UKERC Technology and Policy Assessment

Cost Methodologies Project:

PV Case Study

Working Paper

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Chiara Candelise, Imperial College Centre for Energy Policy and Technology

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This working paper was produced as part of the TPA Cost Methodologies project.

Contents

1 Introduction

Thanks to policy incentives implemented in key countries, such as Germany, Italy, and Spain, the photovoltaic (PV) sector has experienced a massive expansion in the last decade, with worldwide cumulative installed capacity growing from 1.4GW in 2000 to over 67GW in 2011 (EPIA, 2012). This market growth has definitely been policy driven, but it has nonetheless triggered industry expansion and PV module price reductions, with dramatic price drops in the last couple of years. In the UK the introduction of the Feed in Tariff (FIT) scheme in April 2010 has boosted the UK PV sector, leading to a relatively unexpected increase in installed capacity since its implementation. By the end of 2011 PV installations in the UK reached about 750MW, up from about 40MW at the beginning of 2010. Indeed, system price drops and increased installation rate have led the UK Department of Energy and Climate Change (DECC) to undergo a controversial review of the FIT scheme, implying a substantial cut in the tariffs to support PV deployment. Nevertheless, these recent developments have allowed the UK PV industry to grow substantially and to achieve considerable cost reductions in UK PV system costs.

This working paper examines global and UK trends in cost trajectories of PV technologies, at module and system level, with the aim of:

1. Examining key trends in contemporary costs and forecasted cost projections;
2. Discussing major drivers for cost reductions;
3. Identifying implications for the use of available cost estimation methodologies in forecasting PV technology costs.

A photovoltaic system is an integrated assembly of modules and other components designed to convert solar energy into electricity. The main component of a PV system is the module, being the device responsible for the conversion of sunlight into electricity and accounting for the largest share of the PV system cost (about 35%-55% of total system cost depending on applications (Ernst & Young, 2011, Parsons Brinckerhoff, 2012)). All the other components needed to build up a PV system are, by convention, called Balance of System (BOS). Usually, BOS refers to all PV system components and cost elements except for the modules, thus including technical components such as inverter, mounting structures, cables and wiring, battery (for off-grid systems), metering (for grid-connected applications) as well as other costs such as installation, design and commissioning costs.

There is a wide variety of PV module technologies at different levels of maturity. Commercial PV modules can divided in two broad categories: crystalline silicon – c-Si – (also often called 1st generation) which are the conventional PV technologies accounting for the majority of the market share (about 85% (Photon International, 2011)); and thin film (2nd generation),an alternative to c-Si recently gaining market share (more specifically Cadmium Telluride (CdTe), Amorphous Silicon (a-Si) and Copper Indium (Gallium) (di)Selenide (CIGS) technologies). A range of novel technologies (3rd generation) are also emerging, including concentrating PV and organic PV which are under development in laboratories and, in some cases, quite close to commercialization. Most of the data presented in this paper, in particular historical cost trajectories and the discussion on drivers for reduction, refer to c-Si technologies and to a lesser extent to thin film technologies. As such, historical trajectories are actual cost and price data since they refer to already commercialised technologies.

PV systems are divided in two main categories: off-grid, which operate independently from the grid network, and grid-connected. Although off-grid applications still play a role in global PV markets (in particular in developing countries), grid-connected PV currently accounts for the major market share and is responsible for the dramatic expansion of the last decade. In analysing PV system costs this paper will only present data and discuss grid-connected system costs. Grid-connected PV systems can be further sub-divided in grid-connected distributed, where the electricity generated satisfies local loads and only the excess is fed into the grid, and grid-connected centralised, where all electricity generated is fed into the grid. Grid connected PV system can also be divided according to the market segment they satisfy and the system type/size. Typical PV market segments are: residential (systems of small size – below 10kW), commercial (systems of medium size – in the hundreds of kW range), and utility (large ground mounted systems – in the MW range). Residential and commercial systems are generally utilised as distributed systems, and are on top of buildings or building integrated (BIPV) when they displace conventional building materials. This wide variation of grid-connected systems types and sizes implies variation in system costs (as discussed in Section 2.2). PV costs and prices are presented and analysed at module and system level. For the module both prices and production cost (€ or $/Wp) figures are presented. Capital cost (CAPEX) figures (£/Wp installed) are presented for PV systems.

2 Cost trajectories and estimation

This section presents PV costs trajectories and compares forecasted costs with actual out-turns. First, cost reductions are discussed at module level by presenting module price and production costs figures. Then PV system CAPEX cost data are presented, i.e. accounting for BOS costs.

2.1 Module price and production cost

PV module prices have been decreasing over time. Figure 1 shows the average module price trend from the mid-70s to 2011. Data is presented in $/Wp[1]. It indicates a dramatic reduction in PV module prices over the period, mainly due to the development and deployment of crystalline silicon technologies.

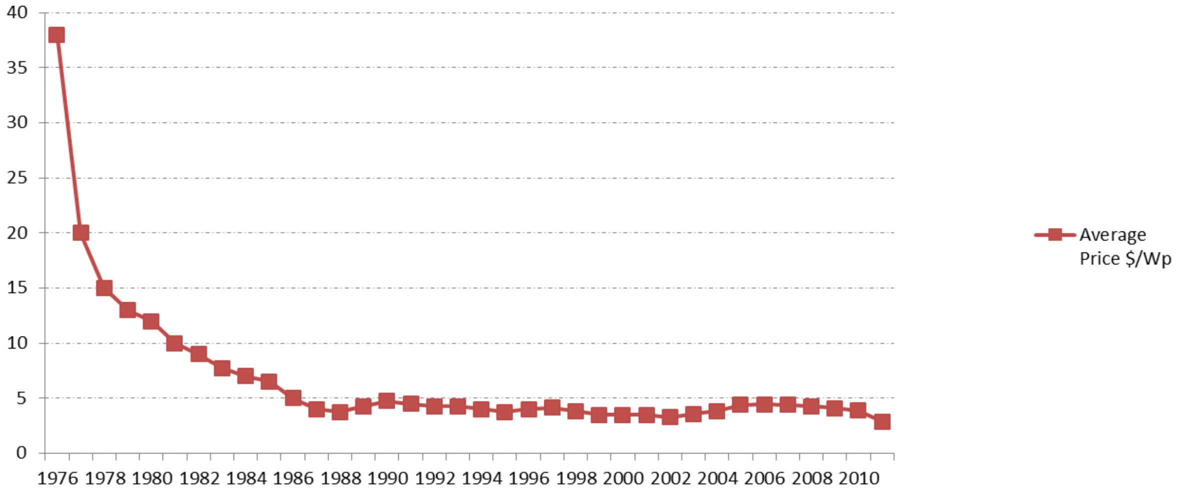

Figure 1. PV module price historical trend (Maycock, 2011, Solarbuzz, 2012)

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[1] Module price figures are presented in the currency of the data collected, i.e. either dollars or euros. This is a reflection of the global dimension of the PV module market and the fact that module prices have been driven to date by developments and market dynamics in countries other than the UK (i.e. the UK PV market has been very small and has had no influence on global price trends). A conversion in £/Wp would introduce a currency effect that could mislead the interpretation of historical module price trends.

Figure 2 focuses on module price development of the last decade i.e. a period in which the global PV market has experienced a massive expansion. It presents average retail prices in Europe and the USA based on a monthly online survey of retail prices (Solarbuzz, 2012). This encompasses a wide range of module prices, varying according to the module technology (with thin film modules generally cheaper than c-Si), the module model and manufacturer, its quality, as well as the country in which the product is purchased[2]. For example, in March 2012 average retail module prices were respectively $2.29/Wp in USA and €2.17/Wp in Europe, but the lowest retail price for a crystalline silicon solar module was $1.1/Wp (€0.81/Wp) and the lowest thin film module price was $0.84/Wp (€0.62/Wp) (Solarbuzz, 2012).

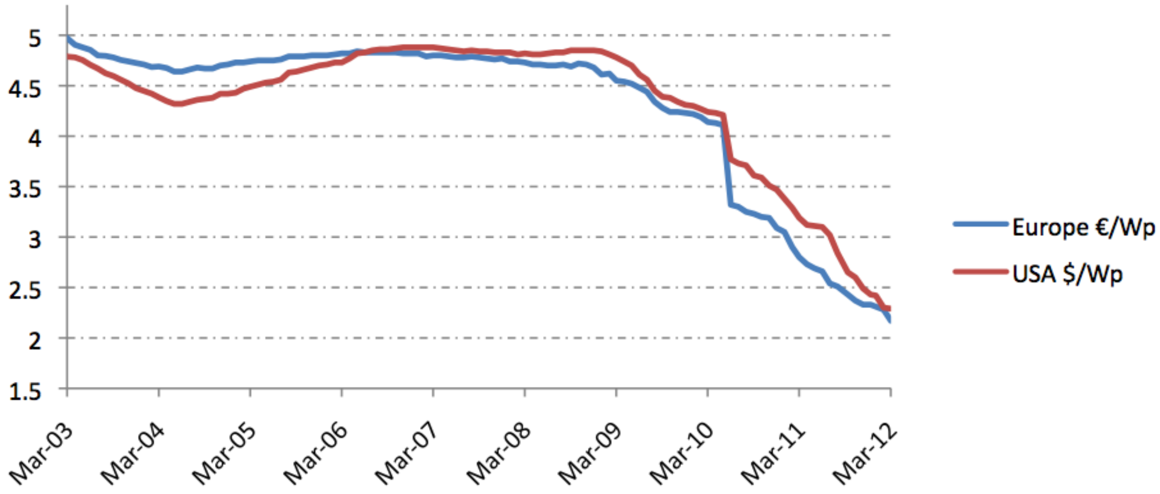

Figure 2. PV module price (2003-2012) (Solarbuzz, 2012)

Figure 2 highlights two major events: an inversion in the historical module price reduction trend shown in Figure 1 in the mid-2000 and a dramatic drop in prices in the last two years. The former was the result of a bottleneck along the value chain, the silicon feedstock shortage. The latter was the result of a combination of learning and market forces, which has led average c-Si module prices to fall by more than 45% from mid-2010 to March 2012 (Solarbuzz, 2012). Both events are discussed in more detail in Section 3.1.

Since the 1970s, estimates of PV module cost had predicted reductions, although the target costs and the timing for their achievement vary within the literature and have not always coincided with actual out-turns. Such estimates were derived both from experience curves and engineering- based assessment and are here divided into those

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[2] Section 3.2 discusses the correlation between PV prices and national PV market size.

made before and after the year 2000. A previous contribution (Schaeffer et al., 2004b) has pointed out how cost reduction projections made before the year 2000 have been too optimistic when compared to actual PV module prices[3], as shown in Table 1. The table also shows the discrepancies between experience curves and engineering assessment estimates and evidence of higher 'appraisal optimism' in the latter.

Study	**Year of study**	**Year of projection**	**Engineering assessment projection**	**Experience curve projection**	**Actual average selling price**
JBL86-31 target	1978	1986	1.63	0.86	11.94
JBL86-31 Cz	1985	1988	2.17	6.35	9.12
JBL86-31 Dentretic	1985	1992	1.02	2.8	7.7
EPRI 1986	1986	2000	1.5	0.79	5.05
MUSIC FM, 1996	1996	2000	1	4.07	4.05

Table 1. Comparing experience curve and engineering assessment production costs projections with actual PV module prices (Schaeffer et al., 2004b)

During the last decade the reverse has happened, with estimates underestimating cost reductions achieved over recent years. Table 2 presents a selection of PV cost estimates made after the year 2000 by both experience curves and engineering assessment studies. Estimates are presented as quoted in the studies, thus they are not converted to account for currency and inflation. This as $1/Wp and €1/Wp have been by convention assumed the benchmark production cost reduction figures within the cost reduction literature of the last 5 years. Therefore, the estimates here presented should not be interpreted as absolute values, but rather considered against such benchmarks.

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[3] This applies even considering manufacturers' mark-ups on top of production costs figures, i.e. the discrepancy between estimated production costs and actual prices is too high to be simply attributed to mark-ups. Implications of the use of price versus production cost figures are discussed in Section 3.3.1.

Study	**Year of study**	**PV technology**	**Year of projection**	**Cost projection**
Experience curve studies:				
Surek	2005	c-Si	2023	$1/Wp
Trancok & Zweibel	2006	Thin film	2022	$0.7/Wp
Engineering assessment studies:				
EU Strategic Research Agenda	2007	c-Si	2013	€1/Wp
EU Strategic Research Agenda	2007	Thin film	2020	€0.75/Wp

Table 2. Experience curves and engineering assessment cost projections (post-2000) (EU PV Technology Platform, 2007, Trancik and Zweibel, 2006, Surek, 2005)

Estimates presented in Table 2 have proven to be over-pessimistic when compared with actual out-turns in PV production costs. Figure 3 presents current and future estimates of production costs for c-Si and some thin film technologies (CdTe, silicon thin film) (Ebinger, 2011, Fath, 2011, First Solar, 2011, Holzapfel, 2011, IHS iSuppli, 2011, IMS Research, 2012)[4]. It shows how c-Si and thin film have got close to the $1/Wp benchmark threshold, well ahead of estimates from both experience curves and engineering based studies presented in Table 2.

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[4] Data points before 2012 are actual production costs, whereas those from 2012 onwards are forecasts and as such should be treated with caution.

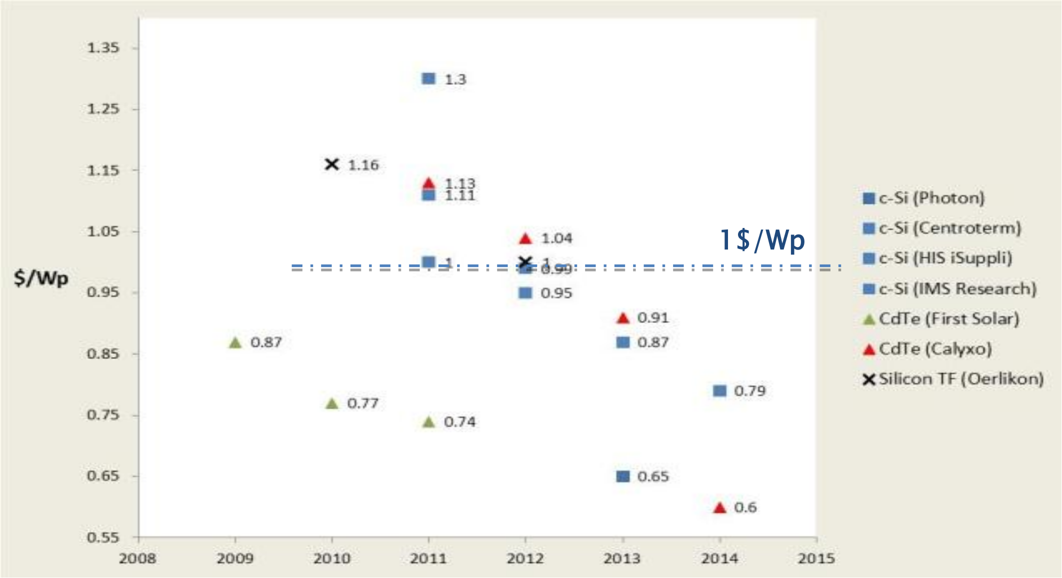

Figure 3. Current and forecasted production costs for c-Si and thin film PV, $/Wp (Ebinger, 2011, Fath, 2011, First Solar, 2011, Holzapfel, 2011, IHS iSuppli, 2011, IMS Research, 2012)

Section 3 will discuss possible reasons behind such discrepancies between PV module cost reduction estimates and actual out-turns.

2.2 System CAPEX

Despite the module being the major cost element of the PV system, what matters for the assessment of PV technologies cost effectiveness is the total PV system capital cost (CAPEX), i.e. including BOS cost.

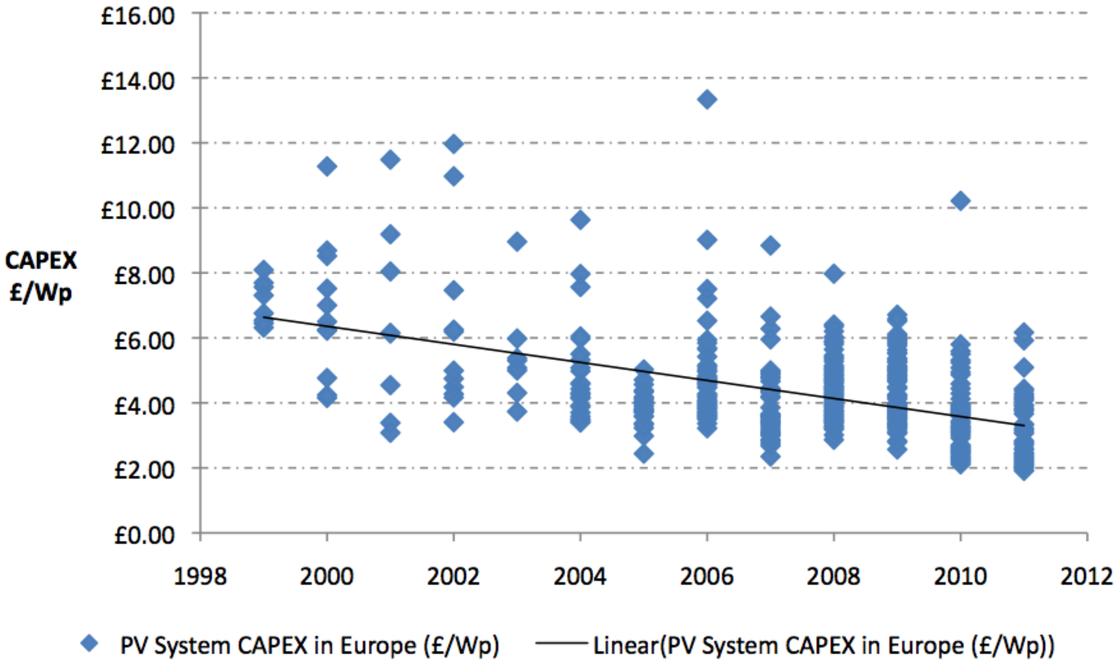

Figure 4. PV system price across European countries

Figure 4 presents CAPEX of PV systems installed in several European countries in the last decade (i.e. Germany, Italy, Spain, Netherlands, Belgium, Austria, Greece, France, UK) (Arup, 2011, Candelise, 2009, Candelise et al., 2010, Castello et al., 2003, Castello et al., 2004, Castello et al., 2007, Castello et al., 2008, Castello et al., 2009, Castello et al., 2010, Energy Saving Trust, 2008, IEA-PVPS, 2005, Mott Mcdonald, 2011, Rudkin et al., 2007, Sonnenertrag.eu, 2011). The data presented are actual PV system prices converted into 2011 British pounds. The variability in PV system prices shown in Figure 4 is due to differences in system prices across both market segment (and system size), system types and countries. System prices do not scale linearly with system size, thus tend to be higher in residential markets compared to medium size commercial systems and large utility scale systems. They also differ across countries and across PV system types, with e.g. BIPV systems being more expensive than standard roof top applications. Despite such high variability, Figure 4 shows a clear decrease in system prices over time across market segments and countries.

Due to the high variability of PV system CAPEX figures across countries, comparison of past estimates with PV system price out-turns is done for the UK only. Figure 5 presents UK PV system future cost trajectories as estimated by several studies commissioned by the UK Government since 2008 (CEPA and PB, 2011, Element Energy, 2008, Element Energy, 2009, Parsons Brinckerhoff, 2012). Trajectories are presented for small, medium (when available) and large size PV systems. The figure shows how previous estimates have underestimated UK system price reduction achieved in the last few years and how estimates for future price reductions trajectories have been progressively revised downward. For example, 2012 UK PV system prices had been estimated in 2008 to be £3,338/kWp and £3,115/kWp respectively for small and large PV systems (Element Energy, 2008). Such estimates are much higher than the actual out-turns of respectively £2,542/kWp and £1,200/kWp for the same PV system sizes (Parsons Brinckerhoff, 2012). Similarly, estimates for UK system costs for e.g. small size systems in 2020 have been revised downward from £2,172/kWp in the 2008 study (Element Energy, 2008) to £1,050/kWp in the 2012 study (Parsons Brinckerhoff, 2012). Drivers behind cost reductions at PV system level are discussed in Section 3.

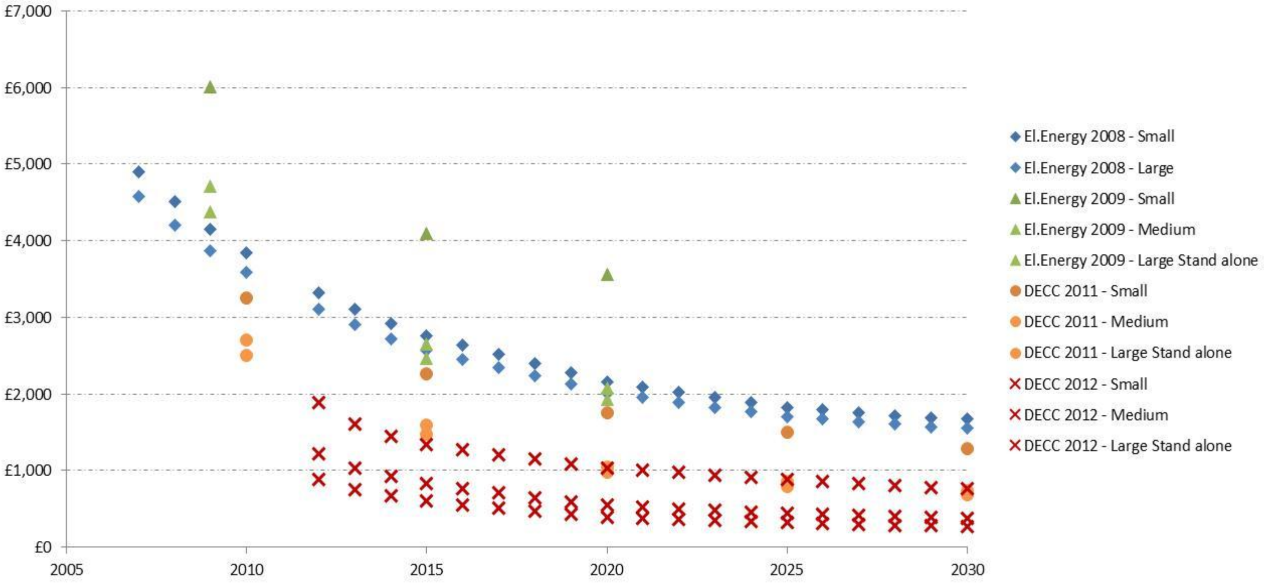

Figure 5. Comparison of UK PV system cost trajectories estimates (CEPA and PB, 2011, Element Energy, 2008, Element Energy, 2009, Parsons Brinckerhoff, 2012)

3 Discussion

The following sections discuss the major drivers behind the reduction in PV module and system prices over time and the possible reasons for the discrepancies between expectations of future costs and actual outcomes.

3.1 PV module cost reductions

The first substantive drop in PV module costs occurred in the mid-70s, when PV moved from space to terrestrial applications. C-Si module price decreased from $90/Wp in 1968 to $15/Wp in 1978, mainly thanks to reduced device quality and reliability requirements, higher product standardization as well as increased market competition. Subsequently, c-Si module costs continued to decrease over time, with the PV industry experiencing historical learning rates in the 18-20% range. Device efficiency and plant size increases (and consequent economies of scale) have been judged to be the major cost reduction drivers up to the early 2000s (accounting for respectively 30% and 43% of price reduction) (Nemet, 2006). Crystalline silicon technologies have also benefited from knowledge spillovers from the already mature semiconductor industry.

Cost reductions at device level (c-Si technologies)

At the device level, the main drivers for cost reductions for c-Si technologies are increases in cell efficiency and power density of the module and a reduction in silicon consumption per Wp. An increase in cell efficiency of 1% alone is able to reduce the cell cost per Wp by 5-7%. Commercial module efficiency has been increasing in recent years, moving from 12-14% in 2007 to 13-16% in 2011 for average c-Si modules, and to 15-17% to around 20% for the best performing modules (EU PV Technology Platform, 2007, EU PV Technology Platform, 2011, Green et al., 2012). Silicon usage in c-Si cells has also been reduced over time, thanks to innovation that has allowed thinner wafers and improving efficiencies in wafer cutting (reducing wastage of material). Wafer thickness has decreased from above 400μm in the 90s to 160-180μm in 2011 (EU PV Technology Platform, 2011, Kazmerski, 2006). Silicon usage has overall decreased from around 13g/Wp in early 2000s to 7g/Wp (Photovoltaics Bulletin, 2003, EU PV Technology Platform, 2007, EU PV Technology Platform, 2011).

Manufacturing processes and scale

Improvements in the manufacturing processes as well as vertical integration (with vertically integrated companies able to purchase feedstock or wafer at cost prices) have also contributed to cost reductions. Over the last decade, module production processes have become more automated, gradually moving away from batch processes toward in-line, high throughput, high yield processing. For many years, most companies grew by specialising in a single activity within the value chain. In recent years, the largest c-Si PV manufacturers have integrated vertically both up-stream and down-stream along the PV supply chain, thus positioning to achieve "best practice" production costs[5]. The size of plants has also played an important role in reducing costs, and the last decade has seen a dramatic increase in c-Si production capacity and average plant size. In 2007 average plant size was c.100MWp/y; this quickly increased to the 500-1000MWp/y range (e.g. JA Solar, the second largest PV manufacturer in the world has established a PV module production facility in Fengxian, Shanghai, with an annual capacity of 1.2 GW (JA Solar, 2012)).

Silicon feedstock bottleneck

In the mid-2000s, because of a sudden increase in demand for PV modules due to demand pull policies implemented in key countries, the PV industry experienced a serious bottleneck - a silicon feedstock shortage. This caused silicon spot prices to go up from $50/kg to over $500/kg in 2008 (Flynn, 2009), increasing production costs and leading to an inversion in the historical module price reduction trend (Figure 2). However, the silicon shortage also stimulated innovation both in R&D and manufacturing to improve material utilization (through lower silicon consumption in devices and efficiency increases), and drove new investments in feedstock production as well as increased R&D efforts in developing cheaper ways to produce silicon (e.g. production of less pure 'solar grade' silicon). Since the mid-2000s, silicon feedstock prices have more closely reflected production costs and production capacity expansion eventually created oversupply in the silicon feedstock market, pushing prices downwards (spot prices were around $35/kg in late 2011) (Prior and Campbell, 2012, Iken, 2012). Cheap silicon feedstock was also a driver of the dramatic module price drop experienced in the last couple of years (discussion below).

Technology differentiation

The silicon bottleneck in the mid-2000s and the consequent production costs increase for c-Si technologies also triggered a new wave of investments in thin film (TF) PV technologies. Among currently commercialized technologies TF PV are generally deemed to have major potential for cost reductions, provided that the expected increases in

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[5] Best practice costs are the lowest observed processing costs at each step of the supply chain, i.e. the sum of polysilicon best practice costs, ingot/wafer best practice cost, cell best practice cost, and module best practice production costs.

production facility sizes and efficiencies are realised (Chopra et al., 2004, EU PV Technology Platform, 2007, EU PV Technology Platform, 2011, Hegedus, 2006, Woodcock et al., 1997, Zweibel, 2005, Zweibel, 2000). Their high cost reduction potential is due to very little use of high-cost semiconductor compared to c-Si and to the fact that their unit of production is more flexible and not constrained by the wafer dimensions, thus allowing larger units of production, continuous production processes and large scale, high-throughput manufacturing. Investments in TF PV production capacity have been increasing, facilities production capacities have reached the MWs range, and turnkey production lines with high cost reduction potential are being developed. TF PV are currently the least expensive to manufacture, with CdTe TF modules produced at a cost of $0.74/Wp by First Solar, a company which has managed to increase production capacity from 25MW in 2005 to over 2GW in 2011 (First Solar, 2011), thus achieving large scale production, which is one of the major conditions to fully harness the cost reduction potential of thin film technologies (Chopra et al., 2004, Hegedus, 2006, Woodcock et al., 1997). Indeed, First Solar is the first PV manufacturer to reduce production costs below the $1/Wp production cost threshold, in 2009, much earlier than predicted in previous estimates (see Figure 3 in Section 2.1).

Beyond production costs – Recent price drop and market forces

As shown in Figure 2 module prices have been dropping dramatically since 2010. Such drastic reductions were largely unexpected, and correlated to a dramatic market expansion. Overall since 2000, total PV production increased more than 30 fold, with annual growth rates above 40% since 2006 (Jäger-Waldau, 2011). High demand and profit margins in the second half of the 2000s drove high levels of investment, with new companies and countries entering the market, expanding production capacity and supply (Jager-Waldau, 2006, Jager-Waldau, 2008). By 2009, many analysts expected a shift from a supply-constrained to a demand-constrained market, leading to price reductions and industry consolidation (Englander et al., 2009, Rogol, 2009). Production overcapacity started to impact the market in 2010 and continued during 2011 leading to a dramatic drop in global module prices. Much of the rapid growth in production capacity has been in China and Taiwan (which together now account for about 50 % of world-wide production (Jager-Waldau, 2010)), with new companies able to supply the global market with much lower price modules. The c-Si module price drop is also due to an oversupply in polysilicon production, with a consequent reduction in silicon feedstock prices and module production costs. Early 2012 evidence and analysts' views also suggest that modules are currently being sold below production costs, triggering PV industry consolidation (several companies have been filing for bankruptcy) and global controversies over module pricing (with some US PV manufacturers filing an anti-dumping petition against Chinese manufacturers and the US Department of Commerce to release in March 2012 a determination on countervailing imports of silicon PV modules from China).

However, it remains unclear how much of these recent price reductions can be attributed to actual reduction in production costs driven by incremental innovation (e.g. device and production process improvements) and economies of scale along the PV module value chain (including production of component materials such as glass), or to market demand/supply dynamics and other factors such as easy access to cheap (subsidized) capital for Chinese manufacturers and industry ‘dumping’ strategies.

3.2 System CAPEX cost reductions

PV system cost reductions are driven by reductions in module cost (discussed above) as well as balance of system (BOS) costs. Cost reduction and learning in manufacturing PV BOS components are relatively less substantial than for PV modules, as PV systems’ BOS components are common, mass-produced electrical and mechanical components with mature markets outside the solar industry. Nonetheless, incremental innovation in some BOS components has led to lower manufacturing costs, in particular for inverters which have experienced a learning rate in the 10% range (Schaeffer et al., 2004b). A similar trend was found in the USA for cost reduction for labour costs attributed to installed PV systems (IPCC, 2011).

Combined effect of several factors

Overall, unlike module cost reductions, system cost reductions cannot be attributed to individual system/hardware components, but rather to the combined effect of several factors in a compound learning system. Cost reductions in BOS are achieved by system design efforts, i.e. reducing the number of BOS parts, improving mechanical and electrical integration of PV modules, array structures and power conversion electronics, and improving mounting systems for easier, faster and cheaper installation. BOS component standardization also helps in reducing cost, as it allows for higher volumes of production (and economies of scale) and to shift system assembly from the field to the factory. Increasing module efficiency also has an impact on BOS costs. For a given installed capacity, higher efficiency modules require less area than c-Si modules, reducing mounting structures, cabling and inverter costs. Learning by doing in design and installation procedures also reduces BOS cost through reductions in labour costs.

PV system costs and market expansion

System cost reductions are also correlated with market expansion. In particular, a more developed PV market tends to imply:

- Higher competition among system developers and installers which reduces margins;

- The development of an experienced network of installers and wholesale distribution network, which allows learning by doing and economies of scale along the supply chain;
- Higher purchasing power of system developers and installers for module and system components in the international market;
- More transparent and efficient administrative rules and grid connection procedures, thus reducing transaction and financing costs due to delays in completion of the PV systems installation and connection.

Some of the above points have been quantified in a recent study showing how, over the last decade to 2010, PV module prices have been 90% and 180% of global average module price in countries with PV markets respectively above 100MW/y and below 5MW/y (Werner et al., 2011). In other words, PV module prices are considerably lower in countries with well-developed markets and supply chains.

To explore the correlation between PV system costs and market expansion, the PV system CAPEX data that was presented in Figure 4 across several EU countries are here presented for Germany, Italy and UK in Figure 6, together with the countries' total installed capacity for the 2000-2011 period. Germany and Italy are leading PV markets. The impressive market expansion in Germany has been driven by the introduction of PV policy support in the mid-2000s, i.e. a Feed in Tariffs (FIT) implemented in 2004 in conjunction with 'soft loan' schemes, preceded by roof-top deployment programmes. Similarly, Italy first implemented FITs in 2006 and started experiencing a major PV market expansion in 2008 (once initial scheme implementation issues were resolved), to become the largest world market in 2011.

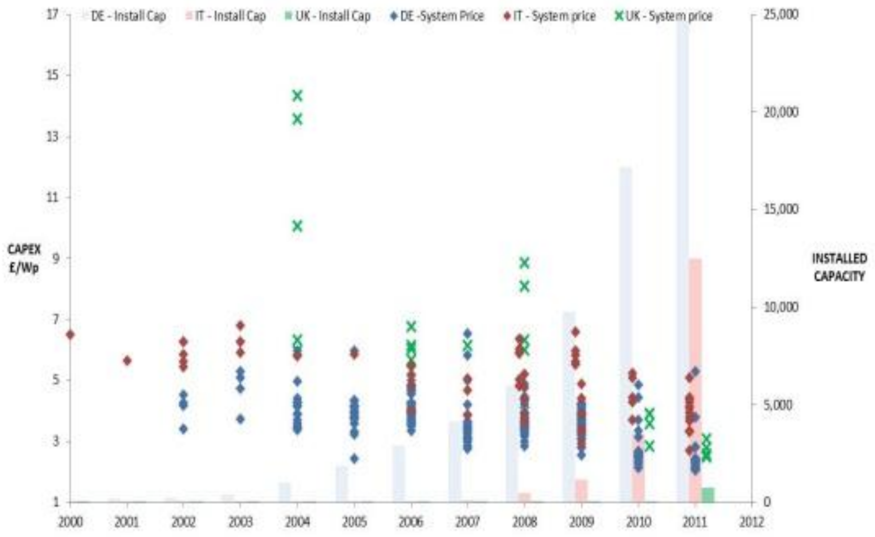

Figure 6 PV system prices against total installed capacity in Germany, Italy and UK

Figure 6 shows that for a given module price, system CAPEX is higher in countries with smaller PV markets. For example, in 2007 and 2008 (years of massive market expansion in Germany (EPIA, 2011)) system CAPEX was on average higher in Italy compared to Germany. Italian and German system CAPEX prices converged in 2010-2011, as the Italian annual market reaches the GWs size. A similar pattern is evident for the UK, which experienced a dramatic drop in system CAPEX after the introduction of a FIT scheme in 2010, causing UK installed PV capacity to grow from about 30MW in 2008 (Cowley, 2009) to 750MW by 2011 (EPIA, 2012). Average system price dropped from £6.71 in 2008 to £3.57 in 2010 and £2.75 in 2011[6]. Module price decreases during the last couple of years (as discussed above) certainly played a role in these rapid system prices reductions. However, evidence shows how UK PV system prices have been falling more than module prices since 2010, with reductions above 50% in the large scale PV segment by mid-2012 (CEPA and PB, 2011, Parsons Brinckerhoff, 2012) (compared to about 45% reduction in average global module prices). This indicates additional drivers behind UK PV system price reductions as well as the drop in average module prices.

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[6] In the available data set (Figure 5) average UK system prices are lower in 2006 compared to 2008. This is due to the data source: 2006 system prices come from the DTI Large Scale field trial statistics, i.e. they represent systems of medium size Rudkin, E., Thornycroft, J., Njoku, C. & Cogzell, J. 2007. PV Large Scale building integrated field trial. Third technical report - Case studies. *Halcrow Group report for BERR.* Department for Business Enterprise & Regulatory Reform. London., whereas 2008 data comes from the Low Carbon Building Programme statistics, i.e. mainly residential systems of small size Energy Saving Trust 2008. Statistics on PV installation funded through Low Carbon Building Programme *Data personally gathered from Energy Saving Trust representative. March 2008.*. The former are on average cheaper than the latter, as system price do not scale linearly with system size.

Indeed, evidence also shows a correlation between market expansion and system / BOS price reduction. For example, in 2007, system CAPEX was higher in the UK (with an installed capacity of c.18MW), compared to Germany, (with over 4GW installed). In 2007 the average UK system price for a standard roof top c-Si system was £5,821/kWp, while in Germany system integrator SolarWorld quoted €4,500/kWp (£3,487) for a similar system (Candelise et al., 2010). In addition, the installation and commissioning share of the total system price was about 19% in the UK and 6.2% in Germany (Candelise et al., 2010), probably reflecting lower competition and a less developed and experienced network of system developers and installers in the UK (Candelise et al., 2010, Jardine C. and Bergman, 2009). The rapid convergence of UK system prices to those in more developed PV markets also suggests rapid knowledge spillovers across countries i.e. new countries and PV markets learning from other countries' experiences (Schaeffer et al., 2004b).

3.3 Methodological issues

This section discusses some of the limitation of experience curves and engineering studies in estimating future PV costs (both at module and system level) and possible reasons for the discrepancies between expectations of future costs and actual outcomes.

3.3.1 Experience curves

The limitations of experience curves in predicting future technology development have often been identified in the literature. For example, it has been pointed out that learning can only partially explain cost reductions and that all factors associated with cost reductions cannot be fully captured by a simple functional relationship between capacity installed and unit cost (Clarke et al., 2006, Junginger et al., 2005, Nemet, 2006, Papineau, 2006, Watanabe et al., 2003, Mukora et al., 2009, IEA, 2000). In particular, some major uncertainties resulting from the use of experience curves for forecasting future costs of PV technologies are here highlighted and discussed.

Sensitivity to input data

The extent and timing of future cost reduction is very sensitive to the estimated learning rate, which in turn is also affected by the underlying data used (the period and the scope covered). Table 3 summarizes the learning rate results from a selection of studies of PV reduction trends. All these studies use price and market expansion data for the historically conventional PV technology, crystalline silicon (c-Si) PV.

Study	Learning Rate	Years	Scope
Williams and Terzian, 1993	18.4%	1976-1992	US
Cody and Tiedje, 1997	22%	1976-1988	US
Schaeffer et al, 2004	20%	1976-2001	Global
Harmon, 2000	20.2%	1968-1998	Global
Maycock and Wakefield, 1975	22%	1959-1974	US
McDonald and Schrattenholzer, 2001	20%	1968-1998	Global
IEA, 2000	21%	1994 - 1998	Japan
Surek, 2005	20%	1976-2003	Global

Table 3. Learning rate variations among selected studies. Source: (Cody and Tiedje, 1997, Harmon, 2000, Maycock and Wakefield, 1975, McDonald and Schrattenholzer, 2001, Schaeffer et al., 2004a, Surek, 2005, Williams and Terzian, 1993, IEA, 2000)

Whilst the average PV historical learning rate appears to be in the order of 20%, even small changes in the learning rate can affects long term estimates of cost reductions, the market expansion needed to reach a given target cost and the potential timing for such an achievement. Similarly, varying forecasts of future market growth affect the estimation of the timing by which a certain cost reduction target would be achieved. For example, in 2006 Trancik J. and Zweibel K.[7] estimated, for a given learning rate, that thin film PV might reach the cost of: $0.7/Wp in 2022 assuming a thin film growth rate of 30%; 0.6$/Wp in 2020 or in 2018 assuming respectively a 40% and 50% growth rate; 0.5$/Wp in 2017 or 2016 assuming respectively a 60% and 70% growth rate.

In reality, and as discussed in Section 2.1, $0.7/Wp is already very close to being achieved by thin film after experiencing very high market growth rates (above 70% in 2010 (Mints, 2011)) - much earlier than estimated (Trancik and Zweibel, 2006). Moreover, historical evidence shows alternating periods of module price stabilization followed by more rapid price decreases (see also Figure 7). Indeed, learning rates have been below 20% in late 1980s-early 1990s and higher than 20% in late 1990s (the latter

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[7] One of the few experience curves studies which used separate experience curves for c-Si and thin film.

not coinciding with a high market growth rate, but possibly instead reflecting the impact of R&D investments made before 1990s) (Nemet, 2006, Schaeffer et al., 2004b). Similar fluctuations have also been experienced more recently as discussed in Section 2.1.

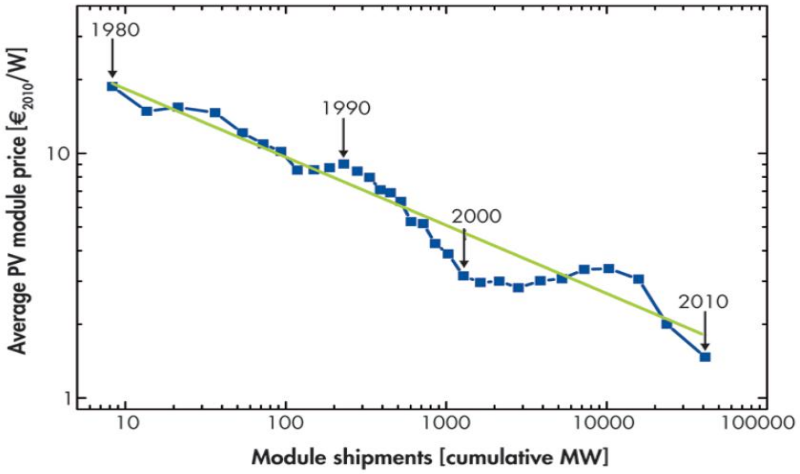

Figure 7. PV module experience curve (1980 -2010) (EU PV Technology Platform, 2011)

Technology differentiation and breakthrough

Experience curve analyses tend not to anticipate discontinuities in the learning rate, which makes them inappropriate for predicting cost trends in discontinuous technology fields. This is a particular concern for PV, as e.g. emerging thin film technologies have already managed to achieve very low production costs earlier than conventional c-Si technologies (as discussed in Section 3.1), and technological breakthroughs are expected to occur when novel technologies under R&D reach commercialization stage. Moreover, available PV experience curves are based on historical data for conventional c-Si technologies and very limited or no data exists for other emerging PV technologies, such as thin film or excitonic devices. Experience curves cannot be built for these emergent technologies (except in a highly illustrative scenario fashion) because of the absence of reliable data over a sufficiently long time period; clearly, this limits their use in forecasting future aggregated PV technologies costs.

Price as a proxy of production costs

Since all manufacturers closely guard their design, construction, and operations costs, it is not straightforward to build up a time series for manufacturing costs. Thus, experience curves generally use PV module *prices* as a proxy for their production costs. However, module prices are the result of a combination of production costs and companies' mark-up (price-cost margin), which in turn is affected by market forces such as demand/supply dynamics and levels of market competition. Such market forces affect prices of PV module and are beyond the learning effects captured by the experience curve analysis, which instead attempt to identify the drivers behind reductions in the module's production cost. Indeed, as has been highlighted in Section 3.1, market dynamics, industry strategies and oversupply imbalance are likely to explain a major part of the recent dramatic drop in PV module prices (rather than actual production cost reductions).

PV as a compound learning system

PV experience curves have been mainly developed for PV *module* costs, yet PV should more accurately be addressed as a compound learning *system*, i.e. accounting also for learning trajectories and cost reductions at the balance of system (BOS) level. There is relatively limited quantitative evidence on the drivers of cost reductions at BOS level, as most cost reductions efforts (and most research literature) have concentrated on the PV module (the major system component). This a reflection of the following difficulties:

- BOS costs differ for different PV applications, e.g. grid-connected versus off-grid and also between different grid-connected applications (roof mounted, ground mounted, BIPV).

- There are wide regional differences in the PV system type of design and implementation and installation, which makes cross-country comparison difficult.

- System level cost reductions cannot be attributed to the learning and cost reductions of individual system/hardware components, but are rather the result of the combined effect of several factors.

- PV system cost reductions are affected by country specific market developments, policy and regulatory conditions.

For these reasons reliable input data over a sufficiently long time period are not readily available for BOS, thus limiting the use of experience curves as both descriptors of past trends and as a forecasting tool for system level costs. Learning rates based on historical module trends cannot be applied to PV system learning nor can system level cost reductions be attributed to the learning and cost reductions of individual system/hardware components. Moreover, as PV system cost reductions are affected by country specific market and regulatory conditions, learning rates experienced in one country cannot be simply transposed to another one with a different regulatory and market context. This particularly complicates the forecasting of future system level cost reductions in countries with a nascent PV sector, as e.g. the UK before 2010, for which sufficiently long historical time series for system prices and installed capacity are not available and an experience curve cannot be built. In addition, a country specific experience curve would not in any case be able to capture learning spillovers across countries, from more mature markets (e.g. Germany) to emerging ones (e.g. UK).

3.3.2 Engineering assessment

Engineering assessment can assist in characterising and quantifying drivers behind technological improvement, and their implications for cost reductions. It can also assist in developing cost projections for those novel PV technologies for which historical data are not available. It generally involves a combination of in-depth and technology specific data gathering and expert elicitation. Therefore, this forecasting methodology entails a degree of uncertainty arising from discretionary judgements (such as the level (and timing) of efficiency achievable by a certain technology) including the possible biases introduced by 'appraisal optimism' (Gross et al., 2007). As discussed in Section 2.1, engineering assessment of PV technology costs have been over-optimistic in assessing future PV costs up to the early 2000s, and have then underestimated PV cost reductions in the last decade. Nonetheless, they have provided a bottom up estimation of the lower bound achievable for PV technologies costs.

4 Concluding remarks

This paper describes the significant reduction in PV technologies costs over time, both at module and system level. It also discusses the major drivers behind module and PV system production cost and price reductions. Overall, it can be remarked that:

1. Cost reductions in PV module technologies have been and will be further achieved by a combination of R&D innovation (mainly at the materials and device level) and incremental improvements of manufacturing and implementation processes.

2. The increase in scale, both in manufacturing capacity and in market size, has been a key factor in reducing costs. Evidence presented here has highlighted how reductions in PV module production costs and prices have been facilitated by a rapid production capacity up-scaling (along the whole production chain including feedstock materials) and the consequent economies of scale and learning by doing,. The dramatic increase in demand and market size in the last decade, coupled with the availability of mature and fairly standardized production processes for c-Si technologies has eased market entry for new industry players and countries (e.g. in China and Taiwan in the last five years), allowing quick ramping up in global production capacity. For thin film PV technologies, turnkey production lines with high cost reduction potential have been developed thus facilitating new investments and further capacity expansion. In the case of CdTe technology in particular, the ability to ramp up production capacity and improve production throughput has allowed one single company, First Solar, to reduce production costs and become a market leader.

3. Modularity of the main PV system component, the module, allows diversity of applications and easy implementation. This has facilitated the quick uptake of the technology and enabled market expansion wherever the economics of the investment have been set ‘right’, i.e. when policy support implemented in key countries has made the investment viable (until grid parity is reached).

4. Correlation between market expansion and cost reduction is even more directly evident at system level. Cost reductions at system level are the result of a combination of learning factors, many of which are related to country specific conditions affecting deployment of the technology and market size. The evidence indicates a correlation between learning at the system level and national market expansion.

Since the 1970s PV cost reductions have been the subject of a growing body of literature comprising both experience curves and engineering-based studies. Overall, such literature has succeed in predicting the cost reductions achieved by PV technologies, although the specific target costs as well as the timing for their achievement has not always coincided with the actual out-turns. In particular, forecasts of PV modules cost reductions made before 2000 have been too optimistic when compared with actual module price out-turns and the reverse has happened in the last decade, with recent cost reductions exceeding previous forecasts. At the system level, UK forecasts of future cost trajectories at system level have also been over pessimistic. UK system prices have reached lower levels than previously predicted and future costs estimates have recently been revised downwards.

Experience curves are an effective methodological tool to illustrate the historical cost reduction trend for different types of technologies, and they are widely used to describe progressive learning and technology change for energy models and scenario analysis. However, uncertainties in their calculation and prediction as well as their inability to predict cost trends for new and emerging technologies mean that caution and care should be applied in using them for the analysis of PV future cost trends and to model technological innovation within energy models and scenarios analysis. Engineering-based assessments can assist in developing future costs estimates for PV technologies, as they provide more detailed explanatory information regarding technological and concomitant cost improvements, and can be used for those novel technologies for which historical data are not available. However, such estimates are also subject to uncertainty as they rely on expert judgement and in practice have proven not to correctly anticipate cost reductions achieved.

In particular, neither experience curve nor engineering based studies have been able to anticipate recent module price reductions and it still remains unclear as to the extent to which these are the result of reduced production costs due to learning associated with massive capacity expansion (something that, in principle, both experience curves and engineering studies could have predicted assuming higher and faster market growth rates) or rather the result of market forces including demand/supply imbalances, country specific industrial policies and industry strategies. Experience curves seem to be ill-suited to respond to questions such as this as they are essentially aggregate observations, describing a simple functional relationship and cannot fully capture all of the factors associated with cost reductions. Moreover, by using module prices as a proxy of production costs they are intrinsically not suited to disentangle drivers affecting production costs trajectories from the market forces influencing module prices. A more detailed parameterised analysis of production costs and price dynamics is probably needed in order to capture the several drivers involved, including multiple R&D, supply chain, manufacturing, market and regulatory forces at work.

This paper also highlighted the challenges in estimating system level future costs and the fact that system costs develop as a compound learning system, and as such are not easily captured by experience curve analysis. Moreover, system costs trajectories are not just affected by global module price trends but also by country specific PV implementation conditions and national market expansion, thus they are subject to national learning. Thus, unlike module prices which follow global dynamics, experience and learning in system prices have a national specific component, mostly associated with market expansion, which cannot easily be transferred from one country to another (despite some spillover that might occur across countries) – which suggests that these factors require careful consideration in any assessment of policy support for delivering PV deployment and improved PV cost-effectiveness.

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