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Source: Dipardiou

# *Next-Generation Datacenter MV Interfaces — Will Solid-State Transformers Meet Their Waterloo?*

**Johann W. Kolar | Jonas E. Huber**

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

***Industry Session 3.3***

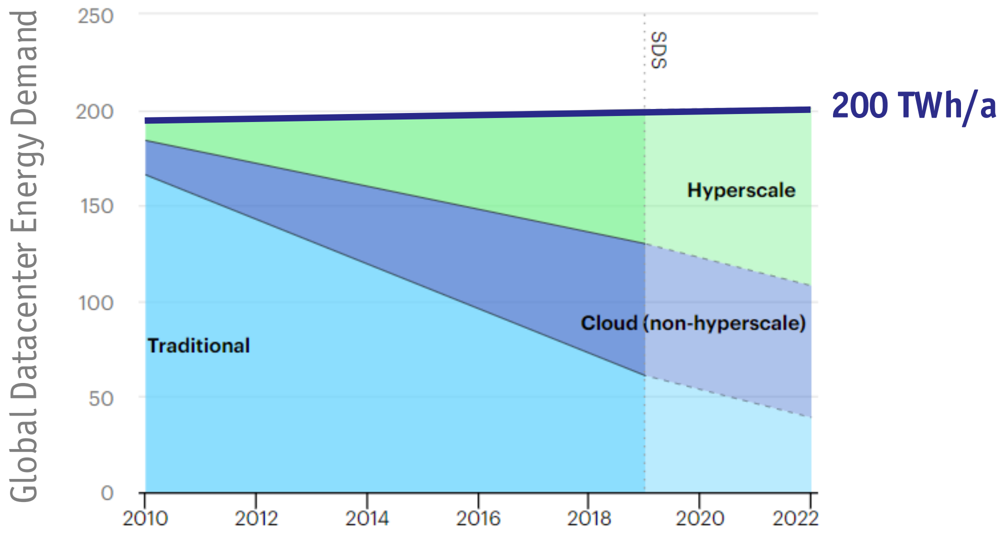
High Performance Power Electronics for High Performance Computing

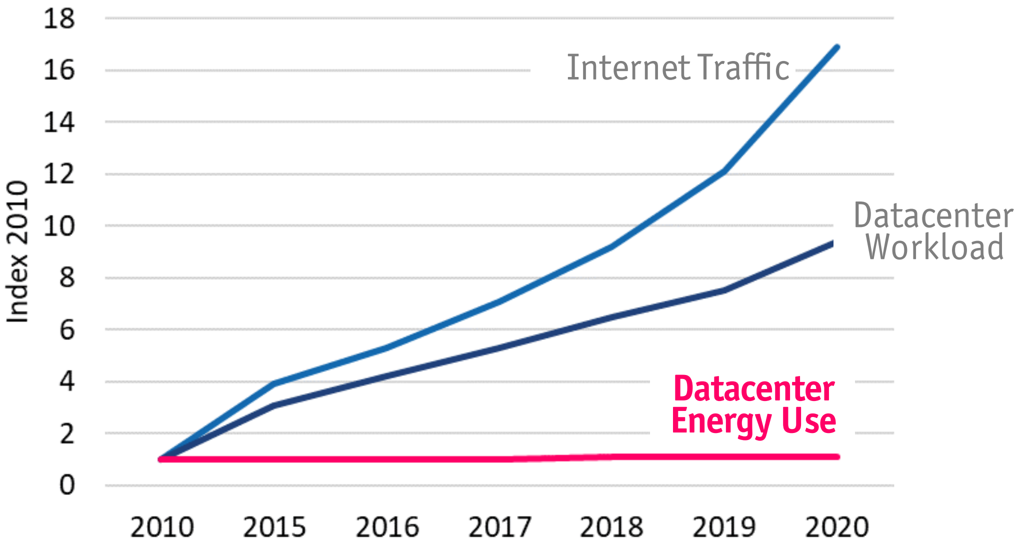

# Outline

- *Introduction*
- *AC or DC Power Distribution*
- *Medium-Voltage AC/DC Interfaces*
- *Comparative Evaluation*
- *Conclusions*

# Global Data Center Electricity Demand

- *Datacenters Consume ≈ 200 TWh/a | ≈ 1% of Global Electricity Demand*
- *Energy Costs Dominate Overall Life-Cycle Costs*



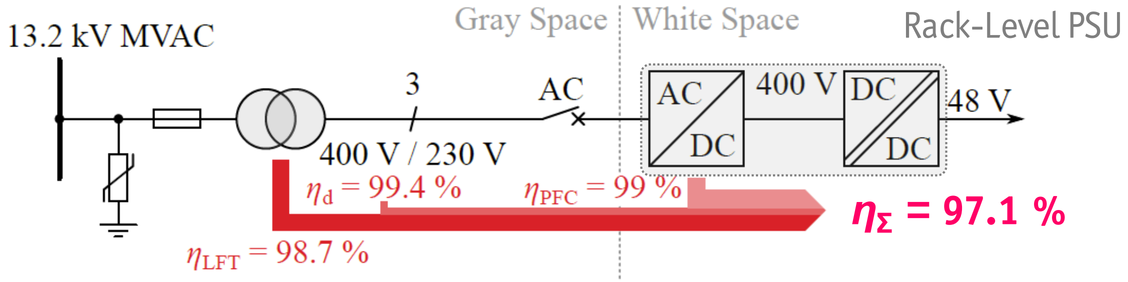




Source: www.iea.org

- *Decoupling of Computing Workload & Energy Use*
- *Efficiency Improvements on All Levels — Computing Equipment | HVAC | … | Power Conversion System*

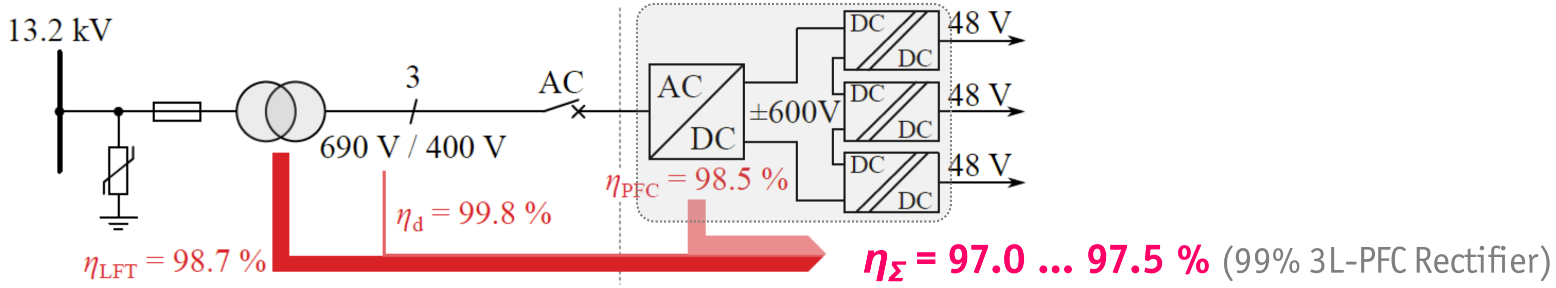
# AC Power Distribution

- *State-of-the-Art Distribution — 400V AC*




(Standard Oil-Filled Distr. Transf.)

- *Increased Distribution Voltage — 690V AC*

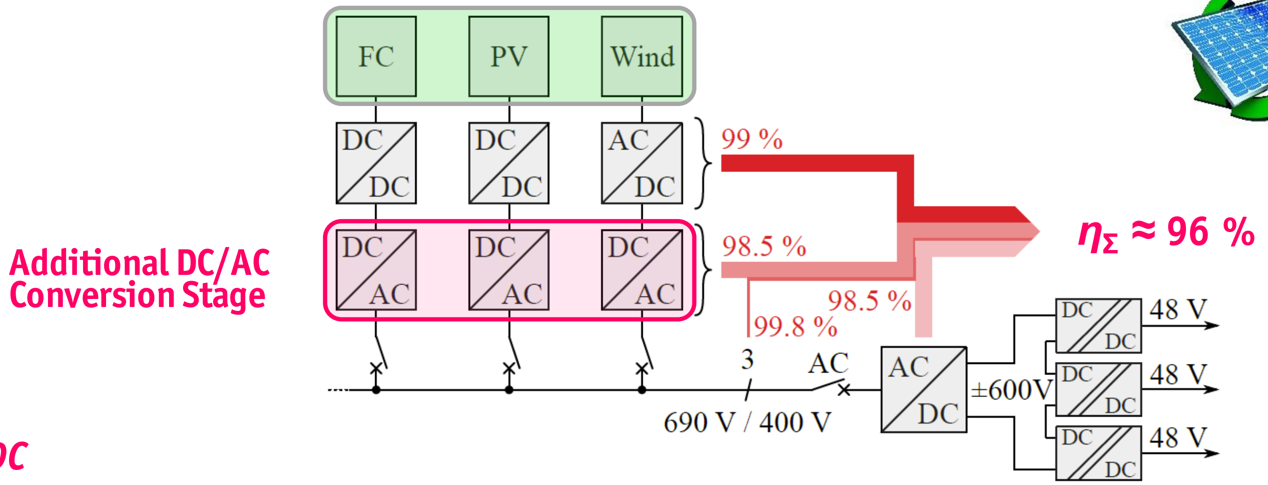



(Standard Oil-Filled Distr. Transf.)

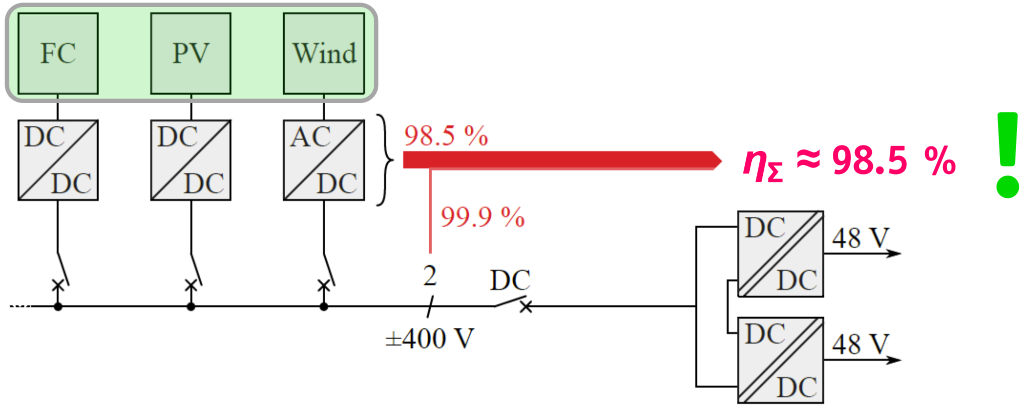
- $\eta_d \rightarrow$ *Distribution Efficiency for 1MW Using Delta EcoTech BL 200A Busbar*
- $\eta_\Sigma \rightarrow$ *Overall Efficiency — MVAC Down to Rack-Level DC/DC Conversion*

# Integration of Renewables — DC Power Distribution

- *690V AC*



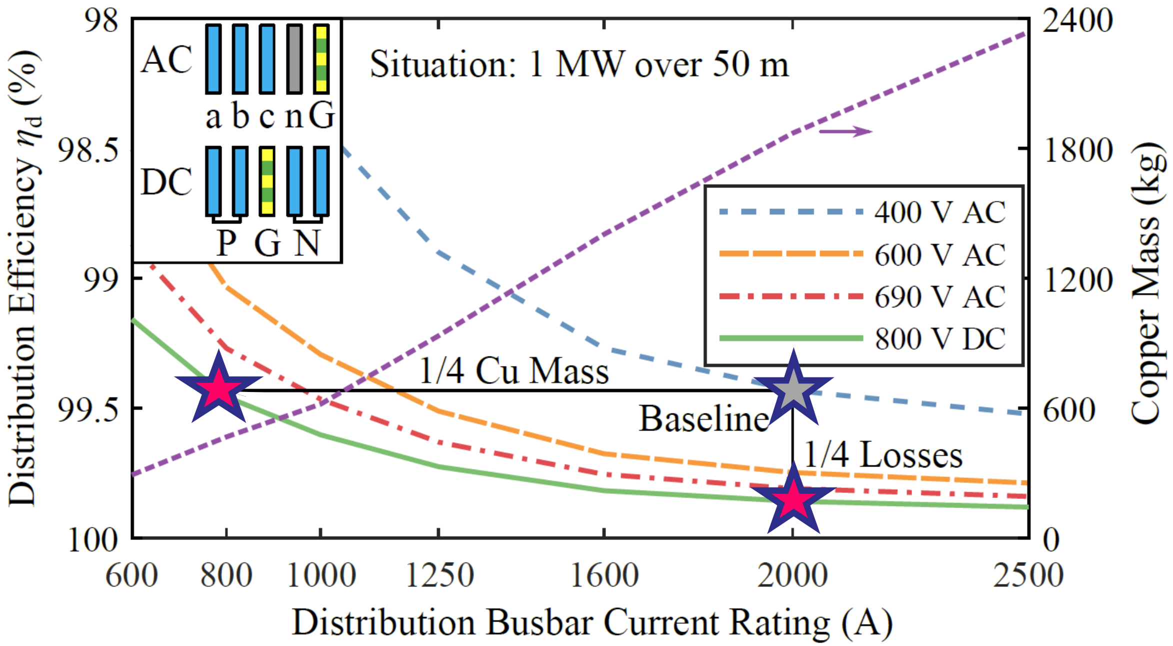

- *± 400V DC*




- *DC Distribution Leverages DC Output of PV / Batteries / Fuel-Cells*
- *Remark — Utility-Scale Renewable Energy System Requires Higher Voltage DC Collector Grid*

# DC Power Distribution

- *400V AC → ± 400V DC (800V DC)*
- *Utilizing Same Busbars as for AC Distribution (Delta EcoTech BL @ 60°C)*

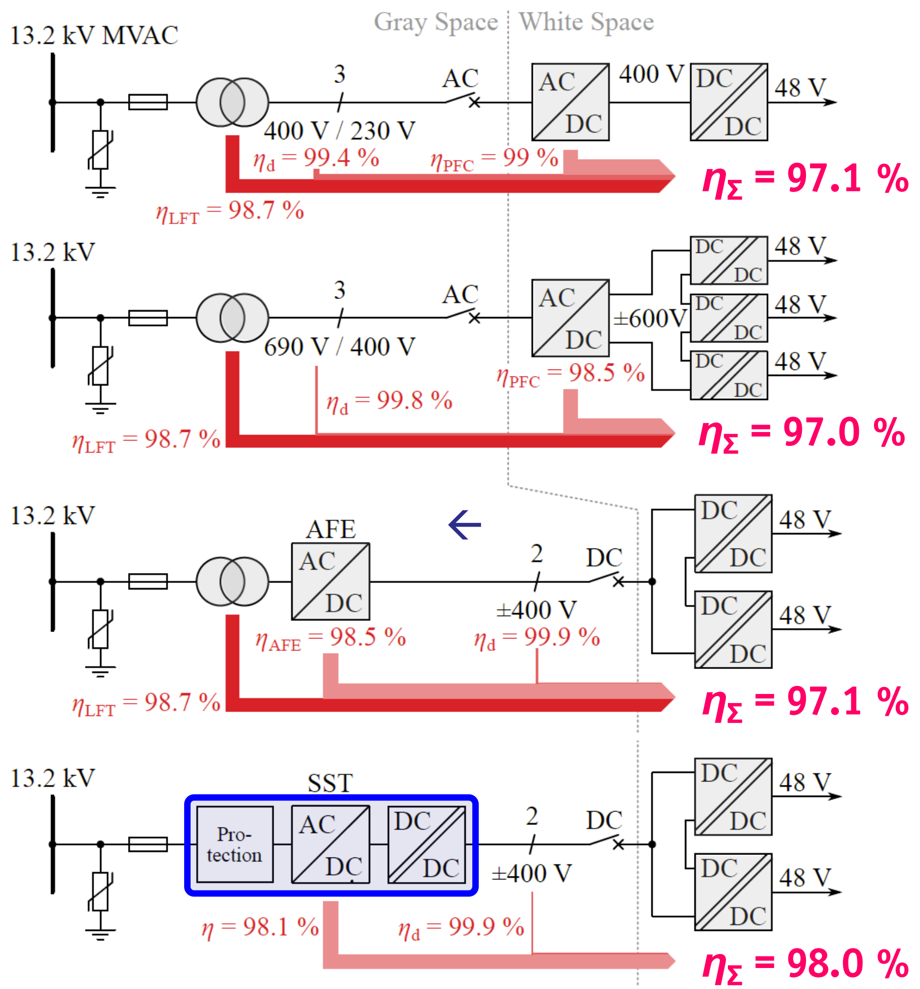



- *-75% Distribution Losses OR -75% Copper Mass*
- *DC Distribution Challenges — Protection | DC Breakers etc.*

# Comparison of AC and DC Power Distribution

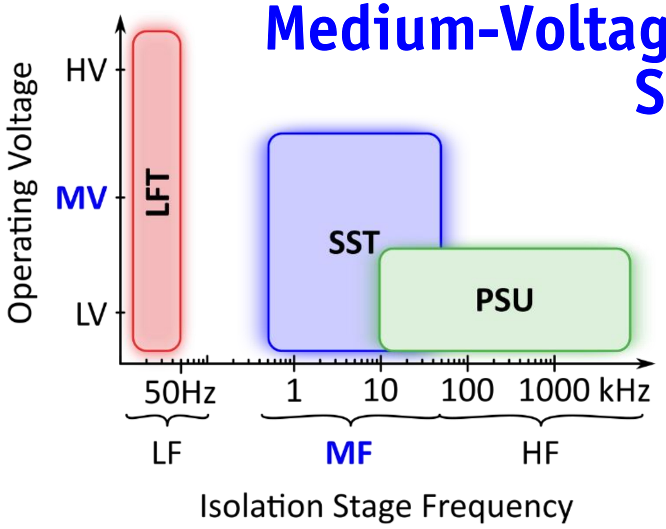
- *State-of-the-Art 400V AC*
- *690V AC*
- *± 400V DC*
- *± 400V DC*

  *Future Solid-State Transformer Based MV Interface*




- *$\eta_\Sigma$ Similar to AC Distribution*
- *$\eta_\Sigma$ Improvement for $\eta_{SST}$ > 97.2%*

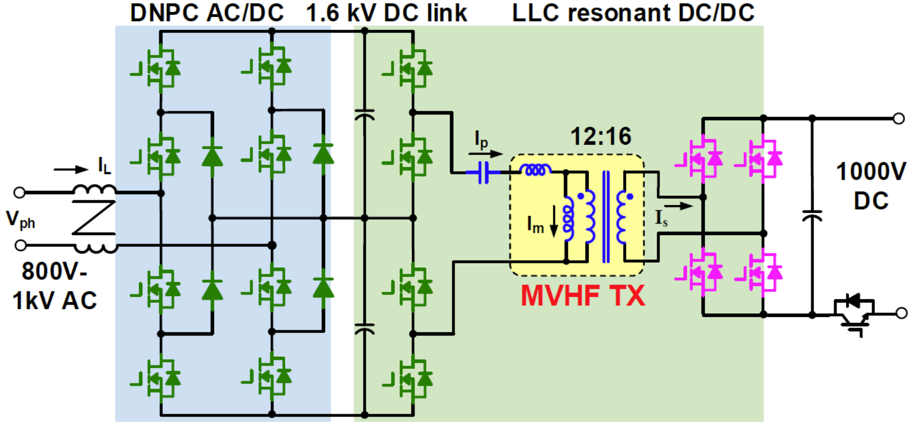
# Medium-Voltage AC → Low-Voltage DC
# Solid-State Transformers

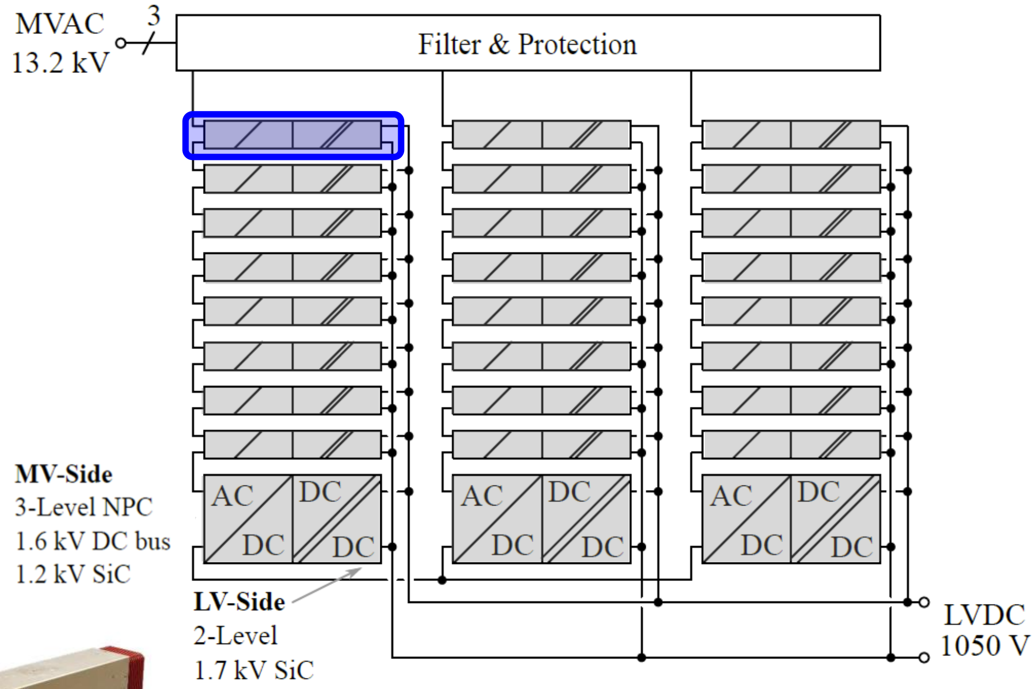


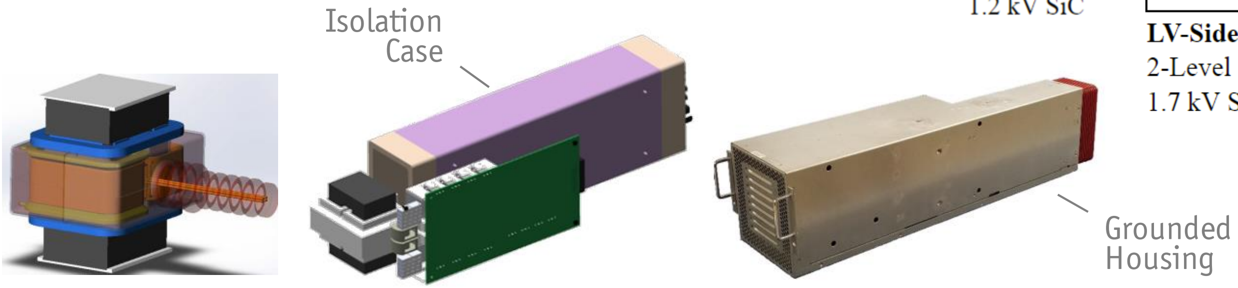
# 3-Φ 13.2kV / 400kW SST-Based EV Charger

Source: Ch. Zhu, 2021

- *Most Advanced Industrial SST Prototype (US DOE Project 2018 - 2021)*
- *3 x 9 = 27 AC/DC— DC/DC Cells → 438 Switches*
- *Forced-Air Cooling*




- *15 kW Cells (≈ 0.5 kW/dm$^3$) / All-SiC Realization | 100+ kHz MFT (≈ 8.5 kW/dm$^3$ w/o Bushing!)*

# 3-Φ 13.2kV / 400kW SST-Based EV Charger

- *Most Advanced Industrial SST Prototype*
- *3 x 9 = 27 AC/DC— DC/DC Cells → 438 Switches*
- *15 kW/Cell / All-SiC Realization*
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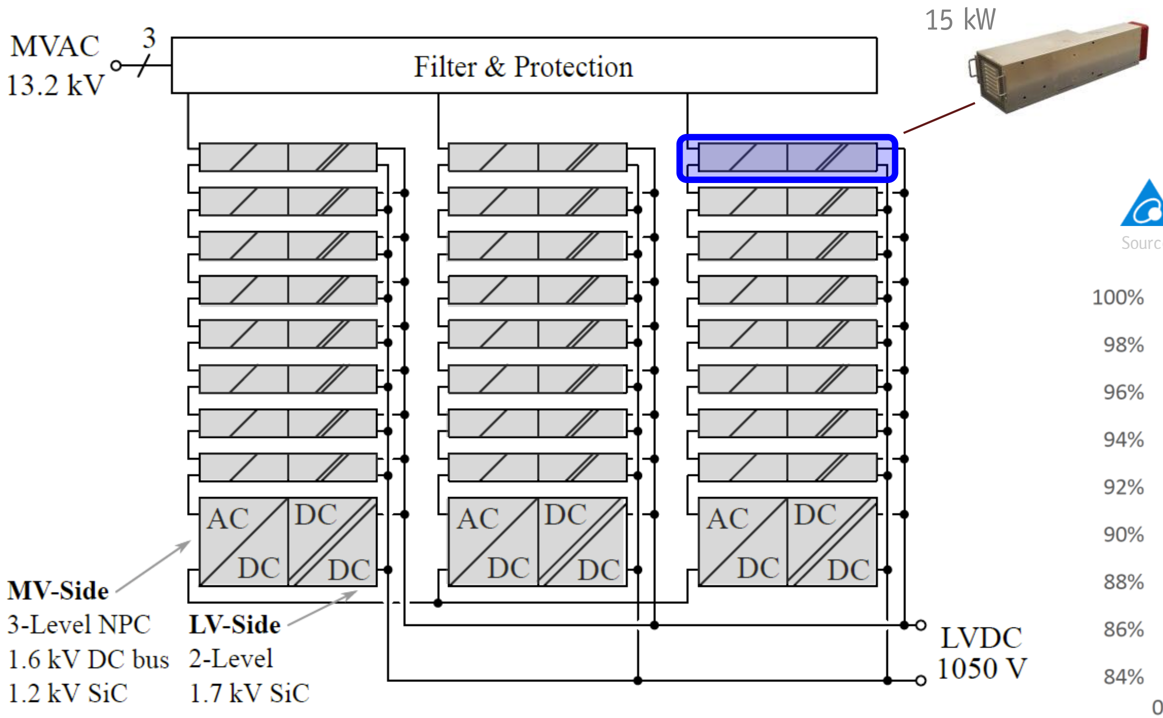
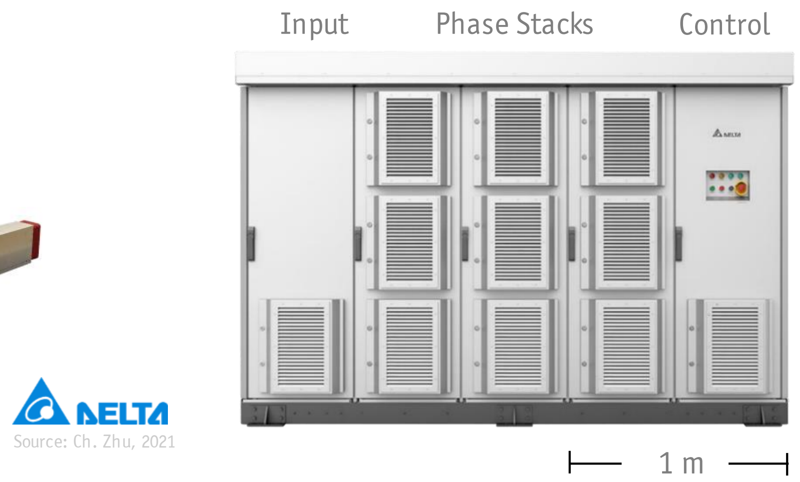
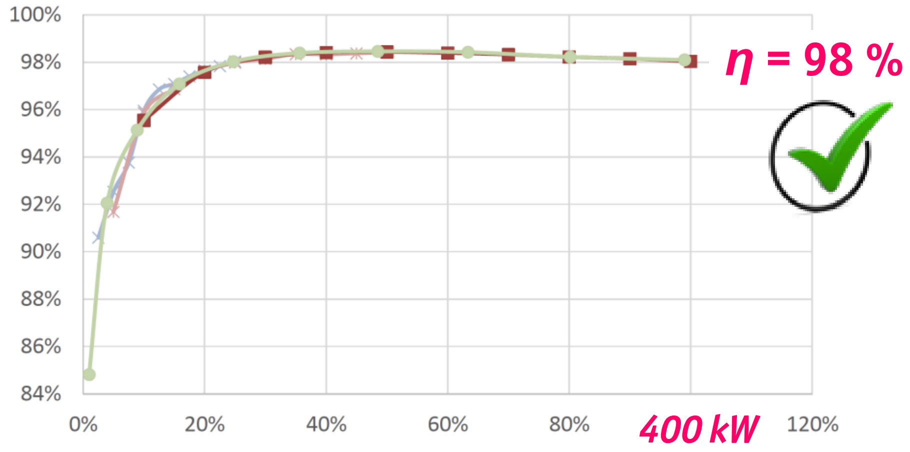


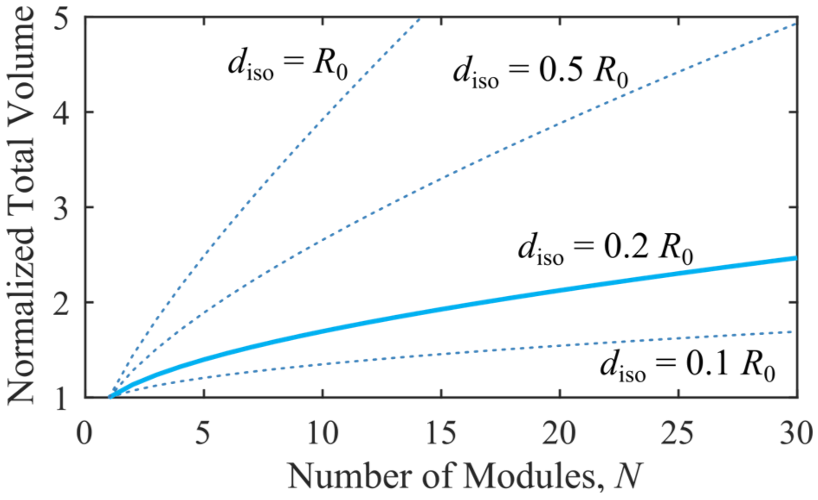

- *3000kgs Weight* | *3100 x 1300 x 2100 mm Outer Dimensions*
- *Power Density → 0.05kW/dm³ (System) | ≈ 0.5 kW/dm³ (Cells) | ≈ 8.5 kW/dm³ (MFT)*

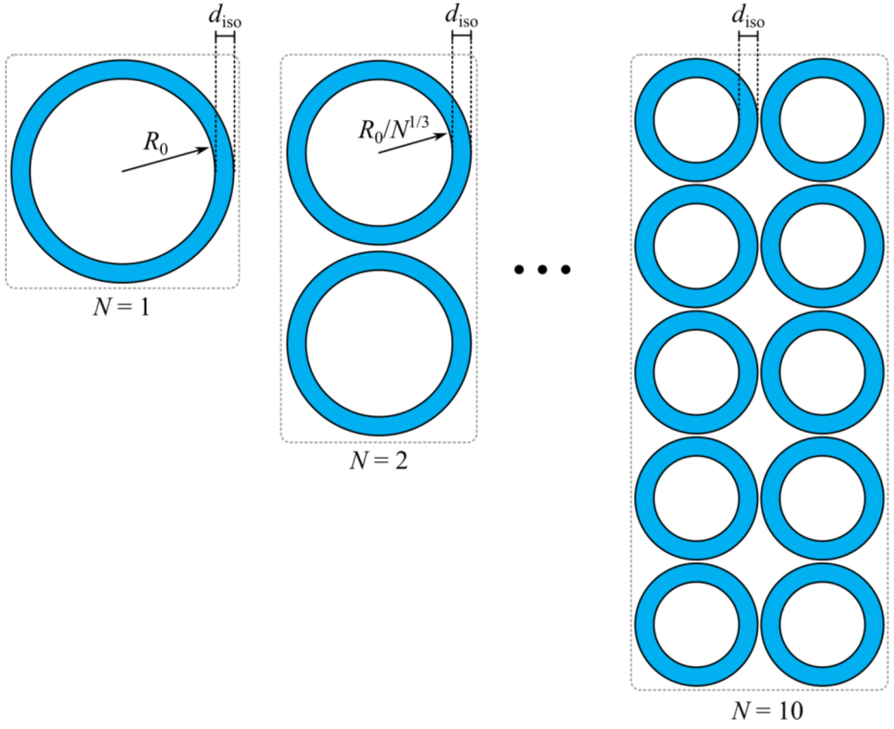
# Modularization Penalty

- ***Highly (!) Simplified Consideration***

— *Power P Processed in Sphere with Radius $R_0$*
— *Modularization Assuming const. P/V [W/in$^3$]*
— *Const. Isolation / Overhead Distance $d_{iso}$*

$$V(N) = \frac{4}{3}\pi\left(\frac{R_0}{N^{1/3}} + d_{\mathrm{iso}}\right)^3 \cdot N$$



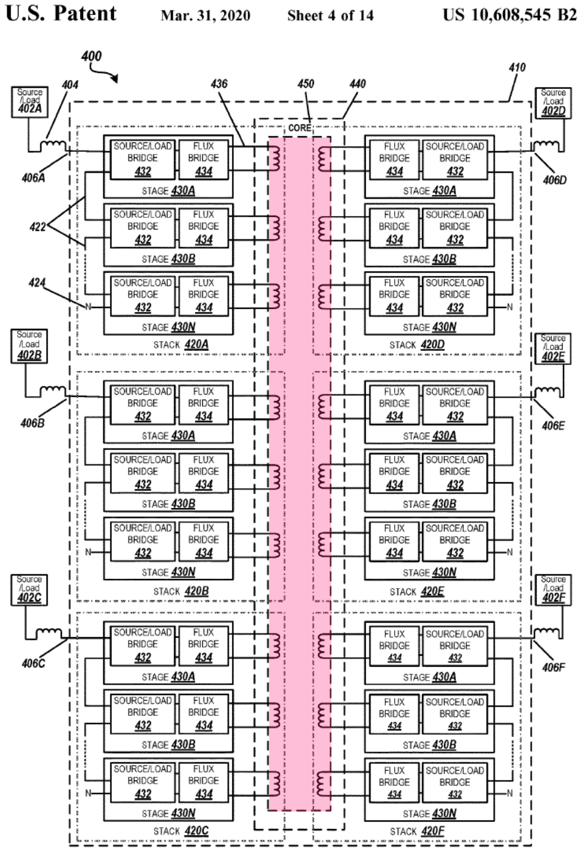

2-D Visualization with $d_{\mathrm{iso}} = 0.2\ R_0$

- ***High Number of Modules → Massive Reduction of Overall Power Density***
- ***Additional Overhead → Input & Output Filters | Protection Equipment | Mech. Assembly | Cabinets etc.***

# 3-Φ 15kV / 3.2 MVA SST-Based EV Charger

- *Fully Modular Topology*
- *25% Redundancy*
- *Zero Inrush Current*
- *125 kV Impulse Basic Insulation Level w/o Arresters*
- *Simple Fuse & Disconn. Switch as MV-Grid Interface*
- *1.5m x 1.6 x 2.4m Outer Dimensions → 0.5kW/dm$^3$*

RESILIENT POWER



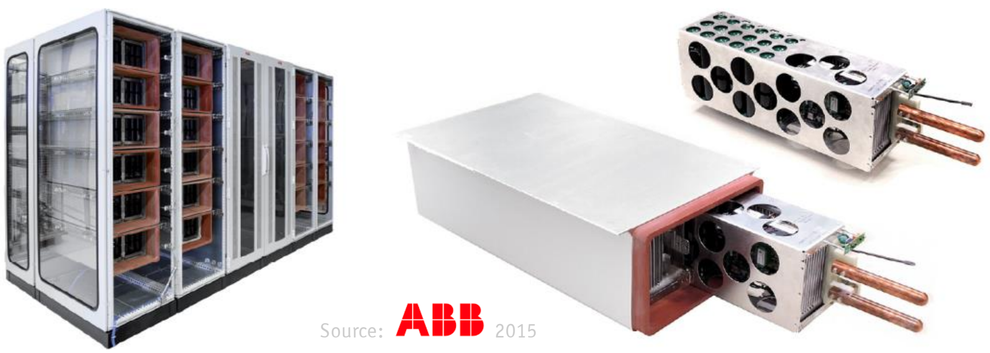

*"Synchronous Common Coupling"*

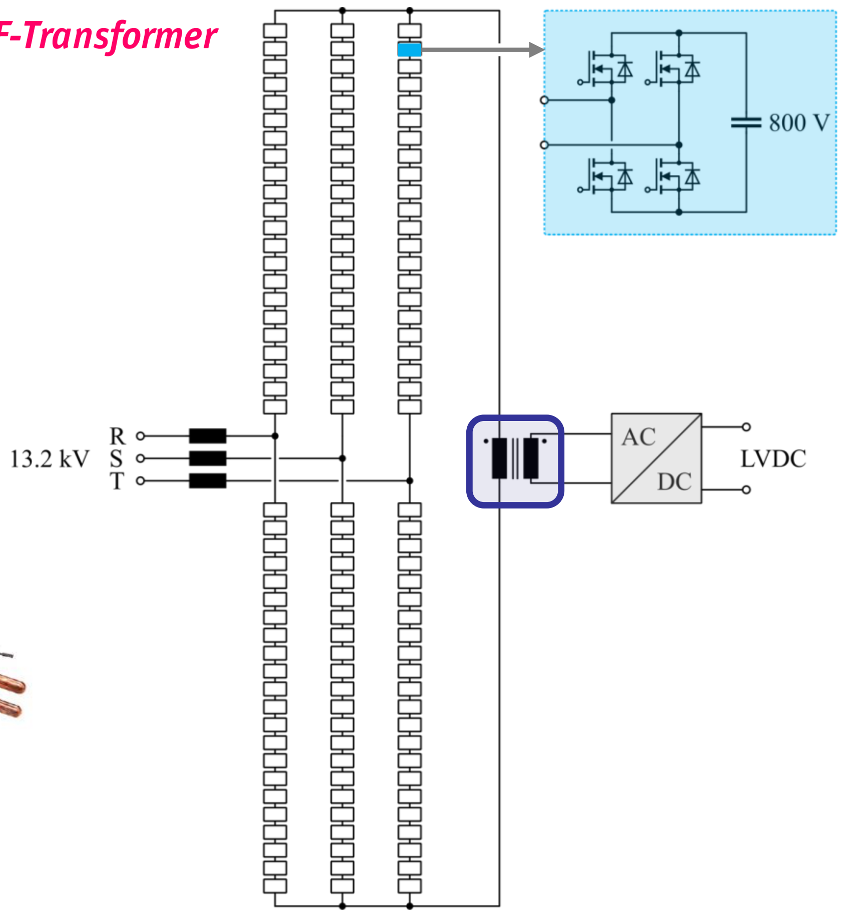
- *Efficiency Not Specified*
- *Insulation Type Not Specified (in Case of Oil → Maintenance / Environmental Issues / Fire Hazard)*

# 3-Φ Modular-Multi-Level-Based SST

- *Modularity Limited to Power Semiconductors* | *Single MF-Transformer*
  - *Example of 13.2 kV Grid*
  - *22 Full-Bridge Cells / MMC-Arm*
  - *528 x 1200V Switches (MV-Side)*

- *Example of Adv. Integration Technology*
  - *4 MMC-Arms*
  - *9 Half-Bridge Cells (1kV, 600A)*
  - *Hot Pluggable Cells*

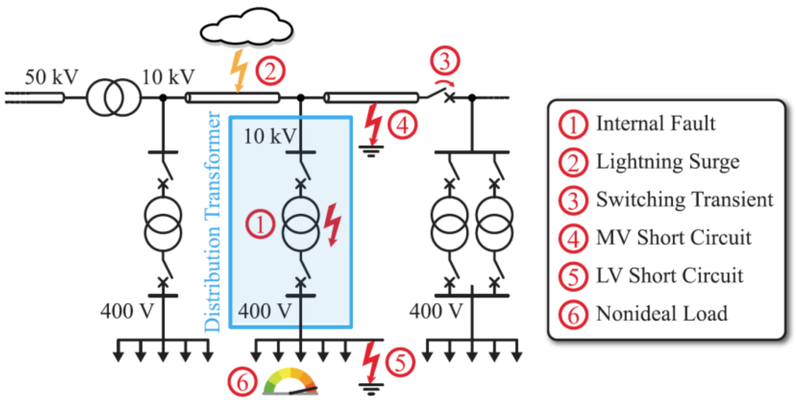


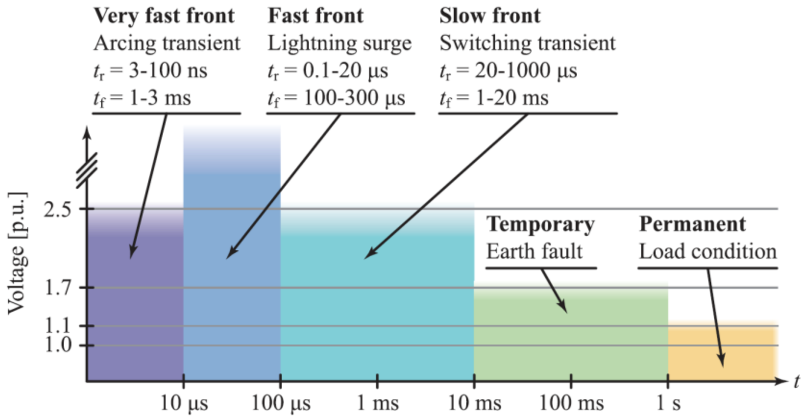




- *Benefits of Modularity* → *Redundancy* | *Availability* | *Economy of Scale*

# Remark Protection of SSTs

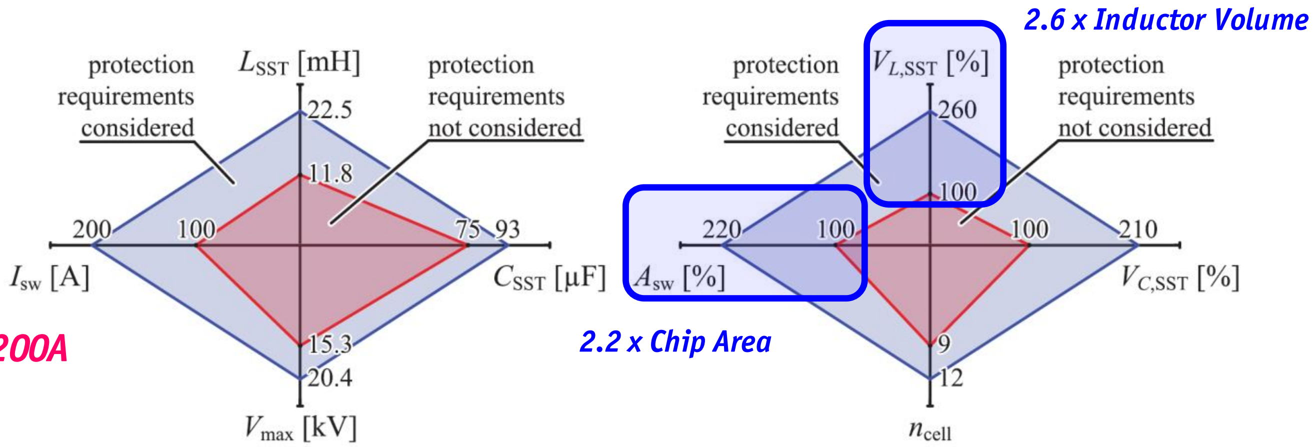
- *MV Grid → Surges, Overvoltages, Short-Circuit Faults, etc.*




- *Example of 1 MVA @ 10 kV*

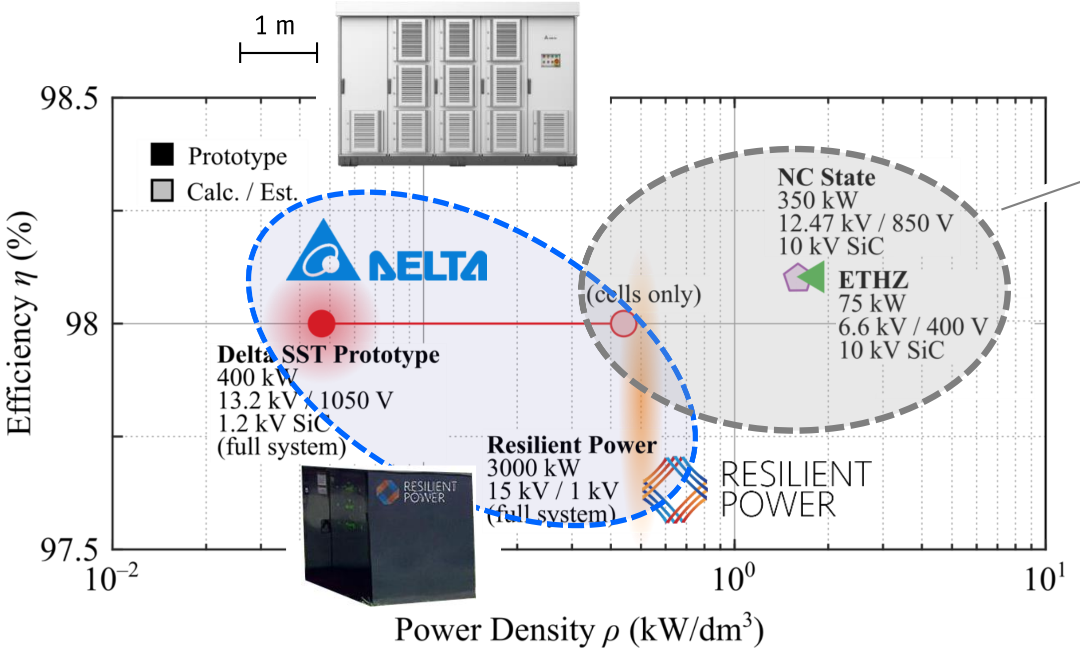
— $f_{sw}$ = 1kHz
— 9 Cells → 12 Cells
— Si IGBTs 1700V/100A → 1700V/200A
— IEEE 519 $L_{SST}$ → SCR ≈ 7%




- *Protection Requirements → Significant Impact on MV-Side Power Electronics Dimensioning*

# Industrial SSTs Performance

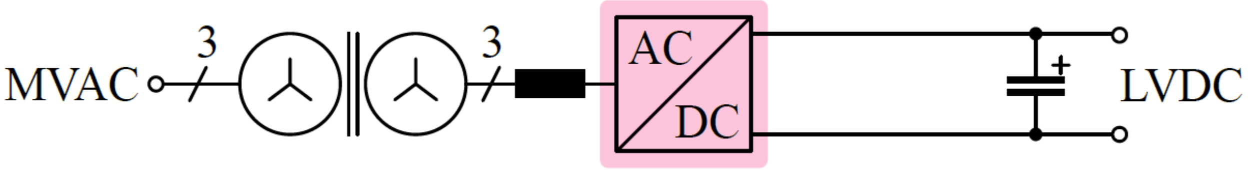
- *Efficiency of Industrial Prototypes* ***$\eta \approx$ 97.5 … 98%***
- *Full System Power Density* ***$\rho \approx$ 0.05 … 0.5 kW/dm$^3$***




*University Research Converter Cells w/o Protection, Cabinet, etc.*

- *Modularity → Redundancy / Reparability / Availability / Economy of Scale vs. Complexity*
- *HV SiC → Reduction of # of Modules (N < 5) | Protection & Robustness as Remaining Challenges*

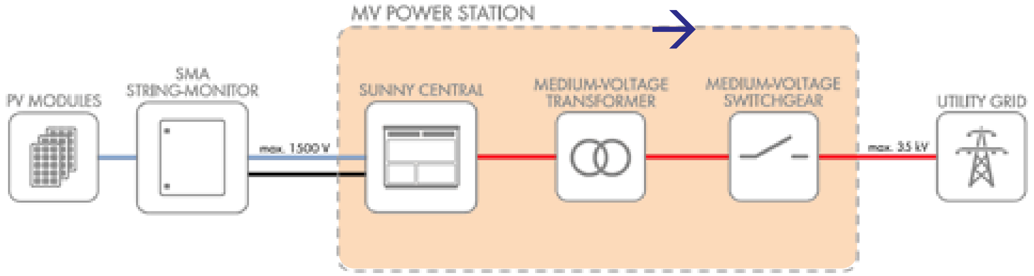
## Low-Frequency Transformer &
## Si or SiC Low-Voltage AC/DC-Converter



# 3-Φ MV Power Station for Photovoltaics

- State-of-the-Art 3 MVA Turn-Key Solution
- 20 ft Container — PV Inverter | LFT | MV Switchgear
- 6.1m x 2.6m x 2.4m → ≈ 0.08 kW/dm³

— 6.6 ... 35 kV Medium Voltage AC
— 1500 V Low-Voltage DC (PV)
— 1200 V Si IGBTs

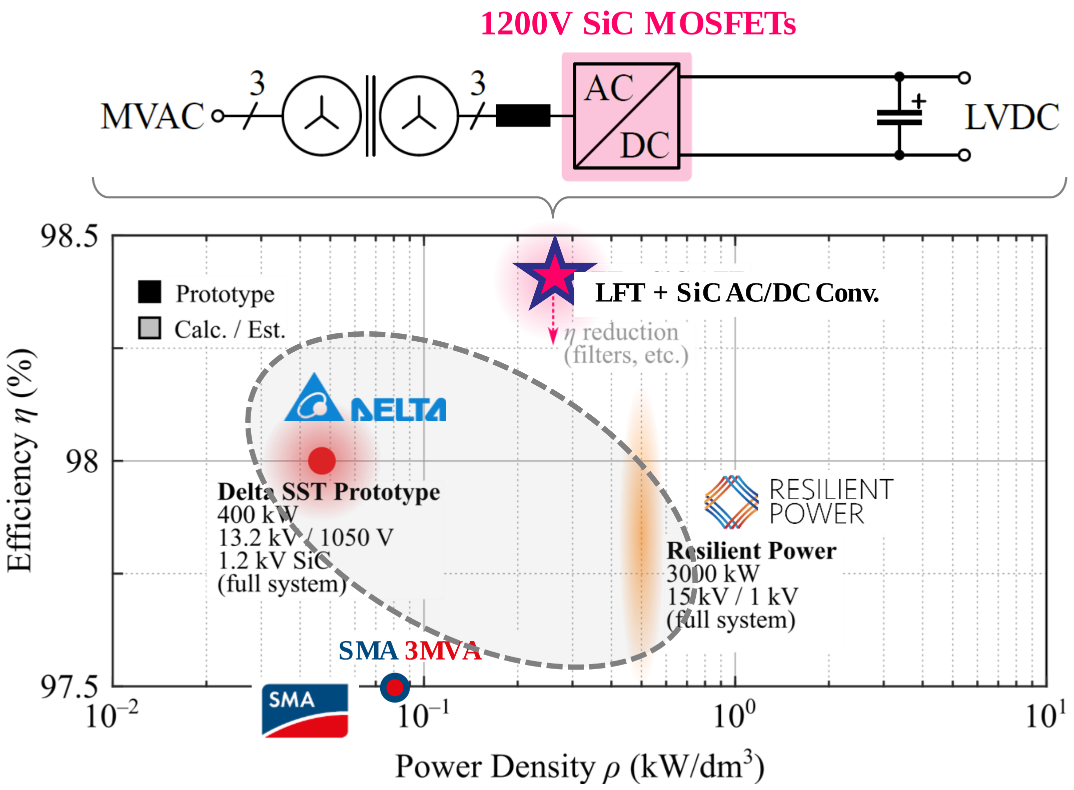




- Inverter CEC Efficiency = 98.5%
- Transformer Efficiency = 99% (EcoDesign, Oil-Filled)
- Overall Efficiency ≈ 97.5% → Improvements for SiC Inverter & Dry-Type Transformer → 98+ %

# Low-Frequ. Transf. & SiC Low-Voltage AC/DC Converter

- *Thought Experiment* — *AC/DC Stage Using Same Total Chip Area as Delta SST*
- *Conservative Assumption of* $\eta_{LFT}$ = 98.7% w/o Filters → *Overall* $\eta$ = 98.4%



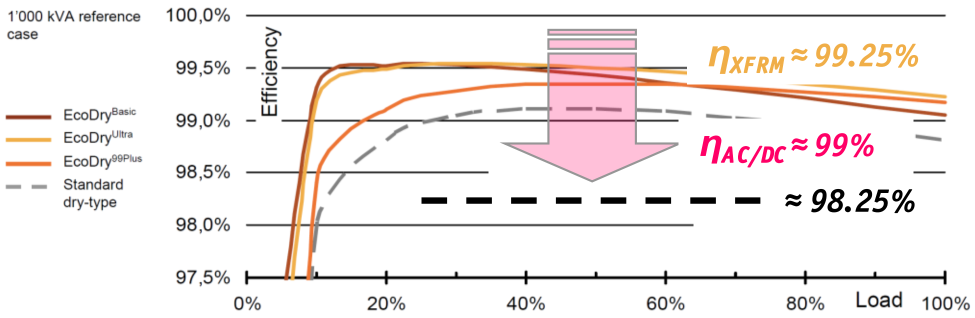

Wolfspeed
1200V / 1.33mΩ / 765 A
Half-Bridge Module

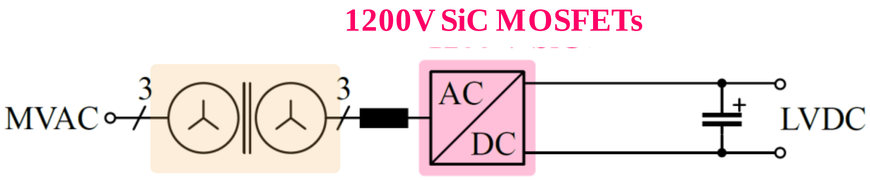
- *Identical Functionality as SST*
  - — *Bidirectional Power Flow*
  - — *Sinusoidal Mains Current*
  - — *Reactive Power Control*
  - — *Active Filtering*
- *High Efficiency / Power Density*
- *High Robustness / Low Complexity*
- *Full Scalability (Voltage & Power)*
- *Compatible with MV-Side Infrastructure*

- *Still to be Analyzed* — *Parallel Interleaving of AC/DC Stages | Size & Losses of Add. Filters*

# State-of-the-Art Dry-Type LFT Technology

- 400kVA EcoDry™ High-Efficiency Transformer
- Vacuum Cast Coils → No Fire Hazard
- Amorphous Metal Core → Low No-Load Losses
- High Overvoltage / Overload Capability
- 1.4m x 0.75m x 1.5m Outer Dimensions



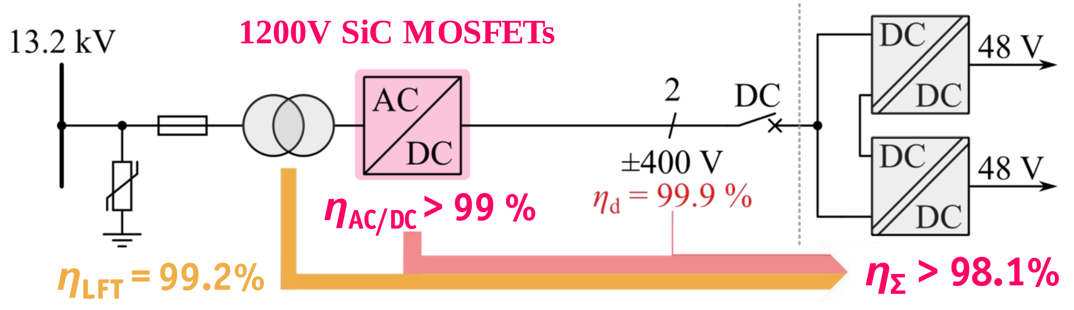





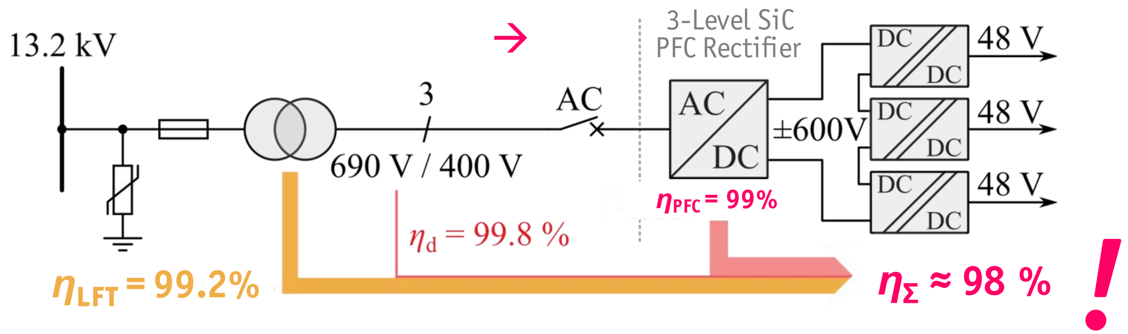
- Utilizing SiC MOSFETs in AC/DC Stage → $\eta_{AC/DC}$ = 99+ % Efficiency
- Higher Efficiency / Power Density / Robustness Compared to SST (!)

# Dry-Type LFT & ±400V DC vs. 690V AC Distribution

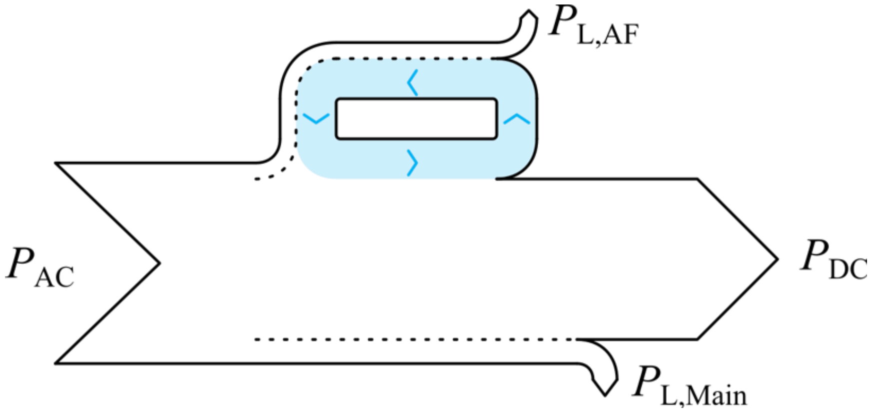
- ± *400 V DC*




- *690 V AC*



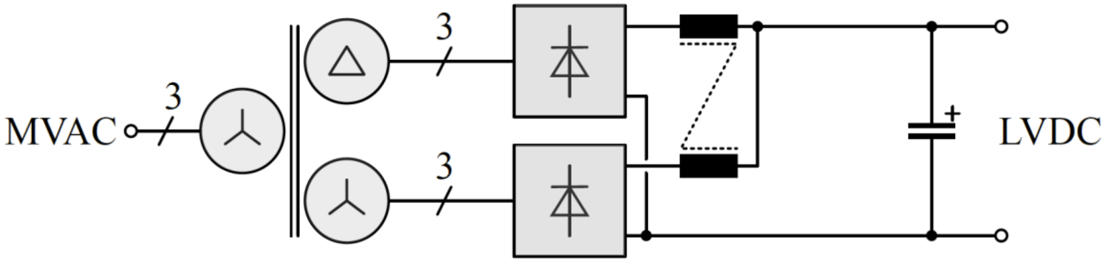

- *Reduced / No Advantages of DC Distribution*
- *Adv. of DC for Integration of Renewables & Backup-Power (Diesel → Fuel-Cells)*

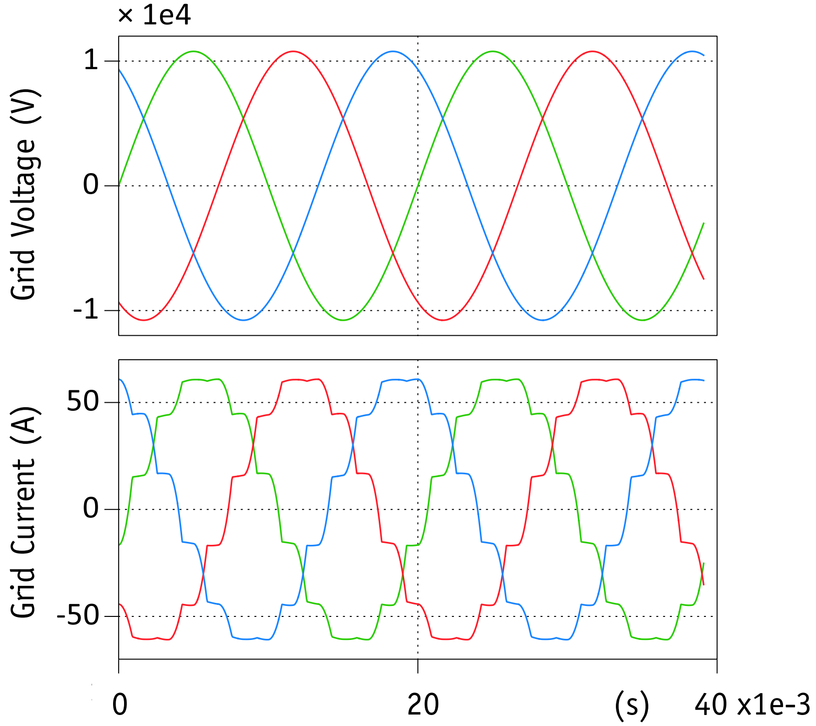



# Partial Switch-Mode Power Processing

# 3-Φ 12-Pulse / Multi-Pulse Rectifier

- *No Explicit PFC Stage (!) → Passive Realization of PFC Functionality with Phase-Shifting Transformer*
- *Low Complexity / High Robustness / High Efficiency*
- *18-Pulse, 24-Pulse For High Power Levels*

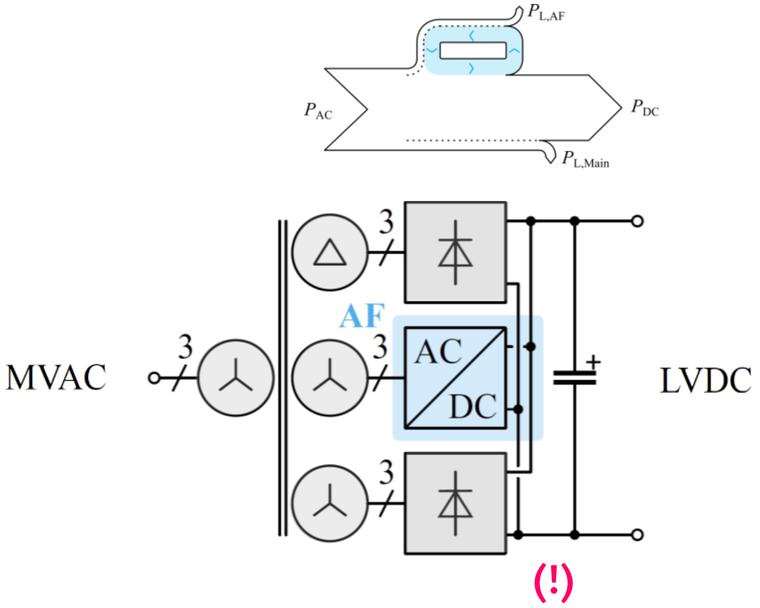


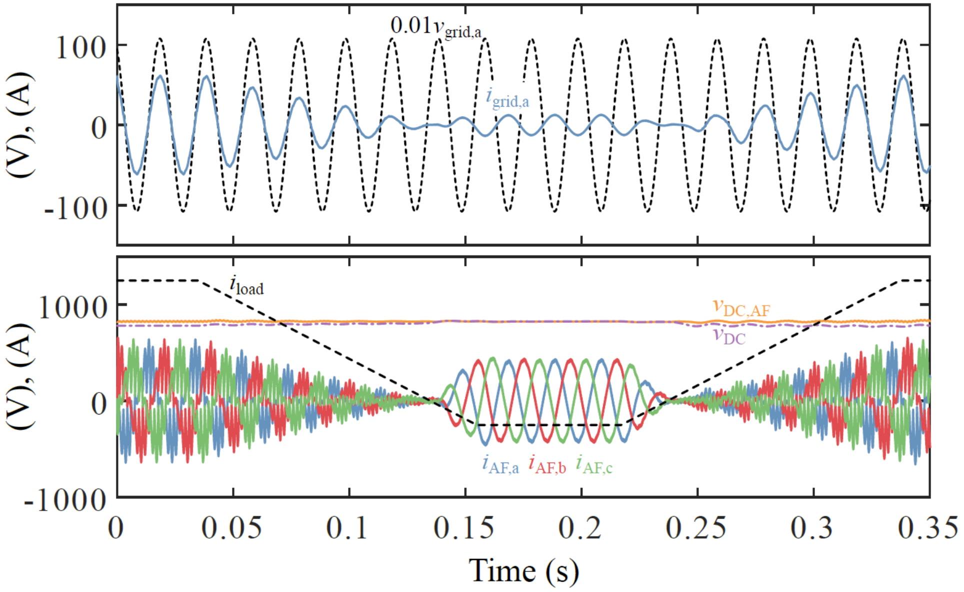




- *Unidirectional*
- *No Active Output Voltage Control (Tap-Changer)*
- *Remaining Current Distortion / Reactive Power Consumption*

# 3-Φ 12-Pulse Rectifier & Active Filter

- *Hybridization / Partial Switch-Mode Power Processing*
- *Active Filter (AF) Module with 15…25% Rating → Sinusoidal Grid Current / React. Power Comp.*
- *Partial Power Processing → Reduces Impact on Overall Eff. — η ≈ 98% with Standard Si Active Filter*



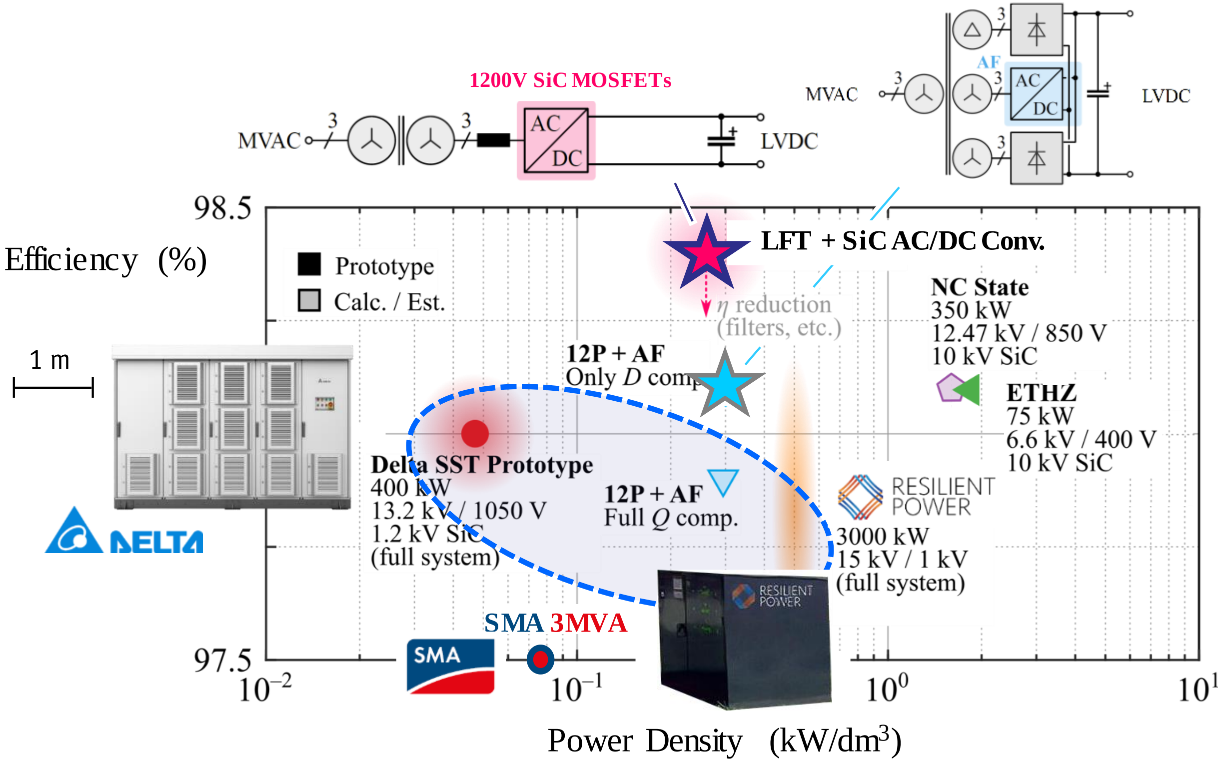




- *No DC-Side Inductors Required (!)*
- *Remaining Passive 12-Pulse Operation in Case of Active Filter Failure*
- *Efficiency Improvements with Dry-Type High-Eff. LFT & SiC Active Filter*
- *Connection of AF to Output DC-Bus → Reverse Power Flow Capability*

# Conclusion

# Comparative Evaluation

- *Industrial AC/DC SST → No Volume / Efficiency / Functionality Adv. Over LFT + SiC AC/DC Conv.*
- *690V AC & Dry-Type Transf. → Competitive with ± 400V DC Distribution*
- *12-Pulse Rect. & Act. Filter → Low Complexity / High Robustness @ Reduced Functionality*



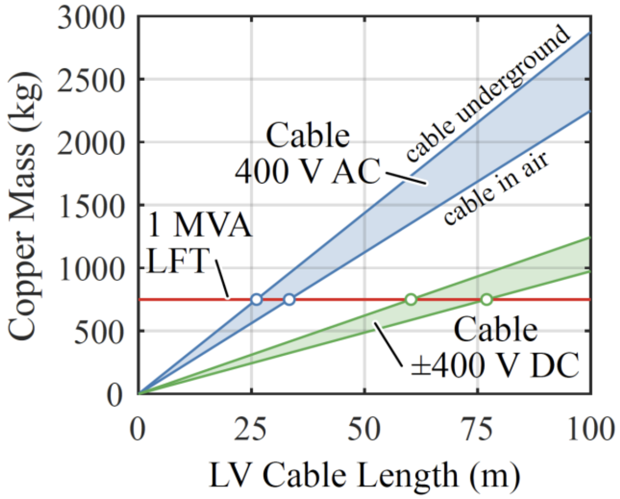


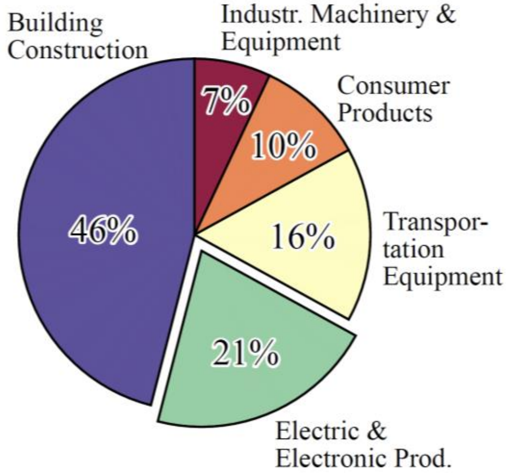
Source: schimandl.nl

- *Add. Considerations on Integr. of Renewables / Fuel-Cell Back-Up Power / Grid Services etc.*

# Ecological Aspects

- *LV Distribution Busbars Dominate the Installed Copper Mass*
- *40 vs. 10 Years Lifetime of LFTs vs. SSTs*
- *Recyclability Advantage of LFTs*



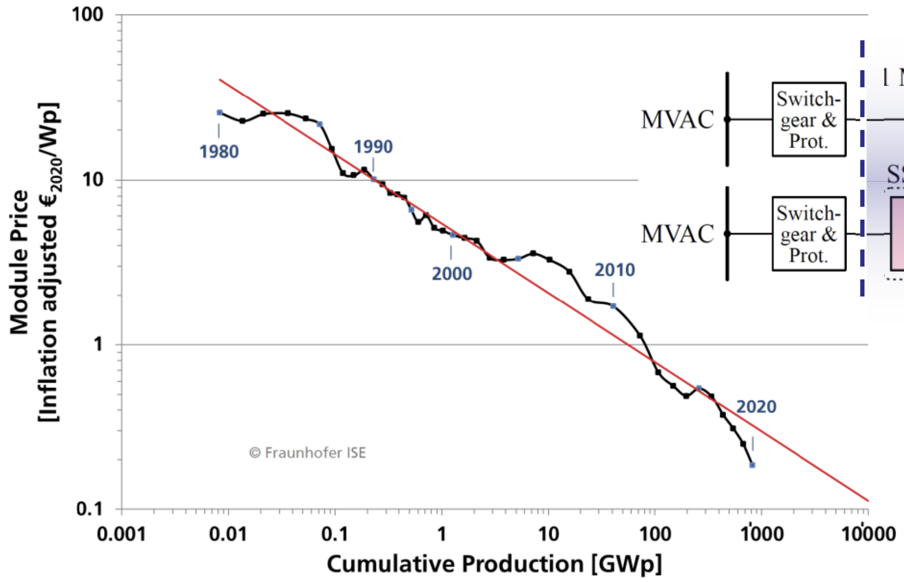



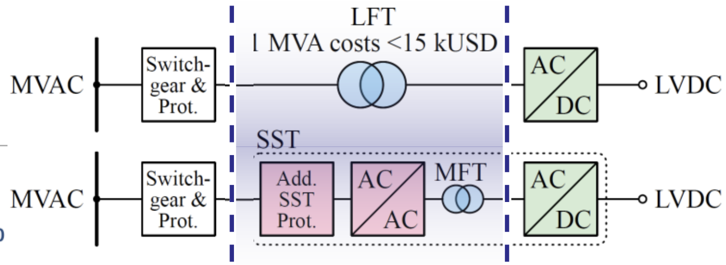

- *Global Copper Usage Largely Dominated by Other Application Sectors*
- *Life-Cycle Assessments — Cradle-to-Grave | Cradle-to-Cradle — Still Missing*

# Outlook — SST Technology Learning Curve

- *Learning Rate → Cost Reduction for Each Doubling of the Cumulative Production / Accumulated Experience*
- *Used for Prediction of Future Costs of a Technology (e.g. PV "Grid Parity") → Long Term Strategies*

*25% Learning Rate for PV Modules*





- *Typ. Empirical Learning Rates of 15…25% → Dramatic Cost Reduction Over Longer Timespan*
- *Can SSTs / SST Modules Ever Become Cheaper than LFT-Based Solutions ? | Procurement vs. Life-Cycle $$$ ?*

# Questions