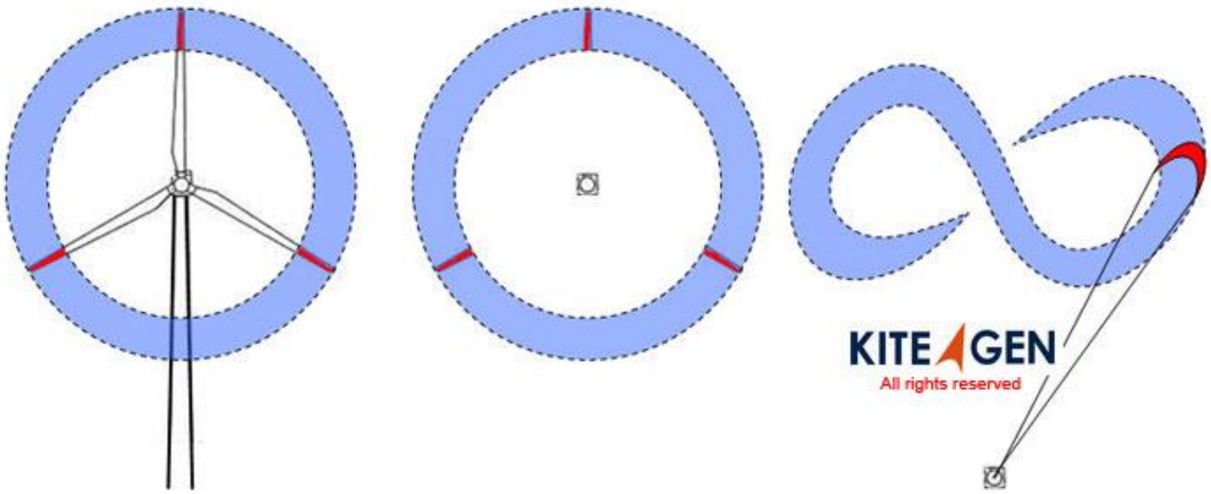
Conventional Turbine and Generator, Turbines could also be Powered by Natural Gas or Oil

Clean Power from the Desert

Revolutionize Wind Power Generation
Using Kites / Tethered Airfoils

- Power of the Wind – Cube of the Wind Speed / Two Times Speed – 2x2x2=8 Times Power

Controlled Power Kites for Capturing High Altitude Wind Power

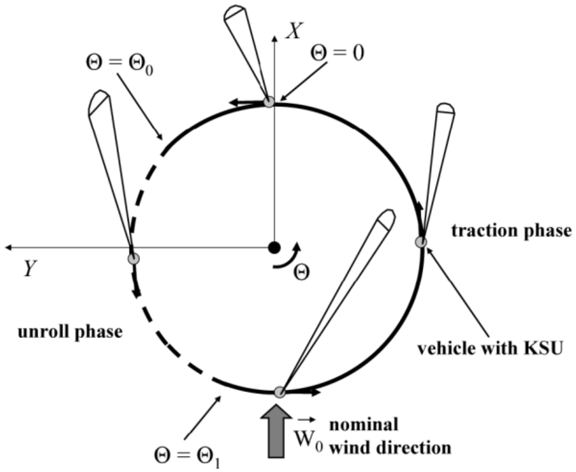


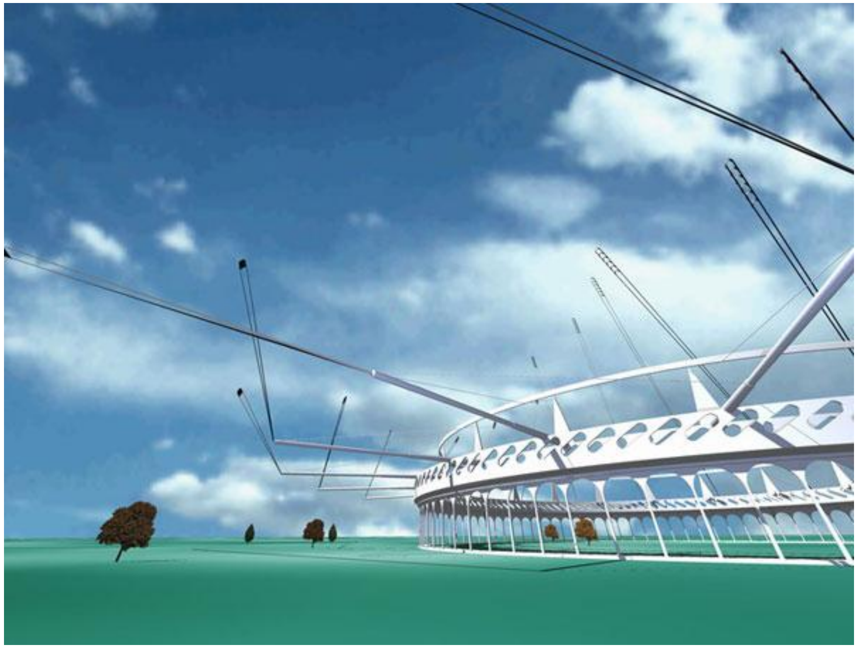
- Wing Tips / Highest Speed Regions are the Most Efficient Parts of a Wind Turbine
- Generator for Power Kites Moved to Ground
- Minimum Base Foundation etc. Required
- Operative Height Adjustable to Wind Conditions

Controlled Power Kites for Capturing High Altitude Wind Power

- ► Lower Electricity Production Costs than Current Wind Farms
- ► Generate up to 250 MW/km², vs. the Current 3 MW/km²
- ► Research at the POLITECNICO DI TORINO

KITE GEN





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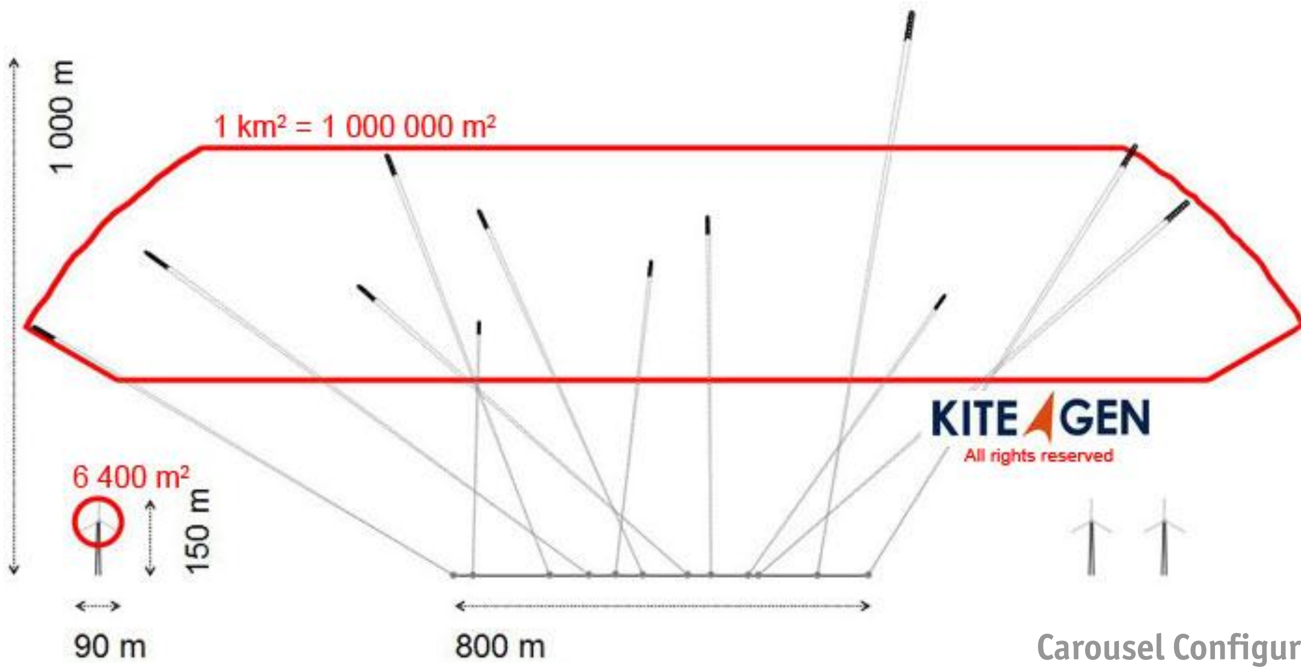
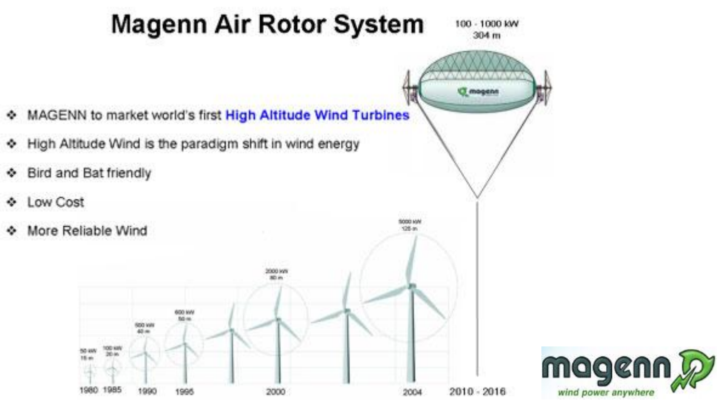
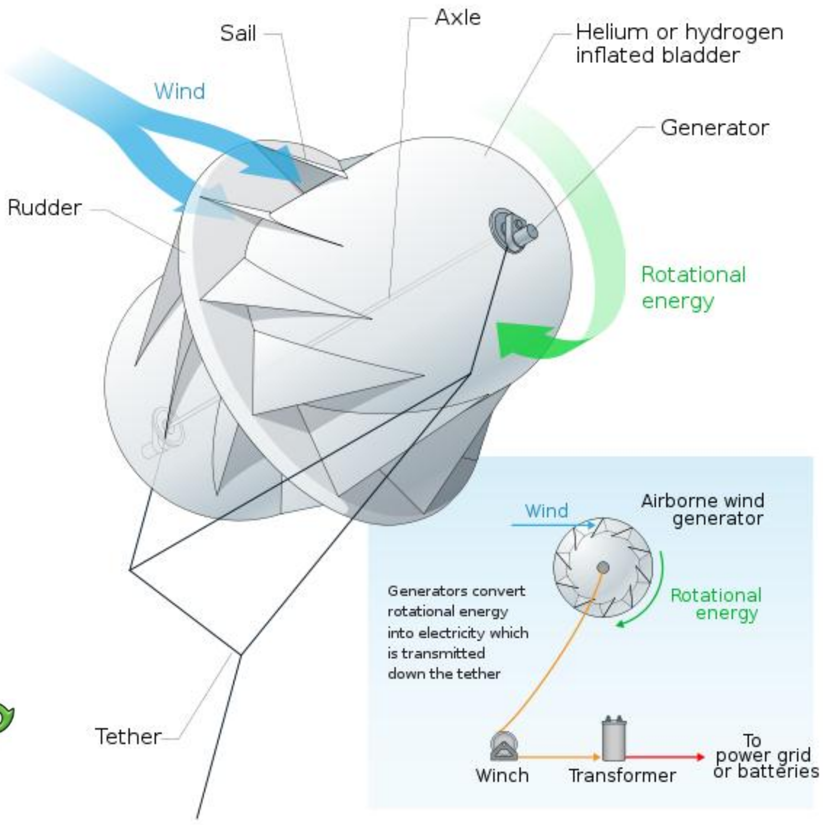


Carousel Configuration

Air Rotor Wind Generator

- ▶ Helium or Hydrogen Inflated
- ▶ Magnus Effect - Additional Lift

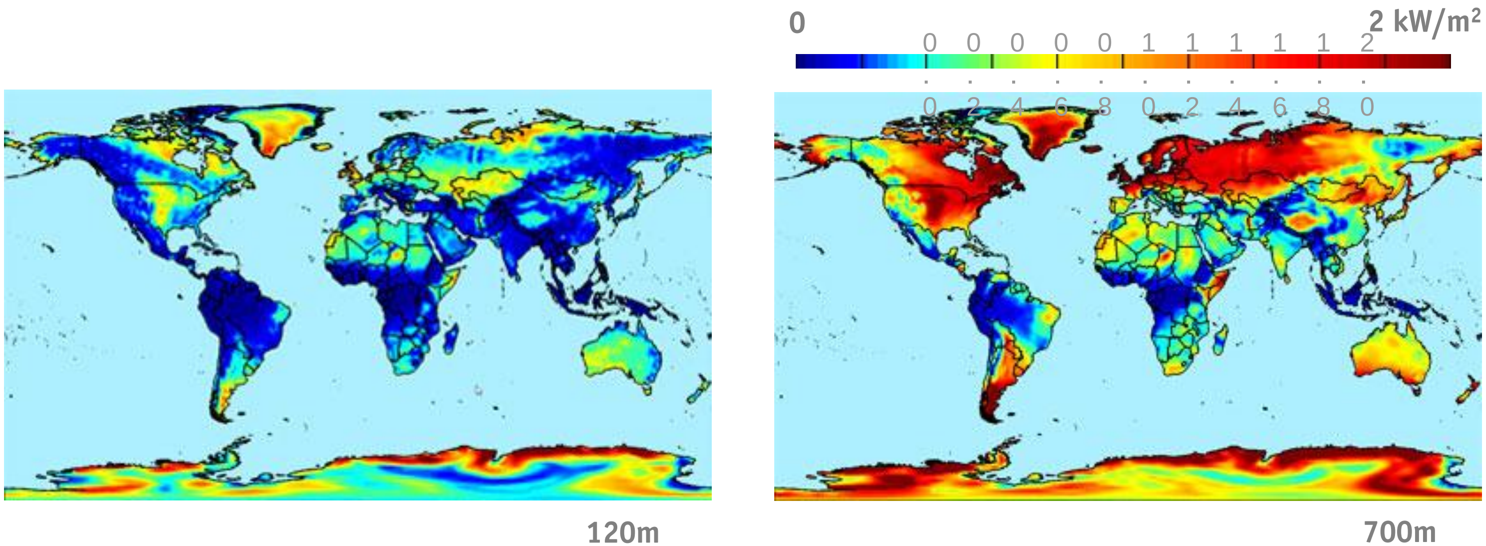




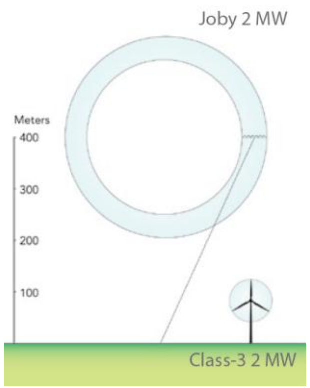
Airborne High-Altitude Wind Turbines

JOBY
ENERGY

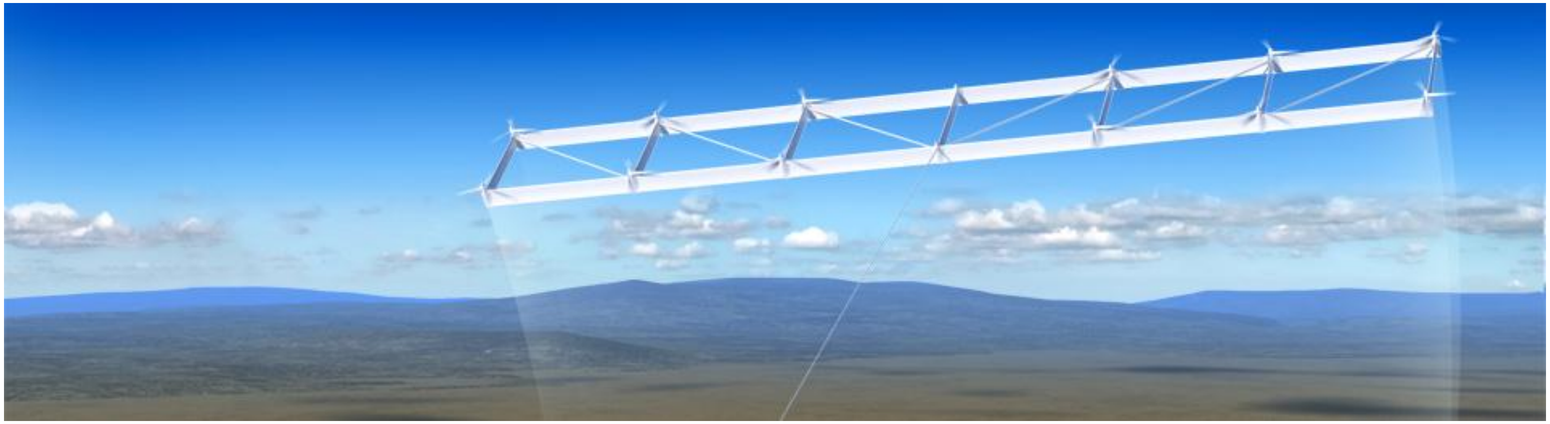
- ▶ Wind at High Altitudes is Faster and More Consistent
- ▶ Float Wind Turbines at High Altitudes or Even in the Jet Stream



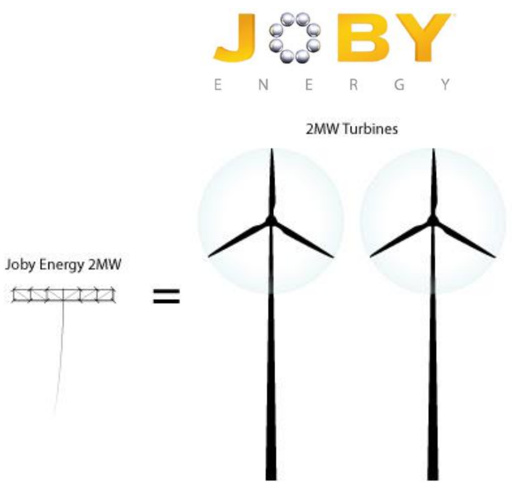
Airborne High-Altitude Wind Turbines



- ► Multi-Wing Airframe Supports an Array of Turbines
- ► Turbines Connect to Motor Generators
- ► Reinforced Tether Transfers MV-Electricity to Ground
- ► Composite Tether also Provides Mechanical Connection to Ground

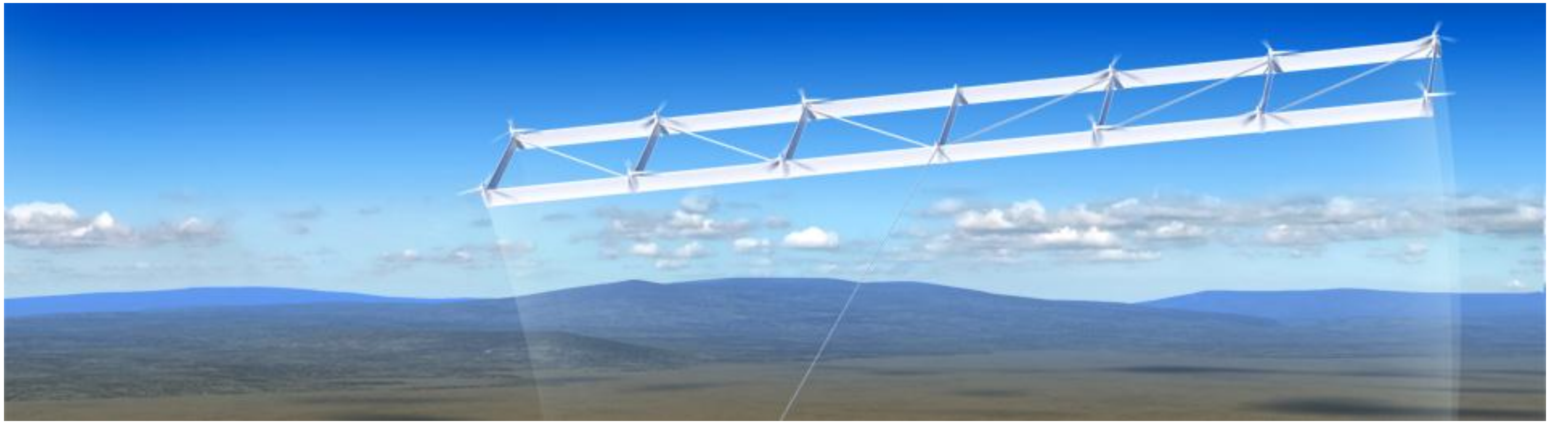


Airborne High-Altitude Wind Turbines



► Electrical System Topology

- 3Φ-AC/DC Rectifier (800V Output) per Turbine
- Connection to Tether via Bidir. 800V/8kV DC/DC Converter
- Weight Limit of 25kg / 100kW (MF Transformer)



Airborne High-Altitude Wind Turbines

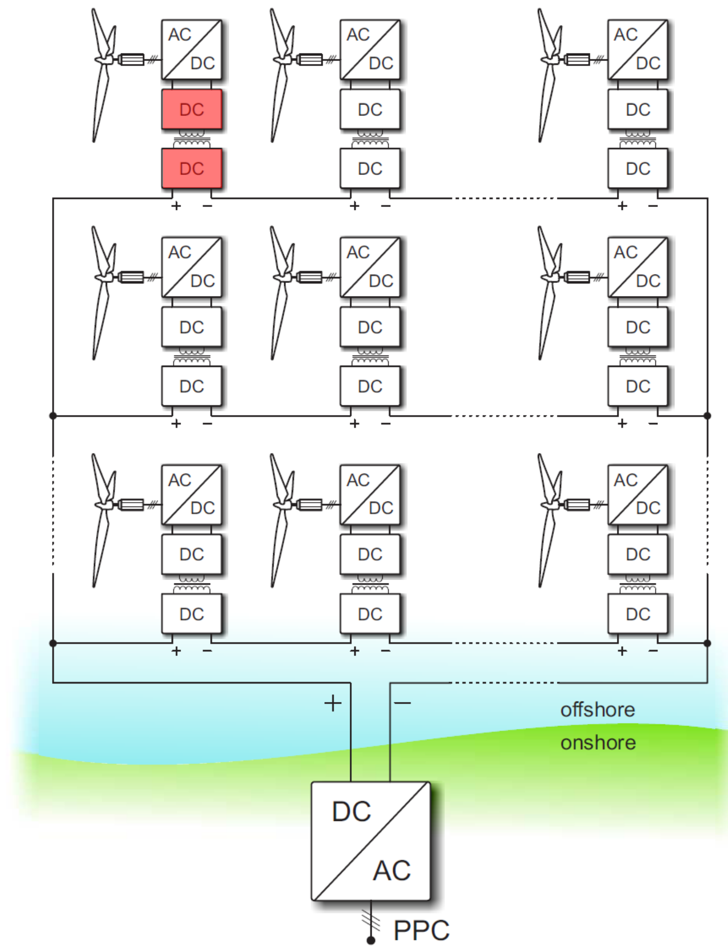
JOBY ENERGY

- ► Reinforced Tether Transfers MV-Electricity to Ground
- ► Composite Tether also Provides Mechanical Connection to Ground

Conventional Off-Shore Windfarms

Medium Voltage Power Collection and Connection to On-Shore Grid

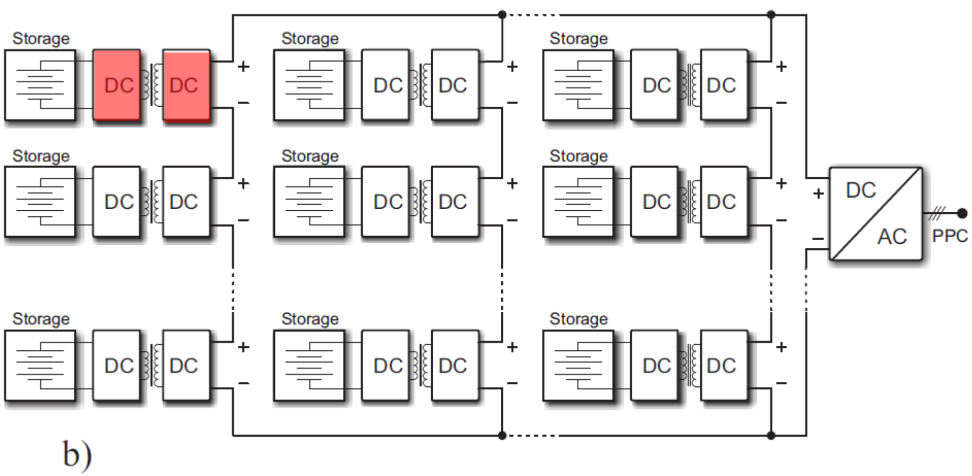
Collection Grids for Off-Shore Wind Parks

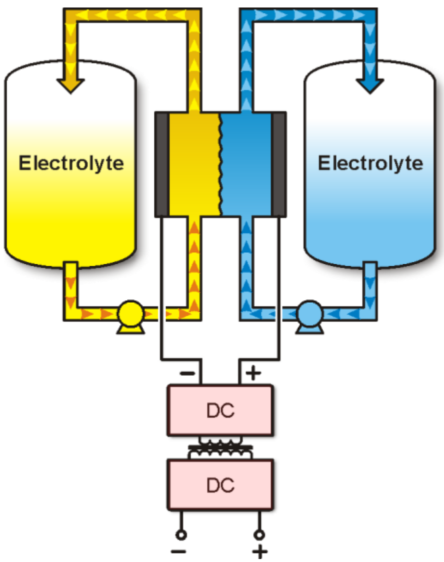


- ▶ High Efficiency DC Energy Transmission
- ▶ Low Weight MF DC/DC Step-up Converter

Energy Storage Systems for Renewable Generation

- Redox-Flow Battery for Individual Scaling of Stored Energy and Rated Output Power
- Bidirectional Step-up DC/DC Converter for Connection to Collection Grid

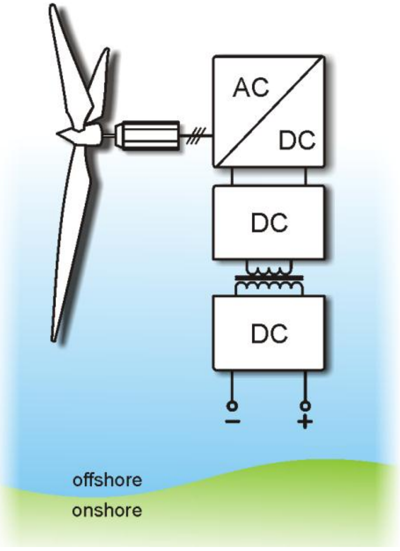


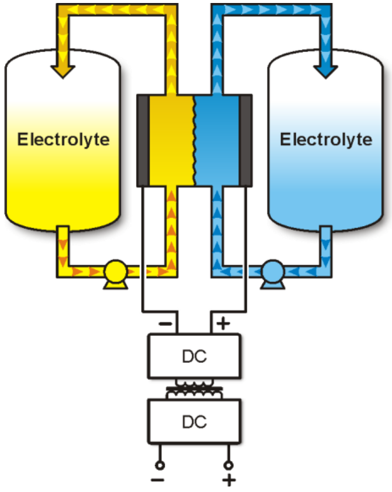


Redox-Flow Battery Concept

ETH *MEGA Cube* Research Targets

- ► 1 Mega Watt Bidirectional DC/DC Conversion
- ► Maximum Efficiency / Minimum Weight Design



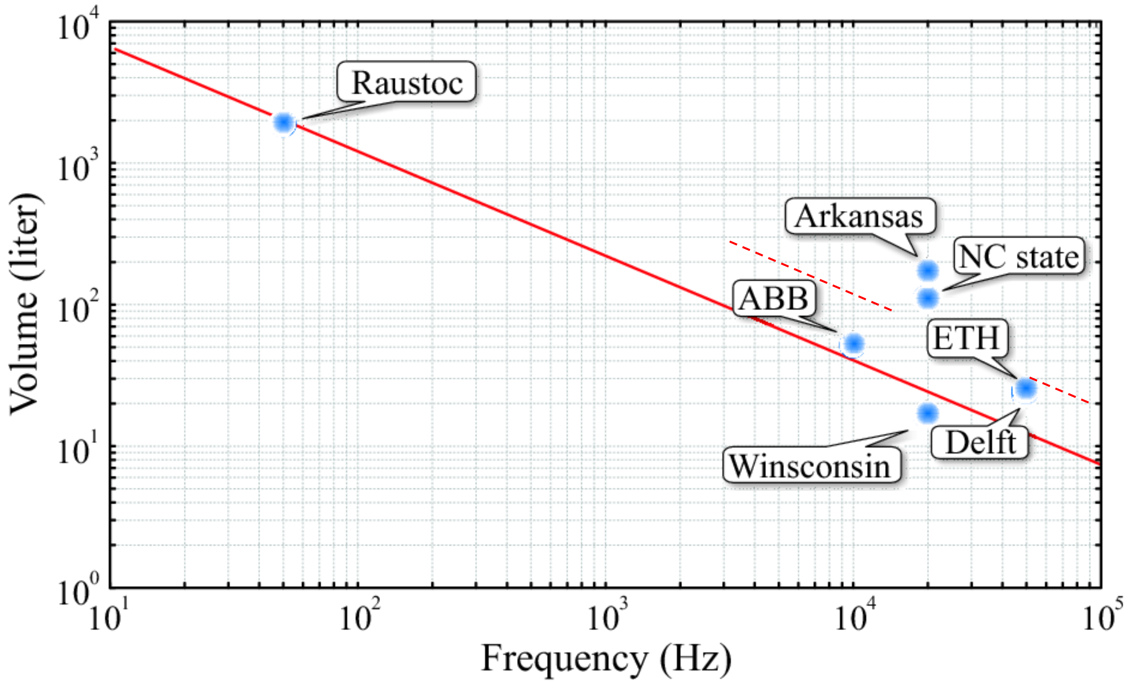


- ► Specifications

- 20kHz Switching Freq.
- Port 1: 12kV
- Port 2: 1.2kV
- 100 kV DC Isolation
- 99% Efficiency
- 250kg Weight Limit

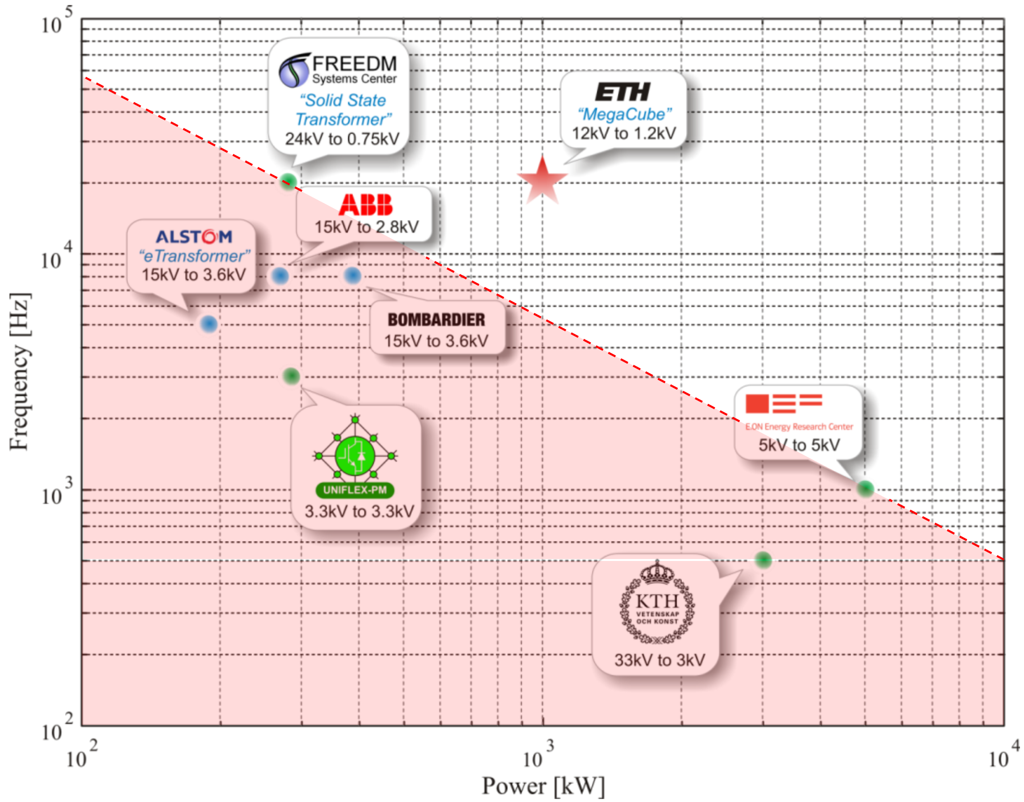
Research Efforts on High-Power MF DC/DC Converters

- Volume vs. Frequency for Published Transformer Designs
- All Scaled to 1MW Power Rating



Research Efforts on High-Power MF DC/DC Converters

2001-2010

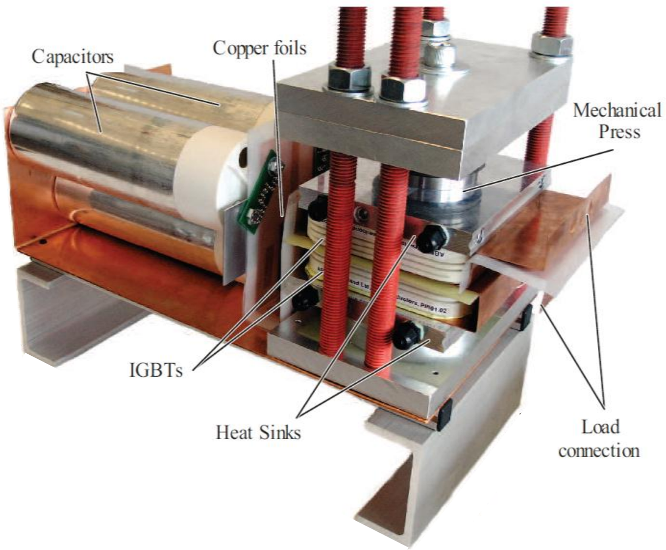


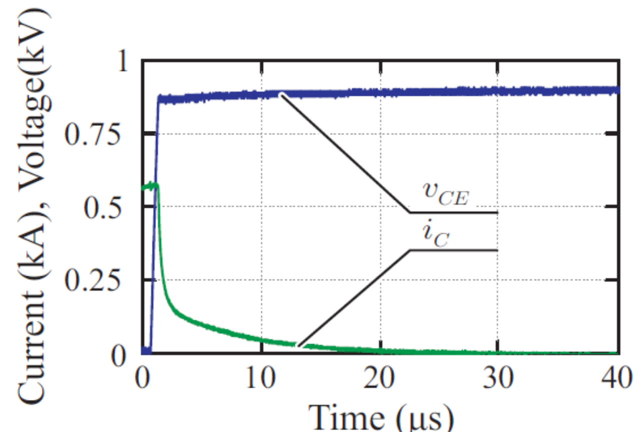
Grid Applications
(UNIFLEX EU)
* Full Modular Construction
* Full Scale Converter: 5MW

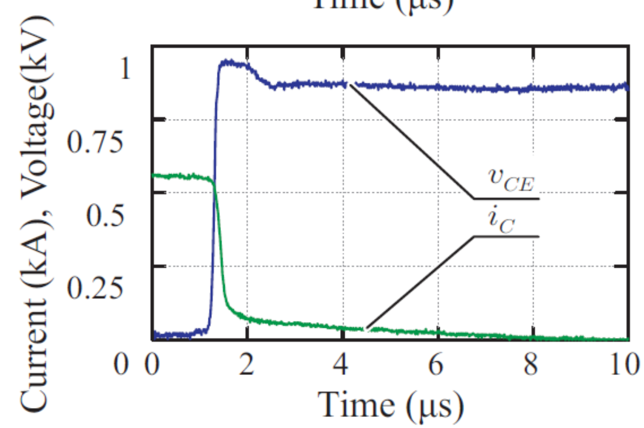
Traction Applications
(Bombardier, ALSTOM, ABB)
* Modular MV Side
* Single LV Converter

4.5kV Press Pack IGBT

- 400A Continuous Current
- Slow Switching Behavior







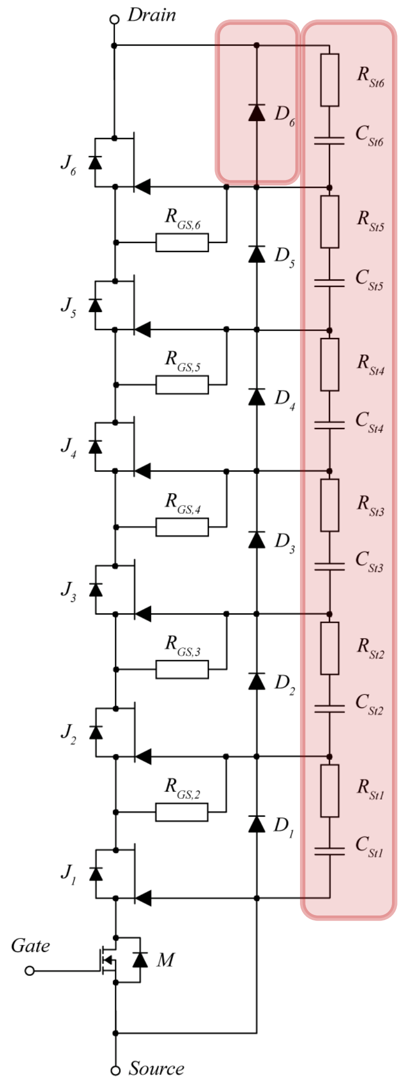
Si/SiC Super Cascode Switch

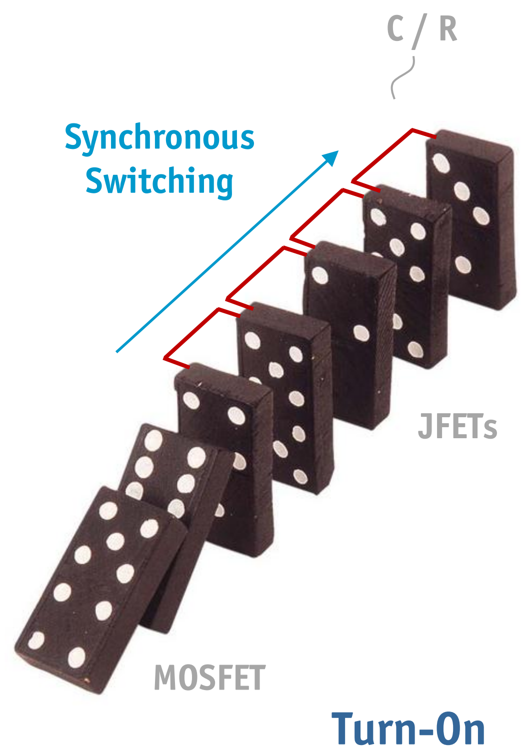
➔ HV-Switch Controllable via Si-MOSFET

* 1 LV Si MOSFET
* 6 HV SiC JFETs
* Avalanche Rated Diodes

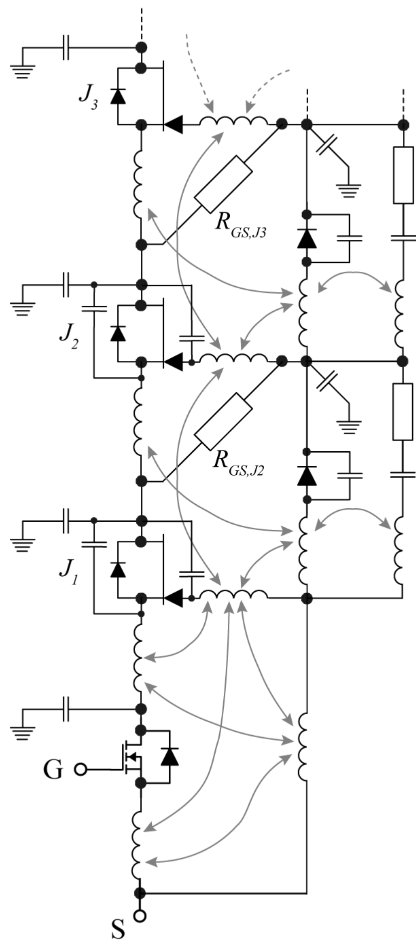
➔ Ultra Fast Switching
➔ Low Losses
➔ Parasitics

* Passive Elements for Simultaneous Turn-on and Turn-off
* Stabilization of Turn-off State Voltage Distribution





Si/SiC Super Cascode Switch



- ➔ HV-Switch Controllable via Si-MOSFET
  - * 1 LV Si MOSFET
  - * 6 HV SiC JFETs
  - * Avalanche Rated Diodes
- ➔ Ultra Fast Switching
- ➔ Low Losses
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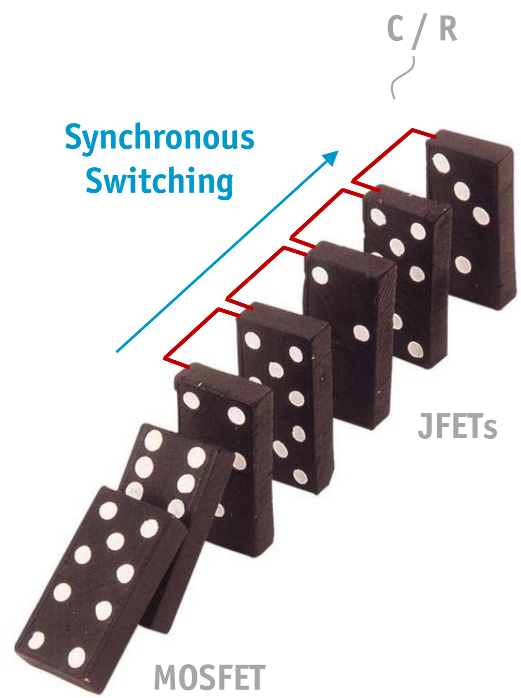
  - * Passive Elements for Simultaneous Turn-on and Turn-off
  - * Stabilization of Turn-off State Voltage Distribution

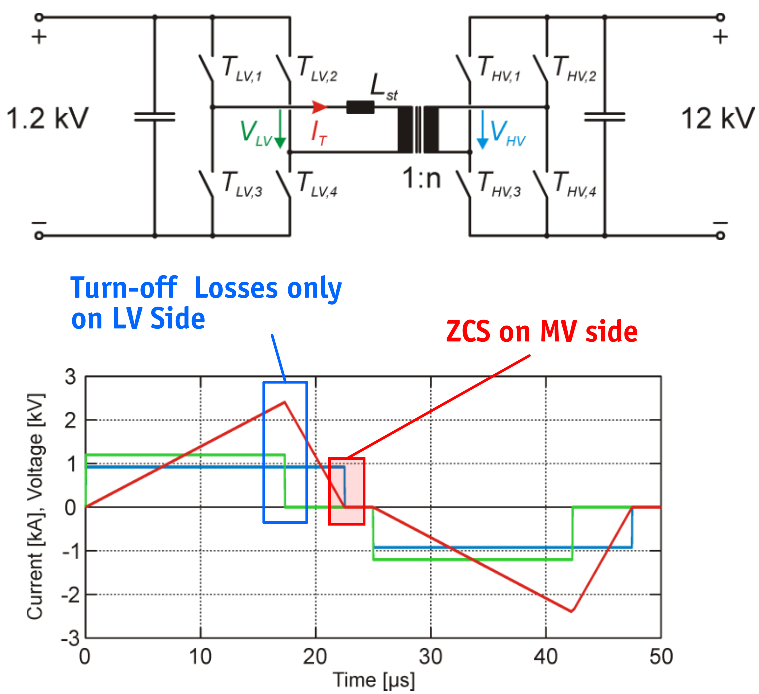


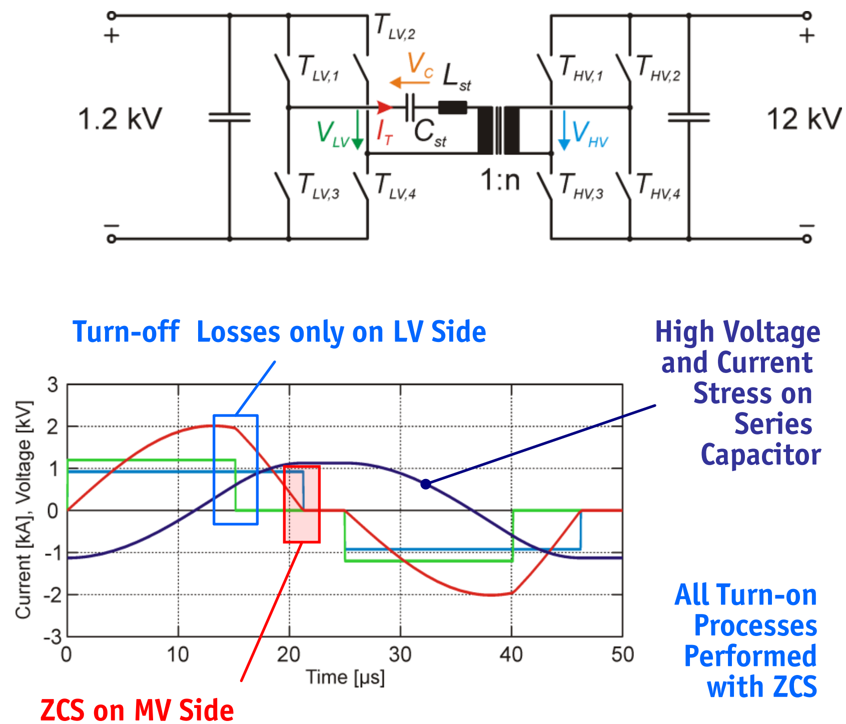
Turn-On

DC/DC Converter Topology / Modulation

- Dual Active Bridge / Triangular Modulation
- Series Resonant Converter

n = 13
L_S = 2uH
L_S /C_S= 5.9uH/12uF (f=19kHz)





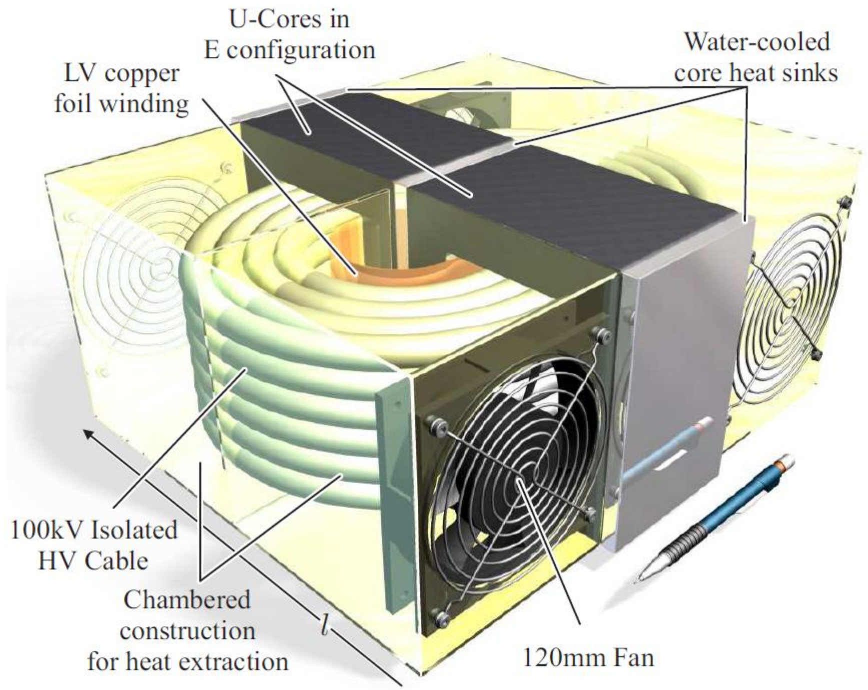
Transformer Concepts

- ▶ Core Material – Vitroperm 500F
- ▶ LV Winding – Loss Optimized Copper Foil
- ▶ MV Winding – Litz Wire / Litz Cable

DBA @ Triangular Modulation

Losses	Core	1.83kW
	Copper	1.93kW
	Total	3.76kW

Efficiency 99.62%
Power Density 84kW/dm^3



- ▶ Shell-Type Concept

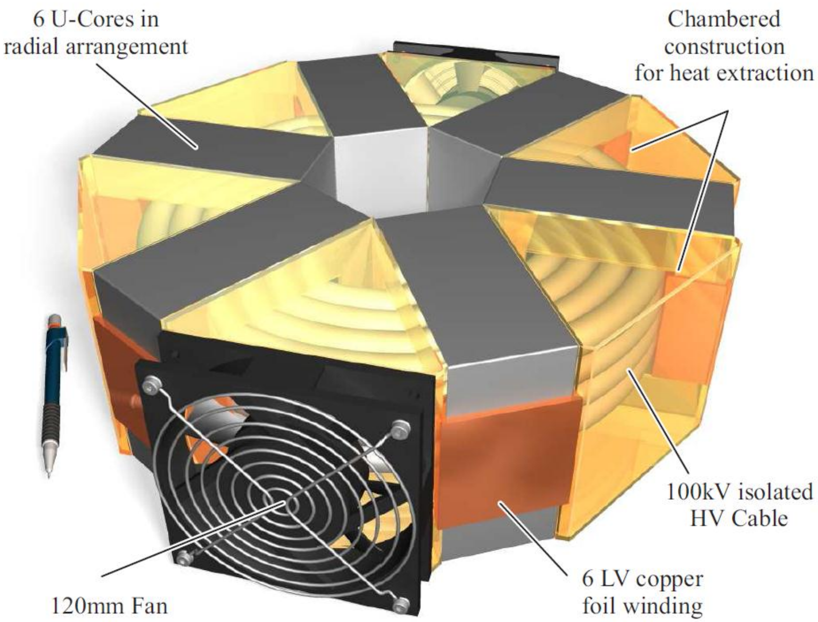
Transformer Concepts

- ▶ Core Material – Vitroperm 500F
- ▶ LV Winding – Loss Optimized Copper Foil
- ▶ MV Winding – Litz Wire / Litz Cable

DBA @ Triangular Modulation

Losses	Core	2.23kW
	Copper	2.28kW
	Total	4.51kW

Efficiency 99.55%
Power Density $91 kW/dm^3$

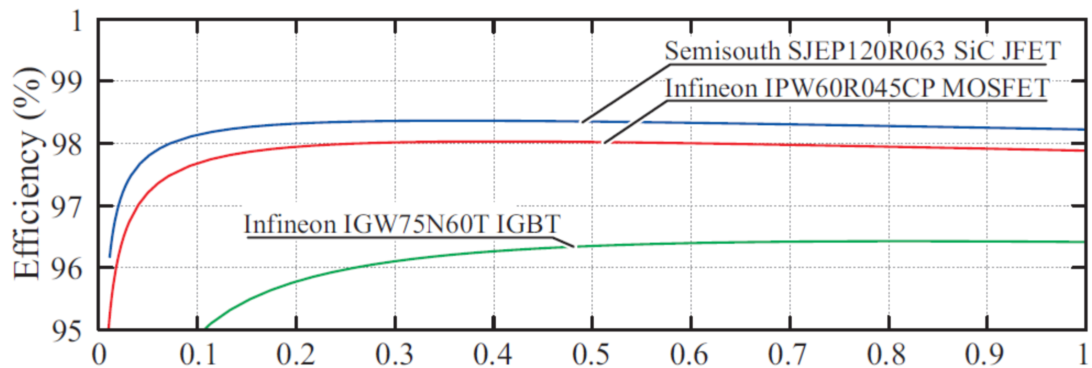


- ▶ Matrix-Type Concept

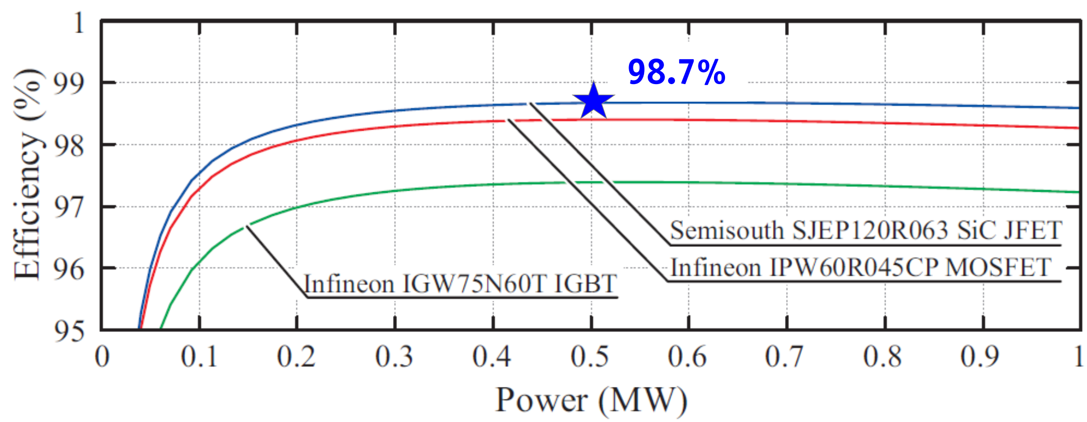
Conversion Efficiencies

600V IGBT/MOSFET 5-Level NPCC
1200V SiC JFET 3-Level NPCC

- DAB @ Triangular Modulation



- SRC @ Constant Switching Frequ.



EEnergy Utilization /
General Power Electronics Application Areas

10^1......10^3 W
10^3......10^6 W
10^6......10^9 W

Extreme Power Range

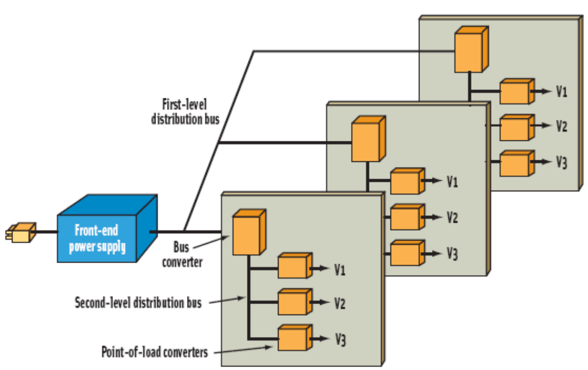
IT Distributed Power Supply

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

Distributed / Modular Power Supply

Power electronics inside

Communications Power Systems 12-V Intermediate Bus Architecture

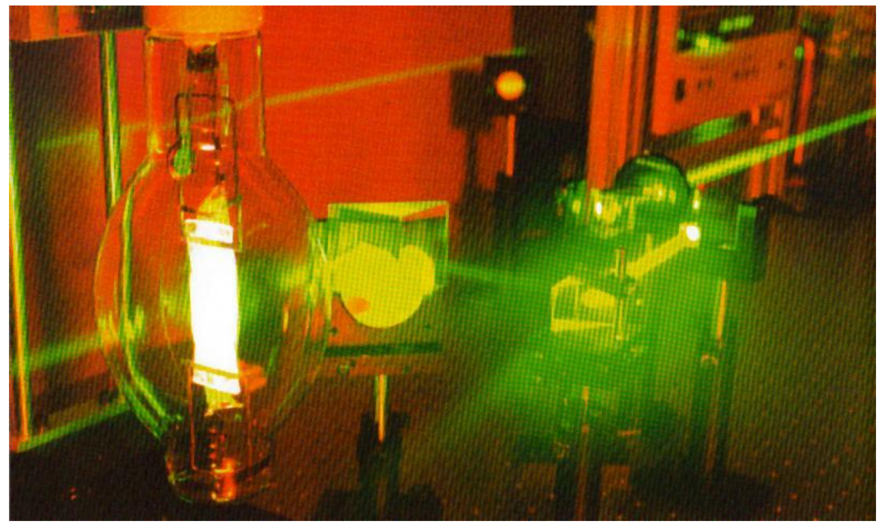


Lighting

33% Comm. El. Energy Consumption US
20% Energy Saving Potential of Light Source

Constant Light
Wide Control Range

Power electronics inside



Lamp Ballasts / Energy-Saving Lamps
Gas Discharge Lamps (Automotive Lighting)
LED (semiconducting, organic)

100,000h
Vibration-Resistant
Efficiency → +30%
Design

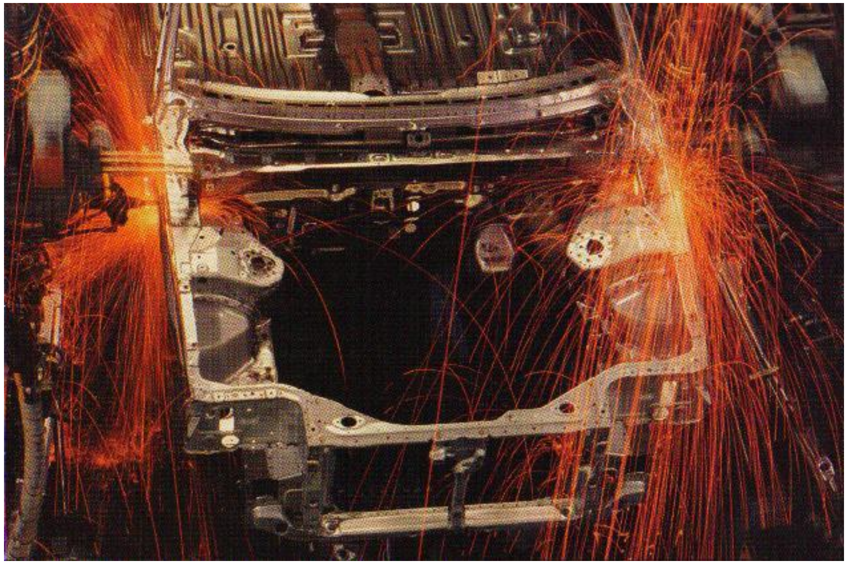
Process Technology

Power
electronics
inside

$1,700 Mio. (EU)
50% Automotive Ind.
Metal Processing
Aerospace Industry

135kA@770V

Welding / Laser Cutting



Plasma Technique
Laser Cutting
Spark Erosion
Ind. Heating / Melting
Aluminium Melting

Drive Systems

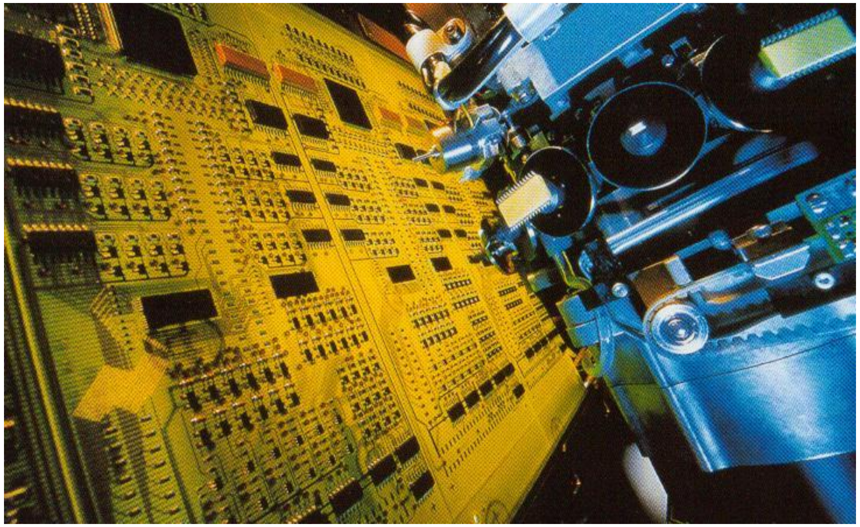
Extremely Wide Appl. Range, e.g. Automation Technology, Assembling, Robotics, HVAC

60% of Electric Energy Utilized in Germany consumed by Drives

Power electronics inside

High Dynamics
Precise Control / Positioning
Bus Interface

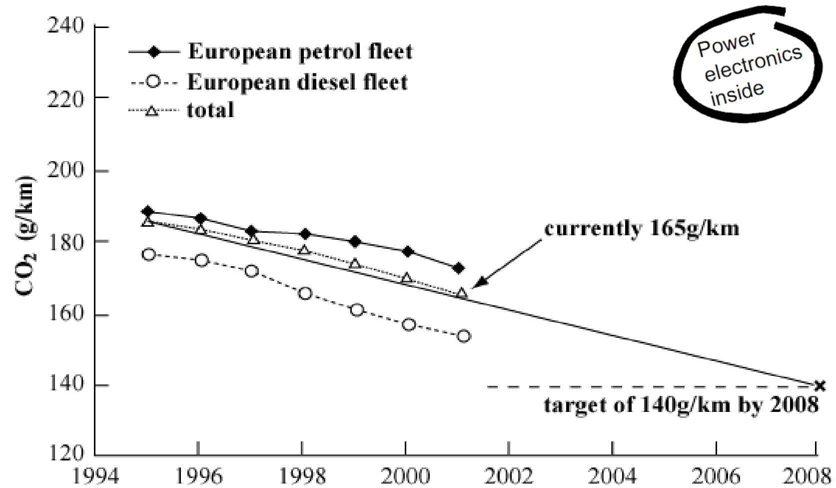
Self-Commissioning
Sensorless
Monitoring

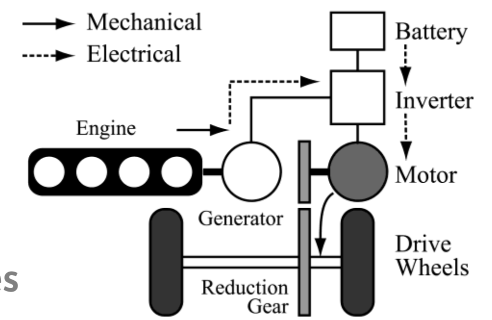


5% Employing Electronic Speed Control
35% Possible Share / 40% Energy Saving Pot. (16TWh)

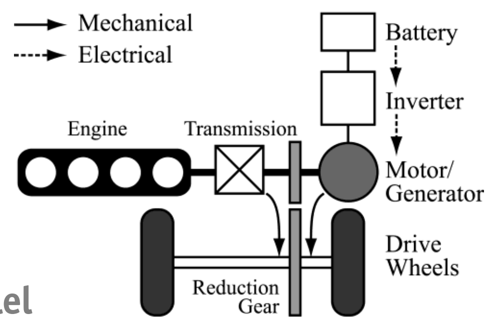
400TWh Drives Energy Consumption in the EU
60% Energy Saving Potential

Hybrid Cars





Series



Parallel

Traction

Power
electronics
inside

Commuter Trains
High Power Locomotives

Multi-Frequency Systems
$16^2/3$ Hz $\rightarrow$ 10kHz / Transformer-less
Super-Cap-Storage for Trams

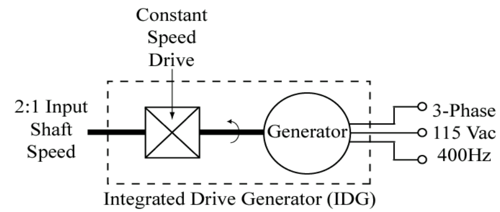
38 MVA
0...56Hz
552km/h

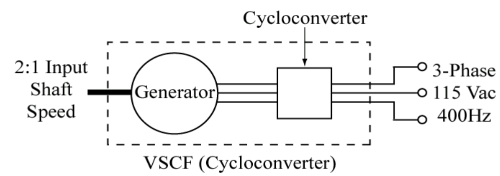
Maglev Trains

More Electric Aircraft

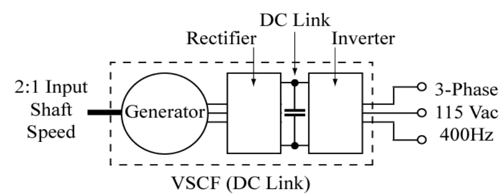
Air Traffic Growth 4.7%/a

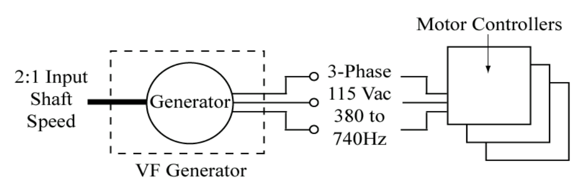
Power electronics inside





360Hz...800Hz VF Power Generation
270V_{DC} Power Distribution
Replacement of Hydraulic by Electric System





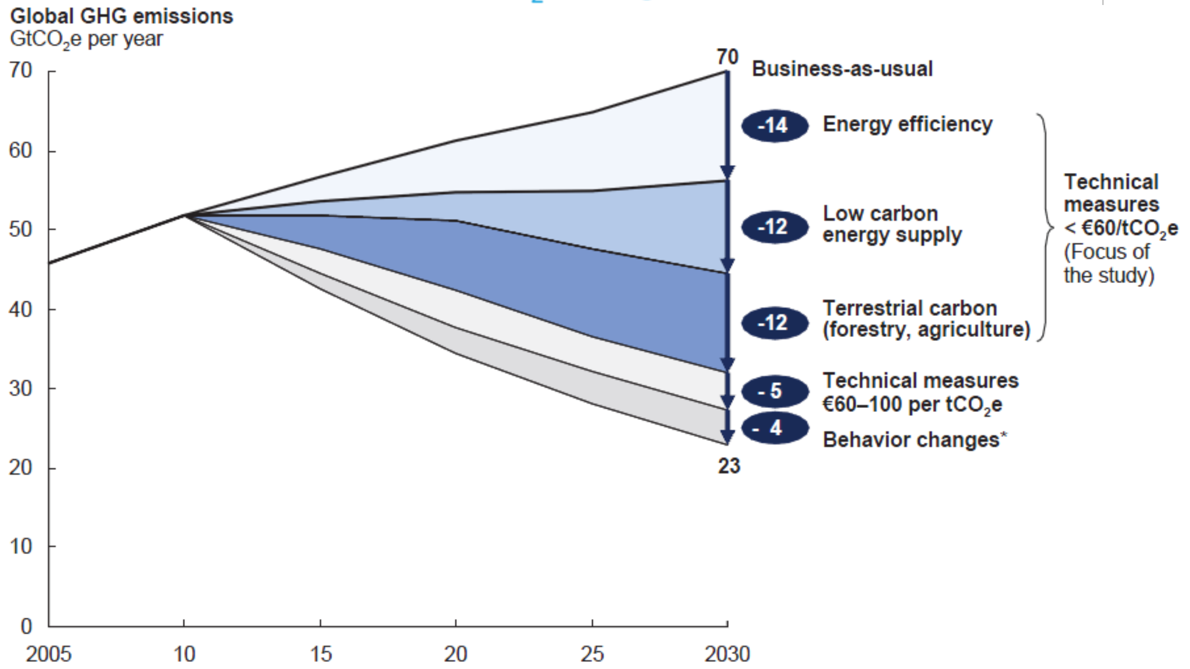
The Efficiency Challenge

EEnergy Supply Chain

Energy Saving Potential of Industrial Drives Systems

Negawatts instead of Megawatts

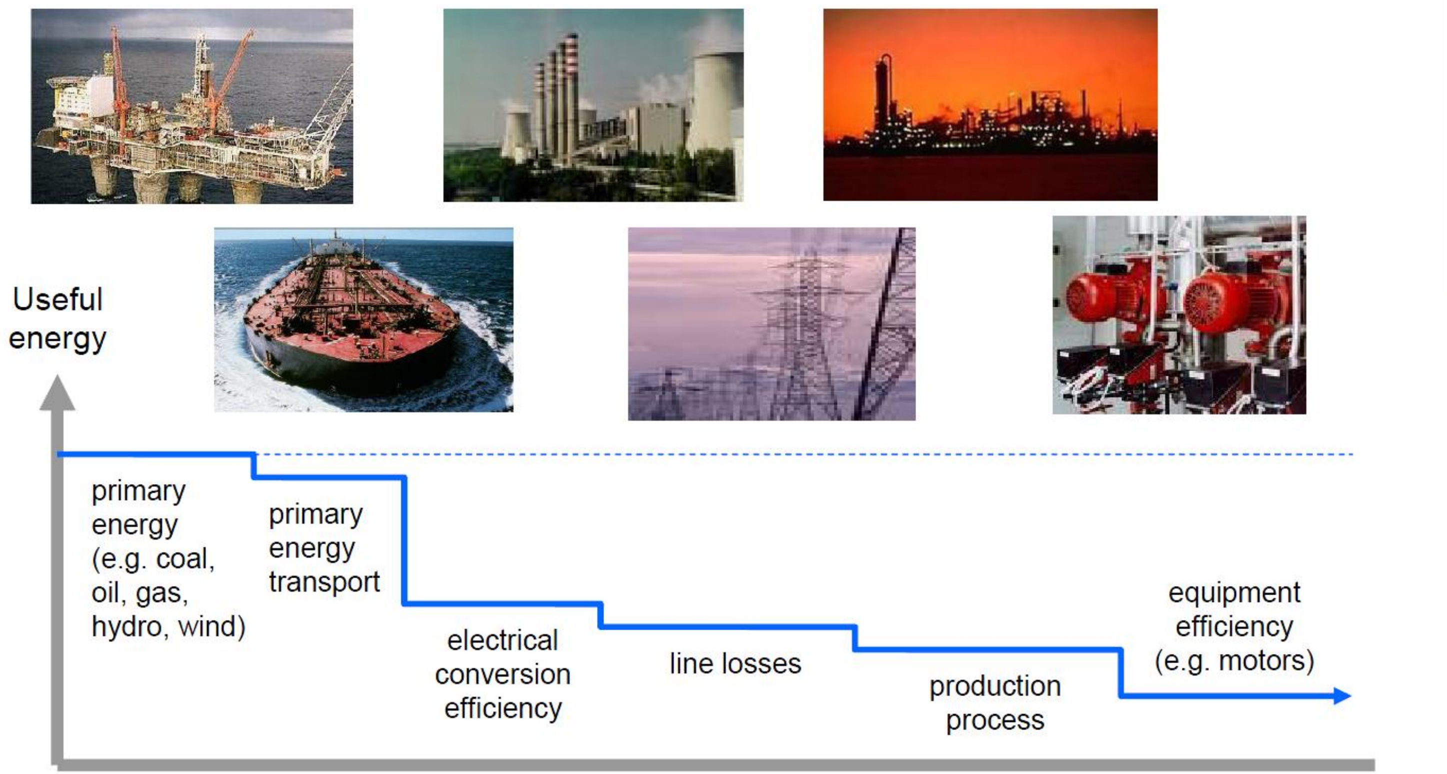
McKinsey Study Finds Energy Efficiency Will Be the Biggest Source of CO_2 Savings



* The estimate of behavioral change abatement potential was made after implementation of all technical levers; the potential would be higher if modeled before implementation of the technical levers.
Source: Global GHG Abatement Cost Curve v2.0; Houghton; IEA; US EPA

Industrial Use of EEnergy

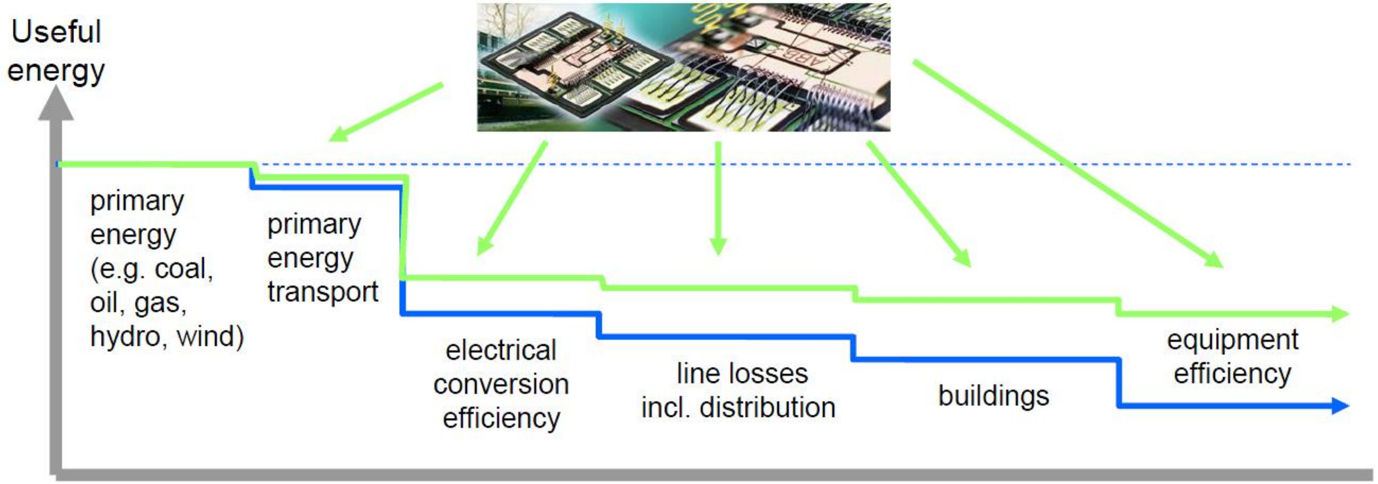
Source: ABB



Potential of Power Electronics Contributions

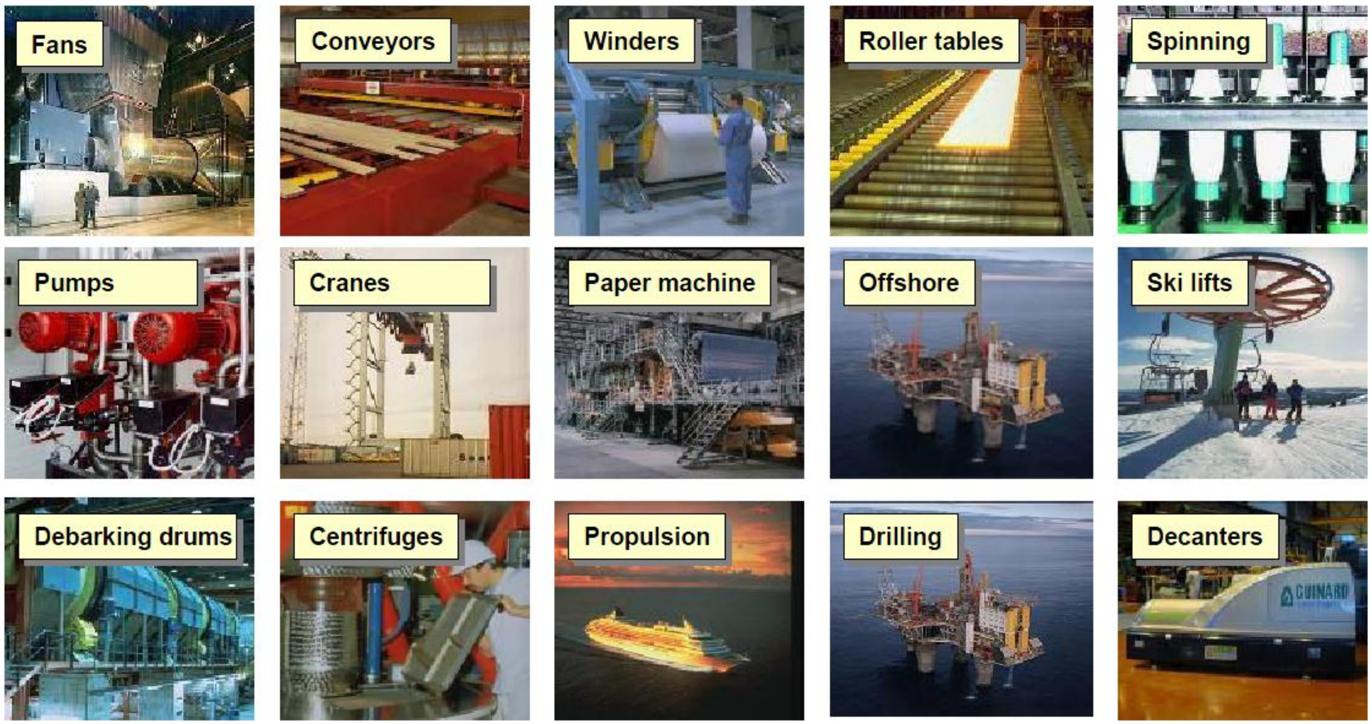
Source: ABB

- Power Electronics is a Cross Cutting Technology
- Allows to Save Energy over all Steps of EEnergy Transportation / Utilization



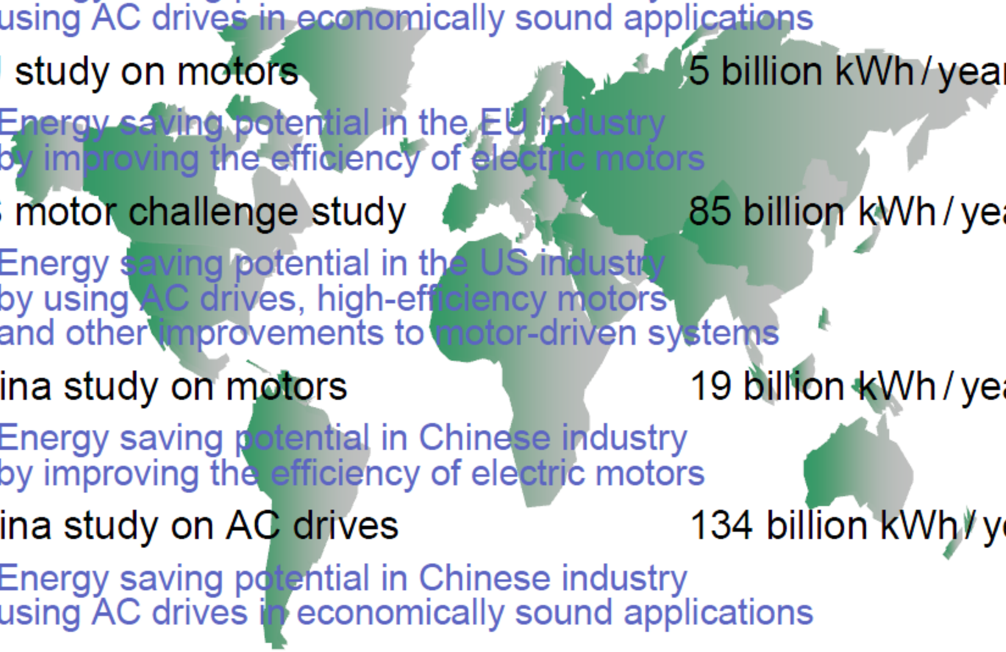
EEnergy Use in Industry / Drives

Source: ABB



Energy Saving Potentials for Industrial Drives

Source: ABB



- EU study on AC drives — 43 billion kWh / year
  - ➔ Energy saving potential in the EU industry using AC drives in economically sound applications
- EU study on motors — 5 billion kWh / year
  - ➔ Energy saving potential in the EU industry by improving the efficiency of electric motors
- US motor challenge study — 85 billion kWh / year
  - ➔ Energy saving potential in the US industry by using AC drives, high-efficiency motors and other improvements to motor-driven systems
- China study on motors — 19 billion kWh / year*
  - ➔ Energy saving potential in Chinese industry by improving the efficiency of electric motors
- China study on AC drives — 134 billion kWh / year*
  - ➔ Energy saving potential in Chinese industry using AC drives in economically sound applications

Energy Saving Potentials for Industrial Drives

Source: ABB

- 60% of Industrial EEnergy Used by Electric Motors
- Motors Frequently Still Running at Fixed Speed / Throtteling
- >40% Energy Saving Potential

- For each 1€ Purchase Costs 100€ are Spent for Energy over Lifetime

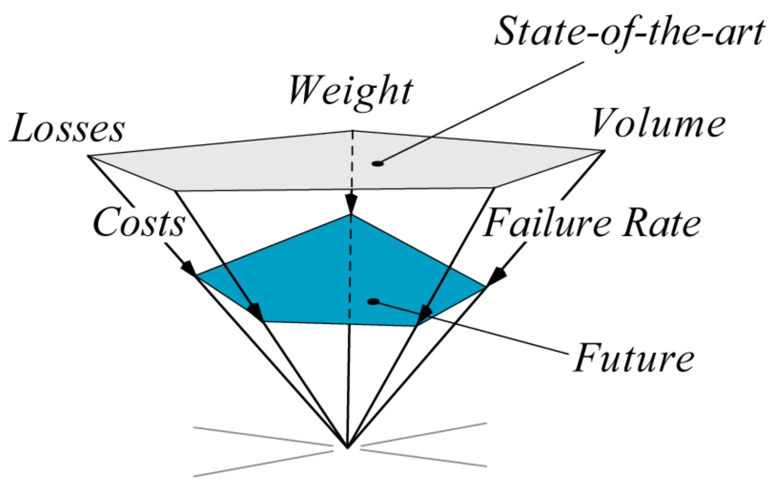
Systematic Approach for Power Electronics Converter Optimization / Evaluation

Performance Metrics
Pareto-Optimal Design
Technology Nodes

Power Electronics
Performance Trends

■ Performance Indices

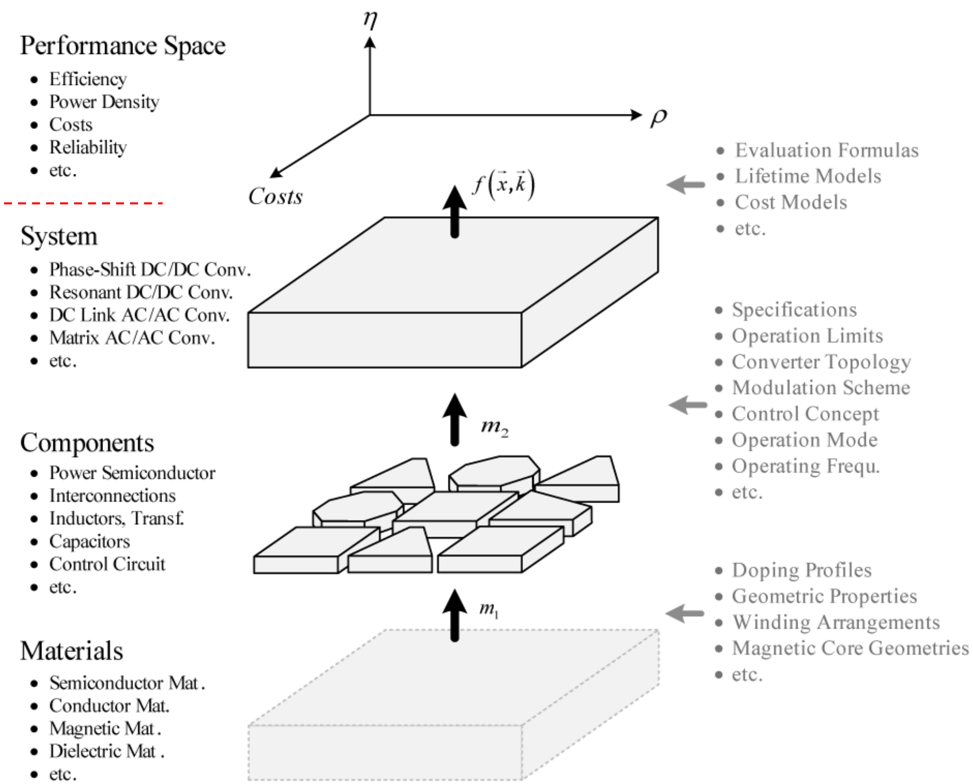
— Power Density [kW/dm^3]
— Power per Unit Weight [kW/kg]
— Relative Costs [kW/$]
— Relative Losses [%]
— Failure Rate [h^{-1}]



Abstraction of Power Converter Design

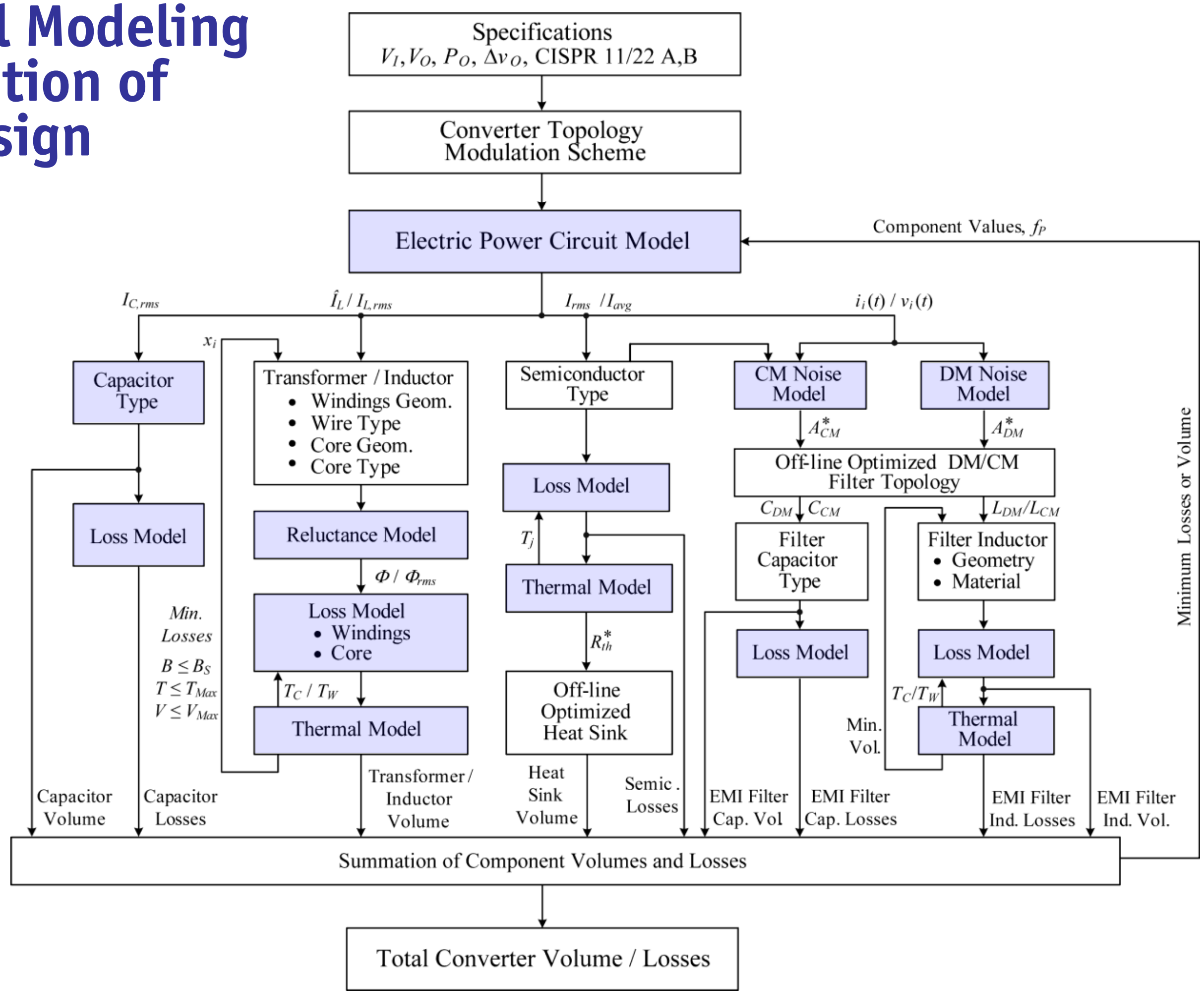
Performance Space

Design Space



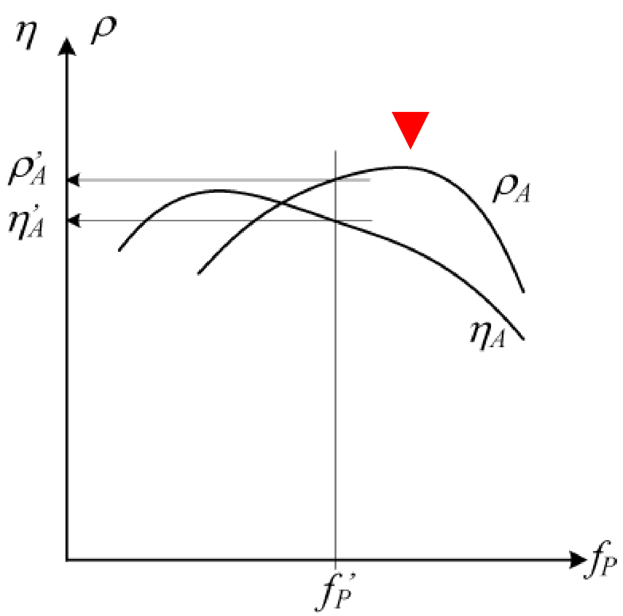
▶ ***Mapping of Design Space into System Performance Space***

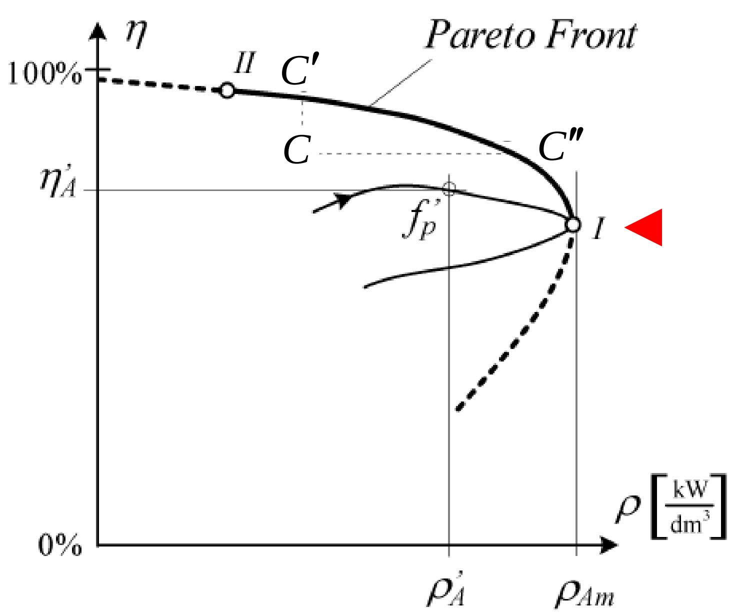
Mathematical Modeling and Optimization of Converter Design



Single-Objective Converter Design Optimization

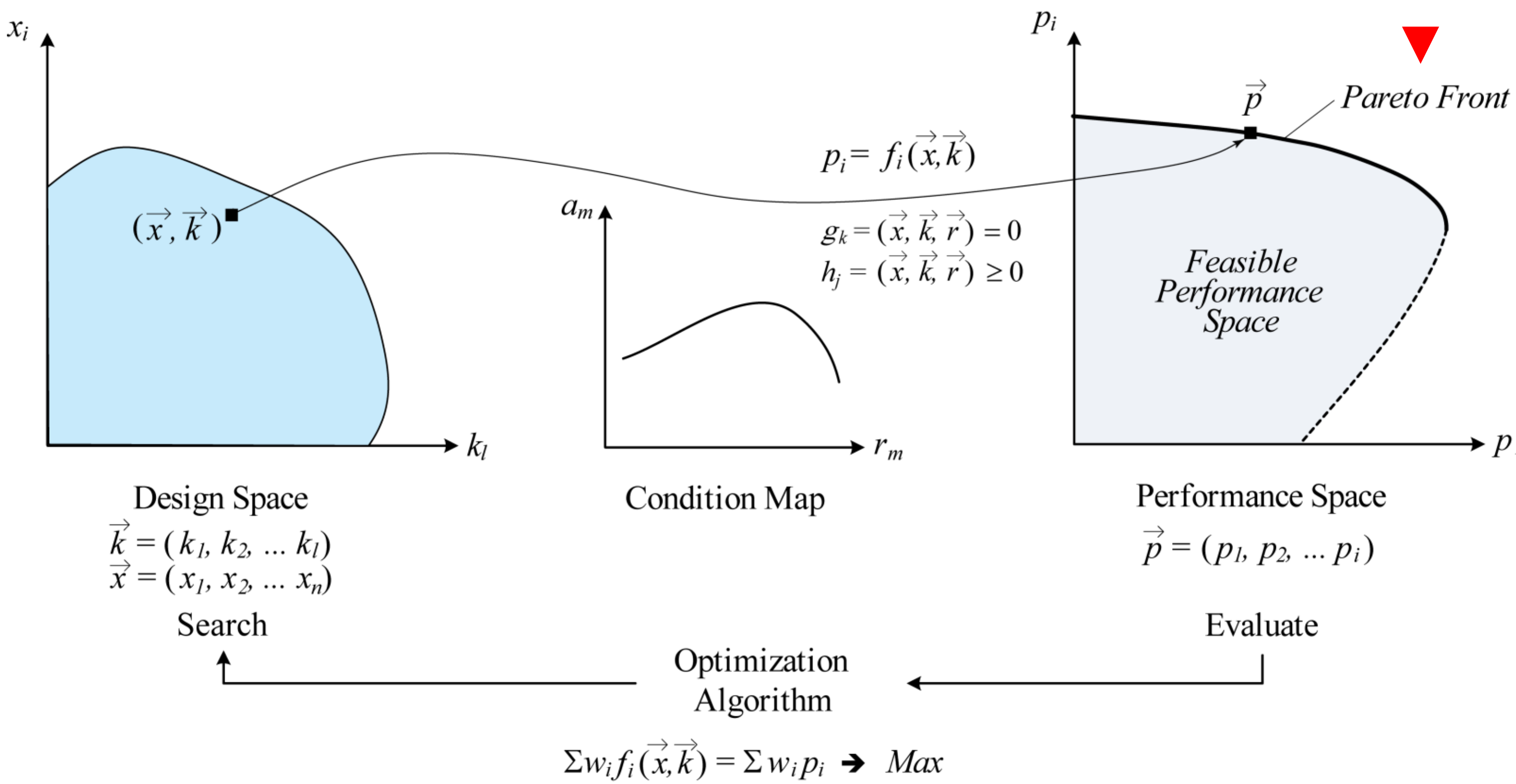
► **Design for Maximum Power Density**





Multi-Objective Converter Design Optimization

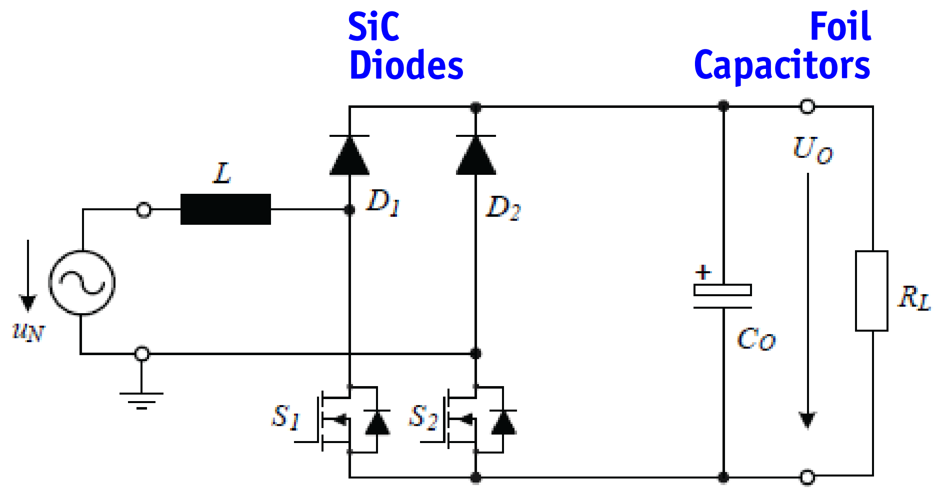
► *Pareto Front* - Limit of *Feasible Performance Space*



Efficiency Optimization

Power Semiconductors
Boost Inductor
Output Capacitor
Auxiliaries

Minimum Loss MOSFET Chip Area

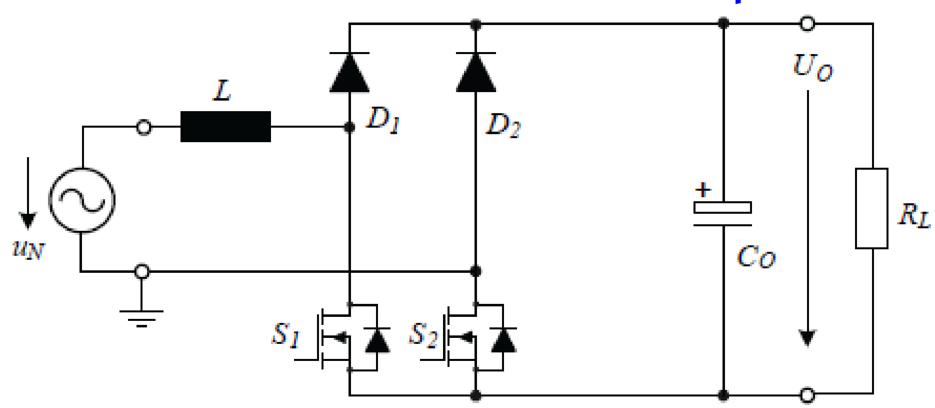


- Increasing A_{chip}

– Decreasing $R_{DS(on)}$
– Increasing C_{oss}

$$P_{V,T} = R_{DS(on)} I_{T,rms}^2 + f_P \frac{1}{2} C_{Eq} U_O^2$$

Minimum Loss
MOSFET Chip Area



- Increasing A_{chip}
  - Decreasing $R_{DS(on)}$
  - Increasing C_{oss}

$$P_{V,T} = \frac{1}{G^* A_{chip}} I_{T,rms}^2 + f_P \frac{1}{2} C^* A_{chip} U_O^2$$

Ultra-Efficient PFC Rectifier Performance Limits

Inductor Power Density

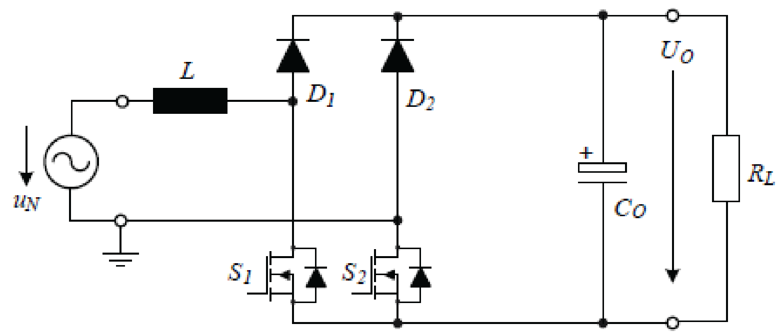
$$\Delta i \propto \frac{U_O}{L} T_P \rightarrow \underbrace{\frac{\Delta i}{I}}_{\alpha_{\Delta i}} \propto \frac{U_O}{LI}\frac{1}{f_P} \rightarrow LI \propto \frac{U_O}{\alpha_{\Delta i}}\frac{1}{f_P} \rightarrow \boxed{LI^2} \propto \frac{\overbrace{U_O I}^{P_O}}{\alpha_{\Delta i}}\frac{1}{f_P}$$

$$V_L \propto \frac{1}{2} LI^2 \propto \frac{P_O}{f_P} \rightarrow \rho_L = \frac{P_O}{V_L} \propto f_P$$

Optimum Semiconductor Area

$$P_{VT} = \frac{I_{T,rms}^{\;2}}{G*} \cdot \frac{1}{A_{chip}} + f_P \tfrac{1}{2} V_O^{\;2} C* A_{chip}$$

$$P_{VT} \rightarrow \mathrm{Min} \qquad \frac{\mathrm{d}P_{V,T}}{\mathrm{d}A_{Chip}} = 0$$



Relation of Efficiency and Power Density

$$P_{VT,min} \propto \sqrt{\rho_L}\sqrt{\frac{G*}{C*}P_o} \rightarrow \boxed{(1-\eta_{max}) = \gamma_T \underbrace{\sqrt{\frac{G*}{C*}}}_{FOM_{\eta\rho,1}} \sqrt{\rho_L}}$$

Ultra-Efficient PFC Rectifier Performance Limits

$$(1-\eta) \propto \frac{U_F}{U_O}$$

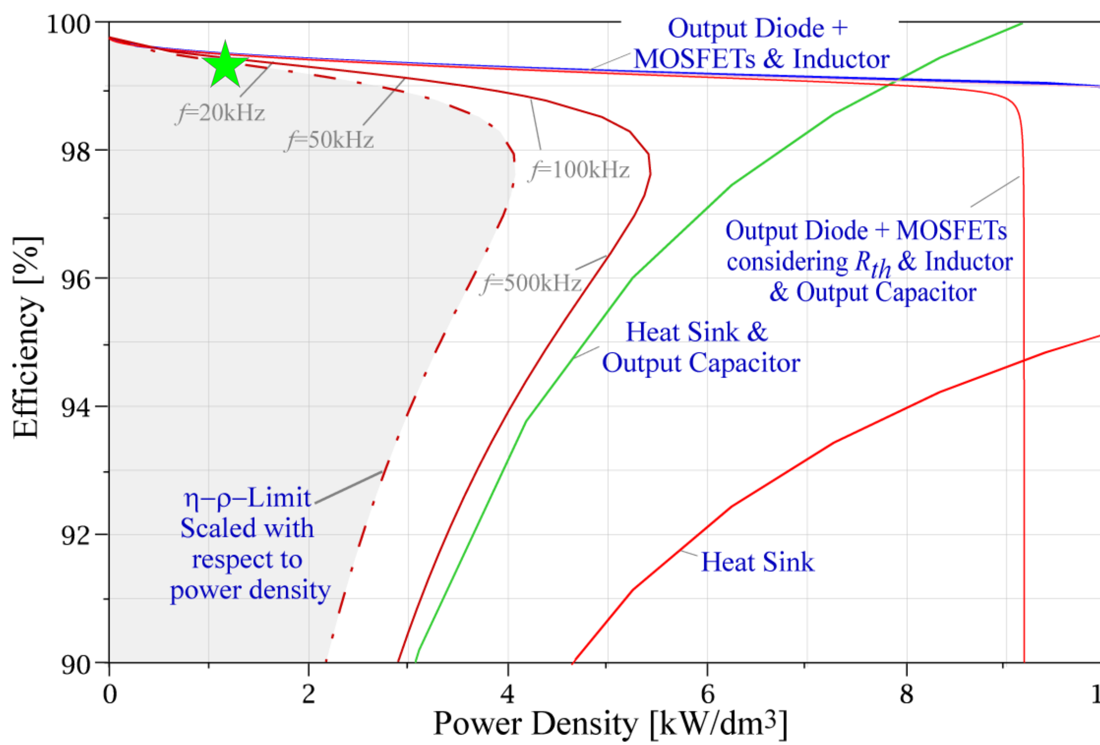
— Output Diodes
— Power MOSFETs
— Aux. Power

— Inductor
— Output Cap.
— Heatsink

$$\rho_{HS} \propto \frac{\eta}{(1-\eta)}$$

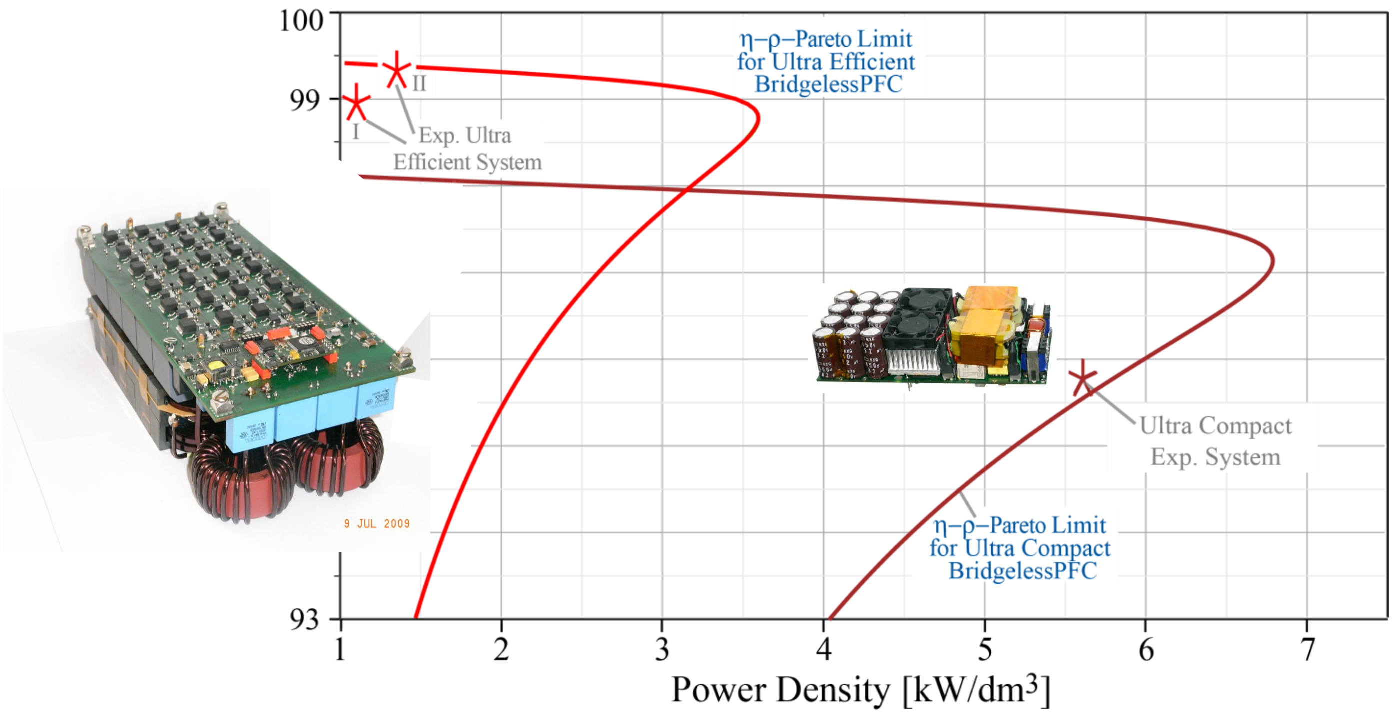
$FOM_{\eta\rho,1}$

$$(1-\eta) \propto \sqrt{\frac{G^*}{C^*}}\sqrt{\rho_L}$$



Feasible Performance Space

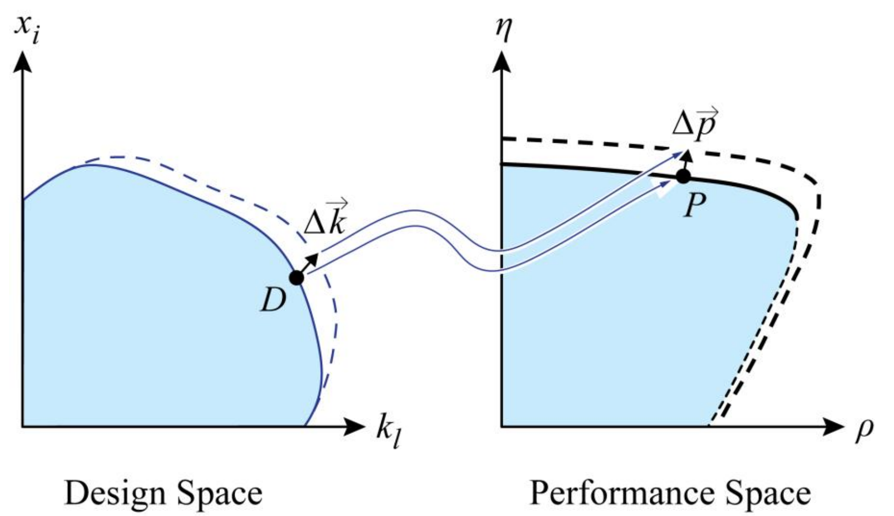
► **Bridgeless PFC Rectifiers @ u_N = 230V**

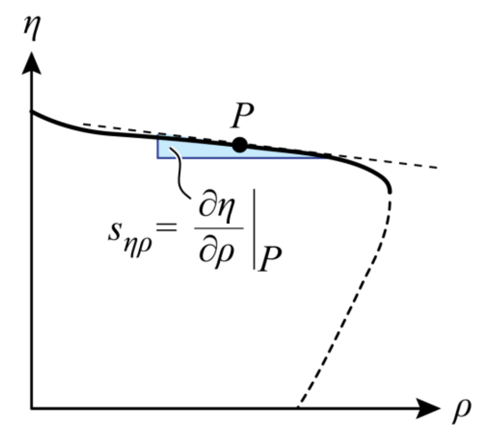


Power Density is Based on Net Volumes ➔ Scaling by 0.6-0.8 Necessary

Technology Sensitivity Analysis Based on η-ρ-Pareto Front

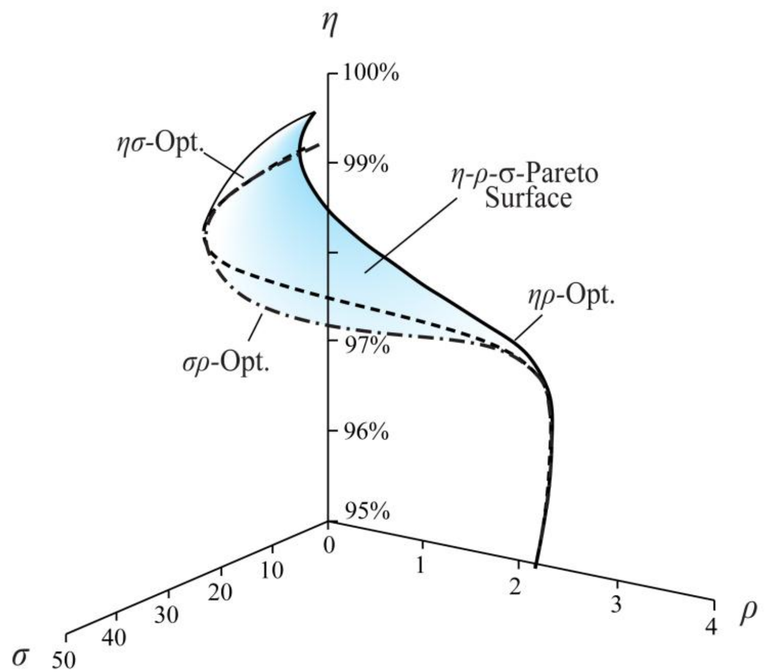
► Sensitivity to Technology Advancements
► Trade-off Analysis

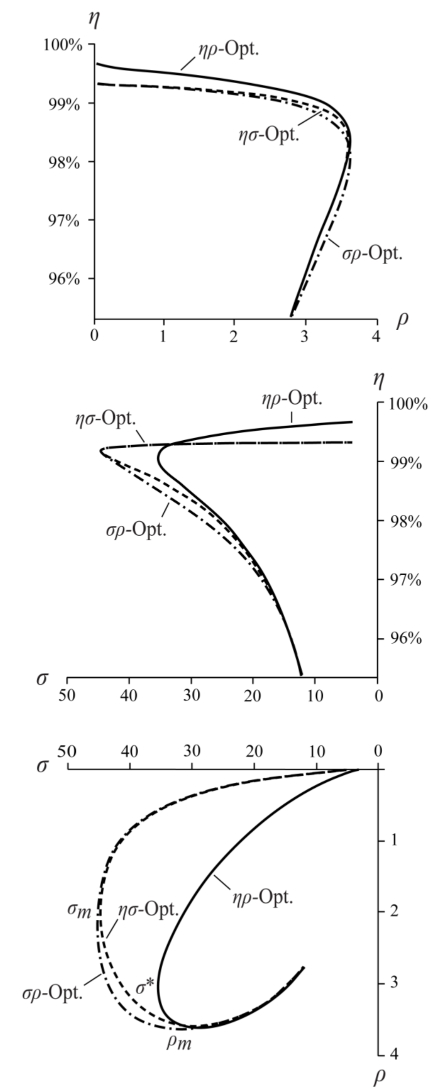




Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface

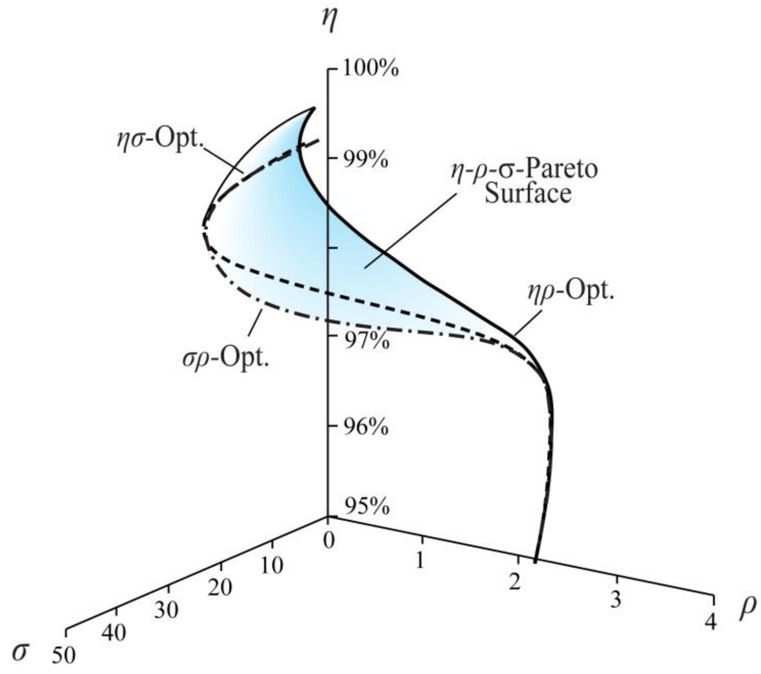
► σ: kW/$

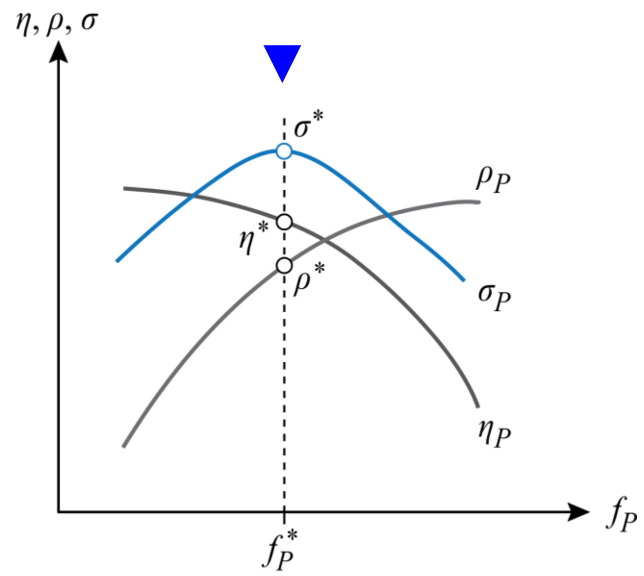




Converter Performance Evaluation Based on η-ρ-σ-Pareto Surface

► ´ *Technology Node*´

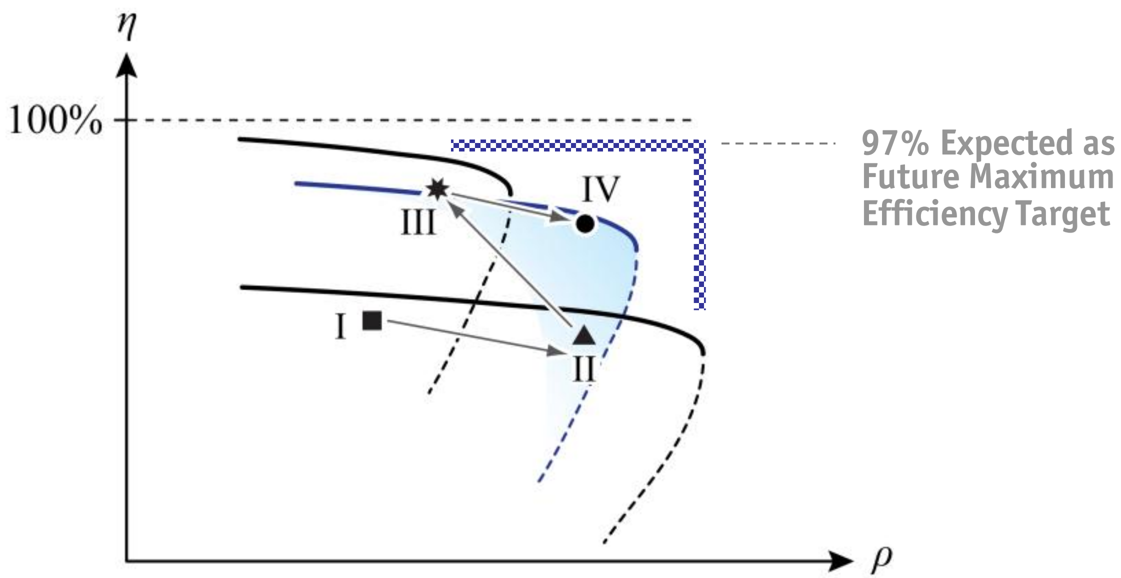




Technology Node: $(\sigma^*, \eta^*, \rho^*, f_P^*)$

Observation

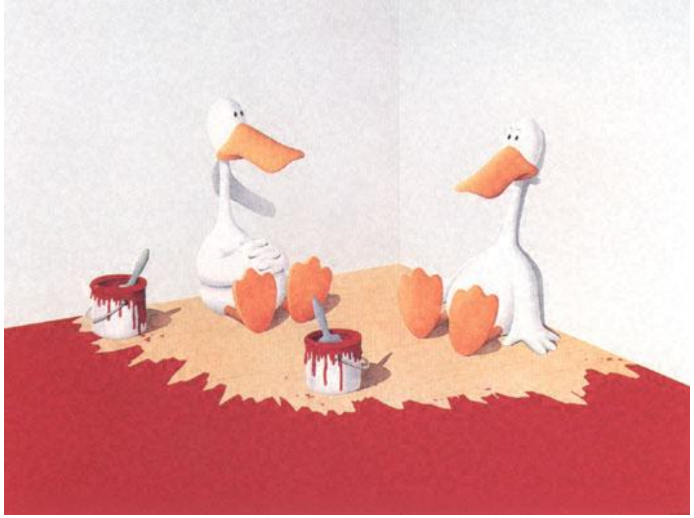
► **Very Limited Room for Further Performance Improvement !**



Observation

► **Very Limited Room for Further Performance Improvement !**

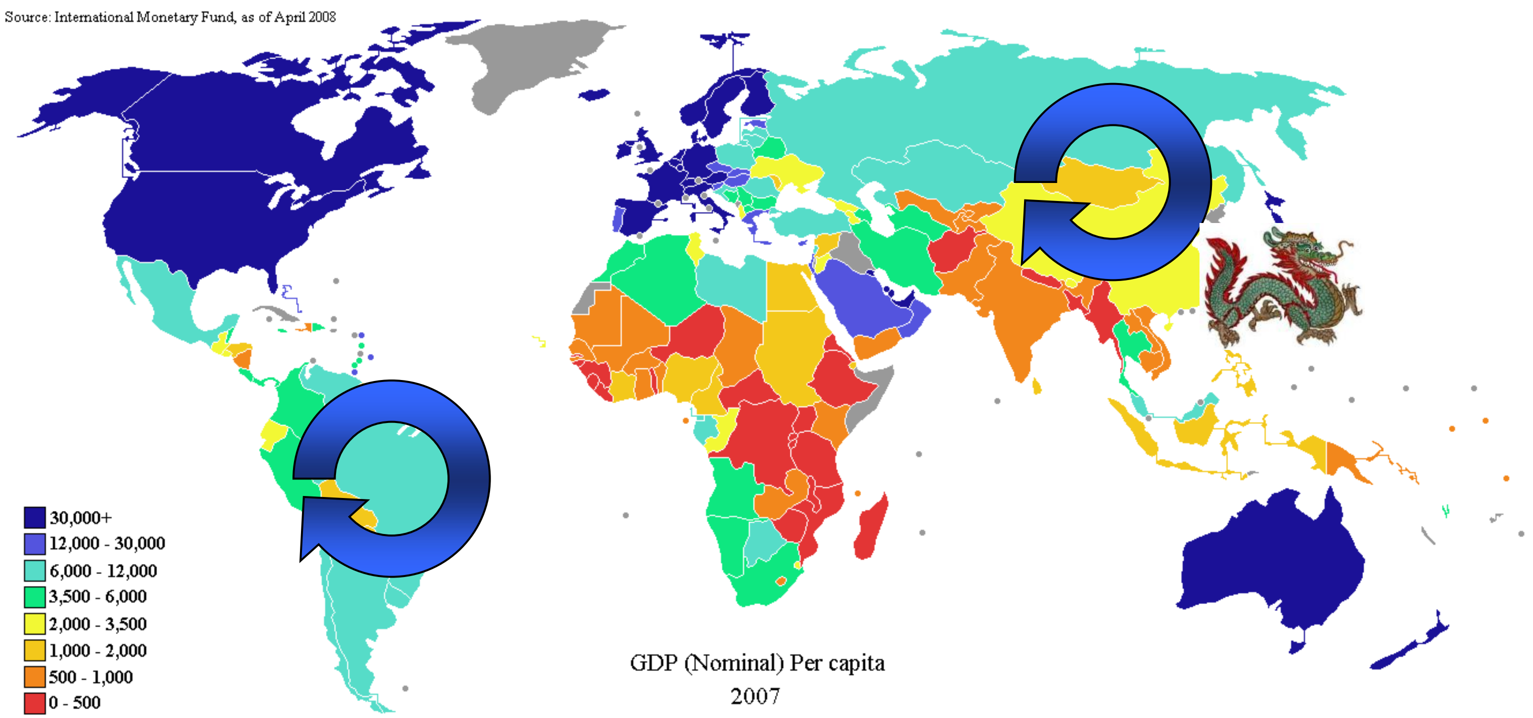
Efficiency



Power Density

Research Contribution of Newly Industrialized Countries

► Revision and Extension

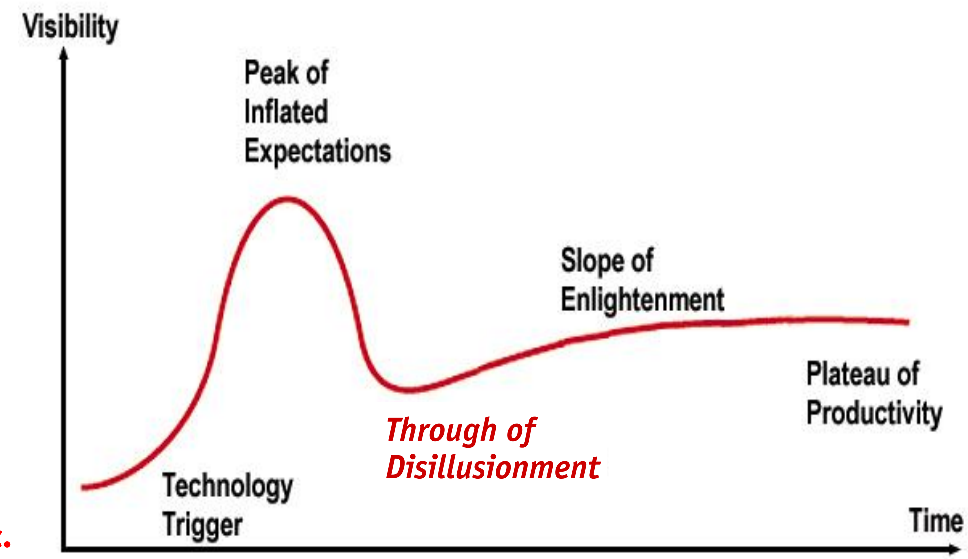


Component Technologies

Power Semiconductors
Interconnection / Packaging
Passives
Cooling

Observation

- ► Overestimation of Progress
- ► Hype Cycles of Technologies

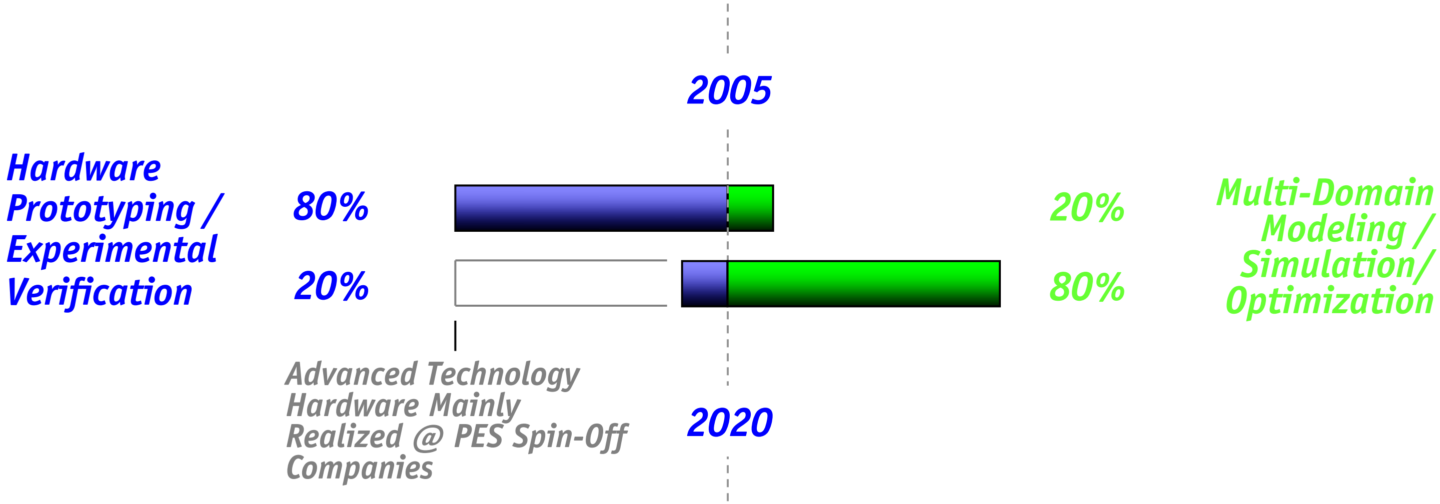


E.g., 3-Φ AC-AC Matrix Converter
vs. Voltage DC Link Converter, SiC, etc.

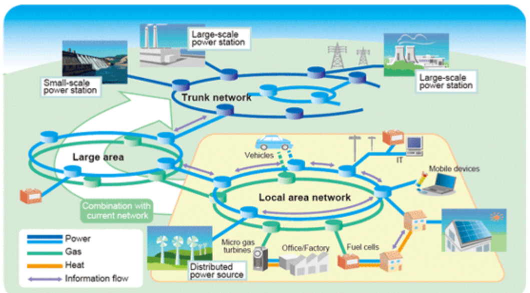
Observation

- ► No ´*Killer Application*´ for Low-Voltage SiC Switch
- ► Early Analysis of Technology Mapping Highly Beneficial !
- ► E.g., Evaluation of GaN

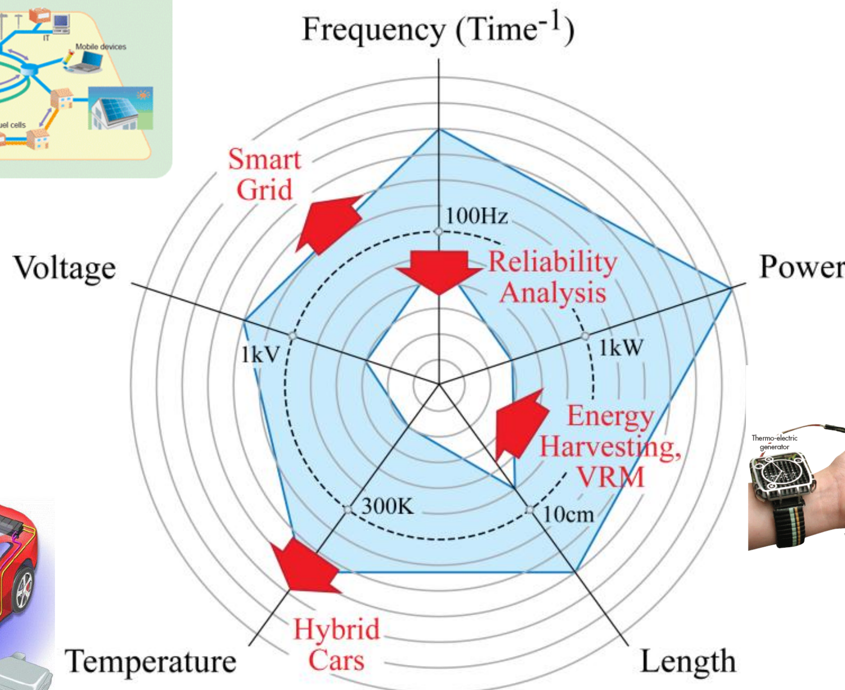
PES Future Activities Profile

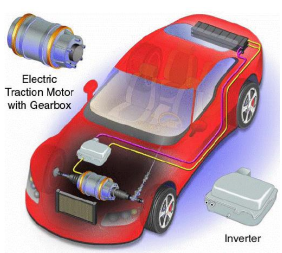


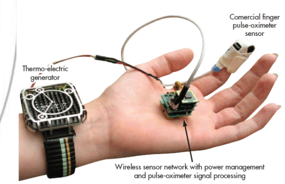
Possible Future Extensions of Power Electronics Systems Applications



Source: AIST





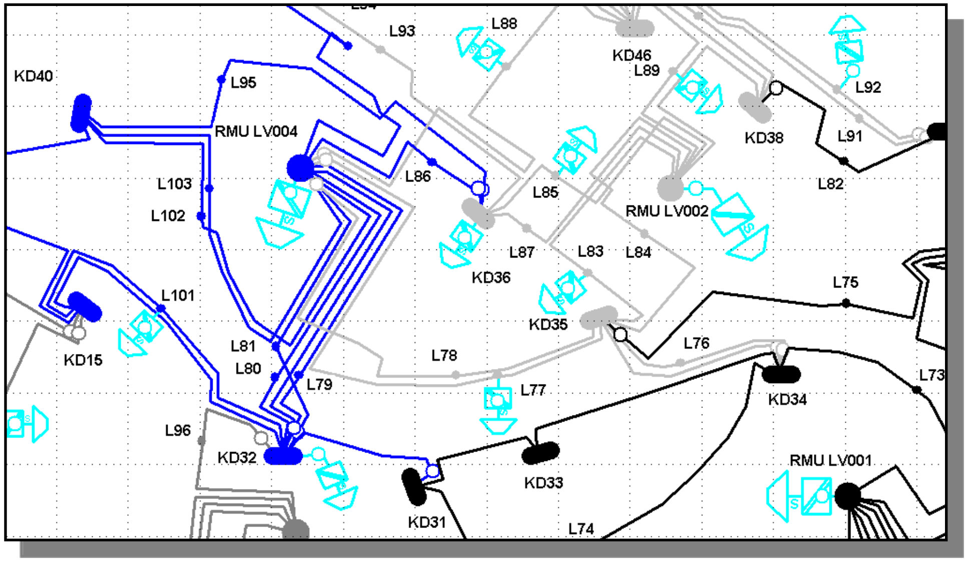


Smart Power Delivery System

Extension of Existing Electricity Network

- Decentralized Energy Generation/DER Integration
- Decentralized Storage
- Decentralized Sensors and Computing
- Data Communication Network
- Advanced Power Electronics Electricity Routers

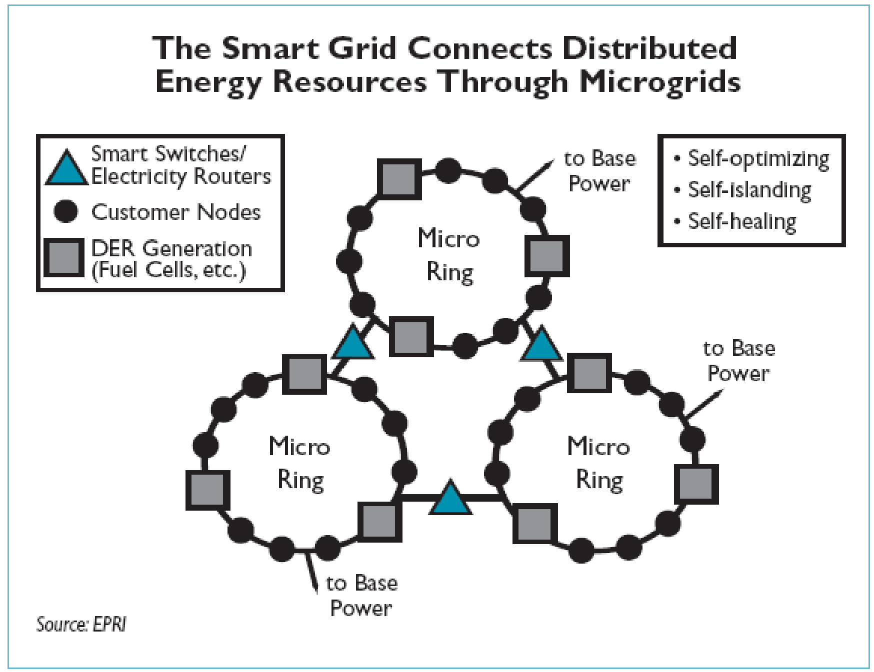
Virtual Utilities Microgrids



Bi-Directional Flow of Energy and Information – Interactive Highly Reliable and Economical Grid

Smart Grid / Microgrid Concept

Solid-State Power Flow Control
Electricity Routers



Looped Configuration
Self-Sufficient Islands
High Reliability / Power Quality

Summary

- ► Virtual Prototyping - Multi-Domain/Objective Optimization
- ► Non-Traditional Topics Still not Well Covered - Reliability/Packaging
- ► Further Standardization

- ► New Application Areas – New Challenges - High Voltage/Frequency
- ► More Application Specific Converters

- ► Systems Instead of Converters - Smart Grid, Green Buildings etc.
- ► Converter to be Seen as Building Block – Continuous Improvement

Challenge

- ► Several Topics Out of Typical Power Electronics Experts Field of Experience - This also Applies for Traditional Academic Education in Power Electronics

Paradigm Shift Required !

- ► It´s Not Going to be an Easy Task

Thank You!

Questions ?

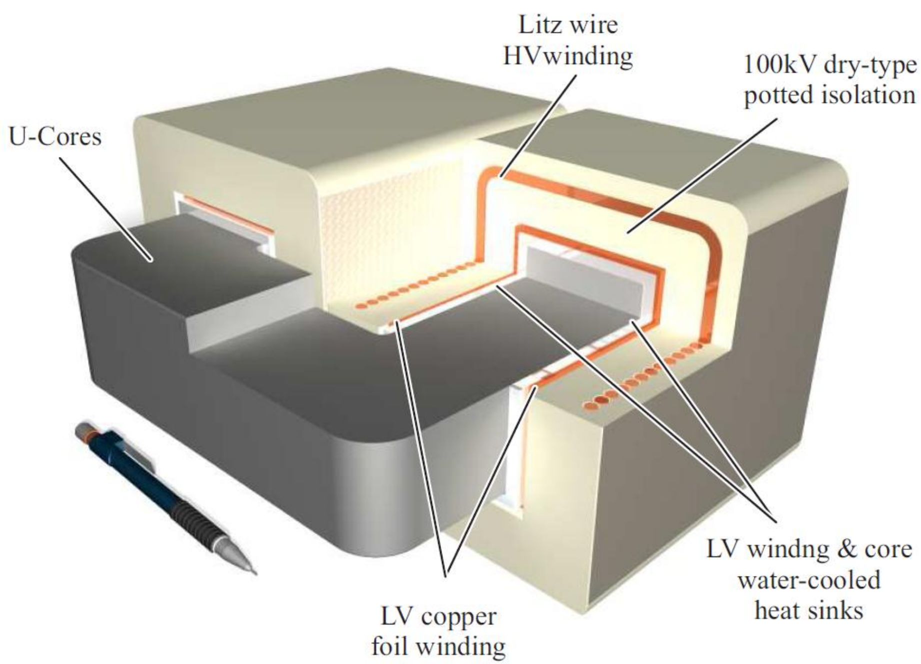
Transformer Concepts

- ▶ Core Material – Vitroperm 500F
- ▶ LV Winding – Loss Optimized Copper Foil
- ▶ MV Winding – Litz Wire / Litz Cable

DBA @ Triangular Modulation

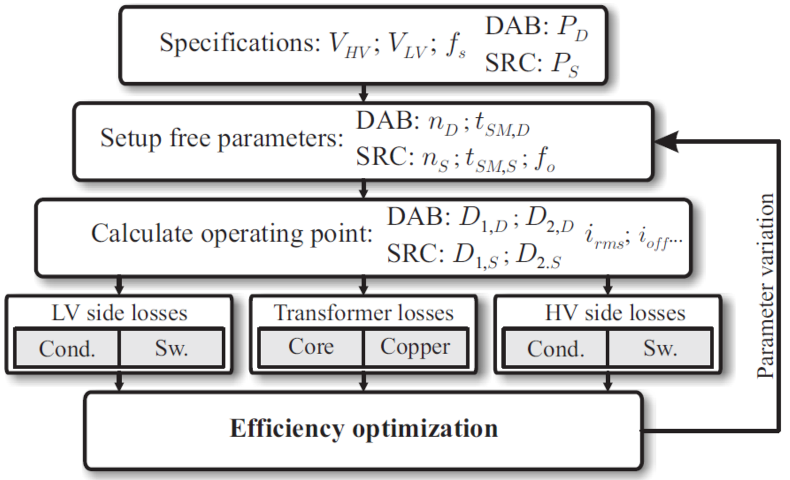
Losses	Core	1.26kW
	Copper	1.55kW
	Total	2.81kW

Efficiency 99.72%
Power Density 232kW/dm^3



- ▶ Core-Type Concept

Converter Design

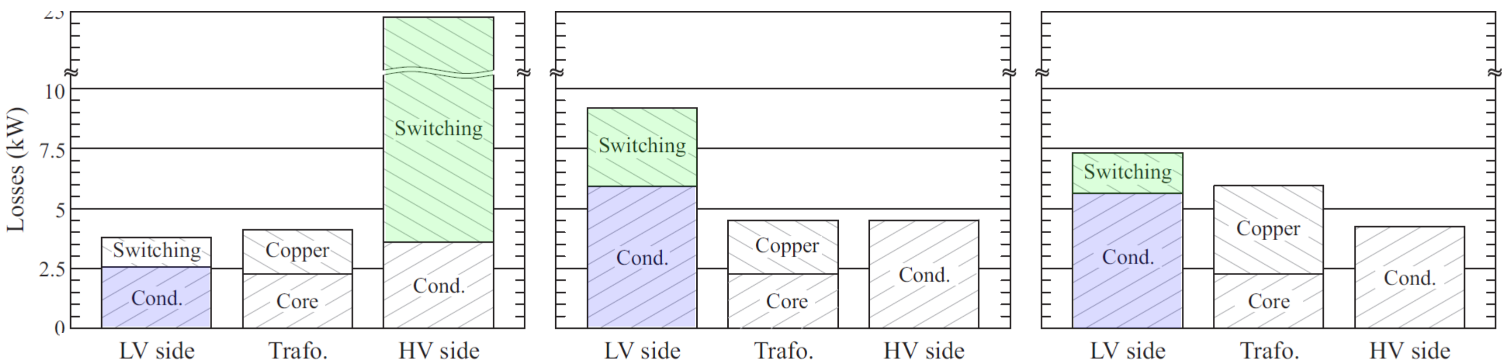


- Transformer Concept
- DAB or SR Converter Topology

Converter Power Loss Partitioning

▶ LV Switch Realized by Series / Parallel Connection of SiC JFETs (SemiSouth)
▶ MV Switch Realized by 4.5kV IGBTs in Multi-Level Arrangement
▶ Matrix-Type Transformer

- DAB Trapezoidal Modulation
- DAB Triangular Modulation
- SRC Constant Frequency Operation



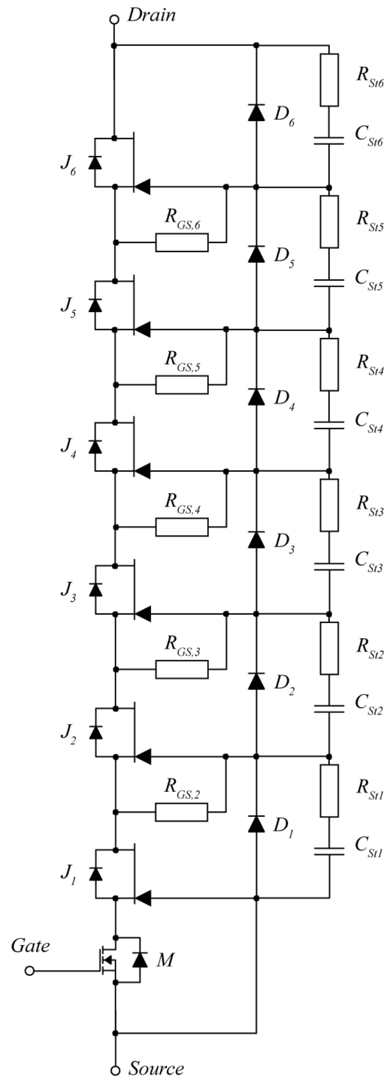
Si/SiC Super Cascode Switch

➔ HV-Switch Controllable via Si-MOSFET

* 1 LV Si MOSFET
* 6 HV SiC JFETs
* Avalanche Rated Diodes

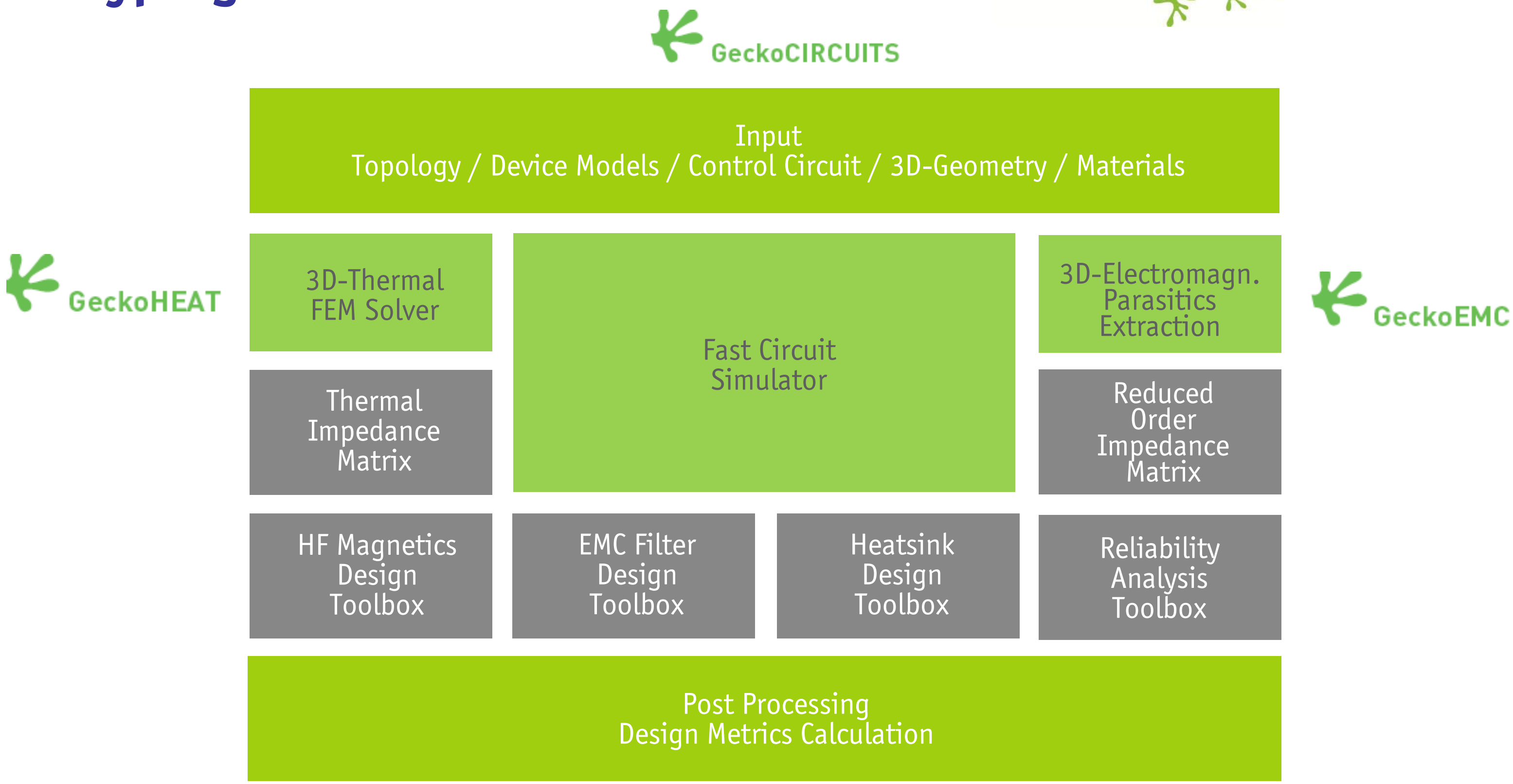
➔ Ultra Fast Switching
➔ Low Losses
➔ Parasitics

* Passive Elements for Simultaneous Turn-on and Turn-off
* Stabilization of Turn-off State Voltage Distribution



Turn-On

ETH Zurich Virtual Prototyping Platform



Device Database
Controls Toolbox
Optimization Toolbox

Inductor Losses in Dependency of Volume

Operating Conditions and Parameters

$$L, f_P, I \qquad \Phi \propto L\, I$$

- **Scaling of Core Losses**

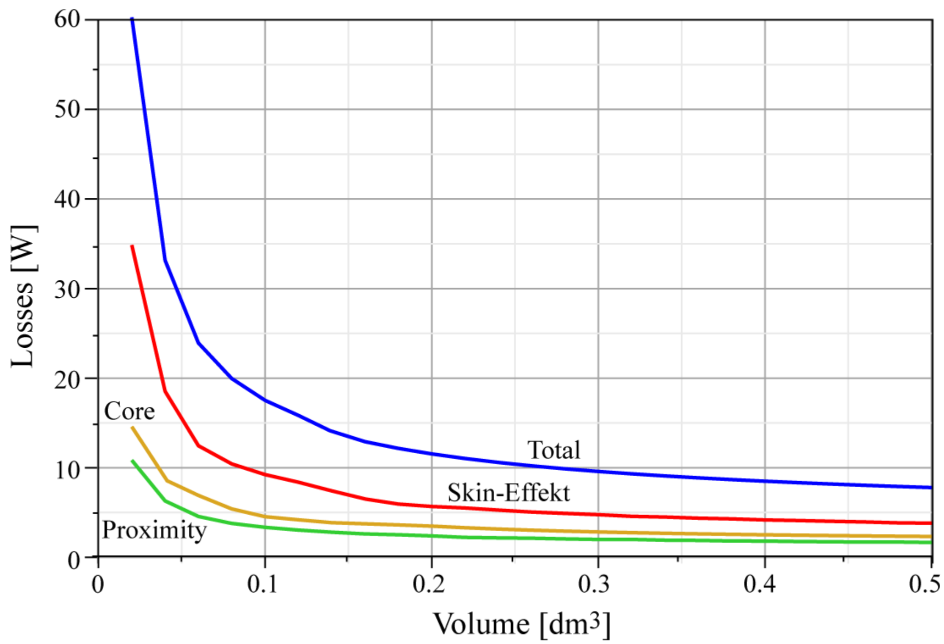
$$P_{Core} \propto f_P (\frac{\Phi}{A})^2 V$$

$$P_{Core} \propto (\frac{1}{l^2})^2 l^3 \propto \frac{1}{l}$$

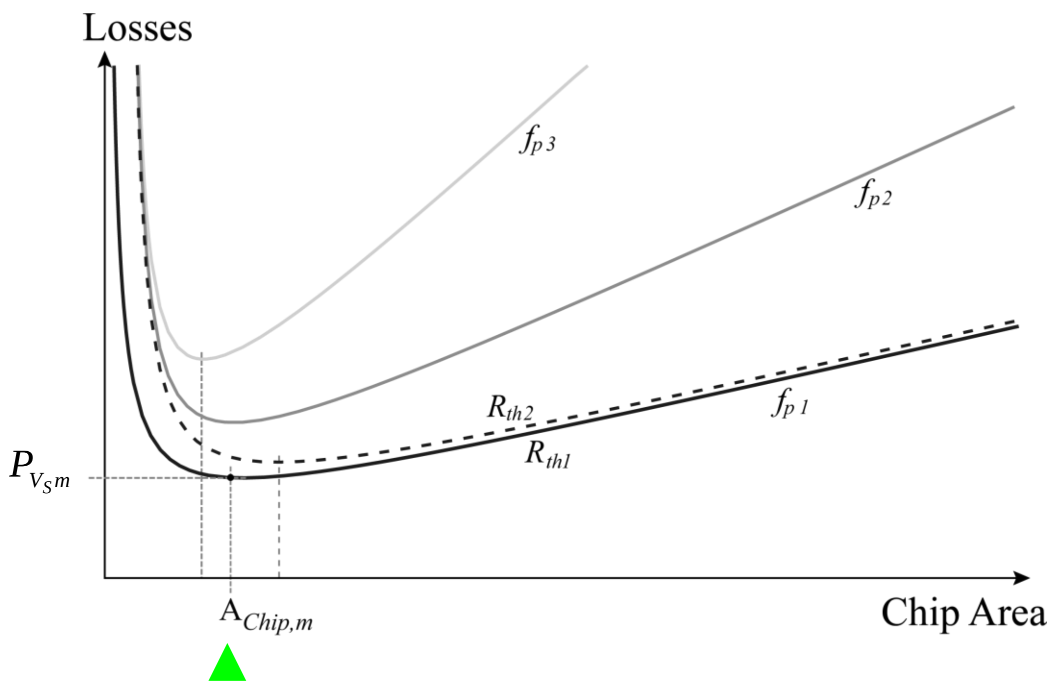
- **Scaling of Winding Losses**

$$P_{Wdg} \propto I^2 R \propto I^2 \frac{l_{Wdg}}{\kappa A_{Wdg}}$$

$$P_{Wdg} \propto \frac{1}{l}$$



Minimum Loss MOSFET Chip Area



- **Dependency on f_P and R_{th}**

Ultra-Compact PFC Rectifier Performance Limits

$$(1-\eta) \propto \frac{U_F}{U_O}$$

— Output Diodes
— Power MOSFETs
— Aux. Power

— Inductor
— Output Cap.
— Heatsink

$$\rho_{HS} \propto \frac{\eta}{(1-\eta)}$$

$FOM_{\eta\rho,1}$

$$(1-\eta) \propto \sqrt{\frac{G^*}{C^*}}\sqrt{\rho_L}$$