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BoS costs: status and optimization to reach industrial grid parity

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ABSTRACT

It is essential to have a complete system overview to optimize photovoltaic (PV) power plants and minimize balance of system (BoS) costs. The described approach leads to a competitive system solution with lower levelized cost of energy (LCoE). Recently, BoS costs have become more important due to rapidly decreasing PV module prices. Improvements for mechanical and electrical BoS costs are validated and benchmarked for PV technologies on a (sub) system level. An example of 30% BoS cost reduction for TF-Si based on a low voltage design, TL inverter, and a new module mounting interface is investigated among others. The BoS cost fractions are expected to fall to 55% (TF-Si) and 60% (c-Si) for ground mounted systems between 2010 and 2016 (including efficiency increase). The annual reduction of BoS costs is expected to be in the range of 8–9.5%. System costs for ground mounted system and commercial roof top plants in Europe and Asia are discussed. In Europe, the system costs dropped from 2.35€/Wp in 2010 to 1.00€/Wp in 2016. LCoE reductions based on sub-BoS optimizations are investigated. Industrial grid parity is expected in 2012 in Italy (with system costs of 1.34€/Wp) and 2016 for Germany (system cost 1.07€/Wp). BoS costs reductions needed for an LCoE of 0.084€/kWh (25% below industrial electricity cost, 2016) and the gas parity level (0.064 €/kWh in 2016) are explored. Evolutionary and revolutionary BoS approaches and cost reductions are discussed to meet these targets. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS
balance of system (BoS); PV power plants; cost reduction; optimization; module mounting interface; levelized cost of energy (LCoE)

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1. INTRODUCTION

Photovoltaic power plant (PVPP) costs can be divided into photovoltaic (PV) module costs and the costs for balance of system (BoS) components. In the past, BoS costs were not treated as the highest priority for cost reduction because the most expensive component was the PV module itself. This changed significantly in 2011 with lower average sales prices (ASP) of PV modules due to worldwide overcapacity and increasing feedstock of polycrystalline silicon. During the overcapacity phase in 2012, prices were below production costs leading to a PV module: BoS cost ratio of up to 35% : 65% for TF-Si type technologies and 55% : 45% for crystalline type modules [1].

The optimization of BoS and its cost reduction were finally identified as a key success factor within the PV community and is today one of the highest priorities for investors, system developers, and PV module producers. This is particularly important for newer technologies with lower efficiencies (η), which have total costs more sensitive to BoS reductions. These reductions are needed to transfer their advantage of lower PV module production cost into the field.

Optimizing PVPP needs a detailed understanding of all the individual components, cell technology, and PV module design. The field performance, inverter sizing, and climatic conditions also have to be considered. The combination of all these parameters enables the development of optimized PVPPs at lowest cost for project specific boundary conditions and markets. The BoS model presented is based on a standardized PVPP design. It enables benchmarking, analysis and forecasting of BoS cost for different PV technologies, applications and regions on a system or subsystem level.

BoS modeling allows the mechanical and electrical parts of the PVPP to be investigated. Requirements for the PV module itself and impact on savings on the PV system level can be shown. Benchmarking the PV module design with best in class solutions for specific applications are also possible.

The optimization potential of the particular BoS subcategories and executed initiatives of BoS cost reduction based on PV module design and reliability are shown. Extrapolation of cost shares into the future is discussed as well. Because not every PV market has the same maturity, BoS costs vary depending on the country and market size. The country with the most BoS experience is Germany, which allows one of the lowest PV system costs.

Additionally, the impact for levelized cost of energy (LCoE) is analyzed for various technologies and concepts in combination with the BoS tool. Financing costs are considered because they represent about half of the total LCoE (although they are project specific).

2. BALANCE OF SYSTEMS

The BoS cost is typically defined as cost per nominal power (€/Wp). BoS cost is part of the PV system costs and is influenced by the PV module design and format.

Photovoltaic power plant costs depend on:

- BoS costs
  - Substructure, foundation
  - Inverter and monitoring
  - Cabling, connection
  - Engineering, procurement, and construction (EPC)
  - Margin
  - Miscellaneous
- PV module
  - Module costs
  - Efficiency, technology
  - Module properties
- Local conditions
  - Array orientation, shading
  - Snow and wind loads
  - Soiling (e.g., clay, rock, and dust)
  - Grid connection
  - Site layout

The BoS can be split into four main categories:

- **Mechanical BoS (mBoS)**, includes all mechanical parts for the installation of the PVPP, substructure, foundation, module mounting parts, and labor work for the foundation and assembly.
- **Electrical BoS (eBoS)**, includes all electrical components to connect and combine the PV modules, strings and so on, and labor work for assembling and installation.
- **Inverter**, includes the inverter itself, the monitoring system, labor work for installation and transformer if needed for grid connection.
- **Miscellaneous**, addresses all work, which are not directly related to the PV system, for example, land preparation, site logistics, fencing, scaffolding, safety equipment, soil assessment, and so on.

For the optimized energy production and lowest electricity costs of PVPP, land lease costs, permissions, and operations and maintenance effort (O&M) have to be included. These parameters depend on location, PVPP size, grid connection, and so on. Another approach according to Wang *et al*. [2] is the separation of the BoS costs into area and power related costs. Area related costs (ARC) are typically eBoS and mBoS. Power related costs include inverter, transformer, and grid connection costs.

ARC, power related costs or both will be used to compare different PV technologies, BoS, and PVPPs. Fixed costs include the business process, financing, and permitting. ARC cost is one specific value depending not only on efficiency, but also the impact of PV module format should be included (see 4.2 for details).

The objective of the BoS model is to monitor, track, benchmark, and analyze BoS costs. The main applications are ground mounted systems (GMS), commercial roof top (CRT) systems and residential roof top (RRT) systems. Locations in Italy (Europe) and China (Asia) are discussed. The model also contains data for the Middle East and North Africa and North America. At CRT and GMS PVPP , the economy of scale is a clear driver of cost reduction. This is not observed for RRT in the same way [3].

2.1. BoS model definition

The BoS model is based on a standardized PVPP design for various applications and regions (installation site definition, ground soil classification etc.). The system definition consists of the substructure including module mounting, DC wiring and collection, inverter and monitoring, miscellaneous (e.g., installation, site preparation, safety equipment), and the PV module itself. In addition to the PVPP definition, EPC and the margin of the EPC are added to the BoS model as a real value. The EPC effort and margin are based on the total BoS costs as a relative value, observed in the range of 12–18% for GMS and CRT systems for 2012. EPC effort and margin vary by project type, application, and market conditions. Cost assumptions are based on market assessments (real quotes from established BoS component providers), literature review, and many expert discussions. Because PV market conditions have changed rapidly in previous quarters, costs of BoS and PV modules may vary significantly from assumed values. All parts of the PVPP definition are driven by actual component price lists with cost reduction on a year to year basis (last cost status update: May 2012). Costs, which also should be considered, are production and raw material costs (especially for the substructure), logistics, and transport costs. The model was discussed and verified by the leading European EPCs and banks in EU and the USA.

For any location, we assume the same quality standard. The lifetime of the PVPP is expected to be at least 25 years and based on static calculations according to local loads (wind/snow).

All materials must resist atmospheric conditions (e.g., ultraviolet (UV) irradiation, temperature changes, etc.) and have sufficient corrosion prevention, UV stability (e.g., combiner box). Significant LCoE variations will be observed if key BoS components do not fulfill their expected lifetime and quality (e.g., undersized substructure when extreme weather occurs, low inverter uptime or breakage) [4]. O&M costs of PV electricity generation systems are lower than for conventional energy generation systems and are found to be in an annual range between 0.5% and 1.5% of the initial investment costs [5–7].

2.2. System definition and application areas

Grid connected systems can be classified by size and application. GMSs are usually utility scale PVPP with a size of several MWp, CRT systems are large-scaled PVPP on roofs (>100 kWp). Residential roof top are small-scaled PVPP (kWp range) and building integrated photovoltaic systems, for example, roof integrated or facade systems.

The GMS PVPP consists of 10 blocks, 1 MW each, total 10 MW inverter capacity, connected to the medium voltage grid. The aluminum substructures are fixed on rammed steel piles. Central inverters, medium voltage transformer, string monitoring, site sensors, and web interface are also considered.

The CRT PVPP consist of three blocks, 100 kW each, total 300 kW inverter capacity, connected to the grid with a three phase TL inverter. Site sensors and web interface without string monitoring are included as well. CRT application can be distinguished between CRT flat roof (CRT-flat) and CRT pitched roof (CRT-pitched) systems. The CRT-pitched system has a 10° pitched roof; the PV modules are not roof integrated. The CRT-flat system is installed on a flat roof with a tilt angle of 25°. GMS and CRT-flat roof systems have a ground cover ratio (GCR) of typically 0.45–0.50; CRT-pitched have a higher GCR due to reduced row distance. The energy yield for CRT-flat roof systems can be optimized by adjusting the tilt angle, which is not possible for CRT-pitched. An upcoming trend to save BoS cost is the east-west orientation of PV systems, which has an impact on the BoS costs, GCR, energy yield, and LCoE.

In this paper, three south oriented systems (GMS, CRT-flat, and CRT-pitched) with fixed nominal power are investigated. Analysts expect that GMS and CRT will represent >75% of the world market [8]. Power plant concepts with fixed area are not discussed here. All these systems have a defined location with its specific boundary conditions. Recent studies show the energy yield variation of <±5%. Here, it is assumed to be the same for all technologies. In Europe, the installation site is Bari in Apulia (Italy) with an expected global in-plane insolation of 2082 kWh/m^2/year, for Asia the region Yinchuan (China) was chosen, with 1962 kWh/m^2/year [9]. Because the soiling class is individual, we assume that soiling is suitable for ramming.

The BoS model does not include costs for the grid connection, lightning protection, AC mains, and land lease. These costs are very project specific and lead to a higher uncertainty for BoS cost analysis.

2.3. BoS subcategories and cost share

BoS costs can be divided into specific subcategories. Some of these are related to the PV module technology, some on the power plant design, and others are independent from the PV technology itself. Analyzing the relative share of different applications allows us to investigate the sensitivity of the main cost drivers for further optimization and cost reduction.

Figure 1 shows the BoS cost share based on 10.8% TF-Si technology for GMS (0.78€/Wp), CRT-pitched (0.63€/Wp), CRT-flat (0.88€/Wp) PVPP applications in Europe. CRT-pitched roofs have the lowest substructure share (19.8%), but the largest share for mechanical installation (21%) and miscellaneous (12.1%). CRT-flat shows the lowest fraction of inverter costs (15.5%) compared with CRT-pitched (21.7%) and GMS (23.5%). For example, cost reductions on the CRT-flat substructure fraction lead to a higher relative total BoS costs reduction than cost reductions on the inverter. Inverter cost reductions have a higher impact for GMS and CRT-pitched than for CRT-flat systems. Inverter and cabling costs are the same in absolute values (more detailed information see Section 4.3). This indicates that every application has its specific costs driver, which must be optimized to reduce the total BoS costs,

In absolute numbers, the main costs difference for CRT-flat versus CRT-pitched are higher material consumption

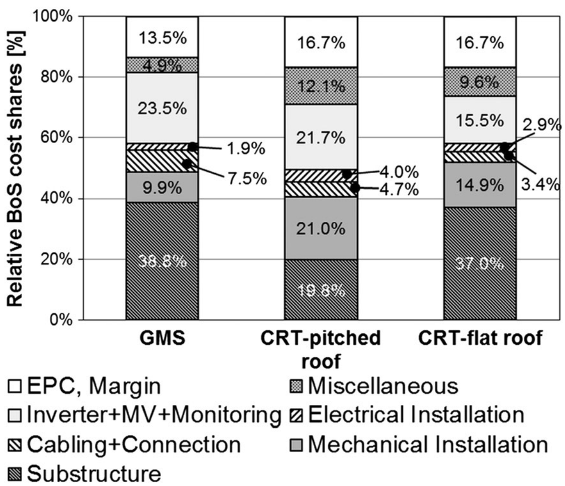

Figure 1. Balance of system (BoS) cost share 10.8% TF-Si, ground mounted system (GMS), commercial roof top (CRT), Europe 2013E.

and installation effort. This is not necessary for CRT-pitched. Due to the static utilization from the existing building, lower substructure costs are possible, still showing a huge potential for further cost reduction. GMS systems have also high substructure cost to fulfill the static requirements of the PV racks. Note that absolute costs will be specific for each application.

2.4. PV modules investigated in this study

Table I shows various PV modules investigated in this study, sorted by efficiency, classified into frameless and framed PV modules.

The selected PV modules include a variety of available PV technologies with specific mechanical and electrical properties and efficiency levels. All are mounted with clamps except PV module K uses the module mounting interface (MMI) approach (back bonded solution, see 6.2). For future BoS cost extrapolation, the efficiency and cost development of the different technologies are considered according to Figures 2 and 3.

The efficiency for standard c-Si technology is expected to increase to 16.7%, CdTe to 15.0%, CIGS to 15.3% and TF-Si to 12.4% by 2016. The PV module costs are assumed to drop to 0.58€/Wp for c-Si, 0.56€/Wp for CIGS, 0.37€/Wp for TF-Si, and 0.48€/Wp for CdTe (Figure 3). TF-Si shows the biggest potential for lowest production cost due to full inline mass production; gross margins are expected between 10% and 20% for all technologies [10].

3. BOS BENCHMARKING

3.1. Unit definition

Normalizing the cost only by nominal power is not sufficient for a comprehensive BoS view because for a given system power the area depends on the PV efficiency, so, for benchmarking area-related BoS costs, cost per m^2 is suitable. Table II gives an overview of the dependencies and definitions.

3.2. BoS cost in €/Wp

PV systems as well as BoS are evaluated on a cost per power (€/Wp) basis. This is a combination of production cost per area and power per area (or efficiency) [12,13]. Also comparisons based on the installed number of PV modules and PV module area are possible. This is limited when comparing various PV module formats. For example, PV modules with a smaller size ($<1\,m^2$) are not cost competitive on CRT-flat systems (H, I, J) due to additional substructure, clamps, and handling effort (Figure 4). CRT-pitched roof is the cheapest application for most PV modules; PV modules E and F have the same module efficiency (14.9%) but a BoS costs difference of 20%. The reason for this is the different PV module format.

Table I. Overview photovoltaic modules, sorted by technology, panel size, and efficiency.

PV module ID	Unit	A	B	C	D	E	F	G	H	I	J	K[1]	L	M
Type	[-]	c-Si	c-Si	c-Si	c-Si	c-Si	c-Si	CIGS[2]	CIGS[2]	CdTe	CIGS[2]	TF-Si	TF-Si	TF-Si
Length	[mm]	1559	1610	1581	1650	1956	1320	1611	1190	1200	1250	1300	1400	1409
Width	[mm]	1046	861	809	992	992	990	665	630	600	650	1100	1100	1009
Area	[m^2]	1.63	1.39	1.28	1.64	1.94	1.31	1.07	0.75	0.72	0.81	1.43	1.54	1.42
Efficiency	[%]	20.1%	18.0%	16.4%	15.5%	14.9%	14.9%	14.5%	12.7%	12.5%	11.1%	10.8%	9.7%	9.5%
Pmpp	[Wp]	327	250	210	254	290	195	155	95	90	90	154	150	135
Voc	[V]	64.9	43.1	46.6	37.6	44.9	30.3	29.1	78.0	62.8	70.4	74.1	85.5	61.3
Isc	[A]	6.5	7.7	5.9	8.2	8.5	8.6	7.5	1.7	2.1	1.8	3.0	2.5	3.4
Frame (Yes = Y/ No = N)	[-]	Y	Y	Y	Y	Y	Y	N	N	N	N	N	Y	Y

[1]Equipped with module mounting interface (MMI), [2] CIGS also includes CIS technologies

Source: Manufacturer Datasheets, last accessed May 2012.

PV, photovoltaic.

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Between PV module B (18%) and D (15.5%), there is no big BoS cost difference visible, even when expected due to the efficiency difference of 2.5%. PV module B has a smaller area than D but the same nominal power. The same number of PV modules is required with similar material and installation effort for B and D. So, the PV module format may lessen the rise in efficiency.

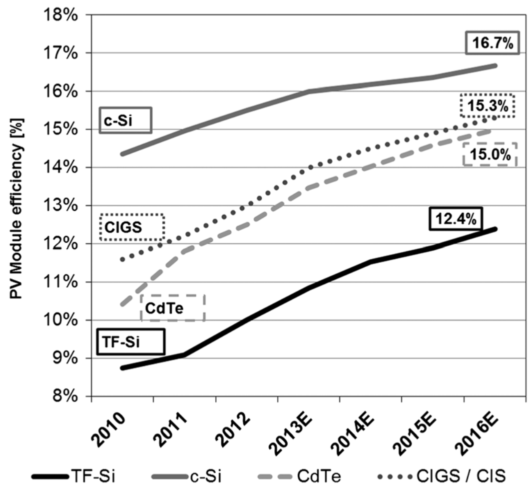

Figure 2. Efficiency trend forecast 2010–2016, since 2013 expected.

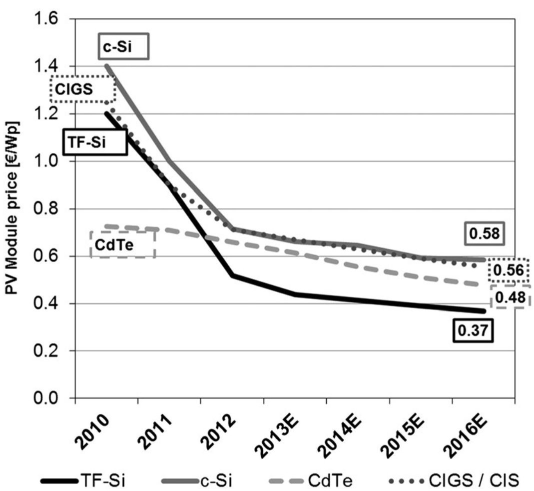

Figure 3. Assumed photovoltaic (PV) module cost trends 2010–2016, since 2013 expected [11].

The BoS costs for GMS varies between 0.52 and 0.90€/Wp; for CRT-pitched, costs are observed between 0.45 and 0.88€/Wp. CRT-flat shows the highest BoS costs up to 1.31€/Wp due to non-optimized concepts. PV modules G and I show lower BoS costs for GMS installations because material effort and installation time for CRT is higher due to the small module format.

3.3. BoS cost in €/m^2

Comparing BoS costs per area at fixed power shows the impact of PV module designs and format. The total costs for inverter, EPC, and miscellaneous are very similar for all cases (Figure 5).

The same area related costs means the same installation costs. Area related costs for GMS are in the range of 83 to 108€/m^2, for CRT-pitched between 67 and 105€/m^2, for CRT-flat between 95and 161€/m^2. Module K has similar cost per area as module E but lower efficiency, showing that for PV modules with lower efficiency there is no inherent disadvantage at a cost per area level with the suitable BoS solution. PV module D has lower €/m^2 costs compared with PV module A, B (larger inverter cost share), because these costs are defined by the nominal PVPP size. The cost reductions based on higher efficiencies do not compensate for this.

The costs are driven by the PV module sizes (Table I). Small sized modules (H, I, J) show higher area related costs due to bigger installation effort (increased number of PV modules, clamps, and electrical connections). For CRT-flat, the scaling effect of the horizontal rails is very small versus CRT-pitched.

For CRT-pitched application, the costs for CdTe system are 60% (PV module I) and for c-Si up to 30% higher (PV module C) than for TF-Si system (PV modules K, L, M). The main reason is that more modules have to be installed leading to longer installation times. Note that PVPP with fixed area gives different BoS costs per area results because inverter costs will vary on the basis of installed power.

Table II. Benchmark parameters for balance of system (BoS) cost analysis.

Declaration	BoS value	Units	Dependency
BoS and system costs, LCoE	$\frac{\text{costs}}{\text{nominal power}}$	$\frac{€}{\text{Wp}}$	Area Efficiency
Technology benchmarking on BoS level	$\frac{\text{costs}}{\text{module area}}$	$\frac{€}{m^2_{\text{module}}}$	Efficiency
Technology benchmarking (BoS and system level)	$\frac{\text{costs}}{\text{PVPP area}}$	$\frac{€}{m^2_{\text{PVPP}}}$	Efficiency GCR Shading properties

BoS, balance of system; LCoE, levelized cost of energy; PVPP, photovoltaic power plant; GCR, ground cover ratio.

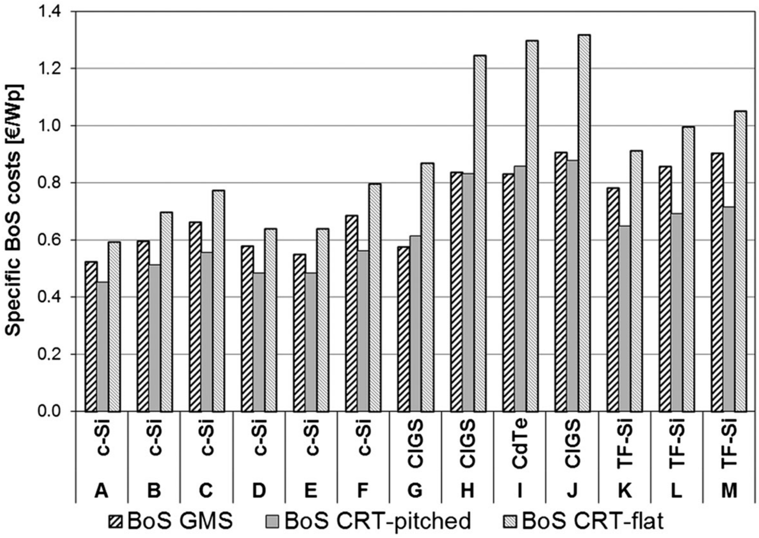

Figure 4. Balance of system (BoS) costs in €/Wp, ground mounted system (GMS), Europe, 2012.

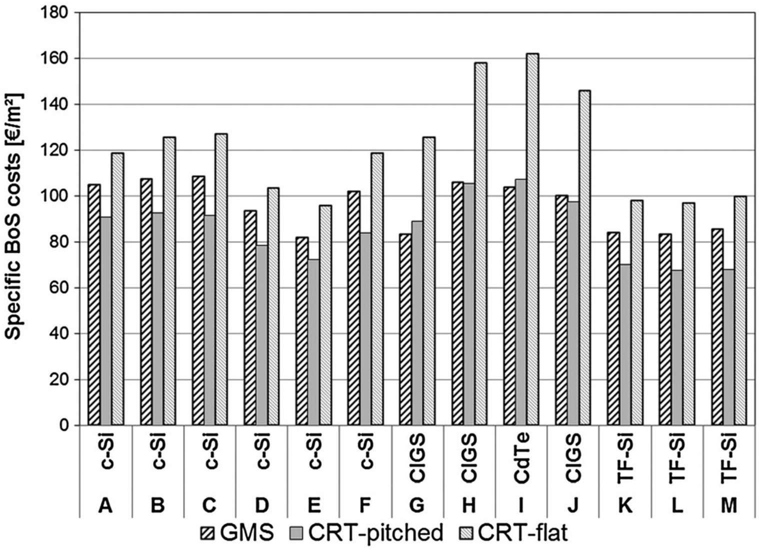

Figure 5. Balance of system (BoS) costs in €/m^2, ground mounted system (GMS), Europe, 2012.

4. PV SYSTEM COST SHARE AND BOS DEPENDENCIES

4.1. Cost share analysis for 2012

The PV system cost share is the sum of BoS cost and the ASP of the PV module excluding value added tax (VAT). Figure 6 shows that the relative cost share between different PV modules (Table I) and BoS for GMS systems is not constant. They depend on the PV technology's respective efficiency level, the PV module design (IV parameters, current vs. voltage ratio), and mechanical properties (e.g., frameless or framed, module dimensions). For most TF technologies, the BoS cost is >50% of the total system cost for all applications, with a maximum of 65% for TF-Si. These technologies compensate the higher BoS costs with their very low production costs. The same pattern is observed also for CRT systems (not illustrated). According to the present shakeout phase in the PV market, the BoS cost share may show significant variation due to very low PV module cost.

4.2. BoS cost share for different PV module technologies

To optimize BoS, the potential of each subcategory has to be evaluated; these are specific to the PV module design, technology, application, and region. Figure 7 shows the BoS cost share for a GMS system in Europe

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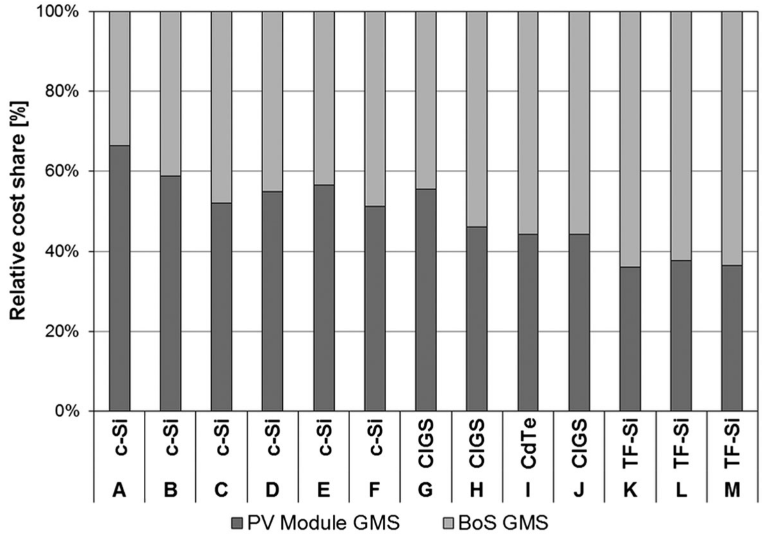

Figure 6. System cost share for various photovoltaic (PV) module types and technologies, ground mounted system (GMS), Europe, 2012.

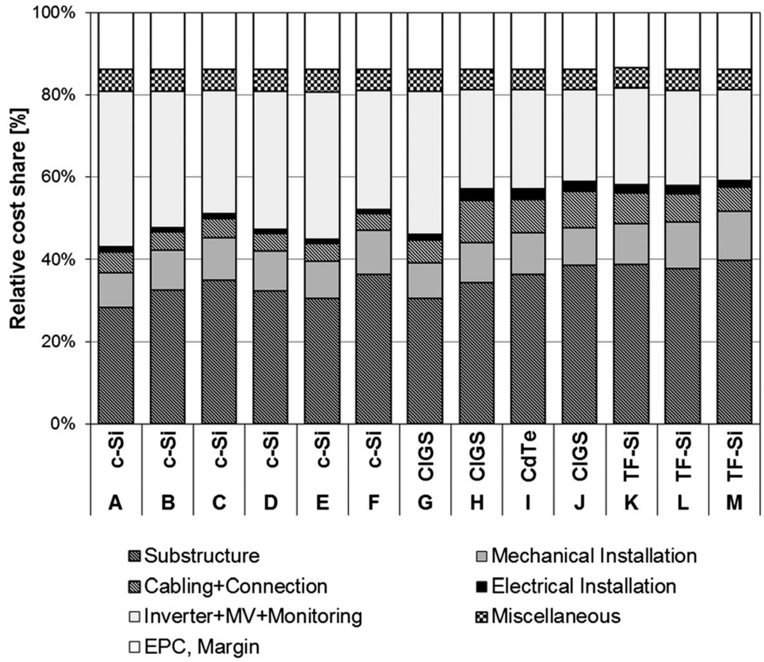

Figure 7. Balance of system subcategories cost share (major photovoltaic technologies/photovoltaic module formats), ground mounted system, Europe, 2012.

for different PV technologies and mechanical/electrical module designs. The relative cost comparison indicates the main BoS cost drivers for each PV module format and technology.

Main costs drivers for GMS PVPP are as follows:

- Substructure (30–40%)
- Inverter (22%–36%)
- Mechanical installation work (9%–12%)
- Cabling and connection (5%–10%)
- EPC effort, margin

CIGS and c-Si show larger relative costs on the inverter side, and the substructure share goes down to 30%. Both have a nonconstant share for substructure and inverter costs because the PV module format changes. For PV

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modules with higher efficiency, the relative inverter cost share goes up to 35% because of the decreasing ARC (e.g., substructure). CdTe and TF-Si technologies show a substructure share up to 40% and the inverter share down to approximately 22%. For high efficiency technologies, inverter costs are the most dominating cost factor; note that the inverter costs are technology independent and in absolute numbers, the same costs for all cases. PV modules with lower efficiency can reduce costs over proportional by optimizing the substructure. Note that absolute inverter costs are the same for all technologies. The effort for the mechanical installation and miscellaneous is approximately the same for all technologies. The cabling effort depends on the string length and is driven by the electrical design of the PV module. Also, the sensitivity of various PV module design for further cost reduction can be concluded.

4.3. Application dependency

Balance of system cost is dependent on the application (see Section 2.2). The illustrated costs show that the specific BoS costs do not show a constant offset between applications (Figure 8) and depend on the electrical and mechanical PV module properties. BoS costs for CRT-flat roof systems have between 32% and 50% higher BoS costs compared with CRT-pitched roof systems. TF-Si has lower costs for CRT-pitched roof application compared with the other technology, due to lower effort for the installation as shown in Section 5.2.

4.4. Regional impact

Regional requirements and standards have also an impact on the BoS costs and depend on the following:

- Market maturity
- Supply chain (local content, import)
- Taxes and customs duties
- Local standards, technical rules, best known practice
- Project development (pre-planning phase)
- Experience of the EPC, installer
- Experience of grid operator with fluctuating PV energy
- Permission and administration
- Labor costs, level of automation
- Market competition

The substructure is often produced locally to avoid additional shipping costs. Established EPCs often transfer their experience to new markets. For China, 25% lower BoS costs can be expected (Figure 9). Lower raw material and production costs due to energy costs, facility costs, and labor rates are the main drivers. The engineering costs (part of EPC work) will be less due to cheaper labor rates. Also, the relative margin is reduced.

4.5. Project specific BoS uncertainties

According to the system definition in Section 2, the soiling properties (e.g., clay, rock etc.) have to be identified for each project. Other subcategories such as cabling and connection and inverter can be adapted from other PVPP blueprints to the actual project. Substructure, miscellaneous, and EPC effort including margin depend on local conditions. For GMS systems, several types of foundation are available. The mBoS costs for a rammed foundation (single pylon) is 12.5% cheaper than a drilled foundation because only one installation step is needed. For drilled foundations, more time and handling effort are necessary. Note: additional civil work is not considered in this analysis; if drilling is needed, the costs for the concrete have to be added to BoS costs.

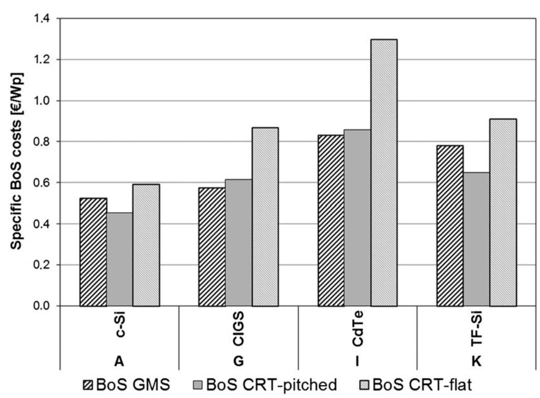

Figure 8. Application dependency of balance of system (BoS) costs for different photovoltaic (PV) module technologies for ground mounted system (GMS), commercial roof top (CRT), Europe, 2012.

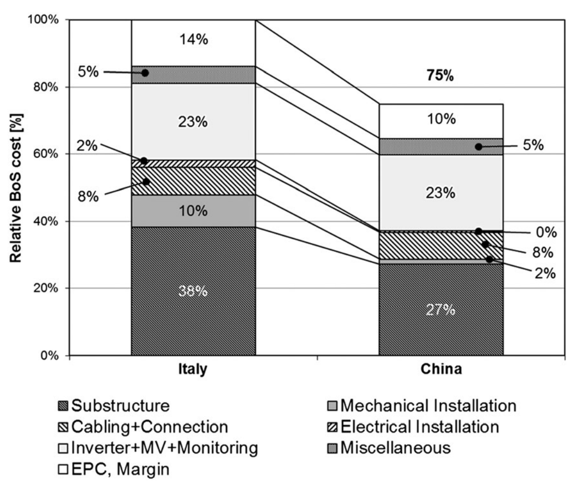

Figure 9. Regional balance of system (BoS) cost for 10 MW ground mounted system, Europe and China, TF-Si, 10% efficiency, 2012.

5. BOS REDUCTION DUE TO IMPROVED PV MODULE DESIGN

5.1. The thin film silicon technology case

For lowest energy generation costs, the mass production of TF-Si PV modules requires technology improvements (cost reduction, efficiency increase) (2012 : 10%, 2013 : 10.8%), and BoS optimizations [14]. The optimization discussed in this section is based on a low voltage PV module design, which saves 3% total BoS costs by doubling the string length. The advanced PV module mounting solution leads to a reduction of 21% (fewer and easier installation steps, lower material consumption, reduced amount of components compared with clamped solutions).

The transformerless (TL) inverter compatibility increases the energy output of the power plant by up to 3%. Less grounding effort and reduced inverter costs lead to total BoS cost savings of 6%. In total, the savings lead to 30% BoS costs reduction for CRT and 24% for utility scaled GMS systems based on 10% module efficiency. GMS systems show an absolute smaller reduction because galvanic isolation via transformers are usually existing at MW systems.

In total, 21% of BoS costs can be saved relative to a clamped solution (Figure 10). Savings are driven by lower material consumption (−15%) and installation time reduction by half (−2%). Miscellaneous, EPC effort, and the margin are reduced by 4% due to lower BoS costs and procurement effort.

5.2. BoS cost dependency based on mounting solution

PV modules can be installed in varying ways (clamps, back rails, and slide-in systems). The MMI approach consists of glued pads on the backside of the PV module (glass-glass laminate) and is designed as a slide-in solution for the substructure assembly [15] with no need for tools. The main benefits of this concept are highest PV module reliability due to lowest leakage currents, optimized stress distribution (lower stress peaks near the mounting points), low maintenance effort due to screwless design and lower breakage rate for frameless module types during installation.

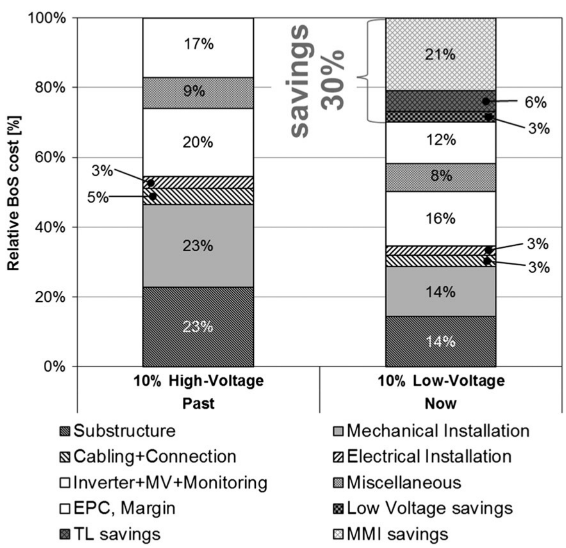

Figure 10. Past and present balance of system (BoS) cost for TF-Si: Improvements due to optimized balance of system concepts, commercial roof top, Europe 2012 [14].

Figure 10 illustrates a comparison of a linear clamped solution[1] and a back bonded solution called MMI™ for frameless PV modules, example application shown in Figure 11. Compared with backrail and framed solutions, the MMI approach has lower material consumption due to its small contact area and enables flexible substructure configurations according to the local loads. The comparison of the installation time and cost for the PV module and substructure interface gives an indication for the cost effectiveness. Changing the PV module mounting technology helps to reduce the system cost and/or reduce the production costs of the PV module because the framing costs can be avoided.

In Figure 12, different substructure interfaces are shown. The benchmark includes the costs for the module installation time, labor costs, and substructure interfaces (clamps, MMI, frame if needed). The MMI concept will reduce the PV module mounting costs for crystalline modules (D) down to 0.03€/Wp and for thin film down to 0.05–0.06€/Wp. It can be concluded that framed solution with clamps are not cost competitive in comparison with glued solutions. The frameless TF-Si PV module with MMI has the same PV module installation costs as a framed c-Si module. Framed PV modules are more

Figure 11. Module mounting interface (glued on the photovoltaic module backside) snapped into the horizontal rail (Source: Oerlikon Solar).

[1] clamps along the complete length of the PV module

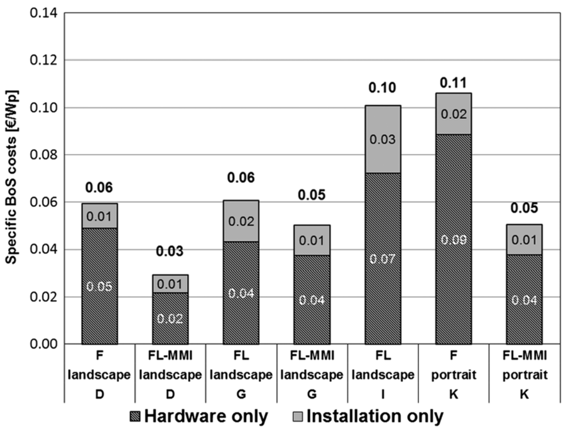

Figure 12. Photovoltaic module mounting benchmark different technologies in €/Wp based on Table I, ground mounted system, Europe, 2012.

convenient to install but do not show the same electrical reliability as glass-glass laminates [16]. More raw materials are needed to achieve the mechanical properties and stability for installation and handling. The comparison of the specific interface costs shows that the costs for frameless solutions with MMI (module K) (0.05€/Wp) are approximately 50% of the costs of a framed solution (0.11€/Wp) for TF-Si. For framed clamped TF-Si, the costs will go down from 11.44 to 5.45€/m^2 (52% reduction). Figure 13 has the same costs per area (€/m^2) for the mounting interface costs. For the crystalline systems (module D), the costs per area for a framed, clamped PV module are 0.06€/Wp respective 9.61€/m^2, and for frameless c-Si with MMI design it will be reduced by 50% to 0.03€/Wp respective 4.76€/m^2. TF-Si frameless PV modules (module K) with the MMI solution have slightly lower cost per power (0.05€/Wp) and per area (5.45€/m^2) than framed c-Si (0.06€/Wp, 9.81€/m^2). Frameless CIGS PV modules (G) installed with MMI show lower installation costs of 0.01€/Wp (1.52€/m^2) compared with a clamped solution. Small sized (<1 m^2), frameless PV modules such as the CdTe type are usually installed with clamps and are not cost competitive due to larger PV module installation effort.

The PV module size influences this cost as larger modules have higher PV module power and lower installation costs per Wp. If the module becomes too large or heavy, an easy installation is not possible anymore and shows increased effort and costs for the installation. Large area PV modules (>2 m^2) have specific requirements for mounting due to the mechanical properties of the PV module according to its deflection and stress distribution under load. This may change with automated PV module installation methods, which are only suitable for utility scale PVPP with acceptable soiling class and terrain.

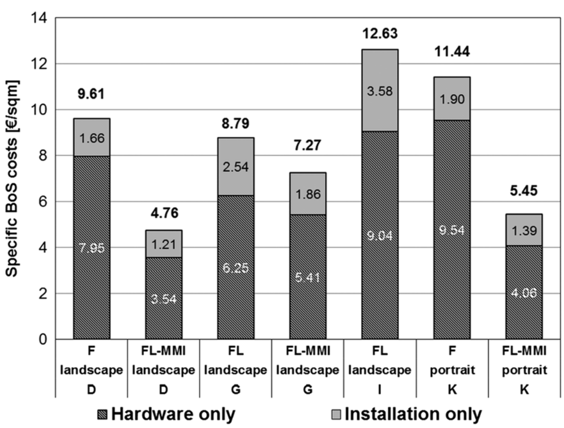

Figure 13. Module mounting benchmark, framed versus frameless for different technologies in €/m^2, ground mounted system, Europe, 2012.

5.3. Table utilization at ground mounted systems

The substructure costs for GMS PV systems are 28–40% of the total BoS costs (Figure 7). These costs can be optimized by project specific GMS table utilization. In Figure 14, the typical GMS table utilization is calculated for a standard load case where all PV modules are portrait orientated, with an assumed table depth of maximum 3 m based on the mechanical load simulation.

The GMS table utilization is typically between 55% and 99%. For GMS PVPP, typically 80–90% of the installation time is related to the foundation and rack assembling. The rest is for the PV module installation. The rack itself consumes 90% of the raw material; the rest is needed for the PV module mounting. Typically, for TF technologies, the segments (laser scribes) have to be oriented top-down to minimize shading, soiling, and thermal impact. Other orientations have to be specified in the datasheet. Optimizing the utilization can be carried out by changing the

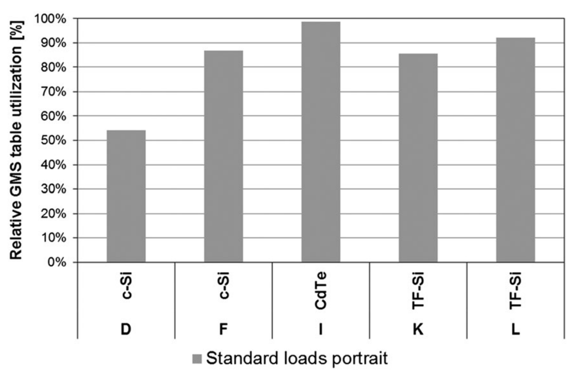

Figure 14. Ground mounted system (GMS) table utilization for different photovoltaic module formats, 2012.

orientation from portrait to landscape. For the c-Si PV module D (1.65 m × 0.99 m), the utilization in the standard load case changes from 54% (portrait) to 98% (landscape).

For PV module K, the BoS costs can be reduced by 3.3% for the standard load case if the GMS table utilization will be increased from 86% to 100%. Module I (CdTe) shows optimized table utilization due to its small PV module format and optimized substructure. The potential savings depend also on the local conditions as defined in Section 2.

5.4. Impact of the electrical PV module design

PV modules have a wide variation in their electrical design. Especially for small PVPP (RRT with string inverter), the inverter utilization and string length has impacts on eBoS costs. The string utilization is defined as the ratio of the total voltage of serial connected PV modules per string and the maximum DC input voltage of the inverter limited by the inverter AC power.

Figure 15 shows string utilization rates between 57 and 100%. PV module F at 700 V system voltage shows 6% additional cabling costs (voltage/power ratio of 0.16). Larger inverters (>30 kVA) show costs <1%. As an example, module D can utilize 64% of the maximum string length due to a voltage/power ratio of 0.15 at a 1000 V system and 15 kW inverter. This leads to more parallel strings with 13% higher eBoS costs.

6. BOS COST FORECASTING AND OPTIMIZATION

6.1. BoS cost forecast

The PVPP cost share depends on the application, region, and PV module technology. In the following sections, we limit the analysis to TF-Si and c-Si technologies. According to recently decreasing PV module costs, the present BoS cost share for Europe is approximately 45% for c-Si (16% efficiency) and 64% for a TF-Si PV systems (10.8% efficiency); in Asia, the cost share is roughly 36% for c-Si and 55% for TF-Si PV systems. With evolutionary BoS development, the costs for a TF-Si system will be reduced from 2010 to 2016 by 26% (no efficiency increase). For c-Si, the BoS costs reduction without efficiency gain is 32.2% due to the higher sensitivity to decreasing inverter costs (Figure 7). With efficiency increase, the BoS costs will be reduced by 45.1% for TF-Si and by 39.7% for c-Si. The main reason is the difference in the absolute efficiency increase of 3.6% for TF-Si and 2.3% for c-Si between 2010 and 2016. The yearly observed BoS cost reduction for TF is approximately 9.5% on a year to year basis. 5% are related to BoS optimizations and economy of scale; 4.5% are due to efficiency increase of the PV modules. For crystalline PV modules, the yearly total BoS cost reduction including efficiency increase is approximately 8% according to Figure 16. BoS costs drop to approximately 55% for TF-Si and 60% for c-Si between 2010 and 2016.

Substructure cost reduction can be optimized because of standardization, reduced material consumption, and load optimization. Inverters can be improved by electrical design and hardware reduction. Mechanical and electrical installation will have more prefabrication and a faster installation time. All areas will benefit from economy of scale but have to accept margin erosion due to competitiveness at the same time.

6.2. Future potential of BoS optimization

For the last few years, improvements were carried out by material reduction and hardware optimization. Also, installation time of each part, pre-fabrication, and pre-assembly were already addressed to meet cost targets. Time as a cost

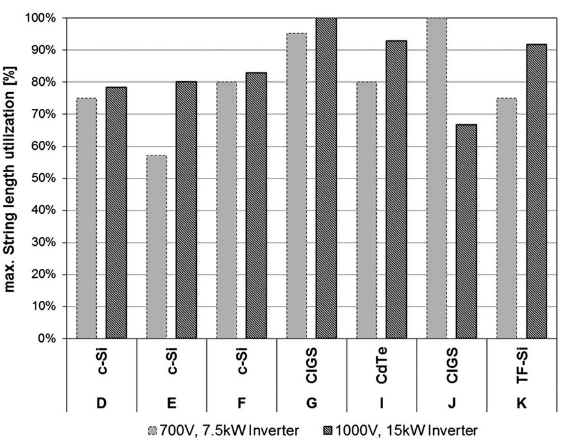

Figure 15. Max string length utilization at different system voltages and inverter dimensions, commercial roof top, 2012.

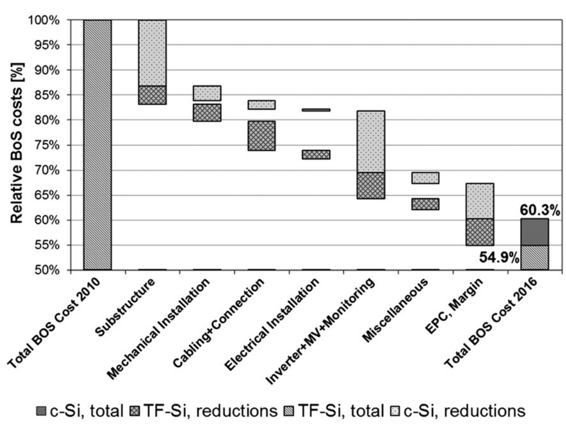

Figure 16. Relative balance of system (BoS) costs forecast for TF-Si and c-Si technologies incl. efficiency gain, ground mounted system, Europe, 2010–2016.

factor depends on local labor rates. For non-specialized laborer, the cost increases will at least compensate inflation and is expected to be approximately 2.5%/year in Europe and 4.5%/year in Asia over the next years [17].

In general, there are two ways to reduce BoS—increasing the efficiency and optimizing BoS costs. If the current available BoS approach stay constant, total BoS reductions >20% are hard to achieve due to increasing raw material costs and labor at the same time. New concepts or further integration are needed and would enable additional BoS cost reduction. The mBoS design, related to wind and snow load, humidity, and temperature, can be optimized. The use of lightweight materials and modular components as well as supply chain optimization is another section to improve.

Reducing material and energy consumption during production is also possible with higher utilization levels, further standardization of the components or highly integrated PV system designs. Also, the development of new solutions that enhance energy production for high and highest DC voltage systems will contribute to lower costs. On the basis of relative increasing logistic and transport costs, the local production of BoS components might be more sensible than shipping them, for example, from Asia to USA. Shipping costs for PV modules are in the range of 0.02 to 0.03€/Wp. Increasing margin pressure for the full supply chain will cure as the PV industry becomes more mature.

7. PV SYSTEM COST AND FORECAST

7.1. PV system cost

In Figure 17, system cost of 1.31€/Wp (TF-Si) and 1.30€/Wp (c-Si) for GMS systems in Europe for 2012 are shown. For China, system costs are 1.10€/Wp (TF-Si) and 1.16€/Wp (c-Si) and are based on the expected PV module costs for 2012. The difference between Europe and Asia is based on relative cost reductions. For CRT-flat systems in Europe (2012), the costs are approximately 1.42€/Wp (TF-Si) and 1.35€/Wp (c-Si). In China, 1.12€/Wp (TF-Si) and 1.15/Wp (c-Si) are expected. The system costs in China are lower than in Europe due to lower labor and material costs. CRT-flat systems show higher installation effort, but due to the lower labor rates this has only small impact on the costs in Asia. Technologies with higher efficiencies have typically bigger production costs per area due to increased process steps. Assumed PV module production costs for c-Si are 0.71$/Wp ($\eta = 15.5\%$), 0.825€/Wp ($\eta = 18\%$) and 0.96€/Wp ($\eta = 20.1\%$) [18,19], based on an exchange rate of 1.3$/€. All numbers are based on the standardized PVPP concept and its boundary conditions.

The overall system cost is a key differentiator to be competitive with GMS and CRT systems. Therefore, additional production costs can only increase to the level where the system costs are equal to standard c-Si. It is also shown that the BoS cost does not significantly decrease for PV module efficiencies ≥18% versus typical c-Si values of 15.5% (Figure 17). If the PV module format is not fully optimized for the target application, efficiency benefits cannot be fully transferred to the system cost level. Compare module B, which has an area of 1.39 m^2 and 18% efficiency, with module D 1.64 m^2 (15.5%), the total amount of installed PV modules for a 10 MW GMS is similar (difference <1%), which leads to similar material consumption for the PVPP installation

For GMS systems in Europe, a c-Si cost share ratio of 55 : 45 (PV module : BoS) and TF-Si cost share ratio of 36% : 64% is observed for 2012. In Asia (China), the c-Si systems have a share of 61% : 39% for PV module versus BoS and a 43% : 57% share for TF-Si. Figures 18 and 19 show the relative system cost; relative inverter cost are similar in absolute values due to technology independency.

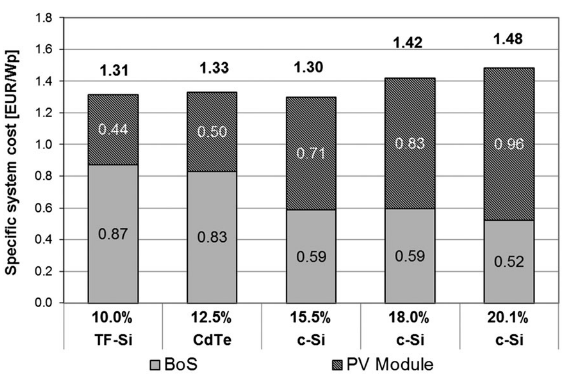

Figure 17. System costs for TF-Si, CdTe, c-Si with different efficiency levels, 10 MW ground mounted system, Europe, 2012.

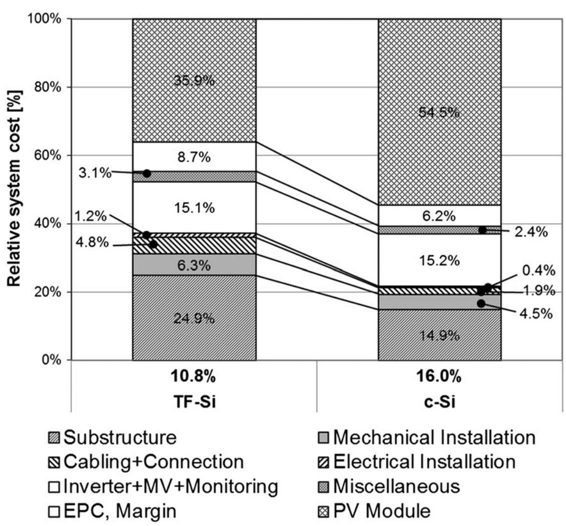

Figure 18. System cost for 10 MW ground mounted system, Europe (Italy), 2013E.

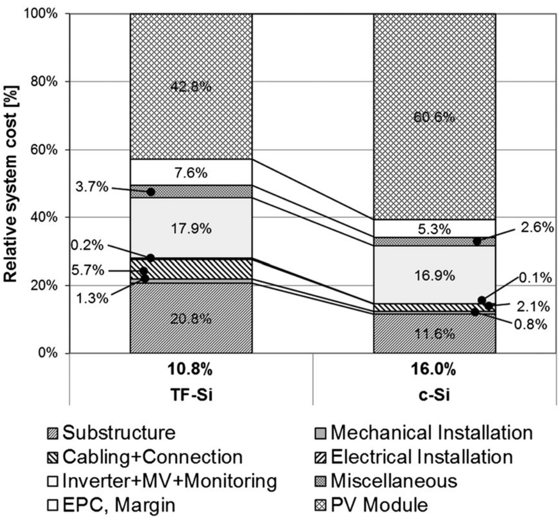

Figure 19. System cost for 10 MW ground mounted system, China, 2013E.

7.2. PV system cost forecast

Figure 20 shows the system cost forecast for TF-Si, CdTe, and c-Si PVPP installed in Europe. The costs drop from approximately 2.35€/Wp in 2010 to 1.00€/Wp in 2016 with evolutionary cost development based on a constant system design. CdTe and TF-Si show similar BoS costs for the GMS application. After 2012, the BoS costs reduction for TF-Si is bigger than for c-Si due to the higher absolute efficiency increase (Figure 2).

For CRT-pitched roof application, the BoS costs for TF-Si will drop from around 1.0€/Wp in 2010 to 0.55€/Wp in 2016 representing a system cost advantage of 17% compared with c-Si (Figure 21). System costs show a spread between 1.21€/Wp and 1.49€/Wp (2012) because the optimization level for CRT-pitched roofs is

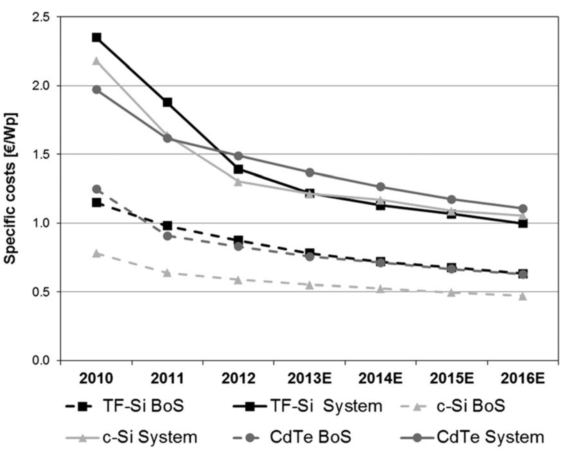

Figure 20. System, balance of system (BoS) cost forecast 2010–2016, GMS, Europe.

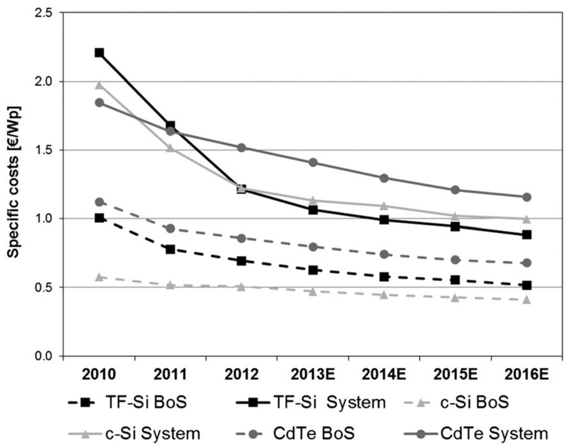

Figure 21. Balance of system (BoS) costs, system cost forecast 2010–2016, CRT-pitched roof, Europe.

not the same for each PV technology. For both applications, c-Si delivers the lowest BoS costs due to higher efficiencies. On the system level, PVPP costs are similar due to lower cost of TF technologies. After 2012, the annual cost reduction decline because the obvious and fast improvements are already incorporated.

Figure 22 shows a cost share forecast for GMS PVPP cost for TF-Si and c-Si Technologies in Europe between 2010 and 2016. The expected share does not show significant changes after 2013 due to overlaying cost reduction at the same time and a constant system design.

7.3. PV system cost share of 50/50

Because newer PV technologies were very successful with a 50/50 cost share in the past (Figure 22), requirements to establish this parity by 2016 are investigated [1].

The costs share in Europe for TF technologies is approximately 36% on the PV module and 64% on BoS (see Section 6). BoS cost reduction of 17% can be expected by 2016 without efficiency increase by evolutionary cost

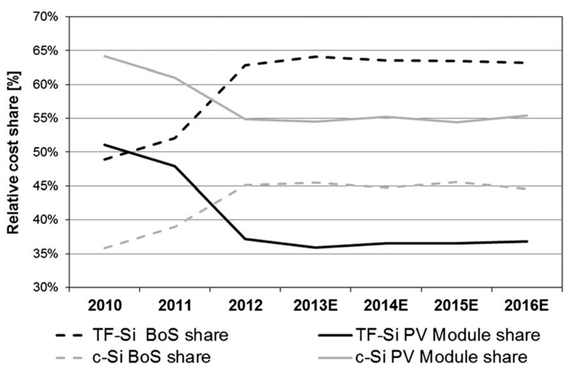

Figure 22. System cost share 2010–2016, TF-Si and c-Si, ground mounted system, Europe.

reduction (Figure 23); when increasing efficiency, a reduction down to 66% of the 2011 BoS costs can be achieved assuming the TF-Si costs from Figure 3.

To achieve the target system cost share of 50/50 based on expected PV module costs of 0.37€/Wp by 2016 (system cost 0.74€/Wp), additional 45% costs reduction in BoS costs are required (no efficiency increase) and 28% (incl. efficiency increase). For this revolutionary cost reduction, new and exhaustive approaches and ideas are essential to optimize each sub-BoS category of the PVPP.

8. REQUIRED SYSTEM COST TO REACH INDUSTRIAL GRID PARITY

8.1. Levelized cost of energy

PV technology must yield sufficient energy (kWh) at competitive cost (€/Wp) to justify its initial investment and O&M expenses during lifetime. The comparison between different energy sources is possible based on

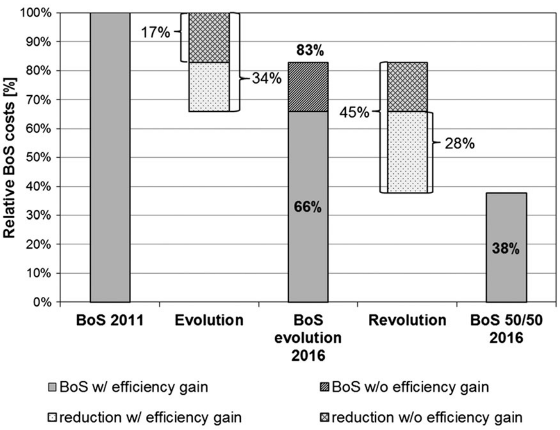

Figure 23. Balance of system (BoS) reduction steps to reach system cost share of 50/50 by 2016 for TF-Si, ground mounted system, Europe.

LCoE assessments. LCoE is defined as the net present value of total life cycle costs of the PV project divided by the quantity of energy produced over the system lifetime [20,21].

The main parameters dominating LCoE are system cost (PV module, BoS), financing cost, and O&M. Other important parameters are system lifetime, local insolation (kWh/m^2/year), climate, taxation, and policy. LCoE estimates for PV vary widely depending on the assumptions made when assigning values to these variables [22,23]. Though, all LCoE values are based on the same method and parameters for a 10 MWp solar farm. Assumptions for LCoE in Italy (Bari) and China (Yinchuan) are weighted average cost of capital of 8.5%, PV module production in China. The efficiencies in 2013 are 16% for c-Si and 10.8% for TF-Si. The project life is expected to be 25 years with an annual degradation of 0.7%/year and O&M cost of 0.7% of the system cost per year. Inverter replacement after 10 years is considered. Cost for land is between 1000 and 2000€/ha. Corporate tax is 30%, and the inflation rate is 2.5%. The project does not get any subsidies.

Table III shows an example of the LCoE sensitivity for various mounting solution for GMS and CRT-flat roof applications. The impact of the module mounting on c-Si systems is 0.04€/Wp (GMS) and 0.06€/Wp (CRT-flat roof) leading to a 3% lower LCoE for GMS and 4% for CRT-flat. TF-Si has lowest LCoE for GMS systems, because it is optimized for this application. Germany (Munich) with approximately 50% less sun hours also shows LCoE values, which are 0.04–0.05€/kWp higher than Bari.

The LCoE values for GMS systems based on Bari are slightly below the offered feed-in tariff of 0.106€/kWh [24], but does not allow a high premium for the project development. The LCoE model gives for Munich 2013 higher values than the offered feed-in tariff (December 2012) of 0.125€/kWh for GMS in Germany [25]. This situation will be very challenging to establish profitable business cases and increase market pressure for further cost reduction. It will also reinforce the search for new business models.

Table III. Levelized cost of energy for different applications, 16% c-Si, 10.8% TF-Si, 2013.

Application		GMS			CRT-flat roof		
Technology		c-Si 16%		TF-Si 10.8%	c-Si 16%		TF-Si 10.8%
Module mounting		Framed	MMI	MMI	Framed	MMI	MMI
PV module ASP	[€/Wp]	0.72	0.70	0.44	0.72	0.70	0.44
BoS cost	[€/Wp]	0.59	0.57	0.78	0.66	0.62	0.91
System cost	[€/Wp]	1.31	1.27	1.22	1.38	1.32	1.32
LCoE (Bari)	[€/kWh]	0.095	0.093	0.089	0.100	0.096	0.096
LCoE (Munich)	[€/kWh]	0.147	0.143	0.138	0.154	0.148	0.148

GMS, ground mounted system; CRT, commercial roof top; MMI, module mounting interface; PV, photovoltaic; ASP, average sales price; BoS, balance of system; LCoE, levelized cost of energy.

8.2. Industrial grid party

Grid parity is a widely used term but there is no exact definition. In this paper, industrial grid parity is defined as follows:

If electricity generation costs of PV systems can be compared with the electricity price of the target group (industry), this is defined as industrial grid parity. The PV generation cost does not include subsidies, discount, tax reduction, or other promotions [13].

In 2011, the average industrial electricity price was 0.112€/kWh in the EU-27 (excl. VAT) and is used here as representative reference. Electricity cost for the industry shows a high variation within the EU-27, highest costs are observed in Cyprus (0.2041€/kWh), and lowest costs in Bulgaria (0.0657€/kWh), Germany (0.124€/kWh), Italy (0.167€/kWh). The real industrial electricity price increase was in average 3.4% between 2001 and 2011 in the EU [26]. The industrial grid parity is expected to be in the range of 0.10–0.14€/kWh in Europe according to Breyer *et al.* [27].

For a location with a system cost of 1.30€/Wp, normalized energy generation of 1650 kWh/kWp/year, the LCoE will be <0.010€/kWh (Table III)—already lower than the average electricity price for the EU-27 member states. Locations with less annual irradiation (e.g., Munich with 1094 kWh/kWp) show an LCoE of 0.142€/kWh, which has a gap of more than 0.03€/kWh (26%). With a system cost development from 2.35€/Wp to 1.00 €/Wp between 2010 and 2016, the assumed LCoE are shown in Figure 24. The industrial grid parity will be achieved in Bari roughly in 2012 and is expected to be reached for countries such as Germany (Munich) by approximately 2016.

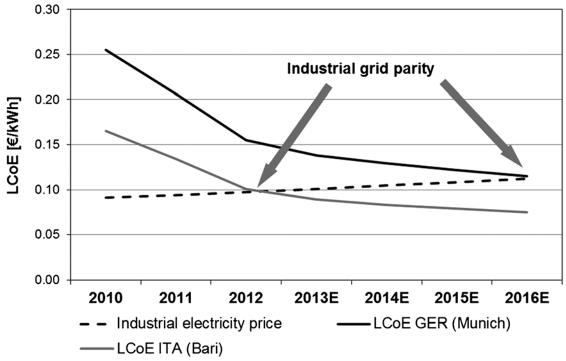

Figure 24. Levelized cost of energy (LCoE) trends for photovoltaic power plant in Germany (Munich) and Italy (Bari), 2012–2016 (evolutionary cost development), industrial electricity price increase by 3.4% annually.

8.2.1. LCoE costs 25% below industrial grid parity

To establish PV as one of the main energy sources for the energy transition, it has to offer LCoE costs well below established values. Therefore, we assume a target LCoE of 0.084€/kWh, 25% below the average industrial electricity price in 2016 [26]. To achieve the target LCoE for Bari, a system cost of 1.14€/Wp is required, which can be achieved with evolutionary BoS development. In 2014, an LCoE of 0.084€/kWh will be achieved (Table IV). For Munich, system costs of 0.70€/Wp are necessary in 2016, and therefore, the BoS cost must be reduced to 52% for TF-Si (Figure 25) and to 51% for c-Si (Figure 26).

8.2.2. Gas parity: LCoE to match electricity generated by natural gas

Wholesale electricity prices are strongly influenced by natural gas (NG) prices. NG fuel costs dominate the cost structure. It has been observed that NG fuel costs correlate with crude oil prices [27]. This price can peak in the future again and show an increasing risk of supply. The next target level for PV electricity will be the competitiveness versus electricity generated by natural gas (peak and base load). LCoE of gas peaking and combined cycle gas turbines (CCGTs) are expected to be in the range of 0.04–0.13€/kWh (depending on the fuel prices and region) [28,29].

The electricity price of natural gas of 0.064€/kWh in 2016 is used here as a reasonable assumption and reference (assuming rather conservative scenario, constant low fuel price scenario, excluding social costs and CO_2 cost impact) [30].

Table IV. Levelized cost of energy, system costs, and required balance of system cost reduction for TF-Si and c-Si and balance of system cost share till 2016 for Italy (Bari), Germany (Munich).

Location		Italy		Germany	
LCoE case	[€/kWh]	0.084	0.064	0.084	0.064
System cost	[€/Wp]	1.14	0.84	0.70	0.50
BoS TF-Si	[€/Wp]	0.72	0.50	0.42	0.30
Evolution	[-]	Expected 2014	37%	37%	37%
Revolution	[-]		1%	11%	26%
BoS c-Si	[€/Wp]	0.52	0.34	0.28	0.20
Evolution	[-]	Expected 2014	20%	20%	20%
Revolution	[-]		22%	29%	44%

LCoE, levelized cost of energy; BoS, balance of system.

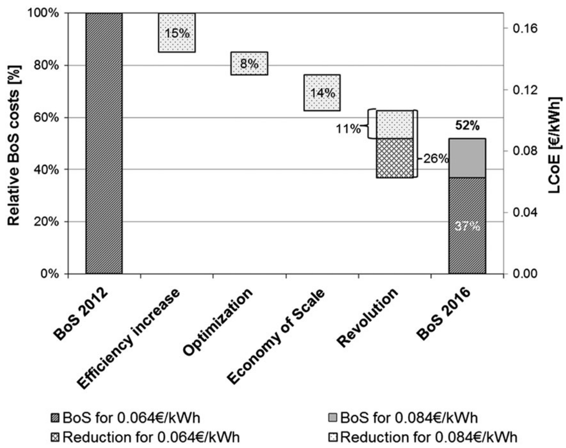

Figure 25. Balance of system (BoS) development to reach levelized cost of energy (LCoE) cost of 0.084€/kWh/ 0.064€/kWh, TF-Si, Germany (Munich), 2012–2016.

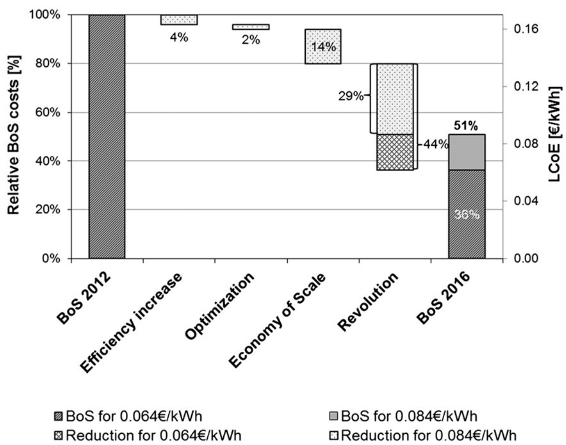

Figure 26. Balance of system (BoS) development to reach levelized cost of energy (LCoE) of 0.084€/kWh/0.064€/kWh, c-Si, Germany (Munich), 2012–2016.

To reach the LCoE of 0.064€/kWh by 2016, system costs of 0.84€/Wp for Bari and 0.50€/Wp for Munich must be achieved, with an expected cost share for c-Si and TF-Si of 60/40 (PV module/BoS) and 40/60, respectively. For Munich, the total BoS cost must be reduced to 37% (0.30€/Wp) for 10.8% TF-Si and total BoS costs of 0.5€/Wp in 2016. The total reduction can be split into 37% of evolutionary cost reduction and further 26% of revolutionary concepts are needed to achieve gas parity (0.06€/kWh).

Achieving this 0.064€/kWh with c-Si in Munich by 2016, BoS cost steps of 4% cost reduction due to efficiency increase, 2% due to BoS optimization and 14% related to economy of scale are expected based on evolution (Figure 16). Additional 44% are required to reach the cost target of 36% of the BoS cost from 2012, based on a system costs share of 60/40.

Technologies with already higher efficiency levels require an additional over proportional increase of efficiencies to reduce BoS costs because only area related costs will be affected, for example, 44% revolution for Munich to achieve the 0.064€/kWh.

This level of LCoE will bring PV in a highly competitive position in the utility electricity market, and its worldwide market potential will increase. When considering that the electricity price will most likely continue to increase as in the past, the crossing lines for PV with conventional energy sources will be even more accelerated [5].

9. CONCLUSION

BoS costs are a critical factor for lowest PV electricity cost (LCoE) and highest PV industry growth. This requires optimized components and design. Particularly, for TF and (high efficiency) c-Si technologies, it is essential to have a comprehensive system view and considering BoS already during the development process for new PV modules designs to get competitive system solutions. The impact of BoS was studied for different technologies (TF-Si, CdTe, c-Si, CI(G)S) and applications (GMS, CRT-pitched, CRT-flat).

On the basis of reference PVPP designs, it is possible to identify and validate BoS improvements and forecasting.

The BoS subcategory share shows that high efficiency technologies profits more from lower inverter costs due to its higher inverter cost share of 36% and a lower substructure fraction of 30%; for TF, this relative share is opposite (22% inverter, 40% substructure).

The BoS costs for the mounting interface between PV module and substructure are in the range of 0.03–0.11€/Wp or 4.76–11.44€/m^2. The MMI optimization with reduced material leads to 50% lower PV module installation costs allowing TF-Si to have the same interface level costs than framed c-Si.

9.0.1. PV module format

The PV module format (mechanical dimensions, electrical design) impact often eliminates the PV module cost and efficiency benefits, which is important when comparing BoS costs in €/m^2. Especially, high efficiency PV modules requires a suitable PV module design; otherwise, this advantage will be limited by larger BoS costs.

Regional differences between Europe and Asia of up to 25% were found (0.22€/Wp TF-Si, 0.12€/Wp c-Si), with labor and raw material cost as the main drivers.

With increased table utilization (sub-PV racks with a group of PV modules for GMS are often called table) from 85% to 100% total BoS costs of 3.3% can be saved.

9.0.2. BoS cost reductions

BoS costs can be reduced by the optimization on the mechanical and electrical side. The initiatives described lead to cost reduction up to 30% for TF-Si:

- TL inverter compatibility for TF-Si technology: 6% lower BoS costs
- Low voltage PV module design for TF technologies: 3% lower BoS costs (double module string length)
- MMI instead of linear clamps for frameless TF-Si PV modules: 21% lower BoS costs. MMI saves between 0.03 and 0.06€/Wp for different technologies.

Several BoS cost reduction initiatives were discussed. Main approaches are simple and fast installation, standardization, margin erosion, and economy of scale. Further options are combination of functions, table utilization, and string length optimization. Also, new business approaches and applications (e.g., H_2 production) or new niche applications are possible. BoS cost reduction for technologies with already higher efficiency levels needs an additional over proportional efficiency increase because only area related costs are affected. During the reduction process, key parts as inverter and substructure design should not be reduced below local standards, as the reliability, and O&M costs will have a significant impact on the LCoE. The ability to maintain this balance will be a differentiator for successful companies in the BoS sector.

9.0.3. BoS forecast

For TF-Si 9.5% and for c-Si 8% of yearly BoS cost reduction is expected. With evolutionary BoS development, the costs for a TF-Si system will be reduced by 26% and 32.2% for c-Si between 2010 and 2016 (no efficiency increase). BoS cost reduction will go down to 55% (TF-Si) and 60% (c-Si) between 2010 and 2016 for GMS systems (with efficiency increase).

9.0.4. PV system cost

Relative BoS cost fractions are typically below 50% for c-Si and more than 50% for TF-Si and show a range of 34–64% of the PV system costs. In 2012, system costs are in the range of 1.30–1.48€/Wp for GMS in Europe, 2012 and the range of 1.10–1.16€/Wp in China. The system cost was approximately 2.35€/Wp in 2010 and will drop to 1.0€/Wp in 2016 for TF-Si, CdTe, and c-Si PVPP installed in Europe. The major PV technologies are expected to have similar system cost level leading to harsh market competition. For CRT-pitched roof applications, the BoS costs for TF-Si will drop from around 1.0€/Wp in 2010 to 0.55€/Wp in 2016, a cost advantage of 15% for TF-Si is observed. System costs show a spread between 1.21 and 1.49€/Wp (2012) because the optimization level for CRT-pitched roofs is not the same for each PV technology.

Investigation to reach a 50/50 cost share (PV module/BoS) for TF-Si in 2016 (GMS application) requires system costs of 0.74€/Wp. Therefore, additional BoS costs reduction of 45% is necessary where 28% of the reduction is expected by efficiency increase.

9.0.5. LCoE

The PV MMI shows a straight LCoE reduction of 3–4% for GMS and CRT applications. LCoE values for GMS (2012) are 0.10€/kWh in Italy (Bari) and 0.14€/kWh in Germany (Munich). The industrial electricity cost is 0.112€/kWh in the EU-27 (excl. VAT) in 2011 with an average annual increase of 3.4% since 2001. The industrial grid parity in Italy is expected in 2012 (with system costs of 1.34€/Wp) and 2016 for Germany (system cost 1.07€/Wp).

9.0.6. 0.084€/kWh—25% below industrial electricity cost

PV will be even more attractive if it offers electricity cost below industrial electricity cost. Therefore, in 2016, 0.084€/kWh (25% lower than industrial electricity cost) have to be accomplished. This is expected for Italy already in 2014 (system cost 1.14€/Wp). For Germany, in 2016, system cost of 0.70€/Wp and BoS costs reduction by 50% are needed. The desired BoS costs are 0.42€/Wp (TF-Si) and 0.28€/Wp (c-Si). The evolutionary reduction is 37% (TF-Si) and 20% (c-Si). The remaining fraction of 11% TF-Si and 29% c-Si must be achieved with revolutionary approaches.

9.0.7. 0.064€/kWh—"gas parity": electricity generated by natural gas

Wholesale electricity prices are dominated by NG prices. The next target level for PV electricity will be the competitiveness versus electricity generated by NG (peak and base load). The rather conservative LCoE assumption of 0.064€/kWh in 2016 is used here as reference. To achieve this LCoE system costs of 0.84€/Wp (Italy) and 0.50€/Wp (Germany) are desired.

For Italy, BoS costs (0.50€/Wp) can be reached for TF-Si by evolutionary BoS cost reduction; for c-Si technology, additional 22% must be reached with revolutionary approaches.

For Germany, the total BoS cost must be reduced to 37% (0.30€/Wp for TF-Si), 37% of the BoS can be reduced by evolution, 26% have to be executed with revolutionary concepts. c-Si systems need BoS cost of 0.20€/Wp where 20% are based on evolutionary cost reduction. The remaining 44% require new innovations. In Italy, the gas parity can be achieved by evolutionary cost reduction only. BoS cost curtailment for technologies with already higher efficiency levels needs an additional over proportional increase of efficiencies because only area related costs are affected. The LCoE levels are a challenge for northern but achievable in southern regions. For all revolutionary BoS cost reductions, new and exhaustive solutions and ideas are required to optimize each sub-BoS category of the PVPP. Next to BoS costs reduction including optimization for target applications, standardization, and the use of further economy of scale also increasing efficiency, lowest O&M costs and improvements on the reliability of the PV systems are mandatory. This will lead to optimized system costs and lower LCoE and allows

PV to be competitive in the (renewable) energy sector because conventional electricity costs are constantly rising.

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REFERENCES

1. Sutterlueti J, Ringbeck S. BoS optimization - insights from a technology provider's perspective. 4th International Workshop on Thin-Film Silicon Solar Cells, Neuchatel, 2012.
2. Wang X, Kurdgelashvili L, Byrne J, Barnett A. The value of module efficiency in lowering the levelized cost of energy of photovoltaic systems. *Renewable and Sustainable Energy Reviews* 2011; **15**(9): 4248–4254.
3. Goodrich A, James T, Woodhouse M. Residential, commercial, and utility-scale photovoltaic (PV) system prices in the United States: current drivers and cost-reduction opportunities. 2012.
4. Ransome S, Sutterlueti J, Kravets R. How kWh/kWp modelling and measurement comparisons depend on uncertainty and variability. 37th PVSC Seattle, 2011.
5. Breyer C, Gerlach A, Müller J, Behacker H, Milner A. Grid parity analysis for EU and US regions and market segments – dynamics of grid-parity and dependence on solar irradiance, local electricity prices and PV progress ratio. In Proceedings of the 24th European Photovoltaic Solar Energy Conference, 2009; 4492–4500. ISBN: 3-936338-25-6
6. IEA. Technology roadmap, solar photovoltaic energy. International Energy Agency, Paris, France, 2010; 48 pp.
7. IPPC. Special report of the intergovernmental panel on climate change, section 3: renewable energy sources and climate change mitigation, 2012.
8. GTM research, executive_briefing_-_Q3_2012, Forecast 2011 – 2016E; Off-grid applications not considered.
9. Meteonorm 7. 2012. http://www. meteonorm.com/
10. GTM research, thin film report, March 2012. Manufacturers data.
11. GTM research, thin film report, THIN FILM 2012–2016: technologies, markets and strategies for survival, April 2012, own estimates.
12. Zweibel K. The terawatt challenge for thin film photovoltaics. In *Thin Film Solar Cells, Fabrication, Characterization and Applications*, Poortmans J, Arkhipov V (eds). John Wiley & Sons Ltd.: Chichester, West Sussex, 2006; 137–230.
13. Sutterlueti J. Grid parity in PV: what are the key success factors, Thesis, University of Liechtenstein, 2008.
14. Oerlikon solar press release: the 1st generation thin Fab 120™, EUPVSEC, Sept. 2010.
15. Urban H, Zapfe C. WIPO patent no. WO/2009/149700, 2009; Huegli A, Susani A, Wachter S, Dillmann JJ. WIPO Patent No. WO2011/054924 A2, 2011.
16. Gossla M, Haelker T, Krull S, Rakusa F, Roth F, Sinicco I. Leakage current and performance loss of thin film solar modules, SPIE Optics + Photonics, San Diego, 2010.
17. Organization for Economic Co-Operation and Development. Consumer prices (MEI): consumer prices – annual inflation. http://stats.oecd.org/ [16.09.2012].
18. Sunpower Corp. Fourth Quarter 2011 earnings, cost reduction roadmap, supplementary slides, February, 16th, 2012.
19. Internal assessment.
20. Cameron Ch, Goodrich AC. The levelized cost of energy for distributed PV: a parametric study, 25th PVSC Hawaii, 2010.
21. Campbell M, Aschenbrenner P, Blunden J, Smeloff E, Wright S. The drivers of the levelized cost of electricity for utility-scale photovoltaics, 2008.
22. Sun Shot Vision Study, February 2012. U.S. Department of Energy, DOE/GO-102012-3027, www.eere.energy.gov/solar/sunshot.
23. Lazzard capital, levelized cost of energy analysis – version 2.0, 2008.
24. McDermott, Will & Emery. Fifth Conto Energia: new feed-in tariffs for photovoltaic energy plants in Italy, August 2012.
25. Deutschland, Einspeisevergütung PV, 2012. http://www.photovoltaik-web.de/finanzierung/einspeiseverguetung-pv-2012.html [15.08.2012].
26. European commission, Eurostat. Energy price statistics, electricity price excl. VAT, industrial consumers, the EU-27 average price is weighted with 2010 national consumption for industrial consumers. http://epp.eurostat.ec.europa.eu [10.09.2012].
27. Breyer C, Gerlach A. Global overview on grid-parity event dynamics. 25th EUPVSEC, 2010.
28. European Photovoltaic Industry Association (EPIA). The sunbelt vision for PV, March 2011.
29. International Energy Agency. *World Energy Outlook*, Organization for Economic Cooperation & Development, Paris 2012. ISBN: 978-92-64-18084-0
30. European Photovoltaic Industry Association (EPIA). Solar photovoltaics, competing in the energy sector - on the road to competitiveness, September 2011.