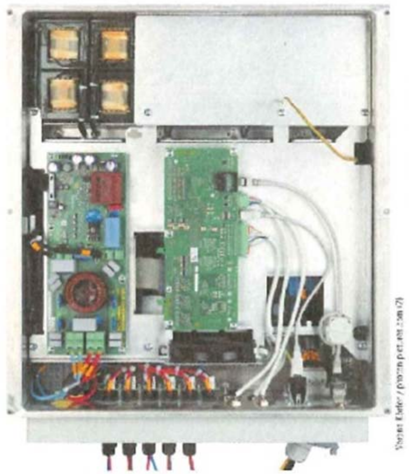
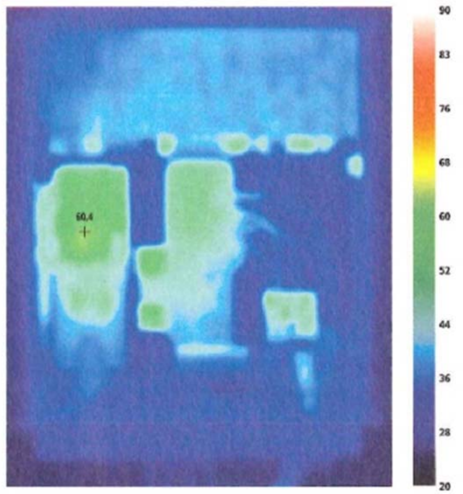
Latest in PV Inverter & Trends





1. Progress of efficiency and inverter design

2. Module oriented electronics and topologies

3. The inverter in the energy system

Prof. Dr. Andrea Vezzini, BFH Bern, Switzerland, Institute for Energy and Mobility Research; andrea.vezzini@bfh.ch

Prof. Dr. Franz Baumgartner, Renewable Energy, ZHAW SoE, Winterthur 2010-03-26; bauf@zhaw.ch; https://home.zhaw.ch/~bauf/

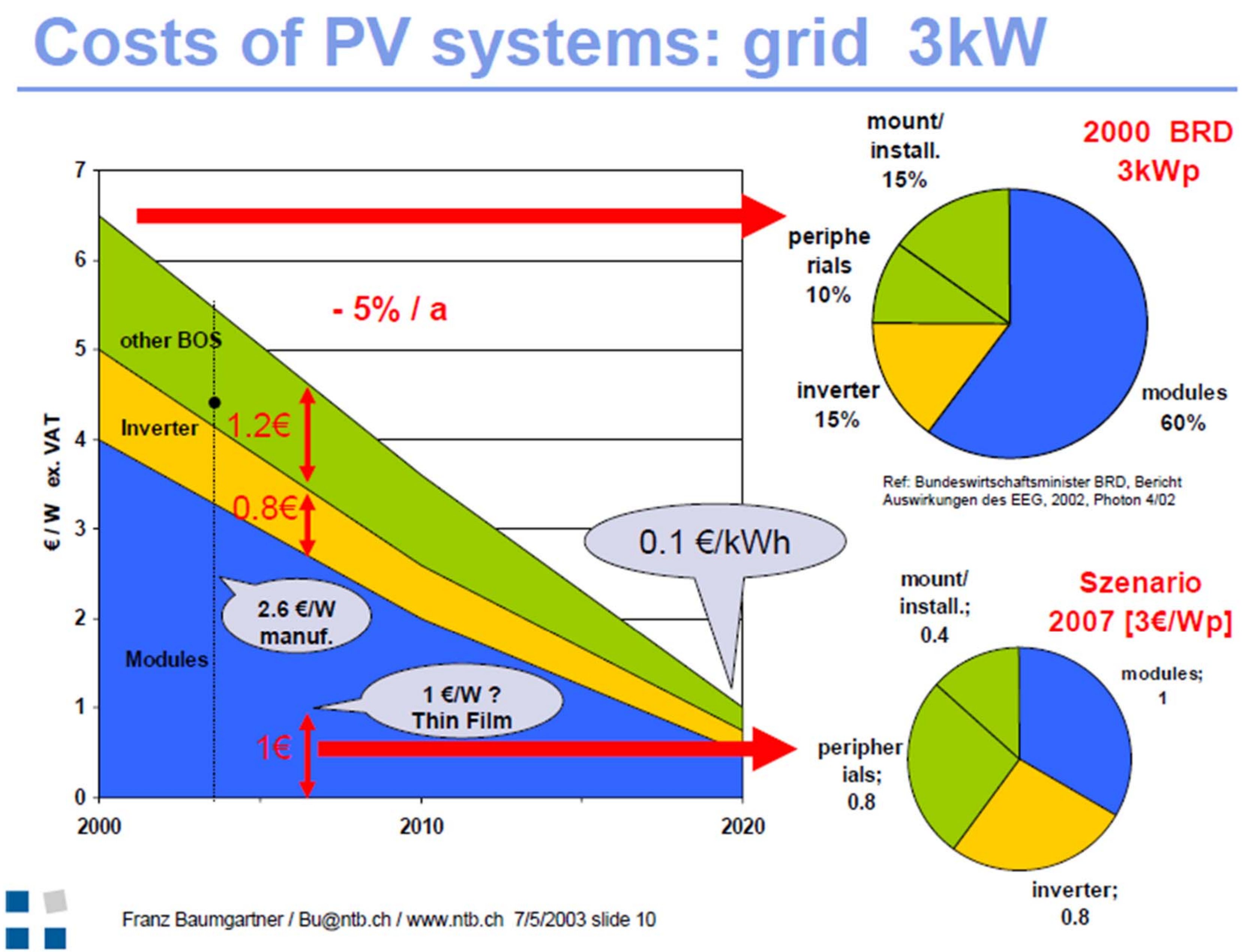
Outline

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

- History : to transformer less topology; inverter efficiency graph
- Saturation of record efficiency – limits
  less components, higher eff, smaller, longer MTBF,
  1% increase for less than 20€/kW higher market price?
- Trend 1: Software - application
  Integration into smart grid, reactive power control
- Trend 2: power electronics + storage
- Vision:
  Hardware solar silicon wafer based power electronics + storage

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Cost predications ten years ago



Remark today:

50% cost reduction of PV Inverter in the last five years since 2007!!

This was nearly doubling the propose -5%/a

Today prices:

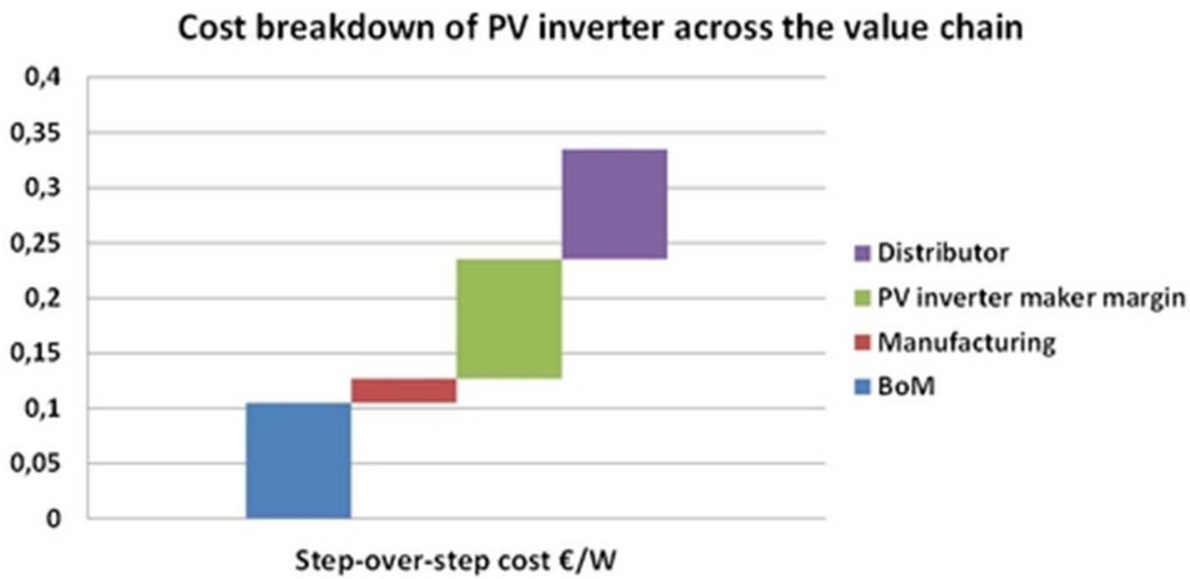
150 to 350€/kW AC

(Ref. Photon Prof.)

Cost and Quality Issues

	Average max efficiency	Cost	Reliability	Additional features adoption policy
	~ 96%	0,19 – 0,2€/W	5 – 10 years	
	~ 97%	0,22€/W	10 – 15 years	
	~ 97,5%	0,2 – 0,21€/W	10 – 15 years	
	~ 98%	~ 0,25€/W	< 20 years	

Qualitative legend	--	-	+	++



Market Development:

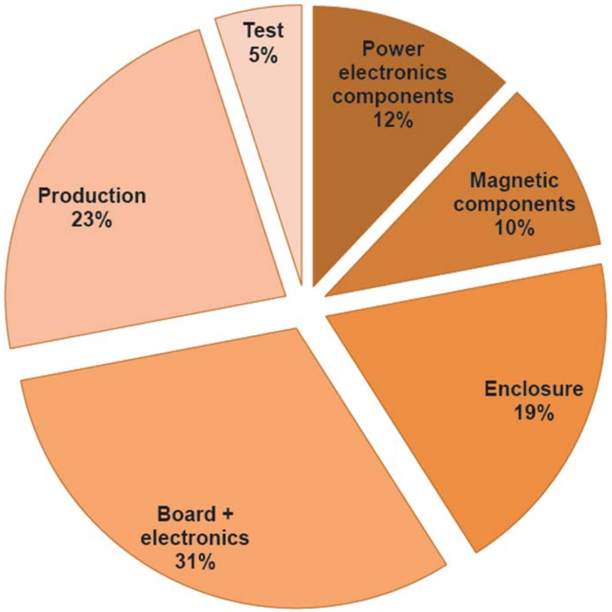
- Reinforcement of US players
- Entry of other players who used to be in train or UPS business
- Arrival of Asian players, each with a competitive advantage: cost (for Chinese players), efficiency and reliability (for Japanese players).
- Inverter cost is decreasing considerably and today’s market in Europe hardly accepts over 0.24€/W solutions. Chinese makers (like Sungrow) can thus easily access the market while Japanese competitors have difficulty.

Yole Développemen PV inverter trends report 2011

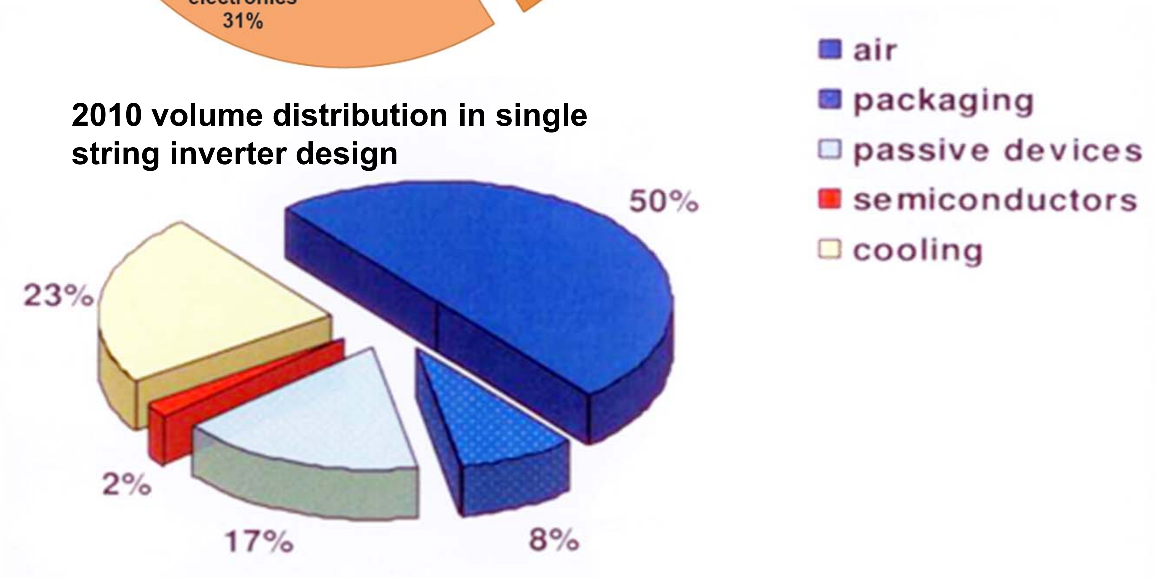
Challenges in Inverter Designs

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

2009 cost breakdown of a single string inverter for residential application
source:Yolé Development, PV Inverter Trends, 9/2009



2010 volume distribution in single string inverter design



source: H. Vetter, Power Capacitors for Advanced Converter Designs, EPCOS

- **Power Circuits**
  - **Module integrated micro-inverters**
  - **Transformer-less**
  - **Single-stage inverters**
- **Power Electronics Devices**
  - **Higher switching frequency**
  - **Use of new Materials (SiC, GaN,…)**
- **Passives**
  - **Low-loss high frequency integrated Magnetics**
  - **Film Capacitor**
- **Packaging**

Reduction of losses

Zurich University of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

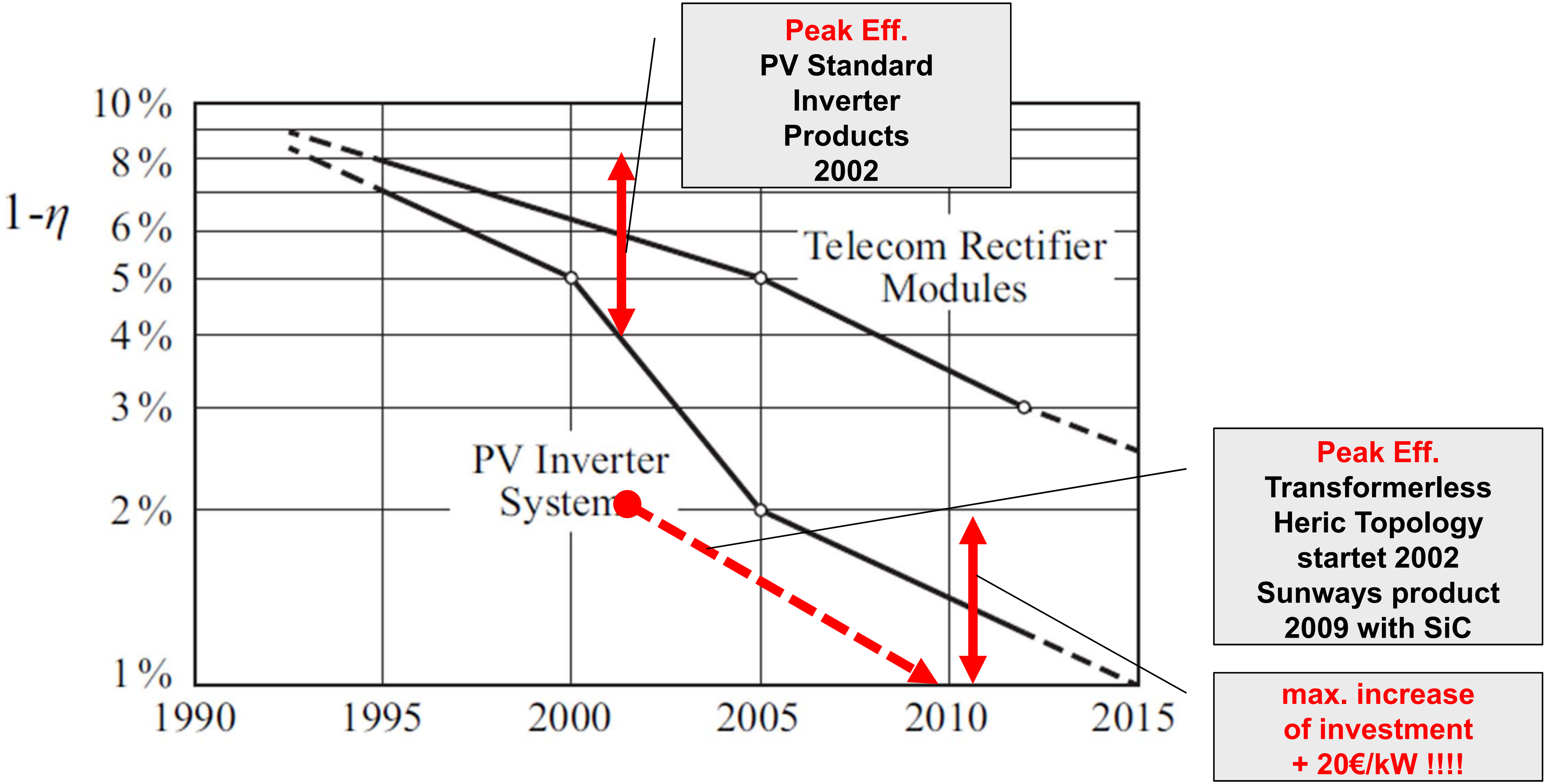


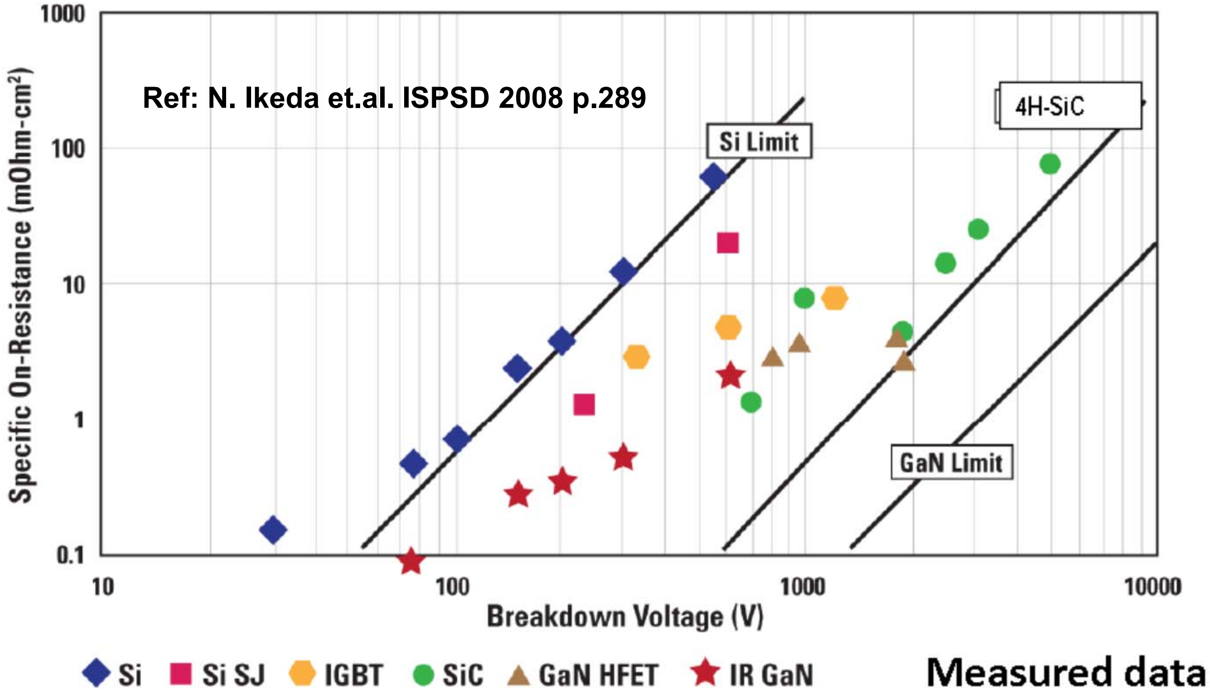
Fig. 1. Development of the (rated power) efficiency of telecom power supply modules and PV inverters since 1995 [2]–[4].

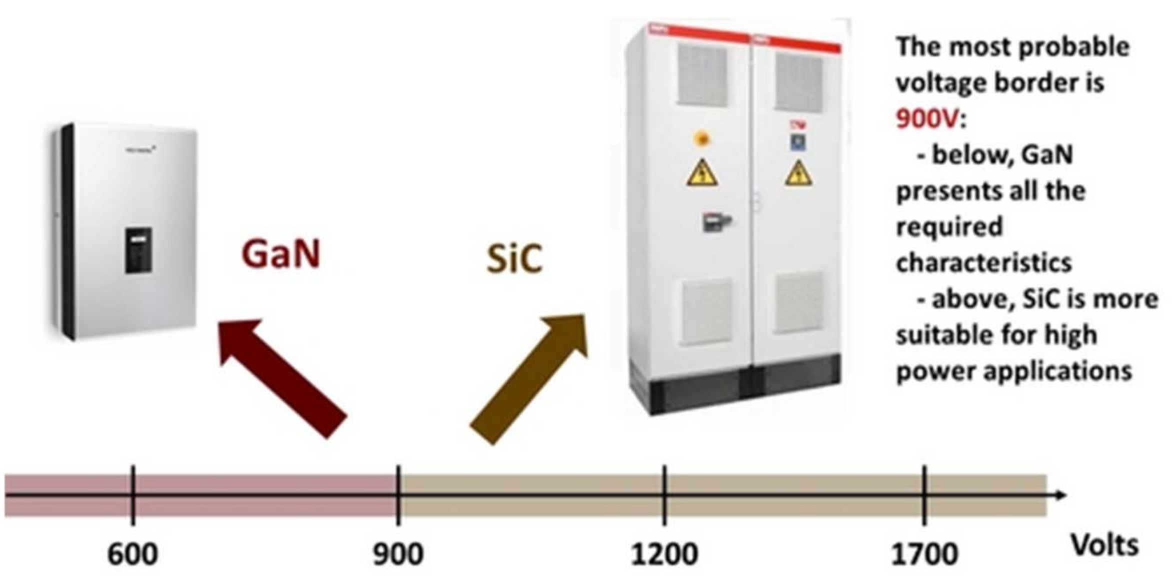
Basic Fig. 1 from with add. remarks in red

J. Kolar et. al. , ETHZ, EEPE; Conf. Integrated Power Electronic Systems CIPS, Nürnberg, March 2012

Semiconductor: Si, SiC and GaN

Zurich University of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering



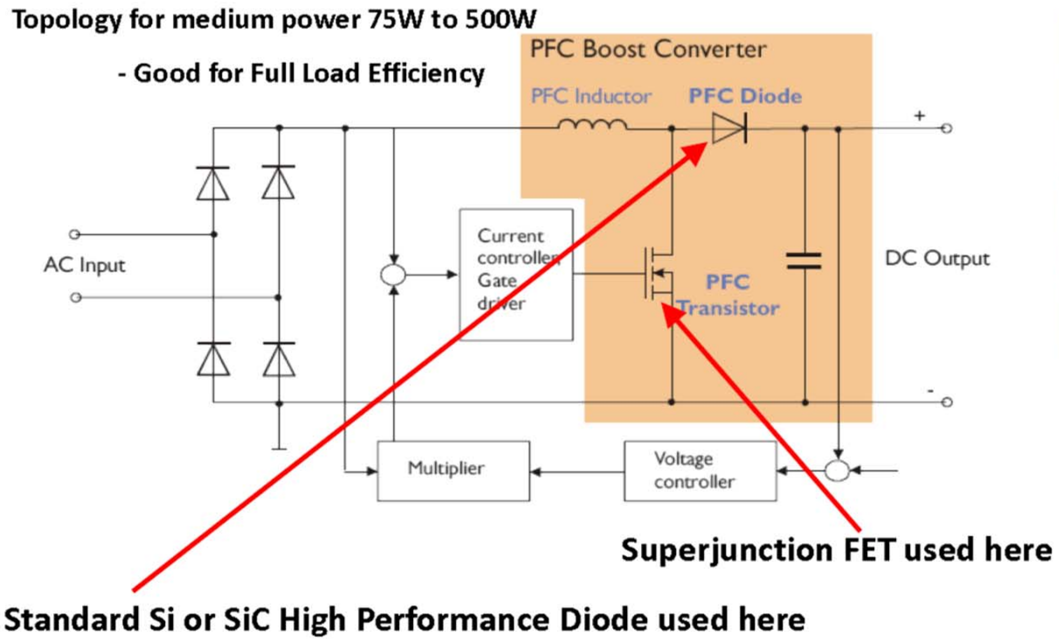


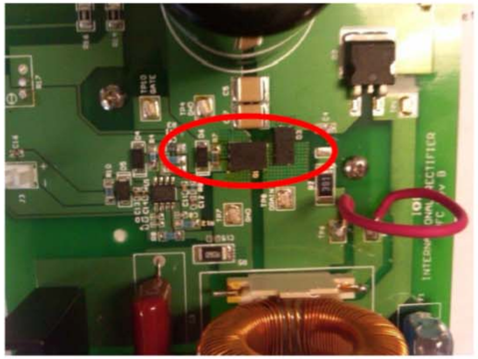
- GaN based Power devices represent an excellent choice for dramatically improved power device performance
- First commercial 600 V GaN product is planned for release in CY 2012
- 2011 is the year of the first SiC MOSFET introduction with simultaneous offers from Rohm and CREE
- SiC technology will dominate the high and very high-voltage applications (1.7kV to 10kV+)
- However, and paradoxically, few players are targeting that high-voltage region
- The pending question remains the same: will SiC be implemented in EV/HEV and when?

Ref: Yole, SiC Market 2010-2020: 10 year market projection

GaN vs Si Superjunction Switch

Zurich University of Applied Sciences
zhaw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

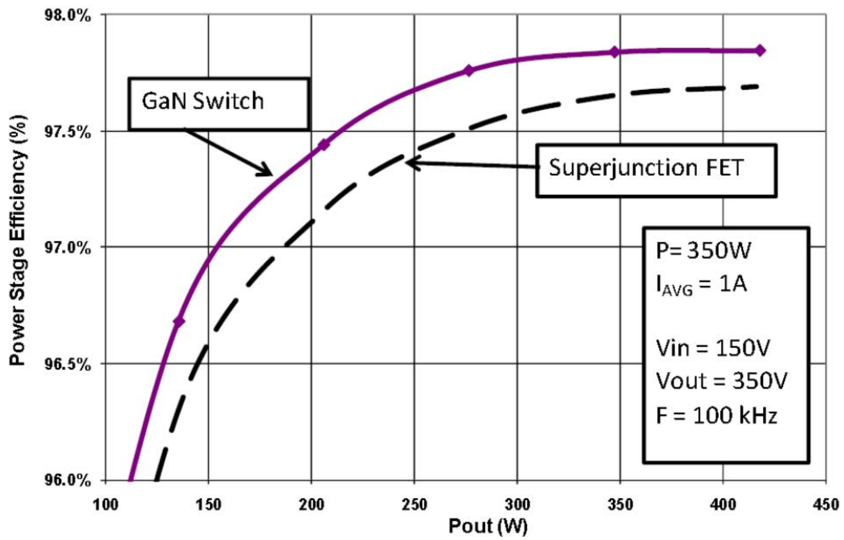




Silicon Solution:
2 x TO-220 with Heatsink
Component Size : 210 mm^2

GaN Solution:
enables SMT implementation
Component Size: 80mm^2

2.6x Size Reduction



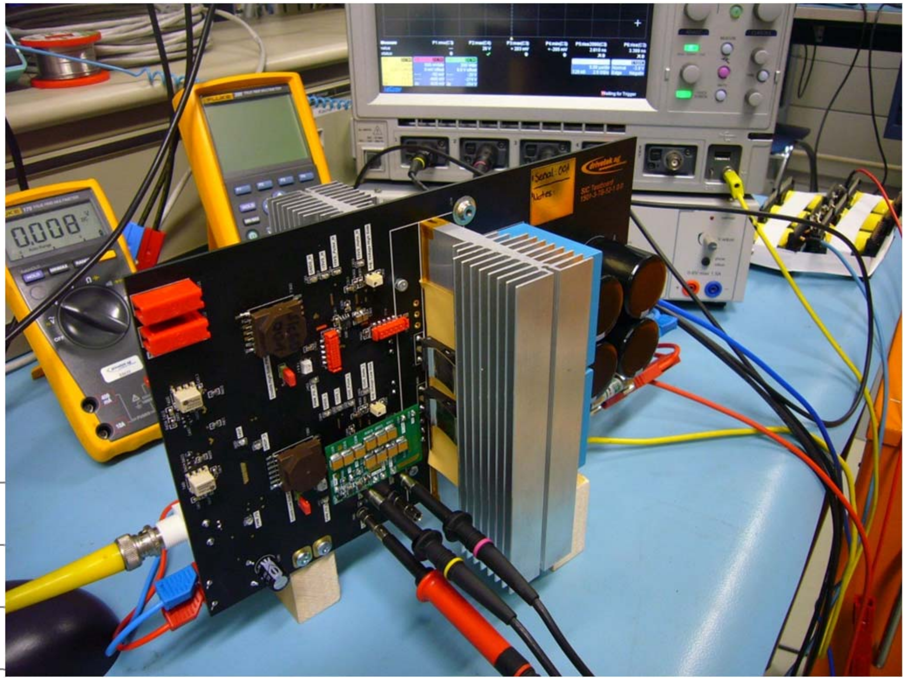
- **GaN Si on power devices have moved from lab curiosity to commercial realization**
- **Product offerings are increasing: Low voltage available since February 2010, High voltage (650V) due out this year.**
- **As GaN based power devices are further developed a wide range of applications and markets will achieve higher levels of density, efficiency and cost effectiveness**

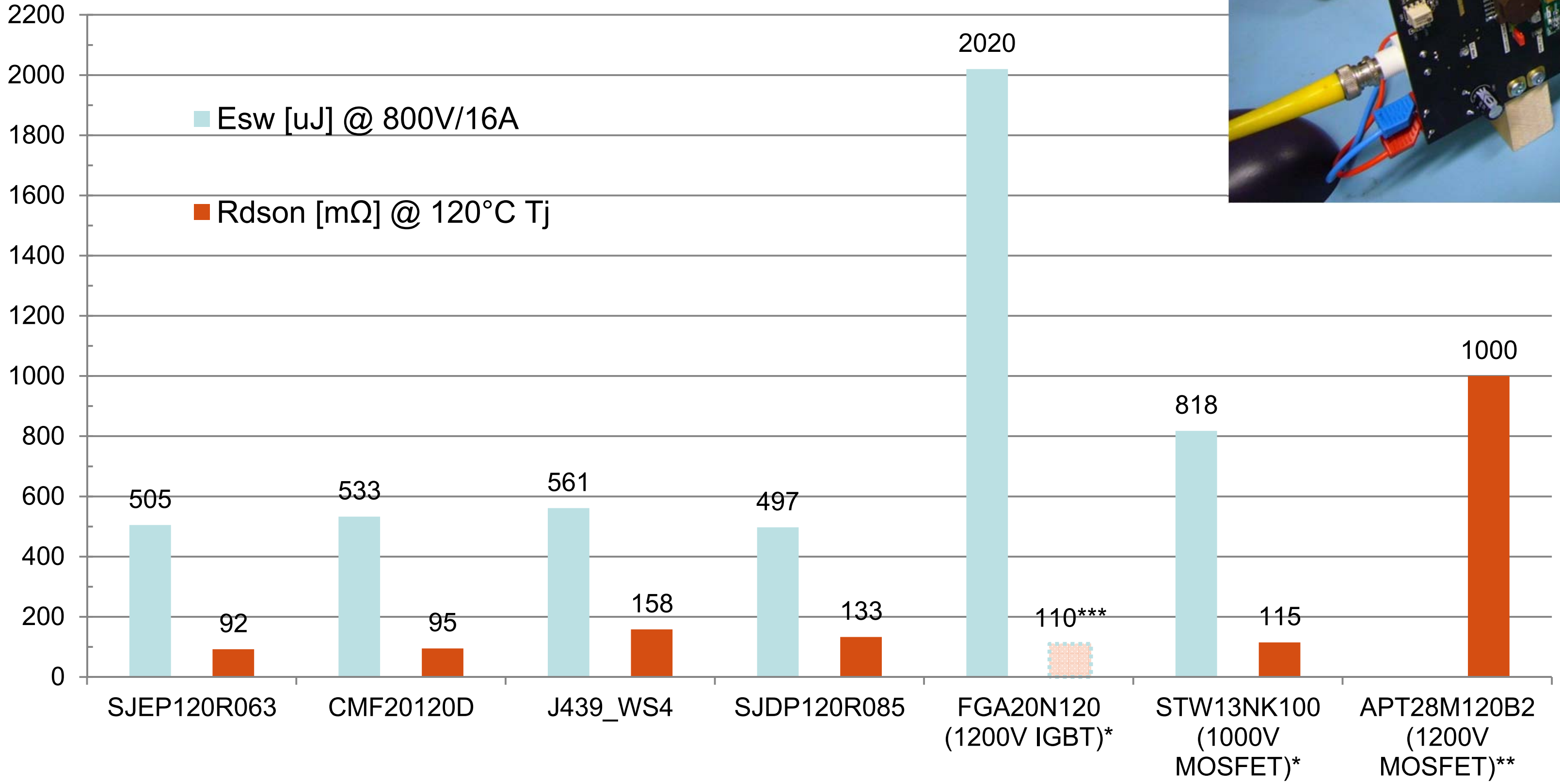
Ref: International Rectifier, GaNpowIR Update APEC 2011

SiC 1200V Comparison

Zurich University of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Power Semiconductor	Technology	Key Parameter
CREE CMF20120D	MOSFET	1200V/80mΩ/17A/TO-247
Infineon J439_WS4	JFET «normally on»	1200V/100mΩ/22A/TO-247
SemiSouth SJDP120R085	JFET «normally on»	1200V/85mΩ/17A/TO-247
SemiSouth SJEP120R063	JFET «normally off»	1200V/63mΩ/30A/TO-247

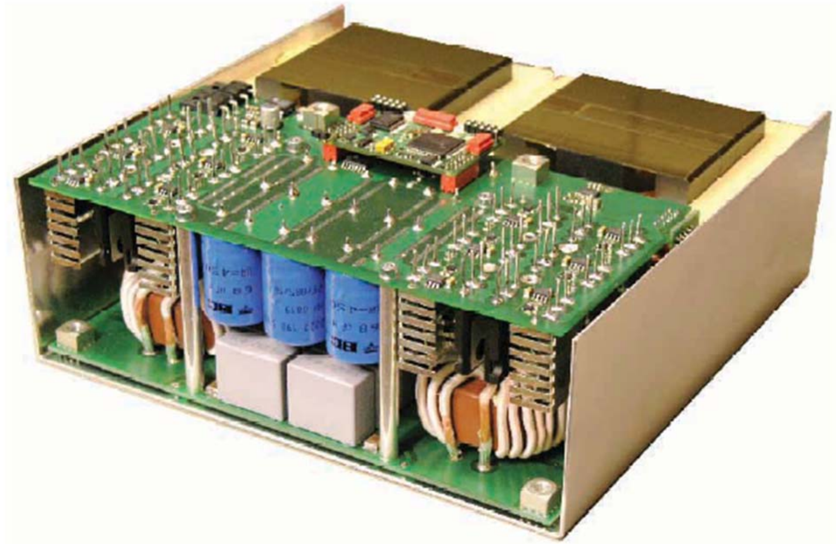




- **SiC allow for 1200V Applications up to 4 times lower switching losses compared to best in class IGBT while having equal or even lower conduction losses**
- **Additional cost and complexity arise due to surrounding electronics and control**

99.3% eff. Compact Rectifier 1.35kW/dm3

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering



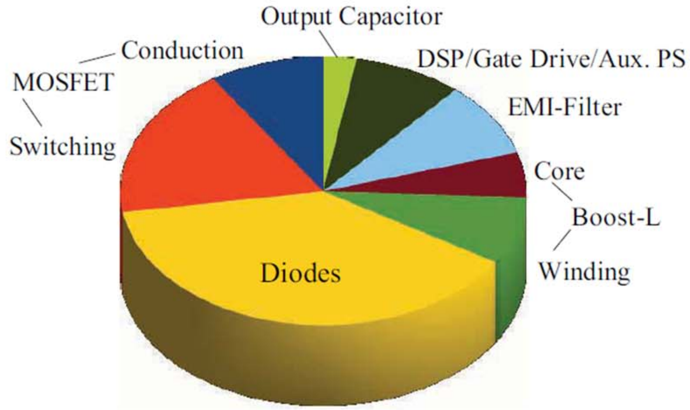


Fig. 10: Loss distribution of the optimised converter system with a switching frequency of 16kHz and a boost inductor of 400μH.

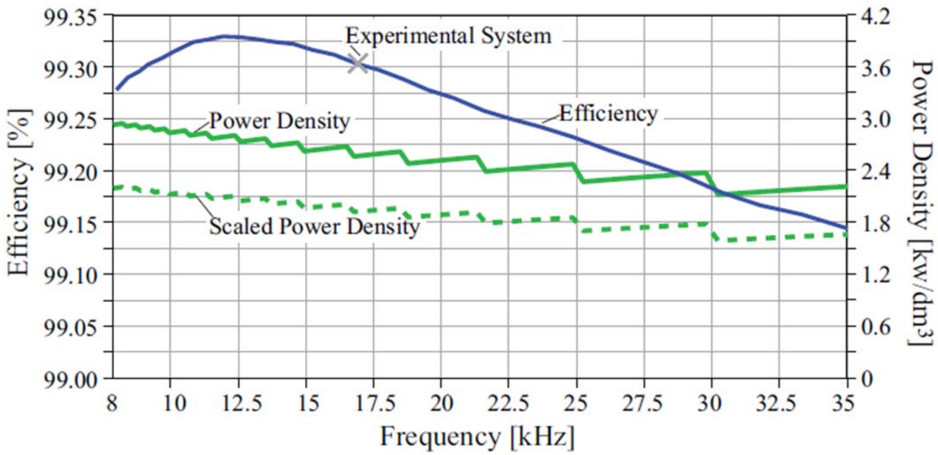


Fig. 12: System efficiency as function of the switching frequency for a fixed inductance L_{DM} = 400μH of the boost inductor. Furthermore, the power density obtained for considering the net component volume and the scaled power density, where also the volumes required for mounting of components, not matching component shapes, etc. is considered, are shown.

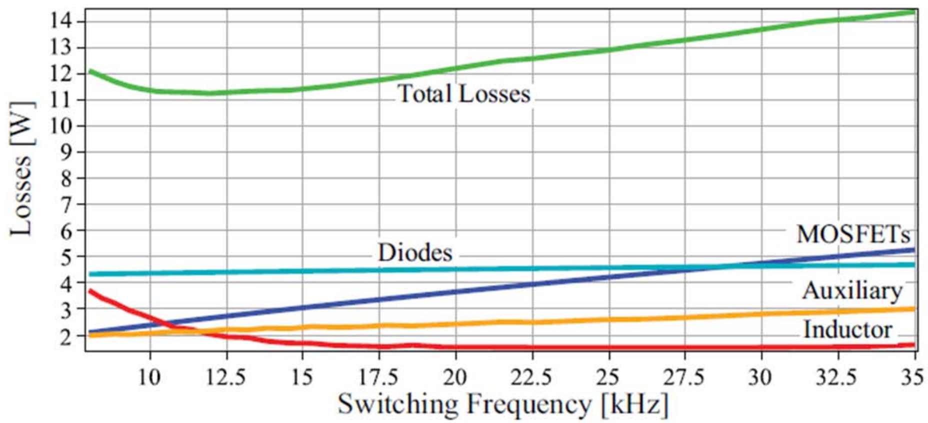
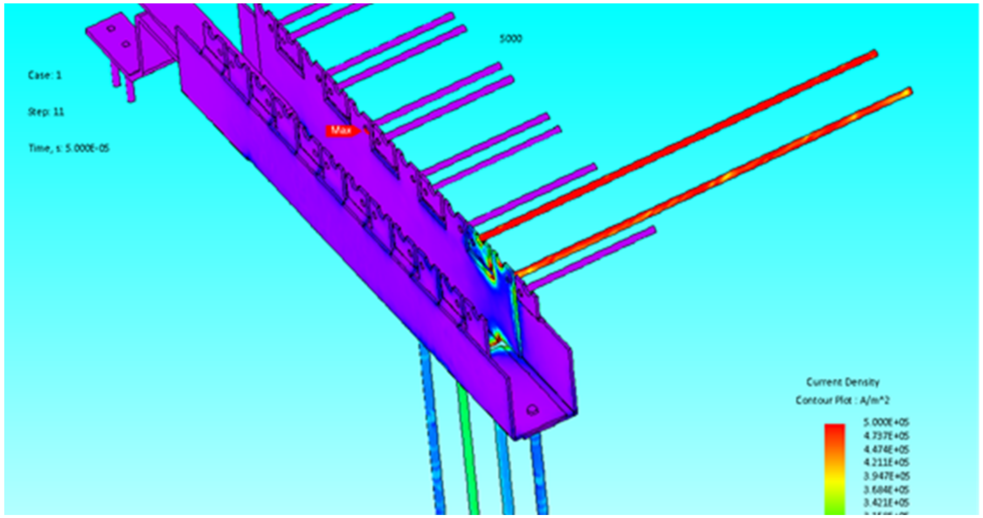


Fig. 13: Losses of the power semiconductors, the boost inductor L_{DM} and the auxiliary components in dependency on the switching frequency f_P. The boost inductor volume is set to a constant value and the inductance is adapted inversely proportional to f_P. Therefore, for increasing f_P a lower inductance value has to be realised in the same volume resulting in lower boost inductor losses.

J. Biela, J. Kolar , G. Deboy et. al. , ETHZ, APEC Applied Power Electronic Conf . Palm Springs, Feb. 2010

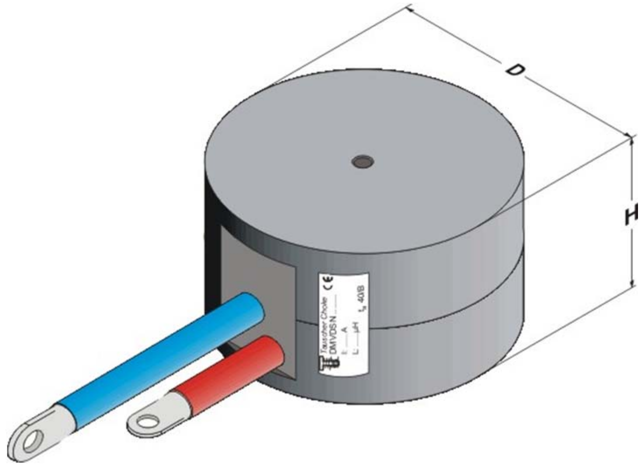
Optimization of Passive Elements

Inverter Busbar Magnetic Analysis



- **Passive Components:**
  - **More than Miniaturization**
  - **Magnetic Technology Needs a Face Lift**
- **Mechanical, Thermal and Magnetic Optimization through coupled FE-Analysis**
- **Size (and cost) reduction through separately controlled multi-phase stages with low load optimized cells**

Traditional single inductor



3-fold interleaving: 3 x 1/9 of Volume

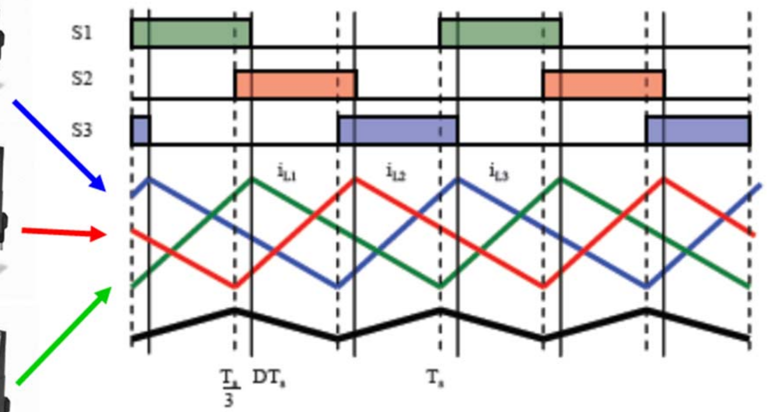


Fig. 4. Interleaved inductors currents

Efficiency single phase 99%max
Three Phase 97.8% max

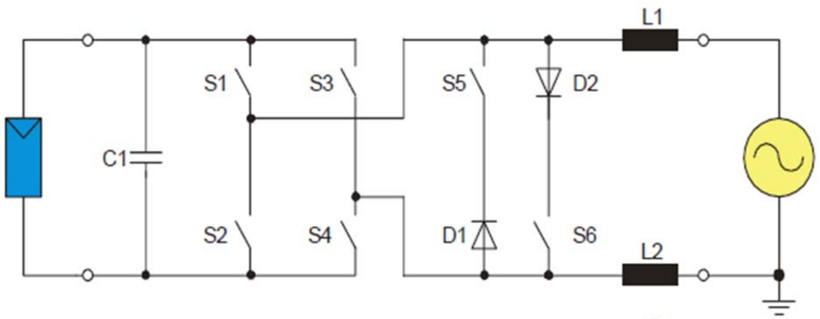
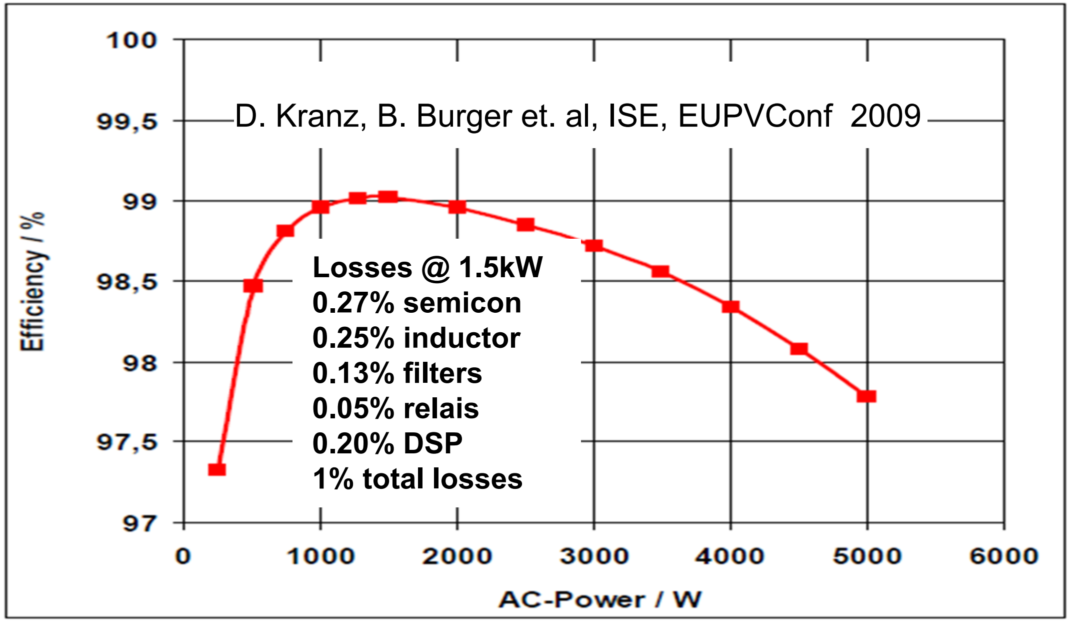


Figure 8: Topology of a single-phase HERIC® inverter



Normally-off SiC-JFET, 16 kHz and 350 DC-link voltage.
This world record in efficiency was set in August 2009.

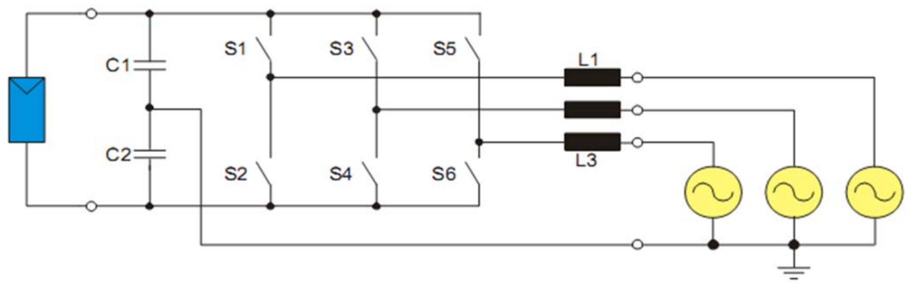


Figure 9: Basic power electronics circuit of the three phase inverter in B6 topology

Table II: Comparison of the efficiency of the three phase inverter with different generations of Si-IGBTs and with SiC MOSFETs.

	Maximum efficiency	European efficiency
IGBT 2	95.4 %	94.9 %
IGBT 3	96.0 %	95.0 %
IGBT 4	96.5 %	95.5 %
SiC MOSFET	97.8 %	97.5 %

B. Burger et. al, ISE, EUPVConf Valencia 2008, 4EP.1.5

Serial 30kW PV product 3 phase near 98% max

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

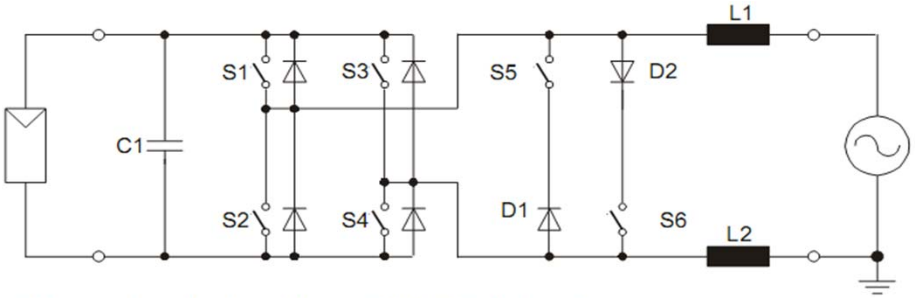


Figure 1: single-phase HERIC-Topology
("Highly Efficient & Reliable Inverter Concept")

The basis for the successful completion of the project was the transfer of the single-phase HERIC®-Topology into a three-phase inverter concept.

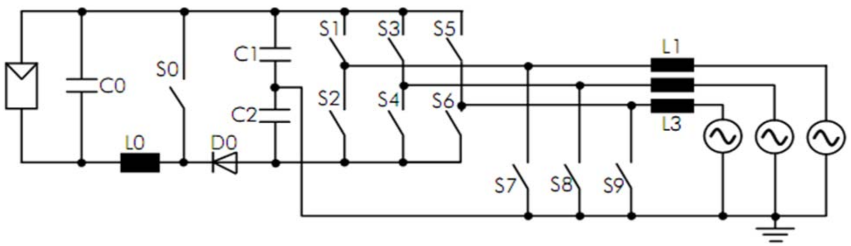


Figure 2: three-phase HERIC-Topology with boost converter

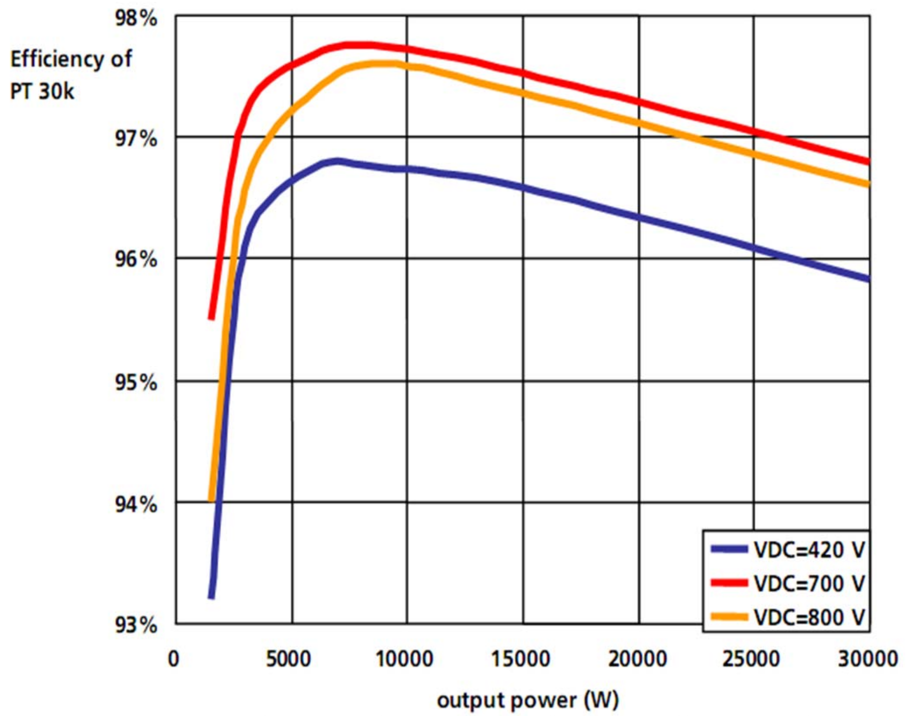


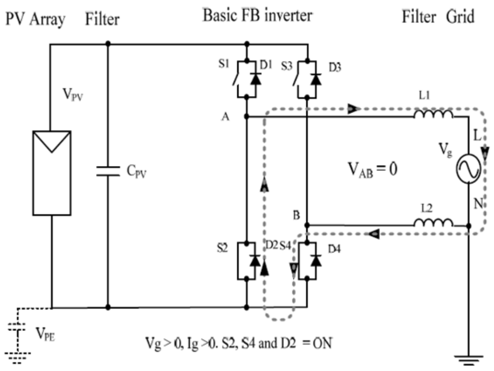
Figure 11: Efficiency of the PT30k depending on the DC input voltage of the solar Generator

Finally a maximum efficiency of 97.7% and a max. EU efficiency of 97.3% was achieved.

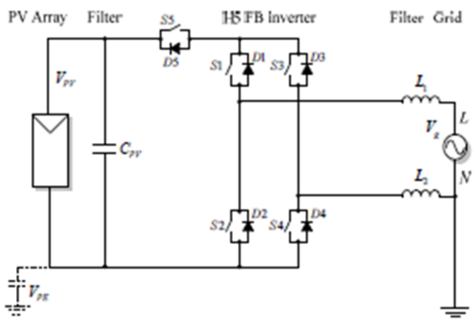
T. Hauser et. al, Sunways, EUPVConf Valencia 2008, 4DO.8.2

Single Phase Inverter Trends

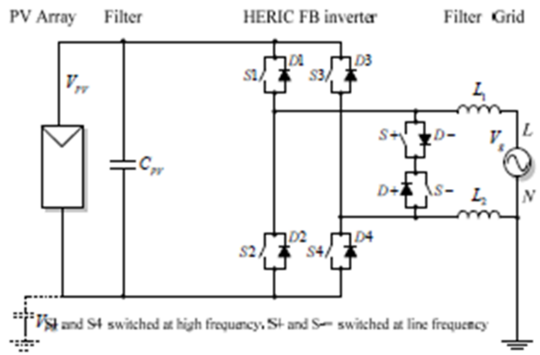
Zurich University of Applied Sciences
zhaw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering



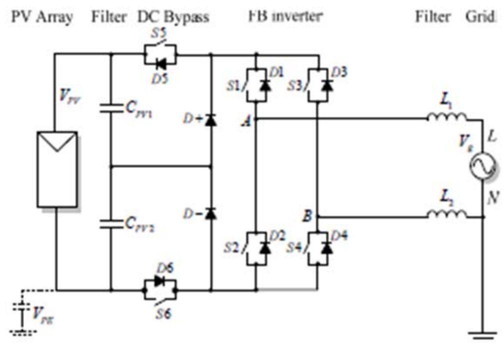
Fullbridge (Bipolar/Unipolar/Hybrid)



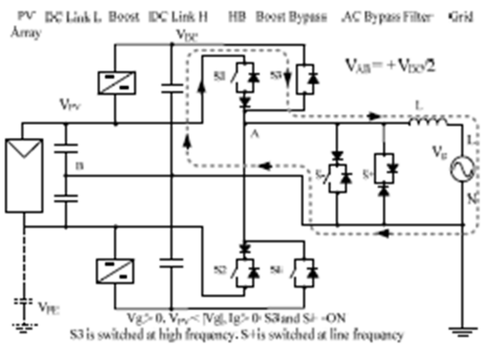
H5 Topology (SMA)



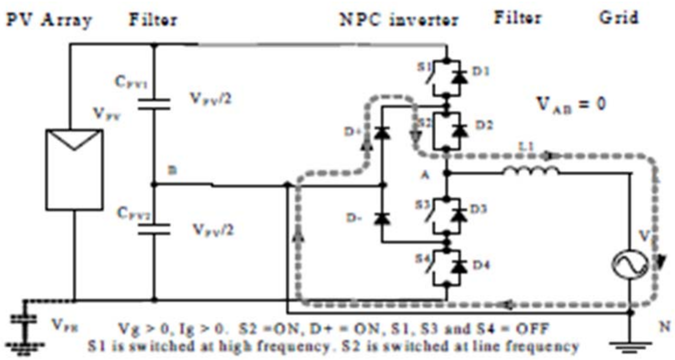
HERIC Topology



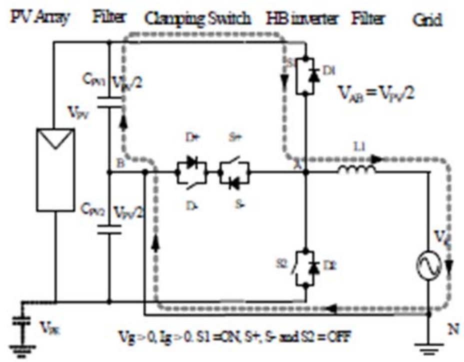
H6Topology (FBDC Bypass)



REFU UltraEta



NPC (Danfoss)



Conergy Topology

T. Hauser et. al, Sunways, EUPVConf Valencia 2008, 4DO.8.2

Topologies Comparison

- **Topologies derived from FB**
  - **Actually both HERIC, H5, REFU and FB-DCBP topologies are converting the 2 level FB (or HB) inverter in a 3 level one.**
  - **This increases the efficiency as both the switches and the output inductor are subject to half of the input voltage stress.**
  - **The zero voltage state is achieved by shorting the grid using higher or lower switches of the bridge (H5) or by using additional ac bypass (HERIC or REFU) or dc bypass (FB-DCBP).**
  - **H5 and HERIC are isolating the PV panels from the grid during zero voltage while REFU and FB-DCBP is clamping the neutral to the mid-point of the dc link.**
  - **Both REFU and HERIC use ac by-pass but REFU uses 2 switches in anti- parallel and HERIC uses 2 switches in series (back to back). Thus the conduction losses in the ac-bypass are lower for the REFU topology.**
  - **REFU and H5 have slightly higher efficiencies as they have only one switch switching with high-frequency while HERIC and FB_DCBP have two.**
- **Topologies derived from NPC**
  - **The classical NPC and its "variant" Conergy-NPC are both three-level topologies featuring the advantages of unipolar voltage across the filter, high efficiency due to disconnection of PV panels during zero-voltage state and practical no leakage due to grounded DC link mid-point.**
  - **Due to higher complexity in comparison with FB-derived topology, these structures are typically used in three-phase PV inverters with ratings over 10 kW (mini-central).**

Source: Bari ISIE 2010

Improving Performance Indices Efficiency versus power density

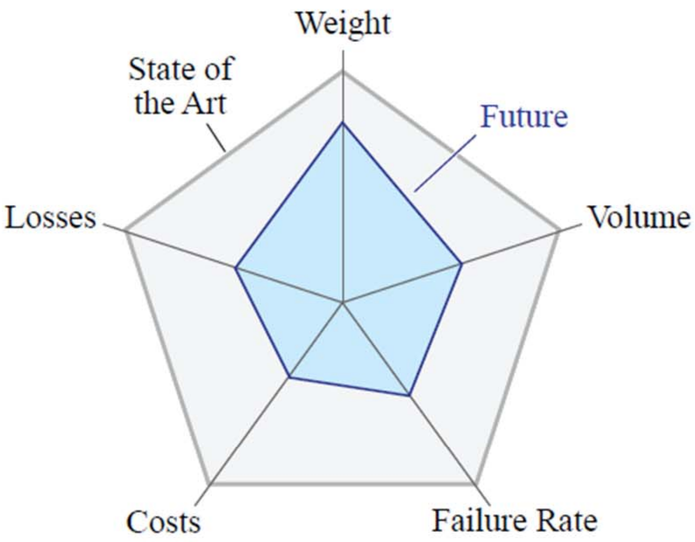


Fig. 3. State of the art and required future performance improvement of power electronics systems. The system performance is characterized by relative quantities, i.e. Performance Indices like output power density ρ (kW/dm^3), efficiency η, output power per unit weight γ (kW/kg), output power related to costs σ (kW/\$), and failure rate (MTBF^{-1}). Further improvement trends like shorter development cycle time or shorter time-to-market for custom designs [6] are not shown.

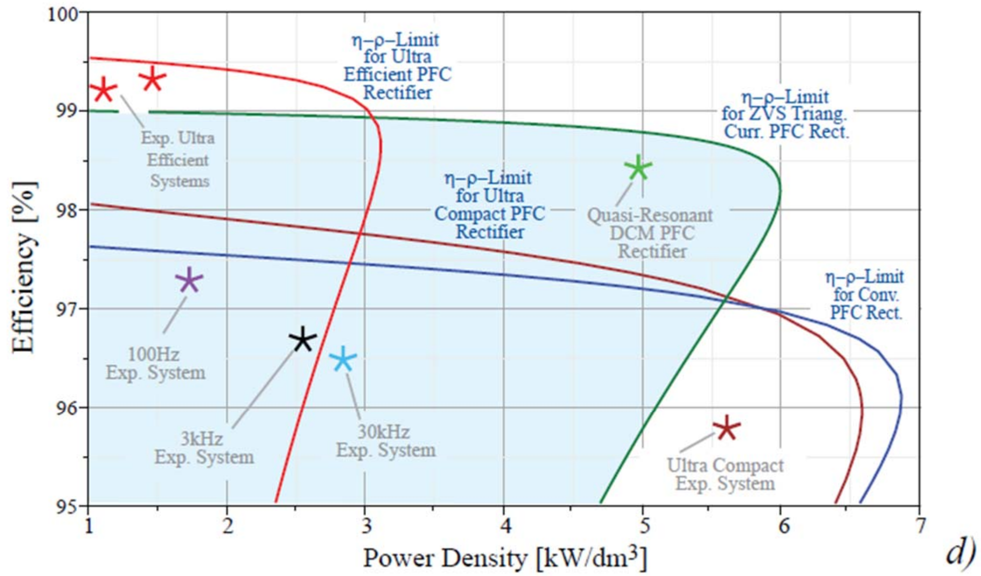


Fig. 12. Basic structure of the power circuit of a conventional single-phase power factor corrected (PFC) rectifier a), a bridgeless PFC rectifier b) and a resonant transition zero voltage switching (ZVS) PFC rectifier c). Furthermore shown: η-ρ-Pareto Fronts of the circuits identifying c) as preferable concerning the trade-off between efficiency η and power density ρ; a power density of 5kW/dm^3 and an efficiency of 98.5% can be achieved.

J- Kolar et. al., Roadmap 2009; http://www.pes.ee.ethz.ch/uploads/tx_ethpublications/ROADmap_send.pdf

Average nominal EURO eff fits closer to eta max

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Status:

Today's high efficient inverters shows small changes at different part load and DC voltages.

Today: Premium products EURO ETA 97.5% also in the 5kW class (about 0.3€/W)

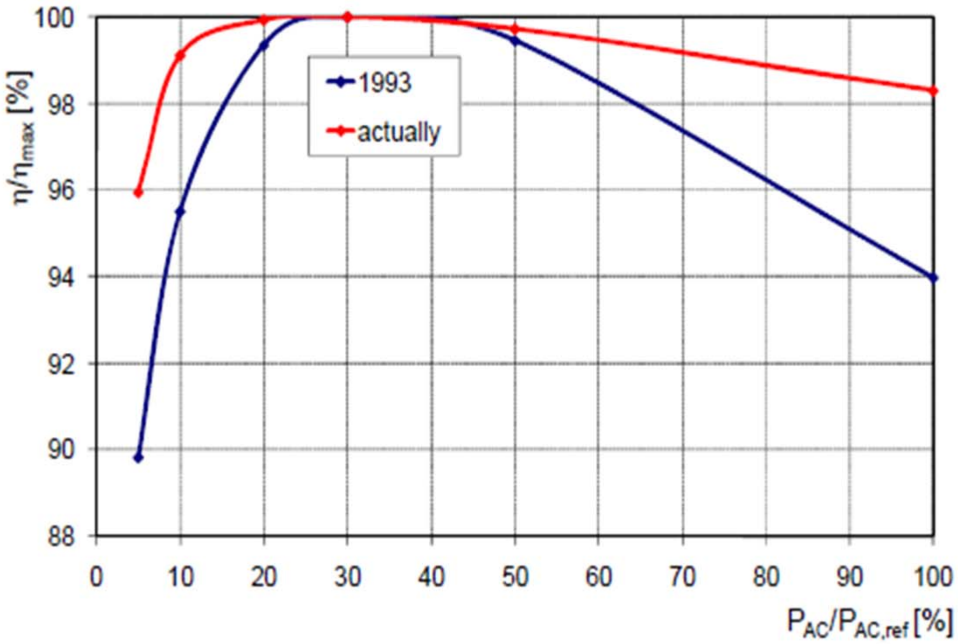
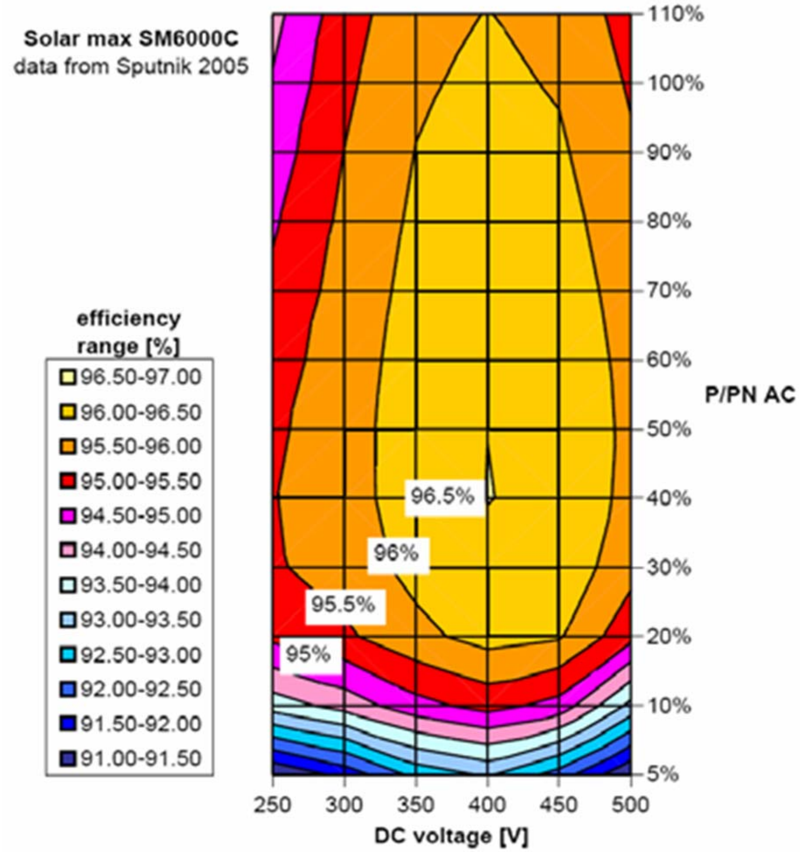


Figure 12: Efficiency normalized to peak efficiency over the AC power derived from the peak efficiency

B. Burger et. al. , ISE, EUPVSE 2010



F. Baumgartner, EUPVSE 2005

Module Integrated Inverter

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

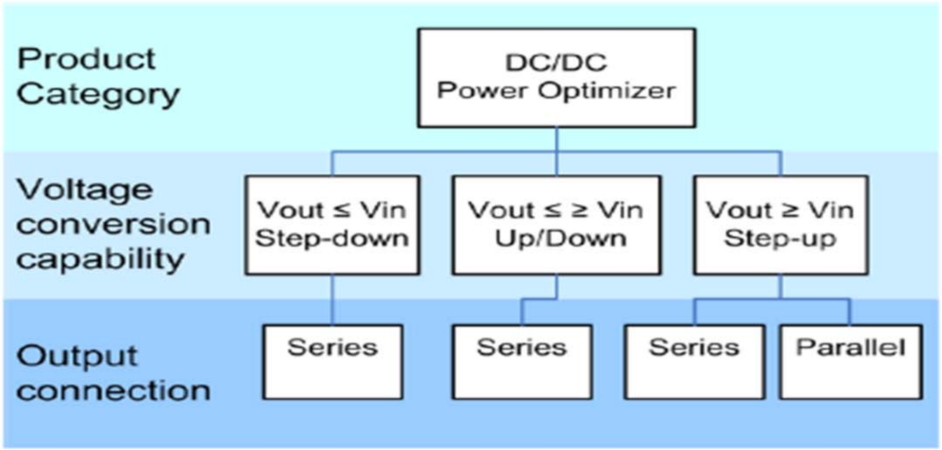


Fig. 1 Categorisation of module integrated DC/DC converters (Power Optimizers), based on their electrical properties.

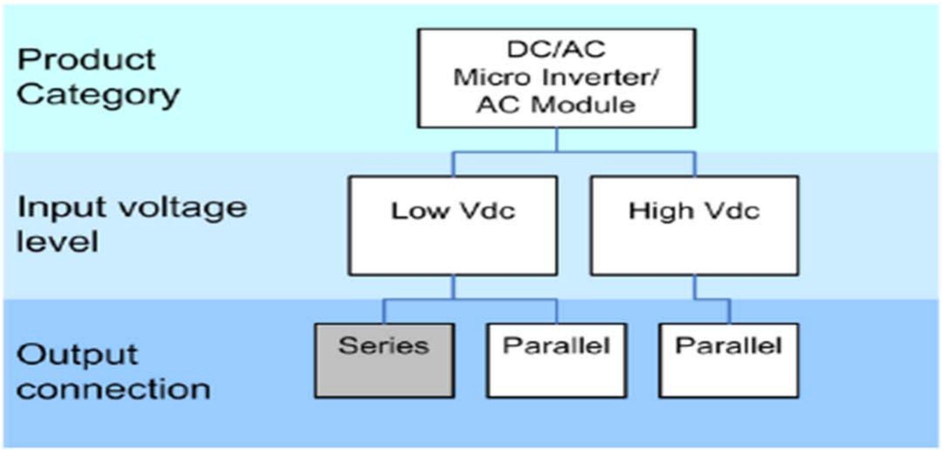


Fig. 2 Categorisation scheme for module integrated DC/AC converters ("Micro Inverters", based on their electrical properties.

Product Category*	**Manufacturer and Model**	**Performance figures**
		Conversion efficiency
Products available on the market today		
DC.UP.S	Solar Edge PB250-AOB [9]	Maximum 98.6 % European/CEC 97.8/97.7%
DC.DN.S	TIGO Energy MM-ES [10]	No information
DC.UP.S	ST Microelectronics SPV1020 [11]	"Up to 98% efficiency"
DC.UD.S	SolarMagic SM3320 [12]	99.5% ("Panel Mode Effi-ciency") No other specs.
DC.UP.P	Tigo Energy MM-EP	No information
DC.UP.P	EIQ Energy vBoost 250 [13]	97% to 98% (peak)
AC.LV.P	Enphase M210-84-240-S12 [15]	Peak 96.0% CEC 95.5%
AC.LV.P	Enecsys SMI -240 [16]	European 92.1% Peak 94.0%
AC.LV.P	Solar Bridge P235LV-240 [17]	Peak 95.5% CEC 94.5%
Devices under development		
AC.HV.P	IWES PV-MIPS (Prototype) [7]	Maximum 97.1 % European 95.7 %
Discontinued devices (for comparison only)		
AC.LV.P	Exendis GridFit 250 LV [14]	European >90%

B. Bründlinger et. al. , ARSENAL, EUPVSE 2011, 3204

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Partial Shading
module oriented power electronics

Status of todays modules DC/DC and AC-Module power electronic products

- For small shading effects still the traditional Parallel Strings is the cost leader,
- Module oriented power electronics, at higher €/W installation costs are economical feasible only at heavy shading condition with high feed in tariffs & high irradiance

Table II: Assumptions for the TCO benchmark

	Acquisition	Installation
Parallel String Inverter	0.475 €/W	200 €
Adapted Parallel String inv. for DC-DC Mod.	0.45 €/W	200 €
Multi String inverter	0.5 €/W	200 €
DC-DC Module	0.4 €/W	20 €
AC Module	0.6 €/W	20 €

	Maintenance	MTBF
Parallel String Inverter	100 €	115 a
Adapted Parallel String Inv. for DC-DC Mod.	100 €	115 a
Multi String Inverter	100 €	115 a
DC-DC Module	100 €	455 a [17]
AC Module	100 €	331 a [14]

B. Burger et. al. , ISE, EUPVSE 2010

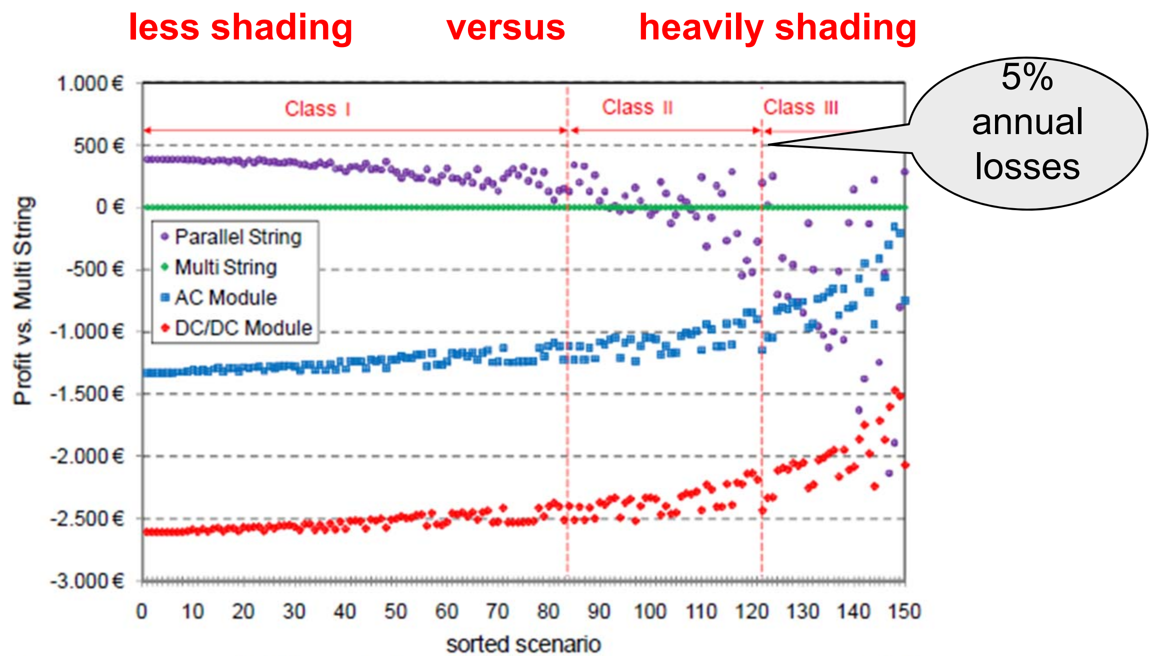


Figure 14: Additional income in contrast to a Multi String solution sorted by decreasing (ideal) yield of the 150 scenarios in total

Thin film inverter are not needed if module producer approve TL inverter

- OC Oerlikon Solar approved their Thin Film Silicon Tandem modules (10% efficiency, low voltage module design) for transformer less inverters
- Thus the inverter cost are reduced to 21% from 25% (savings of about 43€/kWp Investment costs at about 3% higher efficiency for a 300kW roof top system in southen Europe ; (personal Communication von J. Sutterlüti, OC Oerlikon, Switzerland, March 2012)
- Other thin film products needs to be operated by special high cost thin film inverters with offers no negative potential to ground due to their topology.

PV + battery on the market at relative high prices

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

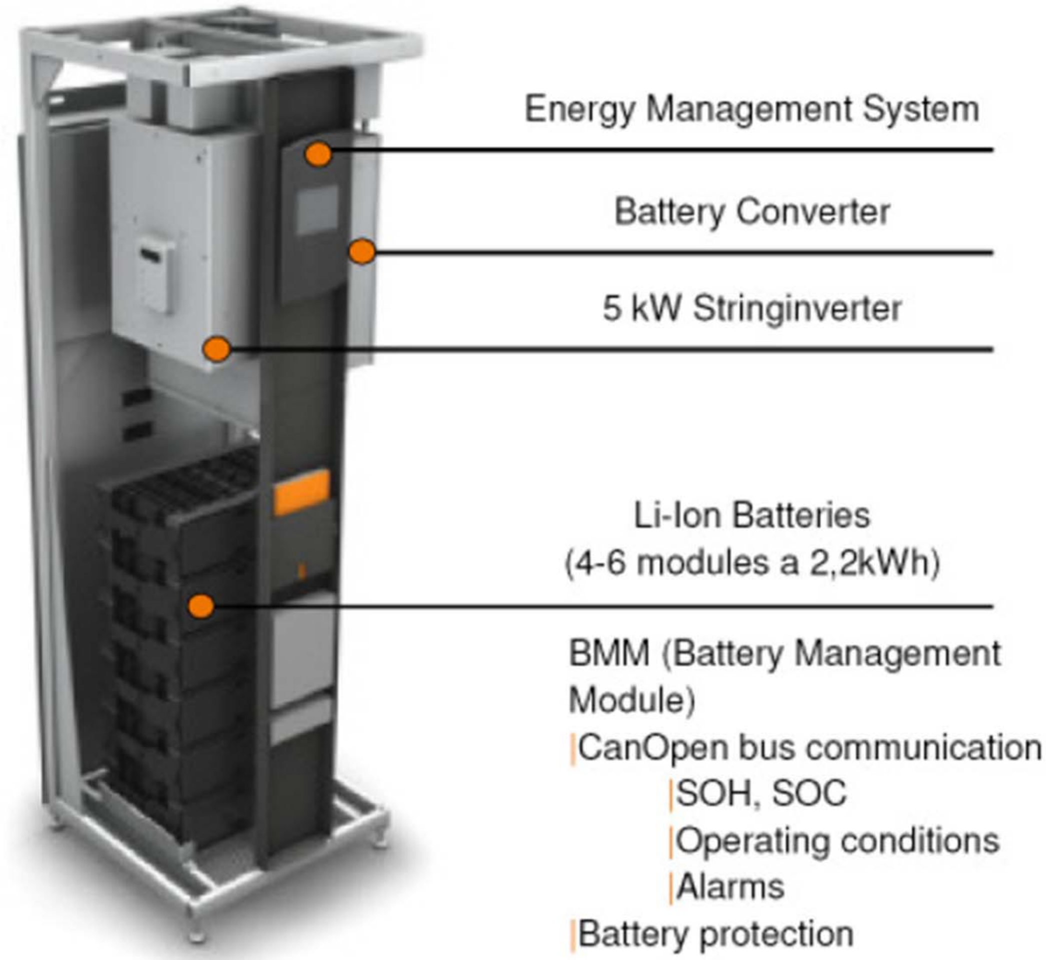
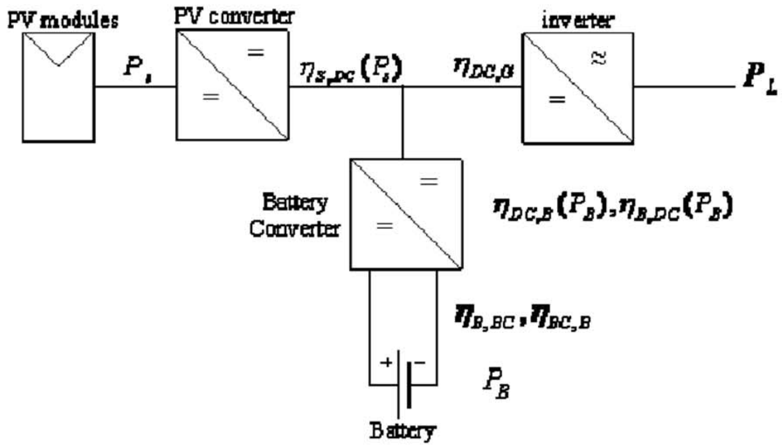


Figure 1: Overview over the Sol-ion system



A. Schmiegl et. al., Voltwerk, Bosch, Saft, IWES.. EUPVSEC 2011, p4152

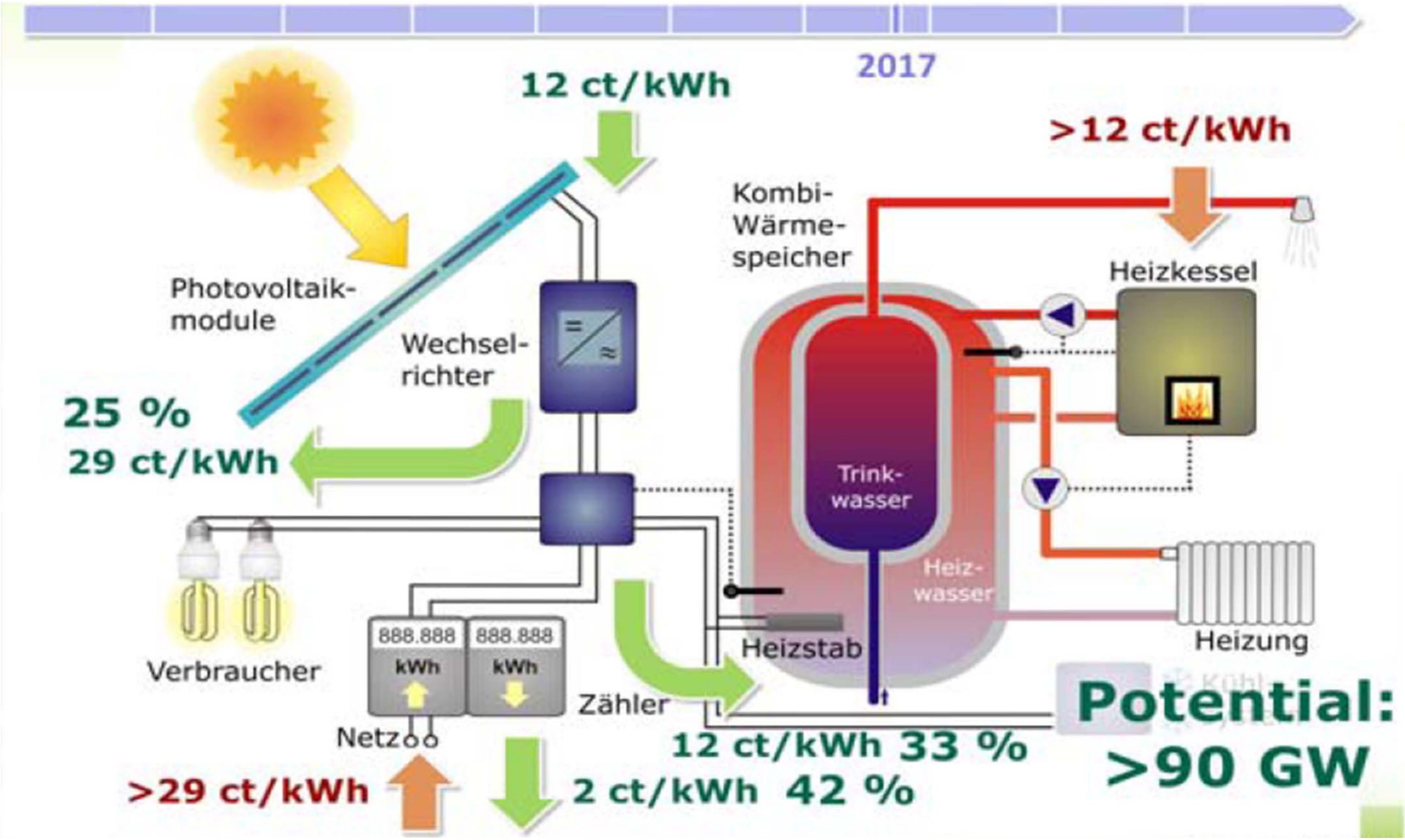
Comment:

Battery System in the cost range of 10 000€

Li Battery costs about 0.5€/kWh

If PV electricity is cheap hot water production is cheaper than a elec. battery

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering



V. Quaschning, HTW Berlin, PV-Konf., Staffelstein, 2012-03-01

PV Inverter Semicond produced directly in the Si solar wafer

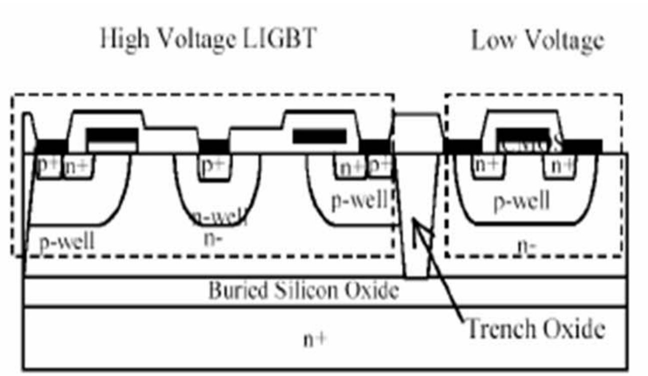


Figure 1: Cross-showing isolation between High and Low voltage devices.

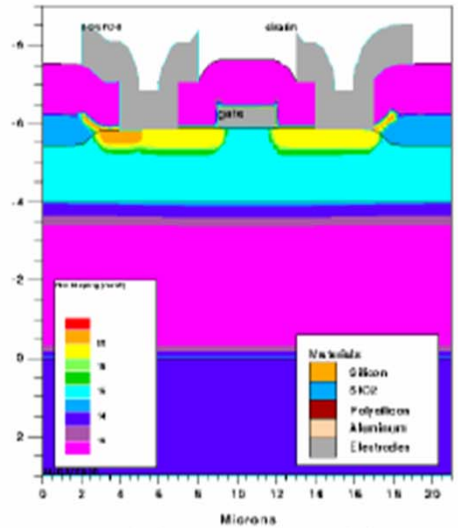


Figure 6a: Cross-section of PMOS devices

Benefits: Power Integrated Circuits (PICs)

- No discrete components one CMOS fab. process
- Reducing wiring costs/ integration PV-module
- Reducing packaging costs
- Increase reliability

Problems:

- Isolation 600V
- Off-chip: C, L, transform.

Status: Hitachi Power IC

A. Mumtaz, et. Al. University of Cambridge, U.K.;
FEASIBILITY OF INTEGRATING PV INVERTER ONTO A SINGLE CHIP
17th European Photovoltaic Solar Energy Conference, Munich, 2001;p930

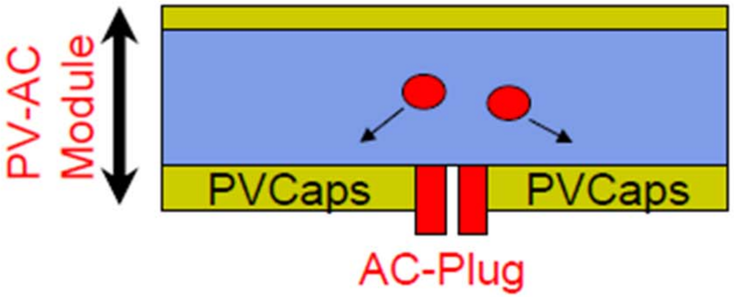
F. Baumgartner; 1st Solar Wind Conference Segovia, Spain July 2003, slide 33

Visions proposed ten years ago

Future Generation of PV Systems – 2030?

PV-AC

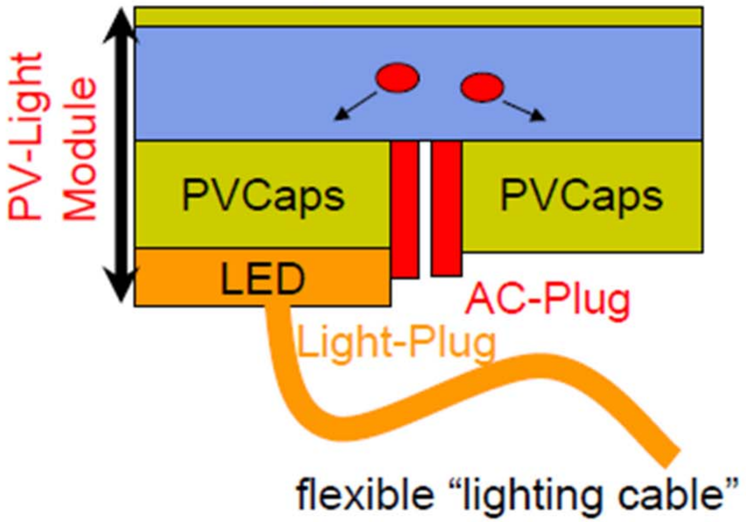
- cell + inverter + control elec. integrated on the same semiconductor



- mechanical and electrical connection of the system by click and place!
- standardized module sizes

PV-Storage

- storage system + appl. integrated in the module
- PV-lighting systems: PV - Battery and "white LED" integrated Module



F. Baumgartner, EU JRC Ispra PV Workshop 11/5/2002

Vision from IMEC: Smart PV Module Power electronics onto the wafer!

low-cost approaches for high-band gap semiconductors as a by-pass Transistor or as a DC/DC stage on the module

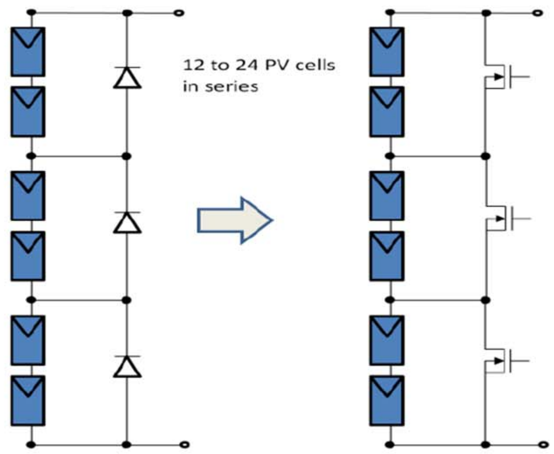


Figure 10a Replacement of bypass diodes by low-loss switches

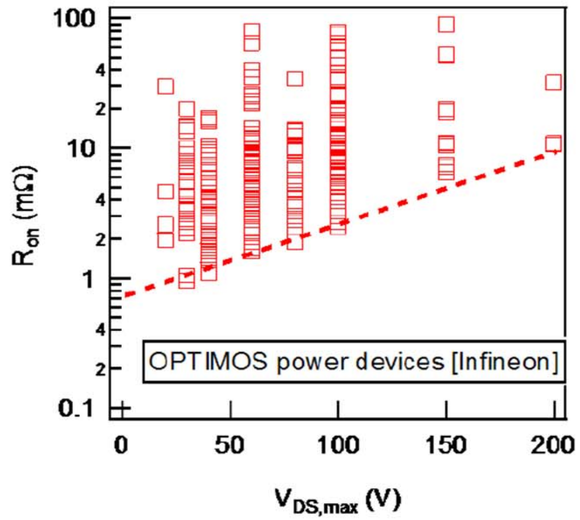


Figure 10b Example of State-of-the-art on low-loss switches

Storage function may be centralized or distributed – possibly micro-storage will be introduced at the module level in close conjunction to DC/DC converters.

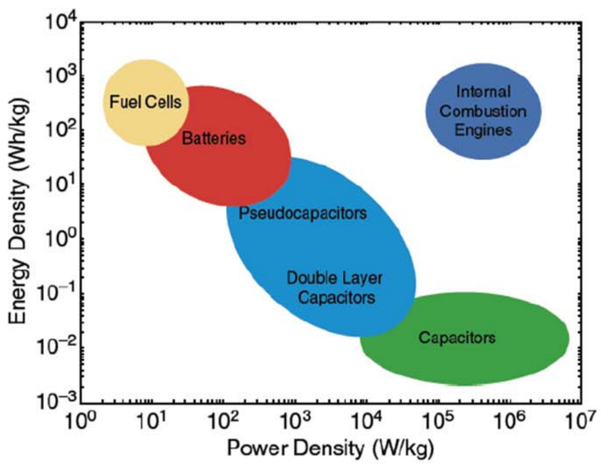


Figure 11a Energy density versus power density for a broad range of storage solutions (taken from [20])

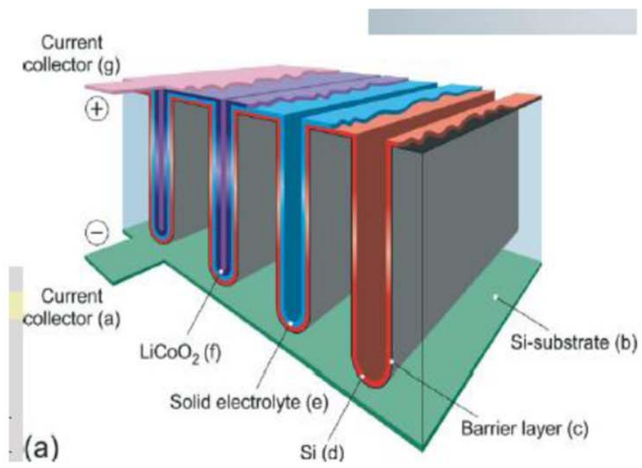


Figure 11b Cross-section of a thin-film battery integrated on a crystalline Si substrate (taken from [21])

J. Poortsman et. al., IMEC EUPVSEC 2011, p3712

Conclusions and Trends

Zurich University of Applied Sciences
zh aw School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

1. No economic driver for eff> 99% (transformer less concepts)
2. Improving service, MTBF Cond. and reduction of overall size
3. Market will change to smaller power inverters due to higher self consumption rate and the benefit in FIT Feed in Tariffs
4. Cheapest battery is the PV water heater or other consumers
5. Smart Grid IT communication, reactive power control, voltage
6. New power electronic centres at home integrates several functions like PV inverter, EV charger + storage + water heater + meter
7. Long term goal: The integration of more power electronic circuits on the PV wafer itself, is still an challenging topic.