APEC 2012, Orlando, FL

Levelized Cost of Energy

from residential to large scale PV

comparing central, string
and micro inverters
current status and future perspectives

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Summary

- ▷ PV system design with Micro-inverter, String and Central inverters
- ▷ LCOE on Residential, Commercial and Utility-scale plants – key metrics and assumptions
- ▷ LCOE vs PV plant size and type
- ▷ Deviations affecting the selection process
- ▷ Future trends: learning processes towards grid parity
- ▷ Challenges: grid-friendly inverters
- ▷ Conclusions

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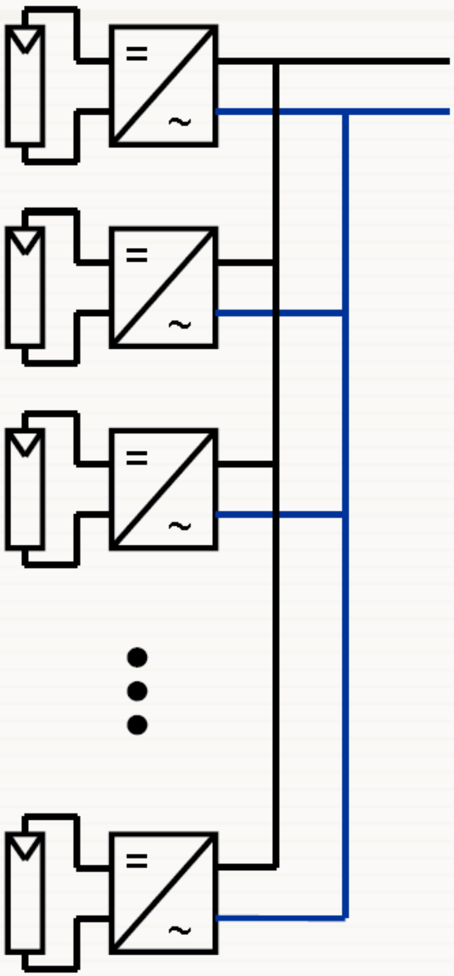
MICRO Application



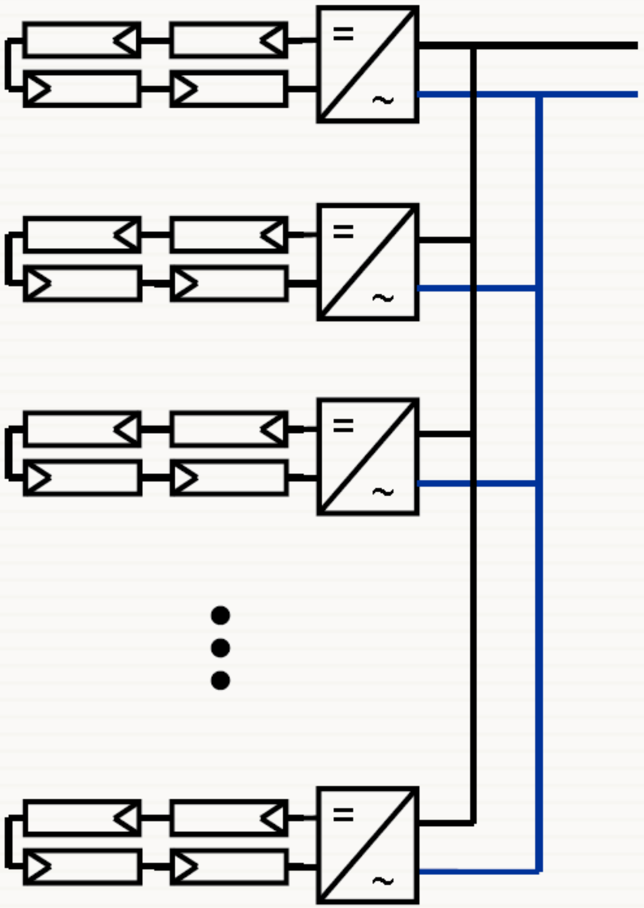
PRO

- Panel level MPPT
- Increase System Availability
- Panel level Monitoring
- No High DC voltage
- Increase Design Flexibility

CONS

- Higher $/W Inverter cost
- Higher Maintenance costs due to the high number of components in the system combined to higher access costs

STRING Application



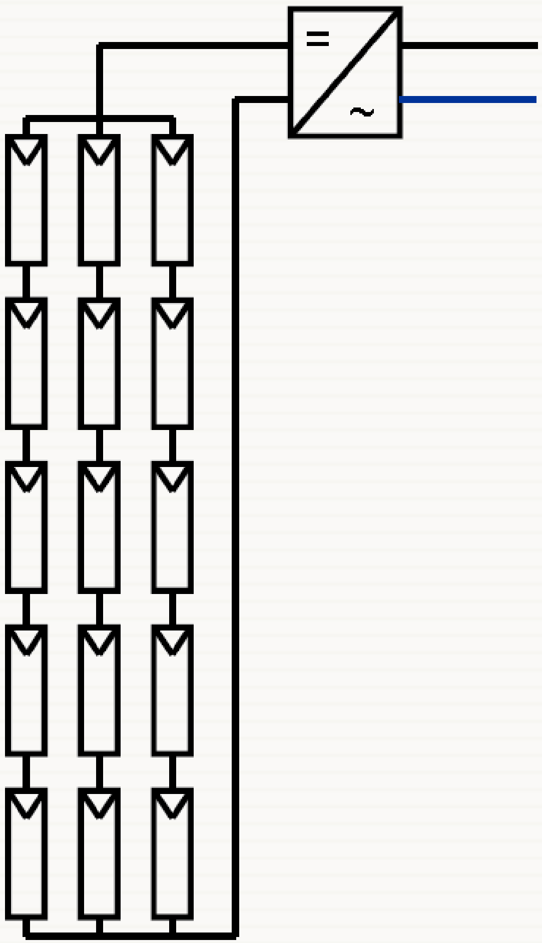
PRO

- High design flexibility for a wide range of applications
- High efficiency
- BoS Integration (DC combiner)

CONS

- No Panel level MPPT
- No panel level monitoring

CENTRAL Application



PRO

- Low capital price per Watt
- High efficiency
- BoS integration

CONS

- Uniform orientation and configuration required
- Dimensions, weight, noise
- Single point of failure

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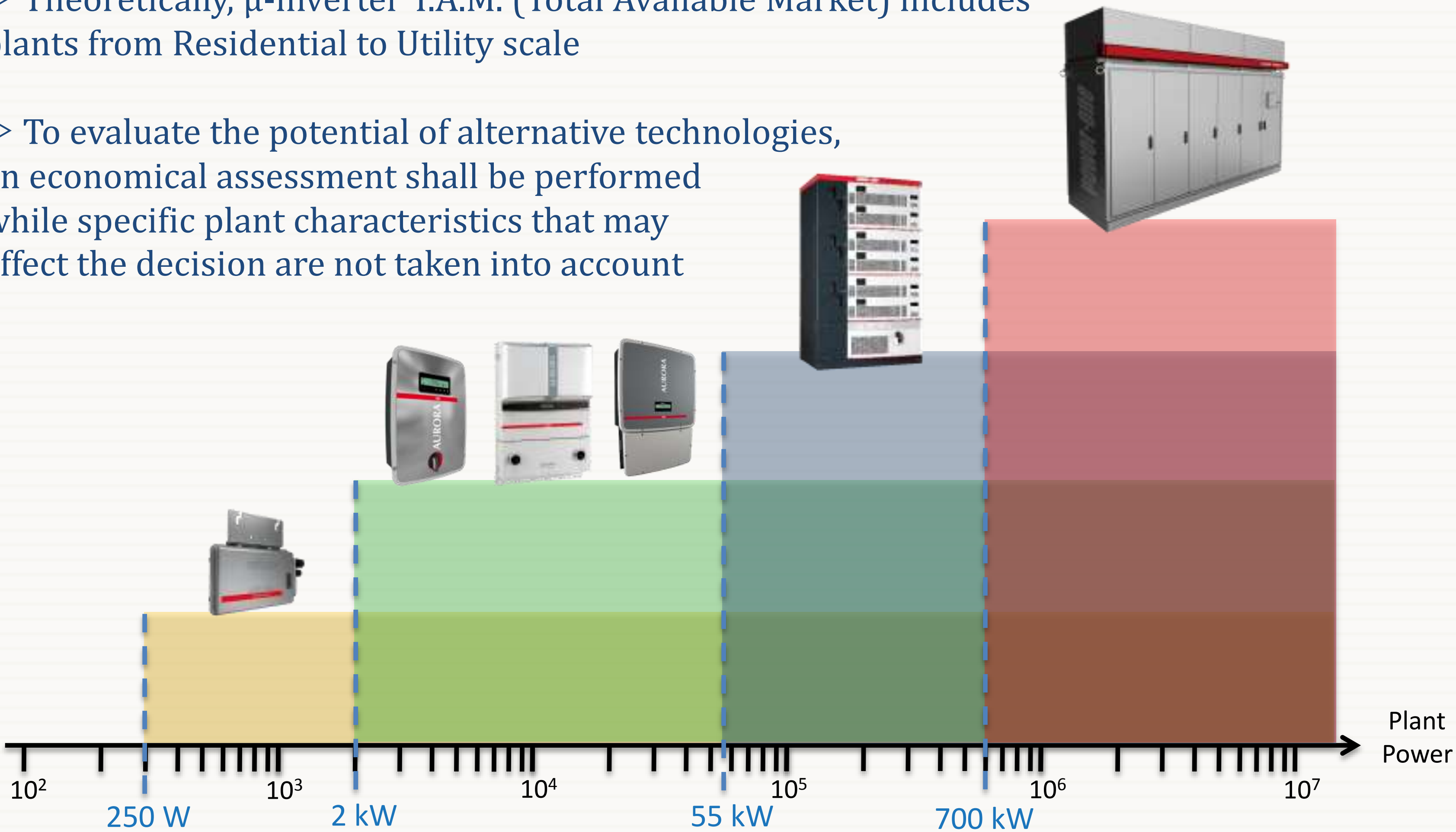
Unconstrained Comparison

▷ Theoretically, µ-inverter T.A.M. (Total Available Market) includes plants from Residential to Utility scale

▷ To evaluate the potential of alternative technologies, an economical assessment shall be performed while specific plant characteristics that may affect the decision are not taken into account



LCOE Model & Metrics

The Levelized Cost of Energy (LCOE) allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both exist.

$$LCOE = \frac{CAPEX_{(0)} + \sum_{t=0}^{N} \frac{OPEX_{(t)}}{(1+\alpha)^t}}{\sum_{t=0}^{N} \frac{E_{net(t)}}{(1+\alpha)^t}}$$

$$CAPEX_{(0)} = IM\ (C_p + C_i + C_{BoS})$$

- IM: Installation Margin (% Material Price)
- C_p: Panel Price ($/kW)
- C_i: Inverter Price ($/kW)
- C_{BoS}: BoS Price ($/kW)

$$OPEX_{(t)} = [Ni_{(t)}\ (C_m + C_r) + C_{op}]$$

- $Ni_{(t)}$: Number of Interventions In Year "t" (Calls/kW/y)
- C_m: Mission Cost ($/Call)
- C_r: Replacement Cost ($/Call)
- C_{op}: Operation Cost ($/kW/y)

$$E_{net(t)} = P_{Plant}\ h_{eq}\ PR_{(0)} (1 - \beta\ t)$$

- h_{eq}: Equivalent Hours at P_{Plant}
- $PR_{(0)}$: Performance Ratio at Year 0
- β: Degradation Rate ($\%P_{Plant}$/y)

LCOE Model: Driving Factors

	Inverter Driven		Plant Driven	
CAPEX	Ci	CBoS	IM	Cp
OPEX(t)	Ni, Cr	Cm & Cop		
$E_{net(t)}$	$PR_{(0)}$ & β			h_{eq}

- ▻ Inverter Price
- ▻ Inverter Installation Cost
- ▻ Inverter Reliability
- ▻ # of Inverter in field
- ▻ Inverter Efficiency
- ▻ Number of MPPT
- ▻ Input/Output Inverter Voltage

- ▻ Inverter DC/AC Voltage: DC/AC Plant Component's sizing
- ▻ Inverter BoS Integration: easy of installation
- ▻ Inverter Accessibility & Localization
- ▻ Small Inverter (Swop), Large Inverter (99% Warranty)
- ▻ Conversion topology (distributed/centralized)

Assumptions

		Specific Price ($/W)	MTBF (years)	Learning Rate (%)	OPEX (%Capex/y)
Inverter Background	MICRO Inverter	0.5 ↔ 0.74	382	25	0.21
	String & Multi-String Inverter	0.25 ↔ 0.5	85 ↔ 130	20	0.12 ↔ 0.18 (*)
	Central Inverter	0.18 ↔ 0.24	10 ↔ 15	15	0.25 ↔ 0.30 (*)

General assumptions:

- Non-incentivized scenario
- Fixed optimum tilt & azimut
- Markup on all materials included in "Installation, Permitting, Design"
- Plant life-time 25 years
- Maintenance not included

(*) 99% uptime included for central and multi-string on large scale plants (> 300kW)

	Residential	Commercial	Utility
Module Price ($/W)	1	0.95	0.9
BoS Price ($/W)	0.3 ↔ 0.4	0.2 ↔ 0.25	0.2 ↔ 0.3
Installation, Permitting Design ($/W)	0.8 ↔ 0.9	0.65 ↔ 0.72	0.35 ↔ 0.45
WACC (%)	4.6	5.5	6.5
Plant life (N years)		25	
H_{eq} (kWh/kWp)		1400	
$PR_{(0)}$ (Unshaded)		0.8 ↔ 0.82	
$PR_{(0)}$ (Shaded)		0.73 ↔ 0.785	

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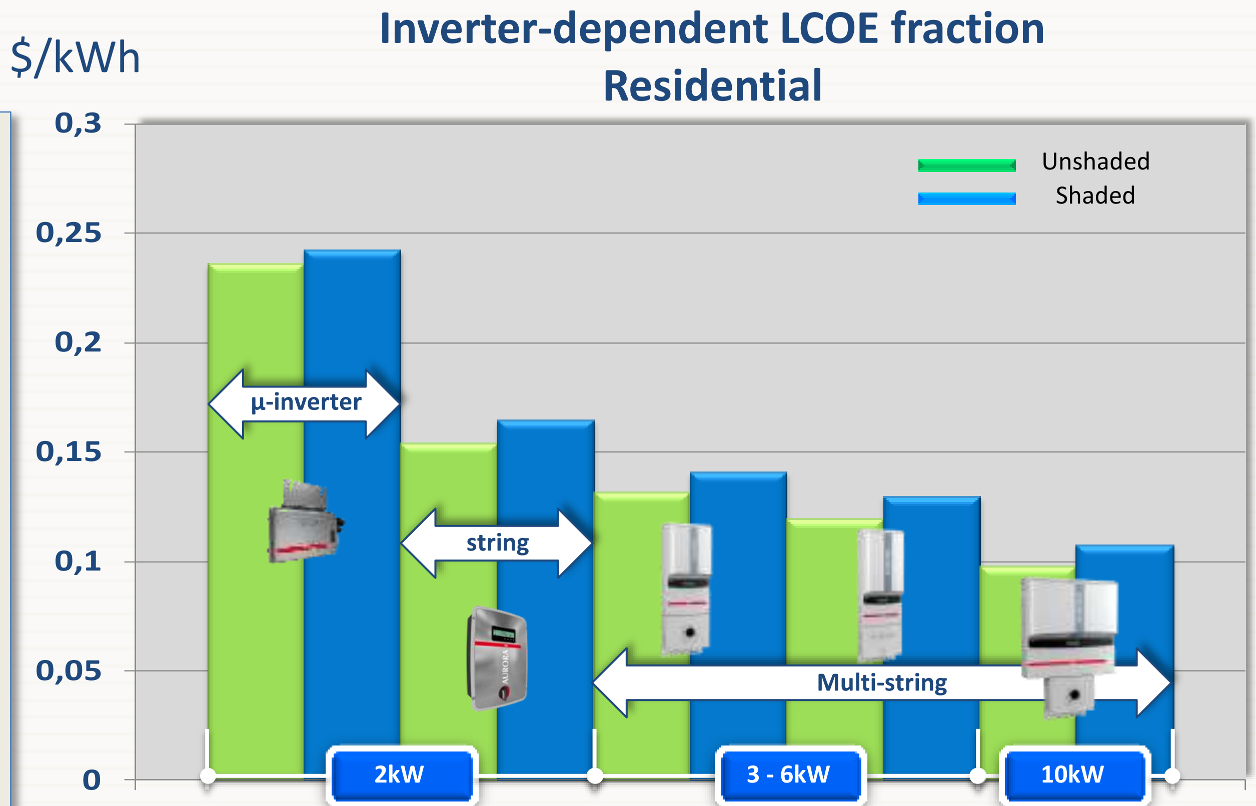
LCOE: comparative analysis
Residential rooftop applications

Facts:

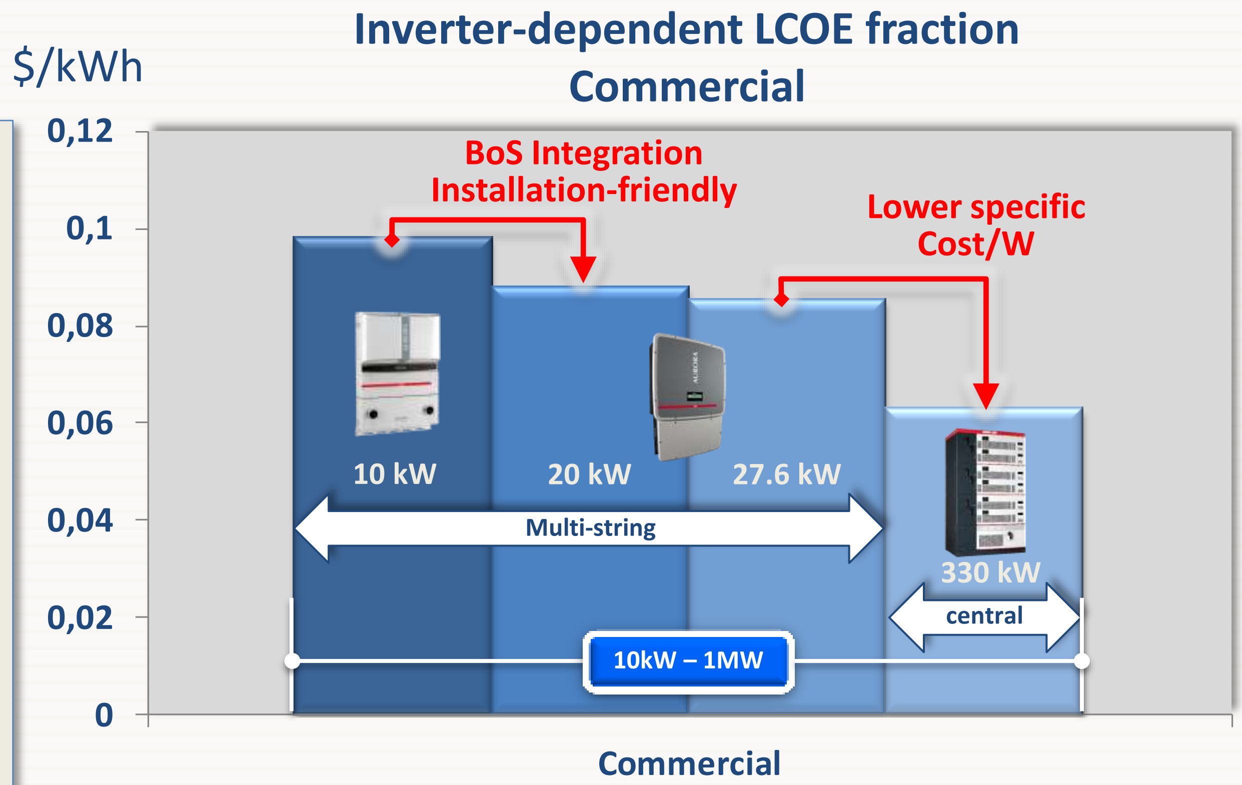
- Distributed conversion increase shadow's immunity but this does not outweighs the higher specific costs
- Despite an high MTBF, the O&M costs of module-based conversion is higher due to the high "Mission cost"
- Due to the strong reduction of specific costs, the best Inverter size is always the one that closely match the nominal system power



Factors:

- Inverter Price
- Inverter Driven BoS
- Opex (no maintenance)
- WACC = 4.5%

LCOE: comparative analysis
Commercial rooftop applications



Facts:

- Efficiency improvements are combined with higher BOS integration and power density on new generation 3-phase string inverters, making them a competitive choice for large rooftop commercial applications
- Further cost savings are possible only increasing the inverter capacity to leverage on the integration of common parts
- The possibility to convert from 1000Vdc have been considered

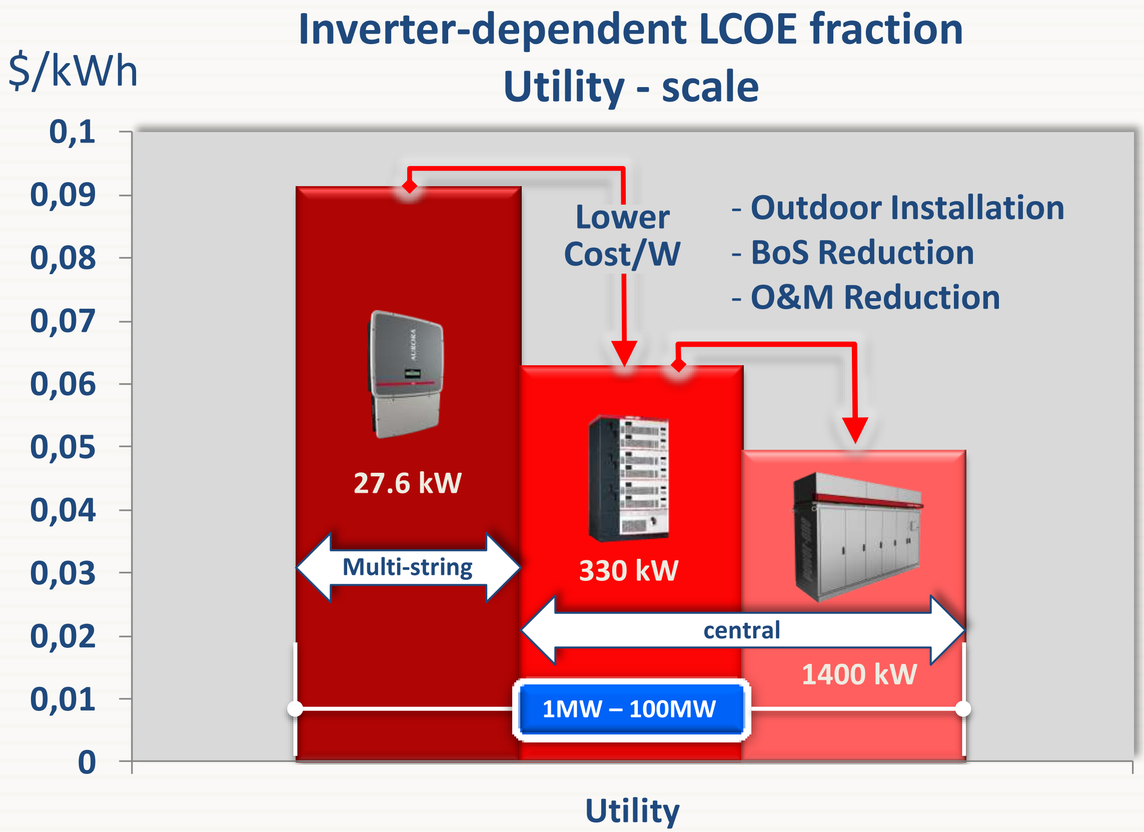
Factors:

- Inverter Price
- Inverter Driven BoS
- Opex (no maintenance)
- WACC = 5.5%

LCOE: comparative analysis
Utility-scale

Facts:

- Lower specific costs combined to lower AC-side BOS costs make central inverter-based solutions more economical for large scale free-field installations
- Further deployment / installation and O&M cost savings are possible with inverter construction tailored to utility-grade system optimization. (outdoor construction)
- Higher AC voltage conversion offers BOS cost reduction and higher inverter power density



Factors:

- Inverter Price
- Inverter Driven BoS
- Opex (no maintenance)
- WACC = 6.5%

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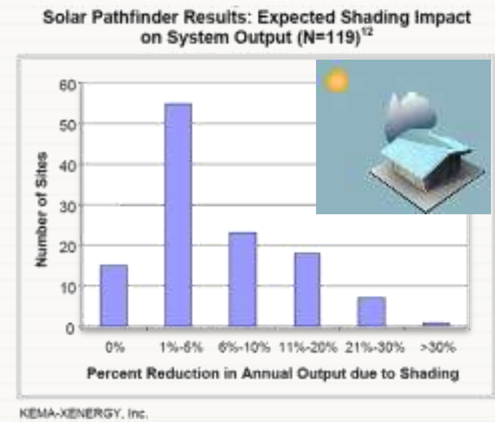
Deviations affecting the selection process

Plant characteristics may affect the LCOE and modify the decision process:

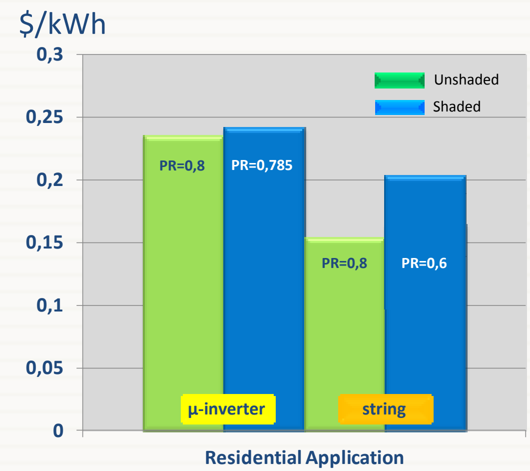
Demystify the effect of Shadows

- According to CEC ERP on-site verifications (Kema - 2005) about 70% of the sites (N=119, avg. size 5kW) were measured to have less that 5% reduction in output due to shading
- Marginal effect on small plants made with few parallel-connected strings (especially with multi-string inverters)



"Long term sustainability" is required

- *Non incentivized PV markets does not pay back systems with less than average PR's due to severe shading*
- *Micro-inverters producing more where the system in any case produce less is a "lose-lose" approach*
- *Module-based technologies will capitalize their advantages on small systems when cost reductions combined to efficiency and reliability improvements will make LCOE competitive as compared to traditional string-based conversion systems*



PR and LCOE of heavy-shaded PV plants

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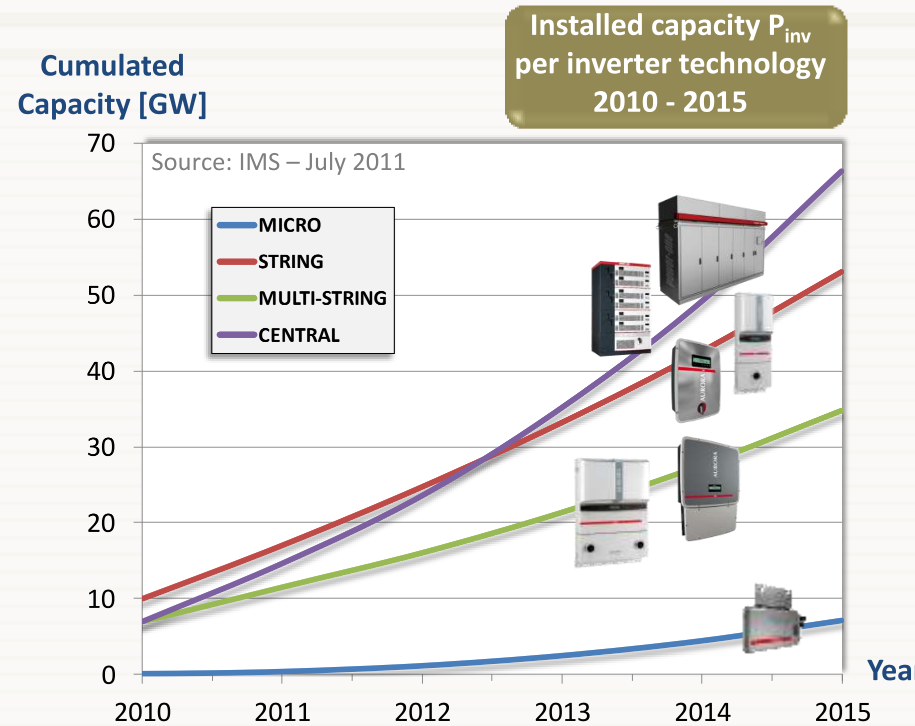
Future trends: learning processes

Technology and cost-driven LCOE improvement

- ▷ *Installed capacity grow ratio will continue to drive the PV inverter (and system) cost reduction over the next decade*
- ▷ *Stable double digit Learning Ratio have been considered for all inverter technologies*
- ▷ *Module level converters learning rate > 25%, boosted by higher grow ratios (6-fold from 2012 to 2015)*
- ▷ *More moderate learning rates are expected for string (20%) and central platforms (15%) as a consequence of more mature technologies and optimized products approaching the floor cost*



Overall installed capacity by 2015: ≈ 160GW

$$LCOE_{Inv.2015} = LCOE_{Inv.2011}\left(\frac{P_{Inv.2015}}{P_{Inv.2011}}\right)^{\frac{\log(1-LR_{Inv.})}{\log 2}}$$

Learning equation - LCOE

Future trends: learning processes

Grid Parity Events: Residential Applications/North America

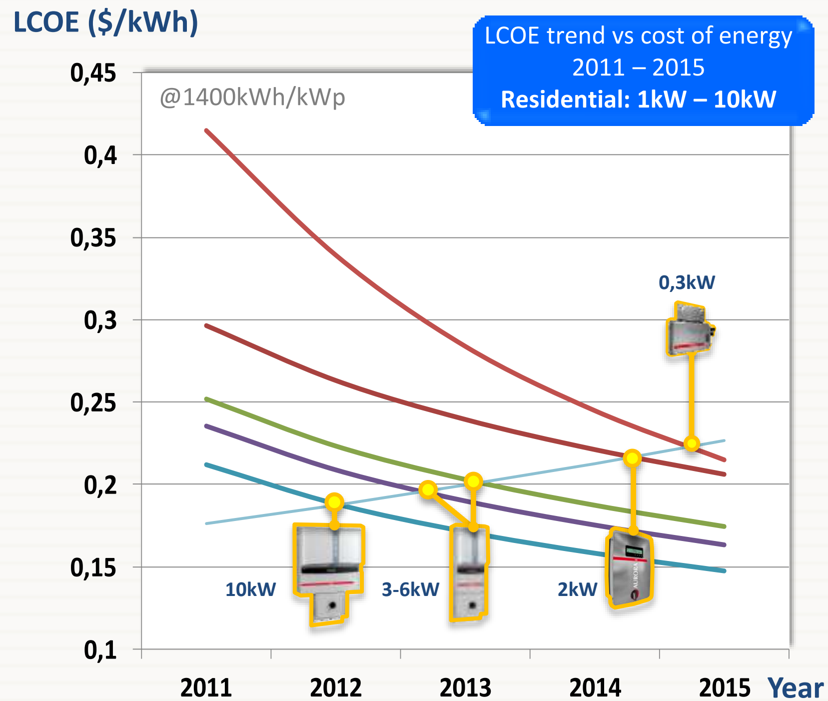
Grid parity is there, also for µ-inverters!!

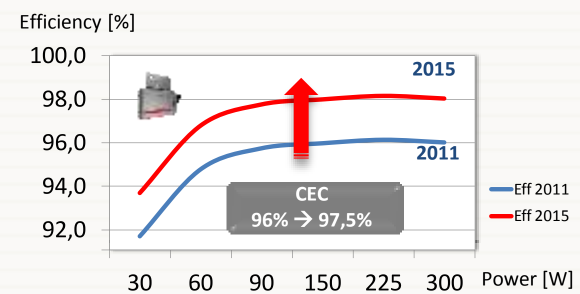
- *Residential PV plants based on 3-phase string inverters will reach grid parity first*
- *Higher cost reductions (Capex + Opex) of micro-inverters stimulated by higher grow rates will enable also small scale PV plants based on this technology to reach grid parity before 2015!*

Technology-driven LCOE reduction

µ-Inverter harvesting & reliability improvements

- *New topologies*
- *New active components (SiC, GaN)*
- *Deeper integration level – enhanced reliability*
- *Improved efficiency = less material → reduced cost!!*





Future trends: learning processes

Grid Parity Events: Commercial Applications/North America

String inverters approaching 99% - what else?

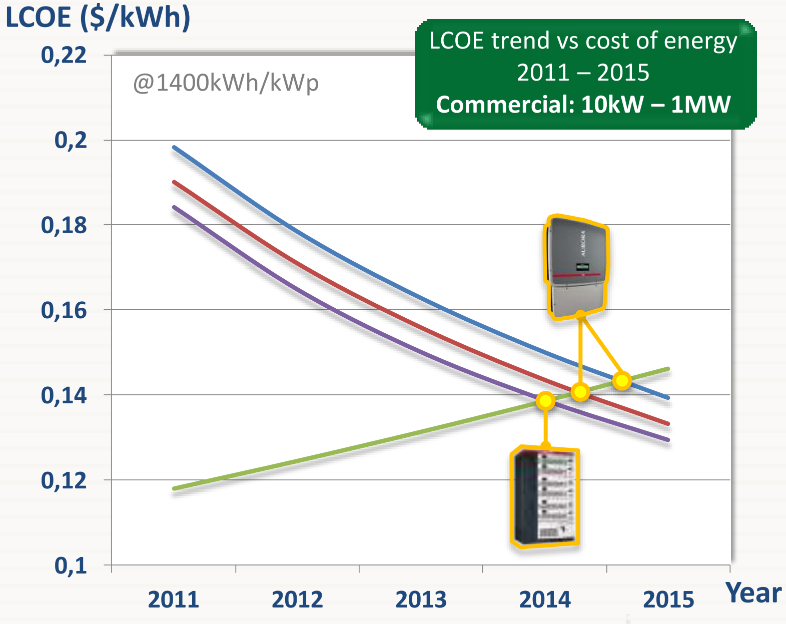
▷ ***Reduction of CAPEX***

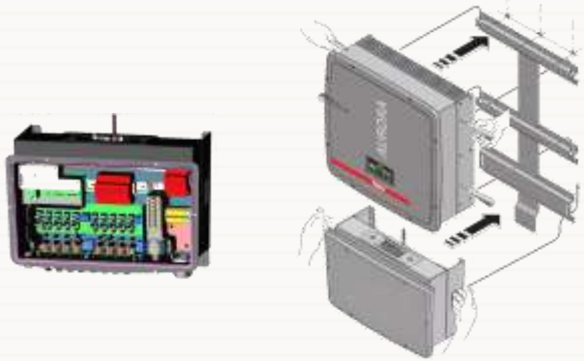
- *Deeper BOS integration: DC re-combiner, AC&DC disconnect, surge protection*
- *Advanced string-level monitoring and diagnostic functions*
- *Increase DC & AC voltage to boost the power density (kW/m³ and kW/kg) and further reduce BOS costs*

▷ ***Lower OPEX***

… Installation / maintenance-friendly concepts

- *Extended Lifetime: Electrolytic-free/Passive cooling*
- *Weatherproof IP65 enclosure*
- *2-parts assembly, with detachable bracket-mounted wiring box and inverter compartment*





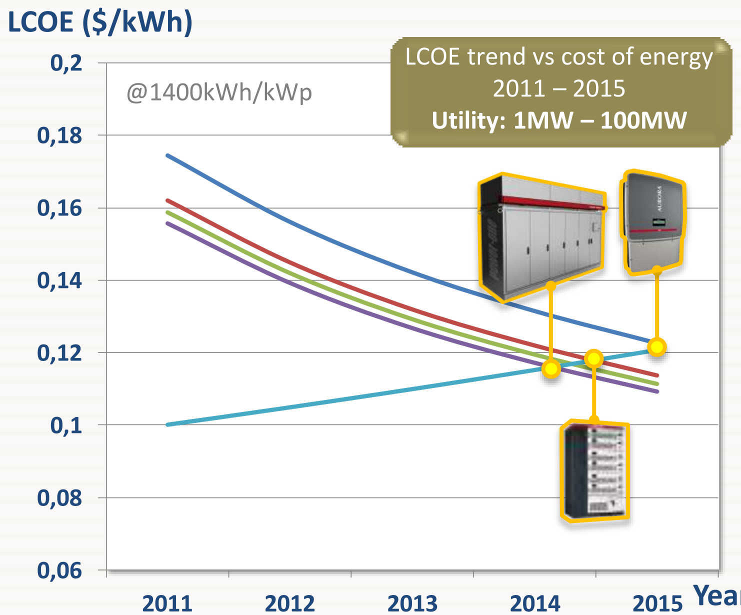
Future trends: learning processes

Grid Parity Events: Utility-scale Applications/North America

Central inverters – the future is MV?

▷ ***CAPEX – total reduction of system-level costs***

- *Migration from low AC voltage to industrial standard 690Vac, while maintaining DC limit to 1000Vdc*
- *AC-side BOS savings: cables/switches/transformers/station*
- *Increase DC voltage above 1000V to further reduce BOS costs and inverter costs thanks to increased power density*



▷ ***Lower OPEX***

Installation / maintenance-friendly concepts

- *Modular construction, lower MTTR and downtime*
- *New outdoor IP65 enclosures with water cooling systems*
- *Reduced deployment and installation costs*

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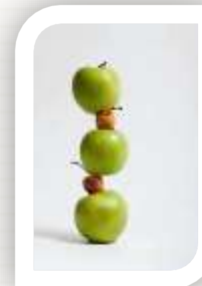
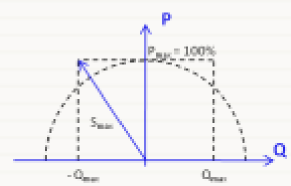
Challenges: “Grid-friendly” inverters

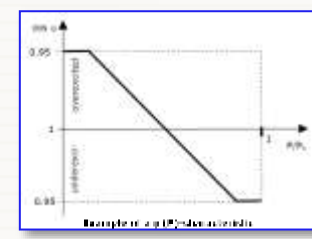
Increase the hosting capacity in the LV and MV Network

MICRO:

- *3-phase feed-in limit extended to low power PV systems < 5-6kW*
- *Capability to offer ancillary services to support the grid*
- *Local and remote VAR control / active power limitation*
- *Many converter topologies will be no longer compatible with grid code-driven requirements*
- *Modification of the architecture and component’s selection*
- *Panel optimizer-based solutions will have some advantage, leveraging the grid support functions implemented by most string inverter designs*





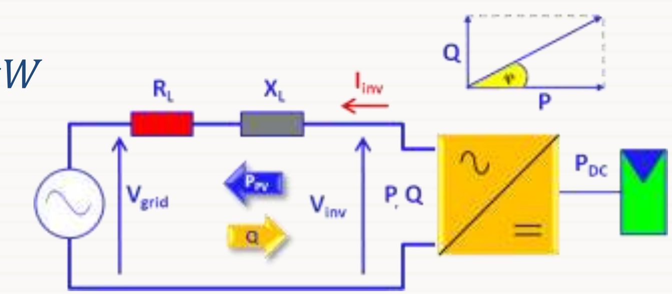


STRING:

- *3-phase feed-in limit extended to low power PV systems < 5kW*

CENTRAL:

- *Extend the operating cycle – reactive power absorption also during the night*
- *Ensure compatibility with energy storage requirements*



Conclusions

- *There's no "One 4 All" inverter*!!! Design shall be optimized to match the different needs of Residential, Commercial and Utility-Scale markets
- In case of unconstrained plant conditions, e*ach inverter technology is tailored for a specific plant type/size* where it offers the best ROI and LCOE
- Among all technologies, *3-phase string inverters offers an optimum "mix"* of flexibility, specific cost, grid support capabilities, BOS integration *to cover the widest range of applications: residential to large scale commercial*
- Utility-scale requires products tailored to minimize system-level capital and operation (lifecycle) costs. *A lot of innovation will be generated to drive large PV plants to grid parity*
- A *broad product portfolio* extending from String, to Centralized and Module-level conversion technologies *is required* to drive to grid parity all market segments, from small residential to the utility scale

Q & A