Imperial College London

The impact of policy on technology innovation and cost reduction: a case study on crystalline silicon solar PV modules.

Working paper

November 2014

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Abstract

The dramatic cost reduction in solar photovoltaic (PV) modules in recent years has confounded expectations. Solar electricity generation cost is now approaching grid-parity, with modules now costing less than $1/Wp. A key question is the extent to which different policies have driven cost reductions, particularly when considering the different phases of solar PV research, development, demonstration and deployment (RDD&D). Focusing on crystalline silicon (c-Si) solar modules, which have dominated the PV market for several decades, this study first reviews the quantitative (primarily statistical) evidence on drivers of PV module price reductions, before considering more qualitatively which policies dominated during periods of rapid innovation and cost reduction. Following c-Si modules' early period of space cell development, the mid-1970s saw the beginning of a dramatic period of innovation in module design and manufacture, in large part driven by the US Jet Propulsion Laboratory's Flat-Plate Solar Array project, which achieved a more than five-fold reduction in module production costs and which helped establish module designs not significantly different to those produced today. Subsequently, increased demonstration and deployment support activities helped to establish larger scale, more automated, lower cost manufacturing, helping to achieve the current sub-$1/Wp production cost which has made many reconsider the economics of PV. This story indicates that at relatively early stages of technology development, governments should support targeted activities to achieve market-ready designs, paving the way for subsequent deployment support to stimulate scale-up and innovation in manufacturing, which could achieve equally if not more dramatic cost reductions in the technology.

1 Introduction

What policy lessons can be learned from the development and deployment of solar power during the many decades since it was first commercially exploited? Recent analysis has suggested that we are now entering the “grid-parity” era of solar-generated electricity, with module prices below $1/W, and in some cases whole rooftop system prices close to that level, generating electricity at a cost of about $0.1/kWh [1].

The dramatic cost reduction in solar PV modules in recent years has confounded expectations. Using a mixture of learning curves analysis and expert elicitations, just six or seven years ago the $1/Wp module price level was expected to be realistic by 2030 [2], [3]. One exception is Swanson’s (2006) analysis [4], which seems rather more prescient in predicting the sub $1/Wp mark would be hit by 2012, which, in the outturn, turned out to be correct [5].

Predictions are now focused on when the $0.5/W mark will be reached, as a result of continued innovation and scale-up in the manufacture of PV modules. Some are talking about full grid-parity, (which might imply no further need for deployment subsidies) by 2030, even for more expensive sub-10 kW rooftop systems [1]. Others assert that grid parity has already been reached in some markets, or is imminent, depending on whether describing parity with wholesale or retail prices [6].

This means that solar PV may be claimed to be a success of deployment policies, and/or R&D policies, and/or demonstration policies, all of which have featured in its different development phases.

A number of statistical, and some bottom-up engineering, analyses have sought to quantify the relative impact of R&D, economies of scale, cumulative deployment, and other factors including silicon and other input prices. As discussed in this paper, these approaches provide important insights into the drivers of price reductions, but come up against a range of challenges including the difficulty of disentangling the interactions between different explanatory factors, the differing influence of these factors at different points of PV development, and the lack of availability of underlying production cost data, as opposed to (at times very different) market price data.

This paper takes a more qualitative approach, by focusing on crystalline silicon (hereafter c-Si) PV modules (which have made up around 90% or more of the market since commercialisation) and identifying when key advances in PV module design and manufacturing innovation have occurred, as well as considering the major policies and market conditions during those periods of innovation. The paper aims to inform policy makers about the efficacy of different policies, as well as other incentives, in driving performance improvements and cost reductions in c-Si PV, with a view to considering what lessons could be applicable to other, more novel forms of PV, or to other low—carbon energy technologies more generally.

The approach combines a review of literature covering the history of PV development, the impact of policies on innovations and cost reductions in c-Si PV (and PV more generally) and the views of industrial and academic experts involved in the development of c-Si PV technology since the 1970s (see Acknowledgements section).

The paper is set out in 6 sections: Section 2 briefly describes the major steps in c-Si PV module manufacture; Section 3 discusses the major innovations and cost reductions achieved in each stage of the process; Section 4 discusses the role of policy and other incentives in achieving these innovations; Section 5 discusses the relationship between innovations and policy and non-policy drivers, and suggests lessons that this provides for future PV and other low-carbon technology development; Section 6 concludes.

2 Solar PV module manufacture

A crystalline silicon solar PV module is essentially a thin wafer of silicon connected to two electrodes, encapsulated in weather-proof materials. When light strikes the module, some of the photons in the light are absorbed by the silicon, freeing electrons from the silicon bonds and allowing them to travel through the silicon towards an electrode. An internal electrical field exists within the silicon wafer as a result of a “p-n” junction, which separates two layers of silicon that have been doped with boron and phosphorous respectively, giving them different propensities to attract and release electrons. This field helps to separate the freed electrons and the positively charged “holes” that they leave behind, before they can recombine. The field drives electrons and holes to opposite electrodes connected to the wafer, from where they enter an external circuit and do electrical “work” (e.g. in lighting and appliances).

The module efficiency (i.e. the degree to which sunlight energy incident on the module is converted to electrical energy) is improved by ensuring the maximum possible light reaches the silicon wafer, which means the wafer surface must not be reflective, and also that the wafer is sufficiently thick that light does not travel through it without most being absorbed. In addition, efficiency is improved by ensuring that electrons and holes do not recombine before they reach the electrodes. Recombination commonly occurs where there are impurities in the silicon, particularly at silicon crystal grain boundaries where the silicon wafer consists of many individual silicon crystals (as in multicrystalline silicon) as opposed to a single crystal (as in monocrystalline silicon), and also where the metal electrodes are connected to the wafer.

Many of the principal innovations in cell design have resulted in less reflective surfaces, more absorption of light entering the wafer, and lower recombination rates of electrons and holes. Other major innovations have resulted in cost reductions through cheaper production of silicon, using less silicon to make a cell, and the development of larger scale, more automated and ultimately cheaper processes to produce cells.

There are 4 major steps in the manufacture of c-Si solar PV modules, as shown in Figure 1, and described in sections 2.1-2.4.

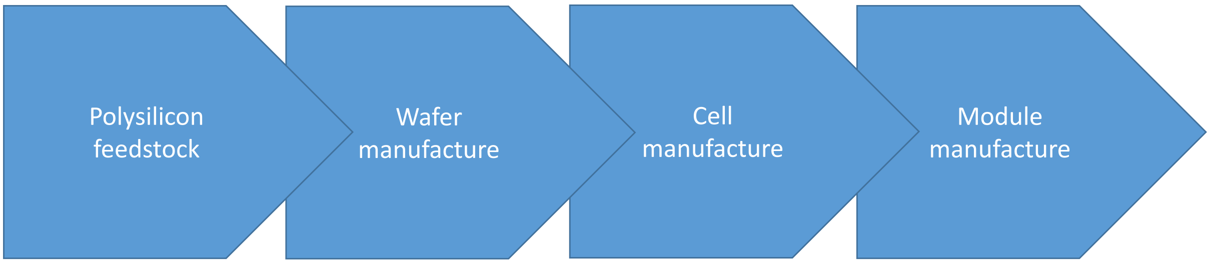

Figure 1: Stages of crystalline Silicon PV module manufacture

2.1 Production of polysilicon

Polysilicon (which is a very pure form of the element) is produced from metallurgical grade silicon, itself produced from the basic chemical reduction of earth-abundant silica (SiO_2). This metallurgical grade silicon contains impurities such as iron and other transition metals. There are three major processes for polysilicon production, all involving the preparation of volatile silicon compounds from the metallurgical grade silicon, which are subsequently purified through distillation and then thermally decomposed into pure silicon and other compounds. The Siemens process, developed in the 1950s, involves the reduction of trichlorosilane ($SiHCl_3$) with hydrogen into silicon and gaseous compounds on a heated silicon rod. A process developed by Union Carbide Chemicals and Komatsu Electronic Materials in the early 1980s involves thermal decomposition of monosilane (SiH_4). A third process (the Ethyl Corporation Process), also using monosilane, deposits the silicon from decomposition in a reducing hydrogen atmosphere onto heated silicon particles in a fluidised bed [7]. The Siemens process has dominated for much of the last few decades, as it is a low-risk, established technology used by the microelectronics industry [8].

2.2 Production of silicon wafers

Silicon wafers are produced from the polysilicon feedstock, through first growing crystals of silicon. Two types of silicon cell have dominated the PV module market for several decades- monocrystalline and multicrystalline. Monocrystalline silicon was used in the first cells to achieve efficiencies of close to 5% [9]. The single crystal of silicon is produced by drawing a seed rod of silicon with a defined crystal orientation from molten silicon held in a cylindrical quartz crucible. This is the Czochralski (heareafter Cz) method and has been used for 50 years, using a technique drawn from the semiconductor industry.

Multicrystalline silicon is produced by melting polysilicon in a rectangular quartz crucible and slowly solidifying to form an ingot, which, unlike in the monosilicon process, produces solid silicon with crystals of the order 2-10 mm in size. The resulting grain boundaries impede the flow of charge from the silicon semiconductor to the electrodes, and in early multicrystalline silicon manufacture in the 1950s efficiencies of only around 1% were achieved, although with slower cooling to achieve larger crystals, this increased to about 6% efficiency in the early 1970s [10] and to closer to 15% (at least at the laboratory level) as a result of a number of other improvements by the end of the 1970s (see Section 3.3 and Figure 2).

The solid silicon (either mono or multi crystalline) is then sawn into wafers, which results in 40-50% losses of material, known as kerf losses [11].

Ribbon silicon production techniques have been experimented with since the 1970s, and a wave of R&D in these techniques in the 1990s led to ribbon silicon cells having a market share of almost 6% in 2001. Although there are a variety of techniques, they share the principle of pulling a solidifying multicrystalline film of silicon from molten silicon, with film thicknesses towards 100 micrometres achieved [11]. Ribbon silicon production finished in 2013 [8] which makes it unlikely to play a major role in crystalline silicon production going forward.

2.3 Production of silicon cells

Commercial cell manufacture starts by taking a doped wafer (normally p-type, doped with boron during the crystal-growing phase). The as-cut wafers are etched in alkaline or acidic solutions to remove crystal damage caused by the sawing process [12]. Moncrystalline wafers which are grown with a (100) (which means flat) crystal surface orientation are alkaline-etched resulting in a (111) (pyramidal) surface texture that increases light-trapping. Multicrystalline wafers are acid etched to generate a rough, low reflection surface. The p-n junction is then created by doping one wafer surface with a phosphorous compound (for example H_3PO_4, $POCl_3$, or PH_3) and heating to a temperature of 900-1000°C to drive the phosphorus into the silicon surface [8]. An antireflective coating is then added, normally through a process called plasma-enhanced chemical vapour deposition (PECVD) of hydrogenated silicon nitride, which also “passivates” multicrystalline silicon cells – this means it lowers rates of recombination by hydrogenating free silicon bonds in the multicrystalline structure, which are prime points for electron and hole recombination. A front electrode is then added typically through screen printing of a silver paste, whose simplicity and low-cost compensate for the lower efficiencies compared to more precise laser, vacuum evaporation and photolithographic methods. Some cell designs use lower cost copper contacts which are buried into laser-formed grooves or surface channels and provide a better balance between low contact resistance to the silicon whilst minimising shading losses of incoming light. An aluminium paste is screen printed onto the back of the wafer, which as well as acting as a rear electrode, also helps to form a back surface “field” which reduces recombination rates [12]. Advanced cell processes have additional steps, including further front and rear surface passivation using for example silicon oxide [13].

2.4 Module encapsulation

Module manufacture consists of interconnecting cells using copper ribbons, and a lamination process which consists of placing the connected wafers between sheets of EVA (Ethylene vinyl acetate), a transparent polymer which after heat treatment bonds to a front glass layer and a rear fluoropolymer layer. Modules are then typically set in aluminium frames for mounting. Finally modules are tested and qualified [12].

3 Major innovations in PV module design and manufacture

A number of innovations have led to efficiency improvements, more efficient and larger-scale manufacturing of both material inputs and the modules themselves, and less material usage, all contributing to cost reductions in crystalline silicon PV modules, as discussed in Sections 3.1-3.5.

3.1 Polysilicon input prices

Polysilicon prices fell fairly steadily from about $300/kg (in US$2002 prices) in the late 1970s to about $40/kg in the early 2000s [3], [4] as a result of increased scale of production, the introduction of new processes including fluidised bed reactor processes and gradual process improvements [8].

With the PV industry growing at around 50% per year since 2000, polysilicon supply failed to keep pace with the growing demand. In 2000 about 4,000 tonnes (metric) of silicon were consumed in the production of PV, which grew to 30,000 tonnes by 2007. This compared to about 2 million tonnes of metallurgical grade silicon for all purposes [7]. Polysilicon production was dominated by silicon chip manufacturers from Japan, Korea and the USA until the early 2000s, with relatively little value attached to the wafer production as it constituted a small part of the overall cost of silicon chips used in microelectronics [8]. Following the price spike around 2008, market entry from several new companies led to significant cost reductions in polysilicon, now produced specifically for PV cells, with prices falling to around $20/kg in 2014 [14].

3.2 Wafer manufacturing improvements

A number of developments have occurred in wafer manufacture since the 1950s, including the increase in Cz crystal rod diameters, larger crucible sizes for multicrystalline silicon production, and faster sawing with lower kerf losses [8]. Wafer sizes have steadily reduced from 300 micrometres to about 180-200, but even thinner wafers present new challenges in handling to avoid breakages. Wafers were originally cut using inner diameter (ID) saws in a process pioneered by the microelectronics industry, but replaced by multi-wire sawing in the early-to-mid 1980s, with lower kerf losses, higher throughput, and the ability to saw thinner wafers [11]. In addition, wafer areas have increased twofold over the period 1979 to 2006 [4], reducing the handling required for a given power output of module.

3.3 Cell efficiency improvements

Major innovations have occurred to cell designs which have increased cell efficiency and therefore lowered the cost of modules in terms of their $/Wp figure. Figure 2 shows how the maximum achieved laboratory efficiency of c-Si cells has developed over the past decades.

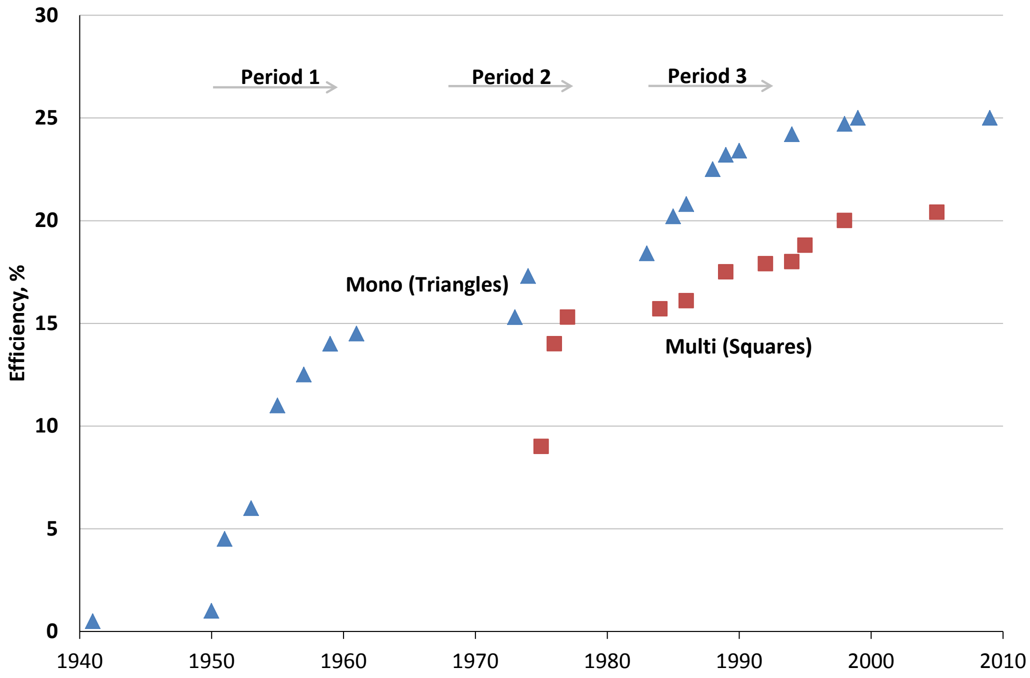

Figure 2: Evolution of mono and multicrystalline laboratory efficiencies [15]

Notes: Efficiency values are the highest reported in that year, under standard test conditions

There have been a number of drivers of laboratory-stage efficiency improvements, many of which have eventually found their way into commercial cell manufacture. Wenham & Green (1996) [16] outline three major periods of efficiency improvement. The first period of space cell research in the late 1950s was driven by improvements in silicon crystal quality, as well as using solid state diffusion to introduce dopants (boron and phosphorous) into the silicon crystals – a superior technique compared to previous methods including helium ion bombardment. Introduction of top metallic grid electrodes (as opposed to both electrodes at the rear of the cell) shortened the distance travelled by electrons in the top n-type conduction band to reach the top electrode, whilst allowing light through to the wafer.

The second period in the mid-1970s saw improvements resulting from the use of aluminium as a rear contact, which served a “gettering” function (meaning it absorbed impurities from the silicon) and also helped to create a back surface field to prevent recombination of electrons and holes. In addition, further refinements to the top contacts were made (resulting in finer, more closely spaced contacts), and titanium dioxide was introduced as an antireflection coating. This period also saw the emergence of cells with pyramidal surfaces (etched in line with crystal planes inherent in the silicon crystal structure) to reduce incident light reflection [16], [17].

Further experimentation from the mid-late 1980s led to further improved passivation at the front of the cell by using a very thin layer of silicon oxide between the n-type silicon and front electrodes, leading to the introduction of the Passivated Emitter Solar Cell (PESC). The PERL (Passivated Emitter and Rear Locally diffused) cell introduced in the late 1980s/early 1990s is similar in design to the PESC cell, but with the rear aluminium replaced by a thin silicon oxide layer (for passivation purposes, and to increase light reflection back into the cell) and *p+* doped regions in the silicon dioxide film. The mid-1980s also saw the development of buried contact cells with copper plated front electrodes in laser-formed grooves, to minimise contact resistance and shading losses [16]. These cells were commercialised by BP Solar and sold from 1992-2008 (Mason, 2014).

As can be seen from Figure 2, these three periods led to laboratory cell efficiencies exceeding 20% (for multicrystalline cells) and 25% (for monocrystalline cells), made possible by laboratory conditions for precise manufacture of prototype cells. Translating these gains in efficiency to commercial cells has proven challenging, with efficiencies achieved in commercial cell production considerably lagging those of laboratory cells, as shown in Figure 3.

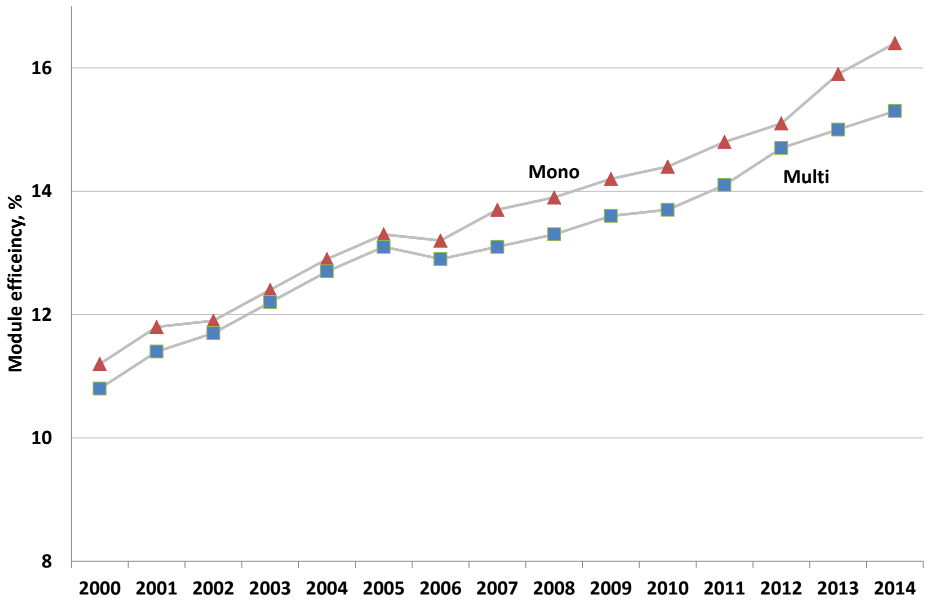

Figure 3: Average commercial module efficiency [18]

Notes: Average module efficiencies from survey of those in the market in given year. Best module efficiencies now exceed 20% [19]

Nevertheless, the laboratory-stage efficiency improvements are gradually being incorporated into cell manufacture, as techniques have been identified which can replicate the lab-stage process much faster and at larger-scale. Much of this innovation has come from learning-by-doing in manufacturing.

3.4 Cell encapsulation into modules

The introduction of better lamination techniques has created more weather-resistant modules, with glass and EVA lamination and Mylar/Tedlar fluoropolymer backings replacing initial designs with silicone rubber lamination, achieving cost savings as well as improvements in durability [20]. Many of these innovations were introduced in the early 1980s during the US Jet Propulsion Laboratory's Flat Plate Array programme, and have remained in module design to this day [21], as discussed in Section 4.

3.5 Automation and scale of cell and module manufacture

Many of the processes involved in module manufacture were performed by hand, when factory capacities were up to ten MW per year until the early 1990s. At this stage most of the equipment used had been developed in-house. Increased automation and increased factory sizes led to cost reductions [4]. Throughput has also increased through the replacement of batch processes with continuous processes, and additional cost savings have resulted from the specialisation of equipment manufacturers now that the PV production market is large enough. In the early decades cell manufacture borrowed heavily from the microelectronics industry, using processes and equipment that were not specialised for PV production [11].

Figure 4 shows the major innovations in commercial c-Si PV module design and manufacture since the 1950s breakthrough in cell efficiency.

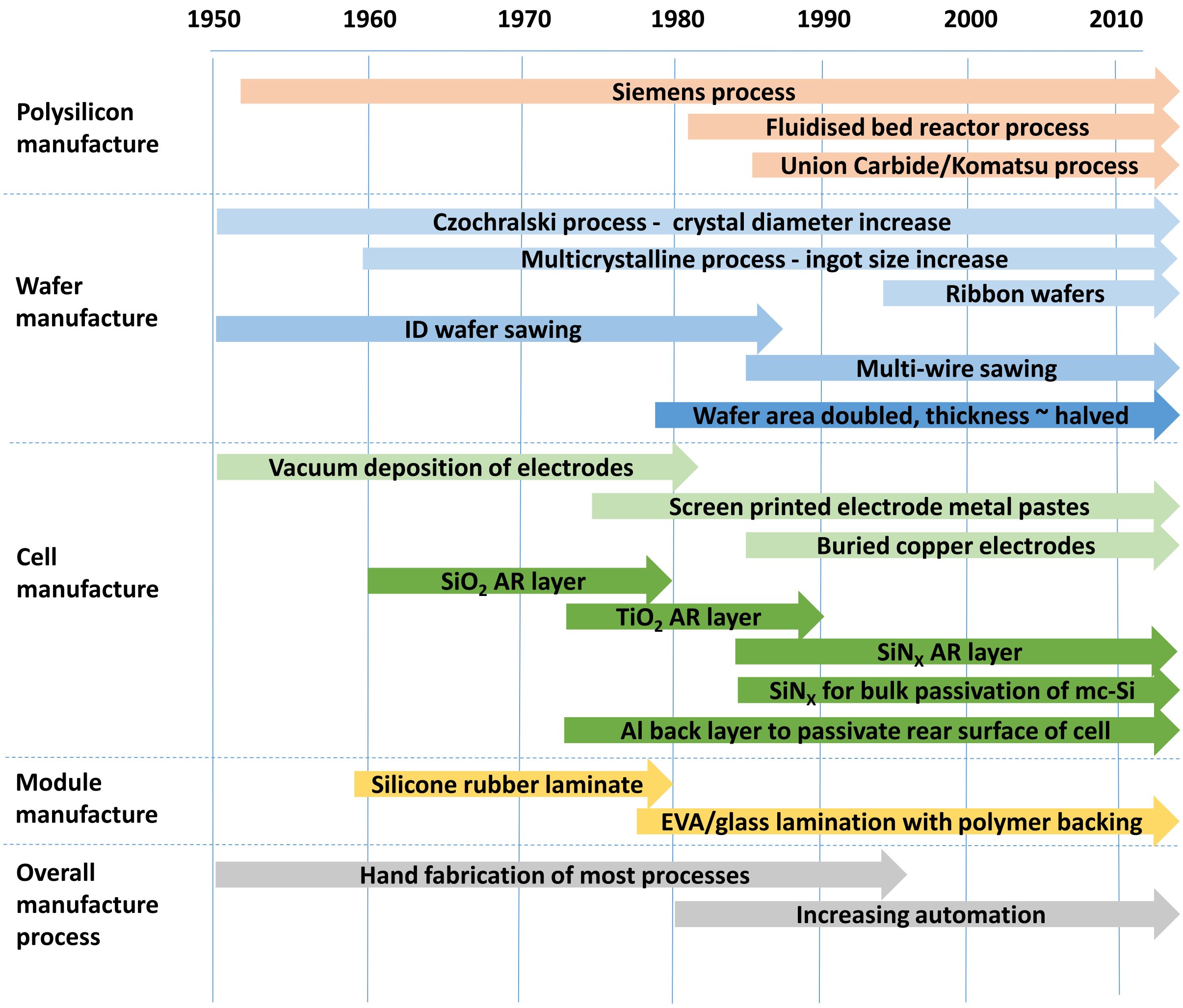

Figure 4: Major innovations in design and process of c-Si PV modules, 1960-present

A key question is what the driver (or drivers) behind each of these major innovations in module design and manufacture have been, which requires analysis on the impact of policies on module designs and costs, as discussed in Section 4.

4 Major policy initiatives in solar PV module development and deployments

There have been a considerable number of policies across a range of countries to support and promote the development and deployment of solar PV. In the last 10-15 years, several countries have implemented market creation policies, most popular amongst them Feed-in-Tariffs (FiTs), which offer guaranteed payments for each kWh of electricity generated by PV systems. In addition, countries have experimented with capital subsidies including investment tax credits and accelerated depreciation schemes, renewable energy certificates, net metering and a range of other measures which have made solar PV a profitable investment (see [22], [23] for a detailed summary of such market creation policies across countries in which significant PV deployment has occurred).

There has also been continued public investment in solar PV R&D. However, Breyer et al (2010) estimate that the public share of total R&D investment in solar PV has declined from 80% in the early 1980s to less than 10% in 2008, indicating that the vast majority of R&D is now driven by private companies [24]. Furthermore, evidence suggests that R&D has become a much less important public policy for solar PV overall than market creation policies such as FiTs. Grau et al (2012) estimate that the value of PV R&D support constitutes only about 1% of the value of deployment support in China and 3% of the value of deployment support in Germany [25]. Before focusing on the specific drivers of c-Si PV module design and manufacturing innovation (in Section 4.2), Section 4.1 first reviews the quantitative evidence on the impact of policies on PV module prices.

4.1 Summary of studies which quantify the impact of different factors on PV costs

A number of statistical analyses have been undertaken to determine how different factors have affected solar PV prices (as opposed to costs, where data is far less readily available). Table 1 summarises key findings from these studies. They have been categorised into three groups: the first which analyses “learning-by-doing” as proxied by the impact of cumulative deployment on PV module prices, which is the most common form of a single factor learning curve; the second which adds R&D as a second factor affecting module prices; and the third which analyses different factors such as economies of scale and silicon prices. All of these studies relate to global c-Si PV prices and global factors unless otherwise indicated.

Table 1a: Studies analysing the learning rate in single factor learning curves

Study	Learning rate	Period of observations	R squared	Comments
Harmon (2000) [26]	20.2%	1968-1998	0.99	R squared as reported in Macdonald and Schrattenholzer (2001) [27]. For all PV modules including c-Si, and thin-film.
Parente et al (2002) [28]	22.8% 20.2% 22.6%	1981-2000 1981-1990 1991-2000	0.988 0.977 0.978	For all Si modules including c-Si and amorphous Si (a-Si)
Van Sark et al (2008) [29]	20.6% 18.4% 16.6% 29.6%	1976-2006 1981-2000 1981-1990 1990-2000	0.992 0.954 0.913 0.954	Deliberately repeats the Parente et al (2002) [28] analysis over the period 1981-2000, but with different source of price data.
Zheng and Kammen (2014) [30]	20.9% 15.2%	1976-2010 1991-2010	0.909 0.841	

Notes: Only those studies with a specified R^2 *value are included here. Additional study details available in* [31]

Table 1b: Studies analysing two-factor learning curves of learning-by-doing and learning-by-R&D

Study	Learning-by-doing rate	Learning-by-R&D rate	Period of observations	R^2	Comments
Miketa and Schrattenholzer (2004) [32]	17.5%	10.0%	1971-1997	0.80	Learning by R&D rate fixed at 10% (and assuming 2 year time lag and 3% annual R&D knowledge stock depreciation) to avoid multicolinearity between R&D and cumulative deployment data. R&D data is public spending. Data for all solar PV, not just c-Si.
Kobos et al (2006) [33]	18.4%	14.3%	1975-2000	0.990	Assumes a 3 year time lag between R&D and commercialisation, as well as an annual 10% depreciation of R&D stock. R&D data is public spending. Data for all solar PV, not just c-Si.

Table 1c: Studies analysing multi-factor learning curves with additional factors

Study	Learning-by-doing rate	Other factors influencing PV module prices	Period of observations	R^2	Comments
Isoard and Soria (2001) [34]	9.2%	Constant economies of scale assumed;	1976-1994	0.54	Specification also includes estimation of single factor learning, with learning rate = 8.6% and R squared 0.47.
	27.8%	Variable economies of scale allowed – median value 0.88.	1976-1994	0.78	Economies of scale value of 0.88 implies a doubling of plant size leads to a 10% increase in module price. Not clear if all PV or just c-Si.
Yu et al (2011) [35]	13.5%	Constant economies of scale at 1.066; Silicon price elasticity = 0.285; Silver price elasticity = -0.138.	1976-2006	0.993	This economies of scale factor suggests doubling plant size leads to a 4.2% reduction in module price. Not stated whether for c-Si only.
De la Tour et al (2013) [31]	20.1%	Silicon price elasticity = 0.385	1990-2011	Not stated	Cumulative capacity included with one-year time lag. Scale and R&D omitted as highly correlated to lagged cumulative capacity. Not clear if only c-Si module prices.
Zheng and Kammen (2014) [30]	12.3%	Learning by R&D rate (not explicitly given)	1991-2010	0.882	R&D represented by cumulative patent count. A separate specification uses just industry production scale to explain price, with a factor of 1.24 (which implies a doubling of scale leads to a 12.4% reduction in module price)

A number of observations can be made from these statistical analyses. There are a broad range of learning-by-doing rates, which vary between 9 and 28% depending on the period of analysis, the other factors included in the analysis, and the data sets used for the analysis. The single-factor learning curves all show a learning rate close to 20%, which implies a 20% reduction in c-Si PV module prices for each doubling of module installed capacity. However, two analyses ([28], [29]) suggest that the single factor learning rate has been higher in the period after 1990 when compared to the period before 1990. Zheng and Kammen's (2014) analysis appears to contradict this (with a lower learning rate over the period 1991-2010 compared to the whole period 1976-2010), but this includes the period after 2000 when module prices actually increased as a result of polysilicon supply shortages [30]. As shown in Section 3, many of the major design innovations in c-Si modules had already been made by 1990, which could suggest that, following the emergence of this "dominant design" (as Abernathy, Clarke and Utterback's technology life-cycle model denotes it [36]), cost reduction occurred at a faster rate because a large number of manufacturers began to scale-up and refine production around a known technology (as opposed to experimenting with several alternatives).

Yu et al's (2011) more in-depth analysis of the factors affecting c-Si PV module prices, as shown in Figure 5, highlights the importance of different factors over different periods [35].

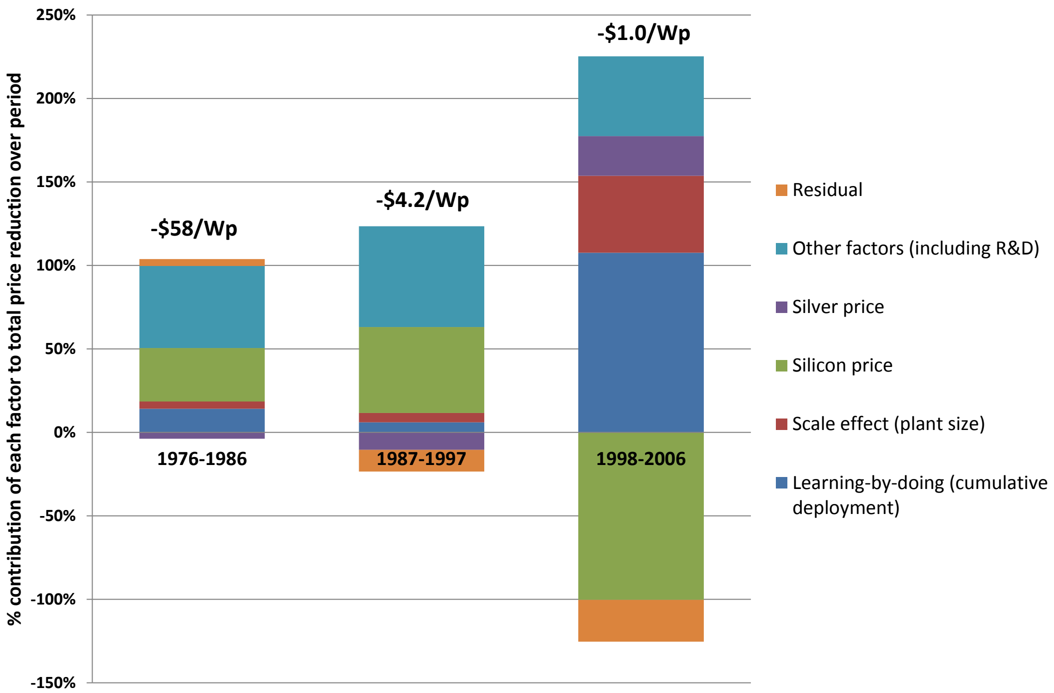

Figure 5: Factors responsible for c-Si solar PV module price reductions [35]

Notes: Absolute module price reduction over period shown in 2006$US; All bars (including positive and negative values) sum to 100%; "Other factors" are those factors not explained *by the model; whereas the residual is the difference between the model and the actual PV module price reductions.*

In the periods 1976-1986 and 1987-1997 the primary drivers of module price reductions were silicon input prices, and “other factors”, which Yu et al (2011) list as labour and capital costs, subsidies, taxes and plant O&M costs, as well as R&D [35]. Although the authors do not mention it in this context, this factor could account for the significant efficiency gains experienced in commercial modules during this period, which may not have been picked up in the learning-by-doing factor. The more recent period of analysis, 1998-2006, shows the majority of price reductions coming from learning-by-doing and scale effects, although with increased silicon prices offsetting much of these reductions, leading to relatively modest absolute price reductions. It is likely that the significant focus on silicon production in programmes such as the US Jet Propulsion Laboratory Flat Plate Array project of 1975-1985 (discussed in detail in Section 4.2) gave rise to the silicon price reductions experienced in the first two periods shown, before supply bottlenecks sharply raised prices in the early 2000s [4].

The period following the mid-2000s, in which PV module prices fell to such an extent that they “caught up” with the previous learning rate, has been examined by Zheng and Kammen (2014), who find that a two-factor model including c-Si PV patent counts and market scale best explains this late 2000s dramatic price reduction [30]. De la Tour et al (2013), by contrast, find that a two-factor specification with cumulative deployment and silicon prices provides the closest fit to prices over the period 1990-2011[31]. These two analyses, identifying different explanatory factors, demonstrate the difficulty in producing a robust, statistically-demonstrated assertion on the ultimate sources of change with regard to module prices. Furthermore, neither of these specifications explicitly invokes the role of massive Chinese module manufacturing expansion since the mid-2000s, which is discussed in further detail in Section 4.2.

Aside from these statistical analyses, an engineering-based analysis by Nemet (2006) attempts to explain c-Si PV module price using a detailed model of module costs accounting for module efficiency, silicon usage, yield losses and plant scale [3]. Of these factors, plant scale and efficiency improvements emerge as the two most important factors in driving down PV module prices in the period 1980-2001, together accounting for about three-quarters of all price reductions (manufacturing = 43%, efficiency = 31%). This does however rely on the assumption that PV plant economies of scale match those from the semiconductor industry, with a doubling of plant size resulting in a 12% reduction in module price – similar to the industry economy of scale found statistically by Zheng and Kammen (2014) for the period 1991-2010 [30], but far greater than the 4% reduction rate found by Yu et al (2011) over the period 1976-2006 [35], and even more divergent from the assertion by Isoard and Soria

(2001) that the PV industry experienced diseconomies of scale in the short run and constant returns to scale in the long run [34]. This could imply that factors other than scale (and not explained by Nemet's analysis) were more significant.

As well as questioning the influence of different explanatory factors over different time periods, it is also worth considering the degree to which the factors identified in the above analyses are interrelated. Peters et al (2012) show that PV R&D (as represented by OECD country patent counts) itself depends on deployment, with national R&D more strongly dependent on PV capacity additions in the same continent than in other continents, implying some form of geographical proximity effect [37]. Huo et al (2011) find that an increase in the size of the PV module market in the USA, Germany and Japan led to innovation (again, represented by patents granted) over the period 1992-2009 [38]. However, their analysis also suggests that PV innovation caused market size increases in Germany and the USA (the "cause" in both cases established by the Granger-causality statistical test). Bettencourt et al (2013) find that PV patent counts are far better explained by a combination of public R&D funding and market size, rather than by total (public and private) R&D funding [39]. They assert that public R&D funding is leveraged by market size, which allows more private research and investments to add to and build upon this public R&D. Hoppmann et al (2013), undertaking in-depth interviews with European, Chinese, Japanese and US firms and experts in the PV industry, argue that over the period 2004-2010, when PV experienced very high growth rates, policy-induced market growth led to an increase in R&D spending in absolute terms, but the intensity of R&D (measured as R&D spend as a share of revenues) fell, as a result of reduced exploration pressure, the need to focus management resources on market expansion, and the increase in supply of manufacturing equipment focused on producing the mature technology. These effects were most clearly shown by firms producing more mature (c-Si) PV modules [40].

Analysis at a national level also suggests a complex interplay between factors. Watanabe et al (2000) relate data on PV module production and prices in Japan to the R&D knowledge stock (as measured by cumulative patents), temporal learning and production scale, over the period 1976-1995 [41]. They find that price depends on production scale as well as knowledge stock. By also demonstrating a statistical relationship between price reductions in one year and PV production in the following year, they assert that there is a feedback loop between PV production, R&D investment, and price reductions.

In summary, the single-factor learning curve analyses over multi-decadal periods of PV evolution provide an apparently compelling relationship between capacity doubling and roughly 20% module price reductions. But this learning rate varies significantly over distinct decadal periods, with the 1980s seeing less dramatic price reductions than the 1990s, and the 2000s seeing a slow-down as silicon prices rose, before once again falling in order to "catch up" with the 20% learning curve. In each period there is evidence that different factors (particularly silicon prices, and factors including R&D) have played a different role, which suggests there is no intrinsic, fundamental causal relationship between deployment and price reductions in the absence of other factors. Furthermore, the factors affecting module prices are themselves interlinked, which suggests that the process of innovation and cost reduction occurring in the PV module market is complex. This makes derivation of policy lessons difficult as it does not indicate a clear strategy of how much R&D to invest in, as opposed to deployment support.

Section 4.2 takes a more qualitative look at the major policies and market conditions during the distinct periods of c-Si PV module design and manufacturing improvements, with a view to identifying whether particular advances can be related to particular drivers.

4.2 Identification of specific policies which have driven innovation and cost reduction

Considering the major innovations in crystalline silicon PV in particular, a number of specific policies (shown in Figure 6) appear to have been instrumental in bringing these forward.

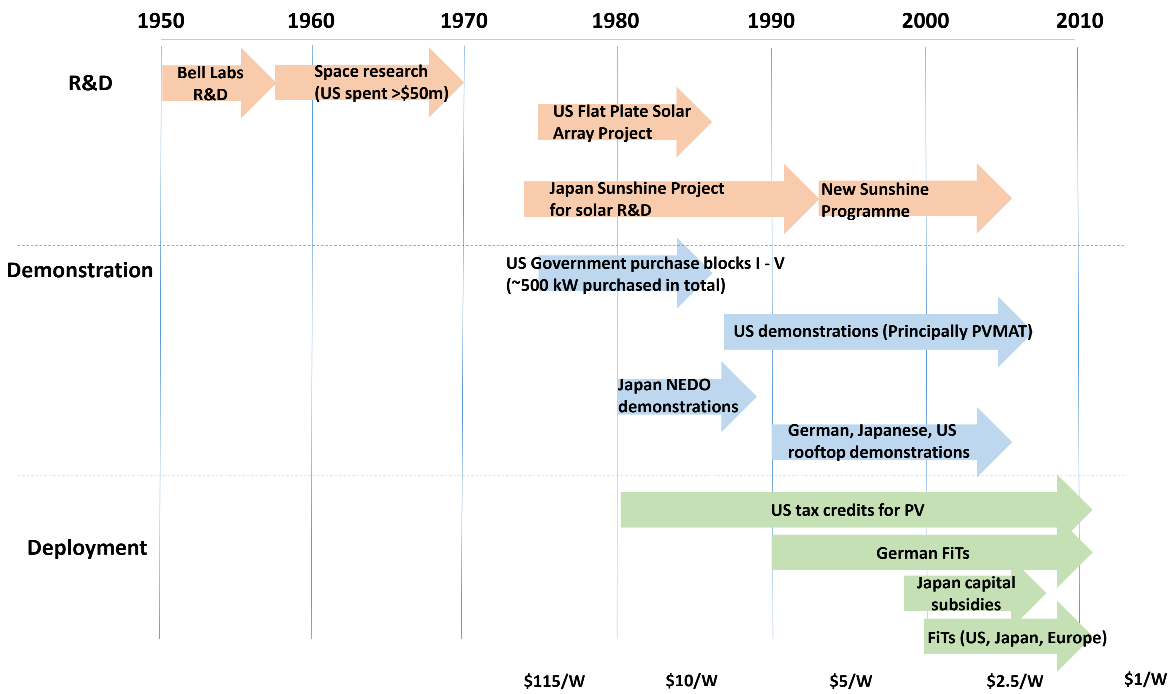

Figure 6: Major policy activity in c-Si PV module development

The significant public investment that went into the US space solar cell research programme in the 1950s and 1960s (totalling $50 million [10]) resulted in improvements in silicon crystal quality, use of solid state diffusion to dope silicon, introduction of metallic grid top electrodes, and silicon oxide antireflection coatings [17].

The US Jet Propulsion Laboratory's Flat-Plate Solar Array project, spanning the period 1975-1985, resulted in a number of innovations to develop these space cell designs for terrestrial usage. The US Government's block purchases of modules which accompanied the project were associated with steady increases in cell efficiency (from around 5% in the first purchase block in 1975-76, to about 10% by 1985). Successive blocks also helped to field test and establish different module encapsulants, with silicone rubber giving way to polyvinyl butyral (PVB) and eventually ethylene vinyl acetate (EVA) as a transparent laminate for bonding the cells to glass on the front and fluoropolymers (such as Mylar and Tedlar) on the back. More densely packed "quasi-square" wafers, multicrystalline square wafers and screen printing also became established during this programme [17], [20]. Concurrent with the Flate-Plate Solar Array project was the "burst of laboratory activity" [17] which brought about significant improvements in cell efficiency through better antireflection coatings (based on titanium oxide rather than silicon oxide), aluminium backings to reduce recombination, and the emergence of etching of silicon wafer surfaces to expose pyramidal crystal surfaces which better absorbed incident light.

As O'Conner et al (2010) assert, "Modules improved so drastically from Block I (1976) to Block V (1984) that the modules evaluated in Block V were not significantly different from those used today." [21]. By the middle of the 1980s commercial cells were being produced with efficiencies of greater than 10%, with the laboratory knowledge to achieve cells with greater than 20%, using passivating techniques which would eventually seep through to commercial cell production and lead to c-Si module efficiencies today which range from 15-20% [8].

During the 1980s itself an increased focus on demonstration projects allowed the field-testing of a number of PV design aspects. In the USA, PVUSA was launched in 1986 as a joint programme between the Department of Energy and numerous utilities, to demonstrate utility-scale PV. PVMAT began in 1990, with the aim of reducing costs, PV Bonus in the 1990s with the aim of developing building applications, and TEAMUP in 1994, to provide energy service provider applications. In Japan a number of demonstration programmes aimed at testing grid connection and PV system monitoring were enacted in the 1980s and early 1990s, including PV for Public Facilities in 1992, as well as the PV systems (roof monitor) programme in 1994, which later became the Residential PV system demonstration programme. The first demonstration programme in Germany was the Rational Use of Energy and the Use of Renewable Energy Sources (REN) in 1988, to support R&D and demonstration across a range of technologies. During the 1980s and 1990s German municipalities and utilities installed several grid-connected systems, in which a large number of different types of module were evaluated [42].

The mid-late 1990s heralded the period of deployment support policies. In 1997 in the USA the Million Solar Roofs programme was launched (to be achieved by 2010). At the same time, Federal programmes such as California's PV Pioneer programme were introduced, to trial 4kW rooftop systems in selected homes. In 1998 net metering laws were introduced in the USA, which stimulated significant market growth. In Germany, the initial FiTs offered (in the early 1990s) at 90% of retail electricity rates were not successful in stimulating the market, but the much more generous rates in 1999, combined with the 100,000 roofs programme, did stimulate rapid growth in the market [42]. Japan's 1997 PV residential system dissemination programme began with a 50% subsidy for residential rooftop systems, with the subsidy rate declining as system prices fell [43]. Several other deployment support policies have followed across the world, including notably generous tariffs (causing a boom and bust, although with a recent market stabilisation) in Spain [44].

Any discussion of PV module price developments over recent years should of course also include the role of Chinese manufacturers. Goodrich et al (2013) assert that the considerable cost difference between Chinese and US-produced modules (analysing data for the first half of 2012) is primarily the result of cheaper inputs due to scale, material discounts, and equipment discounts, all resulting from scale-based advantages of larger manufacturing plants, with typical US plants at 500MW per year, compared to plants approaching 2GW per year in China [5]. These scale-based advantages in total provide a \$0.22/Wp advantage in Chinese PV module costs (at just under \$0.75/Wp, compared to just under \$1/Wp in the USA) with the remaining discount the result of lower labour and financing costs. The authors posit that the USA could achieve similar scale-based discounts to achieve cost competitiveness with China in the long run, assuming that similar plant-based production scale can be achieved. This scale effect approximates to a 9% reduction in module cost for a doubling of plant size – an interesting comparator to the range of economy of scale estimates discussed in Section 4.1 (which imply cost reduction factors from plant size doubling ranging from a long-term value of 0% to 12%).

Considering all of these policies together, as well as the major innovations discussed in Section 3, Figure 7 provides a high-level description of the progress made in c-Si PV module manufacture over the past 5 decades, with a view to identifying the major drivers of cost reductions.

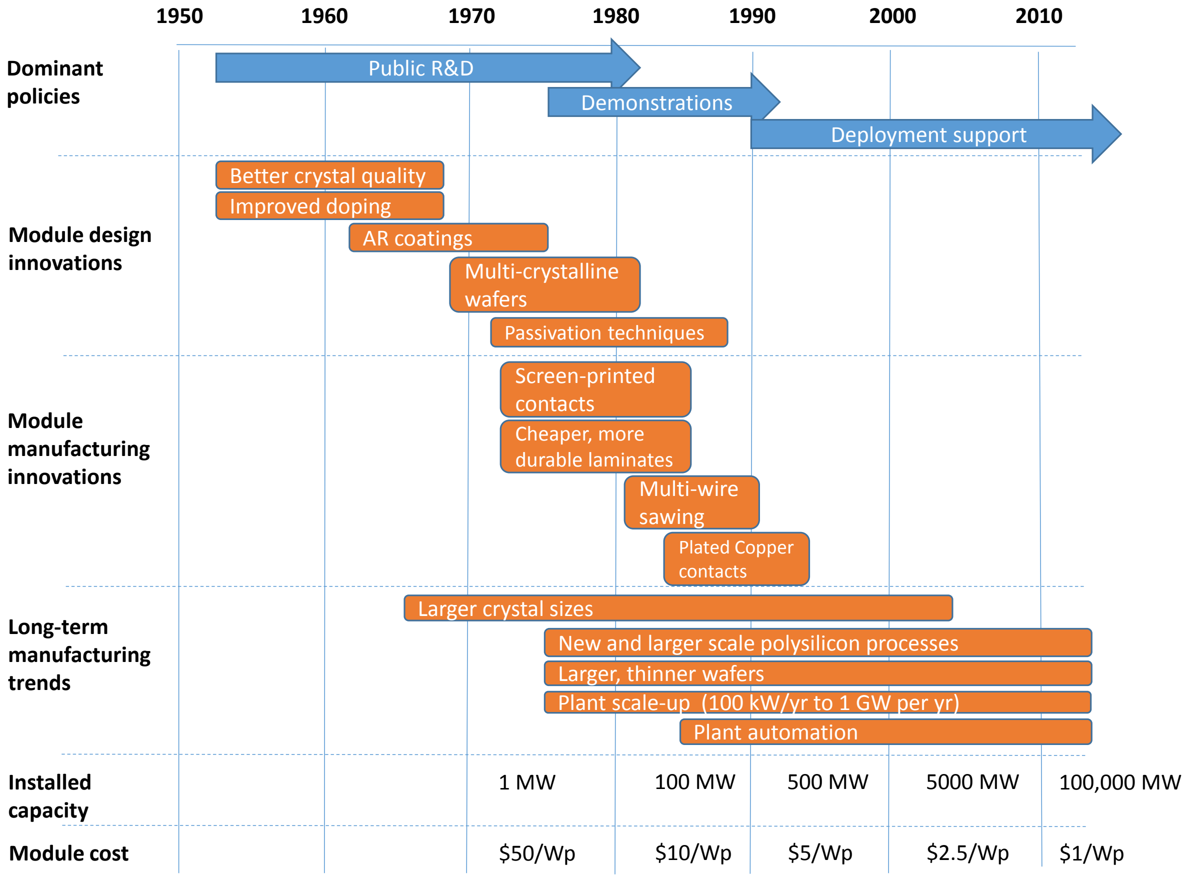

Figure 7: Major innovations and policy environments in c-Si PV module manufacture, 1950-2010

Notes: Installed capacity is global, approximated using data from [4] *to 2005 and various industry reports for current figure (~100 GW). Module production cost data is for US-produced modules, in $US2008 as derived from* [21] *for the period 1975-2005, and* [5] *for current cost.*

The figure could be simply summarised by describing how early public policy R&D and demonstration activity helped to introduce critical design innovations, leading to commercially viable module designs which were then produced at ever larger scale and ever lower cost, in large part driven by deployment support policies. In reality the picture is more complex than this, with significant R&D efforts in c-Si modules continuing to the present day (see for example [30] and continuing R&D activity around a number of alternative technologies aimed at surpassing c-Si modules in cost terms (as described in Kazmerski, 2006 [45]). Nevertheless, this broad mapping of policy environments to particular advances in c-Si PV module development provides an interesting guide to the types of policies that have been used to drive forward this technology over the past five decades or so. It provides empirical evidence that the timing and phasing of policies is likely to be important in driving down technology costs at different stages of technology maturity.

5 Discussion

Crystalline silicon PV modules have experienced significant cost-reductions since the 5% efficiency breakthrough in the mid-1950s. A technology costing over \$100/Wp in the early to mid-1970s has fallen in cost by two orders of magnitude to reach today's sub-\$1/Wp level. Many statistical analyses have demonstrated a close fit of module price to cumulative deployment, with an approximate 20% price reduction in modules for each doubling of installed module capacity (measured in Wp). It is tempting to interpret the relative consistency of the estimated learning curves as evidence for a stable, almost intrinsic relationship between module deployment and price reductions. This might indicate that further price reductions could follow from continued deployment, which in turn supports policies to further expand demand at a time when PV is still in many regions more expensive than higher carbon alternative technologies. However, there is a well-established critique of the use of such single factor learning curves in determining on-going relationships between technology costs and technology deployment levels ([27], [3], [46], [47], [48], [49], [50]). Criticisms include the differing relationship between price and underlying technology cost depending on market dynamics, the possible existence of floors below which technologies' costs cannot fall, the question over causality between deployment and technology price or cost, the importance of other factors such as R&D, scale economies and input prices in driving technology cost developments, and the difficulty of separating exogenous technical change from that induced by deployment or technology-specific R&D.

Some of these shortcomings have been demonstrated through comparison of the statistical studies presented in this paper, with different periods exhibiting different learning rates, different factors (including silicon prices, scale effects and R&D) explaining price reductions over different periods, and large variations in the impact of different explanatory factors on price reductions depending on the other factors considered. This variety of findings does not offer any simple policy prescriptions in terms of setting out whether further price reductions should be achieved at least-cost through continued or even increased deployment policies, increased public funding of innovation activities, or other public activities such as demonstration programmes for new designs and manufacturing processes.

It is therefore important to investigate what specific innovations and improvements in module design and manufacturing process have led to particular cost reductions, and the extent to which these advances have been driven or supported by policies. For c-Si PV modules, there were specific periods of module design innovation, particularly in the mid-1970s to mid-1980s, which established the essential elements of today's commercially-deployed PV modules. What followed was a period of PV system monitoring, demonstration and eventually market expansion, with the refined PV modules being produced in ever-larger scale factories, and with manufacturers achieving significant reductions in key material inputs (such as polysilicon), incremental improvements in efficiency and (as exemplified by Chinese firms' entry into the PV module production business) massive scale of production to achieve cost reductions which have confounded most expectations.

Technology life-cycle analysis [36] suggests that many competitors try to introduce a variety of designs of a new technology in an initial "fluid" phase of invention and innovation, before a "dominant design" takes hold, heralding a "transitional" phase where innovation shifts to manufacturing and learning by doing in the use and refinement of the technology. It appears that c-Si PV modules with the design features exhibited in the mid-1980s (including antireflection coatings and etched wafer surfaces to aid light absorption, wafer surface passivation to prevent electron/hole recombination, glass and fluoropolymer lamination to achieve durability at low cost) emerged as a dominant product design, with a further ten-fold reduction in production cost over the next 27 years (1985-2012) following from manufacturing scale-up, incremental design improvements (such as even greater efficiencies through improved passivation and metal contact designs) and cost reductions in key inputs (especially polysilicon).

Detailed roadmaps (for example Goodrich et al, 2013[51]; ITRPV, 2014 [52]) now exist for how c-Si PV modules can begin to approach the $0.5/Wp sustainable cost production figure which could make them truly competitive even without subsidy. These innovations include cheaper polysilicon production using an increased share of Fluidised Bed Reactor-produced silicon, manufacture of higher quality wafers, replacement of silicon carbide cutting fluid and steel wires by longer lifetime, less contaminating diamond-coated steel wires for sawing wafers, producing even thinner wafers, replacement of silver electrodes with cheaper copper, increases in efficiency through use of thinner contacts and better passivation, and achieving scale and bulk discounts in manufacturing equipment and processes.

A key question is what policy support, if any, will drive this further cost reduction. Zheng and Kammen (2014) highlight the importance of patenting in explaining recent dramatic reductions in c-Si PV modules prices [30], but as Breyer et al (2010) show, most of the R&D in PV now comes from private, rather than public, sources [24]. Whilst analyses such as Bettencourt et al (2013) highlight the importance of both public R&D and market size in PV module price reductions [39], it appears that a healthy PV market is necessary to ensure that manufacturers continue to search for ways to cost-effectively manufacture at scale the known cell designs demonstrated in the laboratory from the mid -1980s onwards, when cell efficiencies of 25% were exceeded (in monocrystalline Si cells). Indeed this provides an analogue to the silicon chip market, whose "Moore's Law" of a regular doubling of memory capacity or computational power has been achieved through continuing investment in chip improvements by manufacturers, as a result of a growing market and growing revenue projections [53].

As well as helping to consider how to further advance innovation in c-Si PV itself, the experience of c-Si PV may prove instructive for emerging PV technologies. The dramatic reductions in c-Si PV module cost which resulted from the period of publicly-funded R&D and demonstration during the mid-1970s to mid-1980s period presents the possibility that a similar push for next-generation technologies might result in the emergence of even lower-cost PV modules. A number of previous initiatives aimed at developing inorganic thin-film technologies such as amorphous silicon (a-Si) and cadmium telluride (CdTe) have already tried and failed to achieve the goal of toppling c-Si PV (see for example Braun and Skinner's (2007) account of BP Solar's attempt to commercialise these technologies [54]). Nevertheless, analysis suggests that "printable" PV (such as organic PV, perovskites, and dye sensitised cells) presents the possibility of very low-cost PV modules [55], [56], [57], should numerous shortcomings around stability, efficiency and in some cases material toxicity be overcome. It may be that these challenges are best addressed through ambitious programmes such as the US Flat-Plate Solar Array programme, which included targeted initiatives to overcome multiple shortcomings in c-Si module design. Such programmes are likely to require a strong "interface" function between module designers and users to ensure that R&D and module field-testing and deployment activities interact with each-other [58].

Finally, the c-Si PV development story presents an important challenge for other forms of low-carbon energy, particularly those which are less mature and where analysis suggests that R&D has a very important role to play in cost reductions [59]. Such a shift has arguably happened for other low-carbon technologies as well, such as onshore wind power during the California "wind rush" of the early 1980s, when US patenting in several competing wind turbine designs died down as deployment support policies incentivised a significant acceleration in the installation of a particular design (the vertical, three-bladed, horizontal axis, upwind turbine) which proved optimal in terms of performance and cost [60]. The challenge for policy makers will be to understand when a dominant design has emerged, such that focus can shift more firmly towards market creation policies in order to achieve manufacturing scale-up and innovation to produce this "good-enough" version of the technology.

6 Conclusions

This paper has reviewed the most important developments in c-Si PV module design and manufacture since this technology was first commercially introduced in the 1950s, as well as the major policies aimed at driving forward innovations and cost reductions. By mapping periods of policy activity to innovations and cost reductions, as well as reviewing the numerous quantitative analyses linking module prices to a range of factors, the paper offers a perspective on how and why c-Si PV module prices have fallen over time.

Following c-Si modules' early period of space cell development, the mid-1970s saw the beginning of a dramatic period of innovation in module design and manufacture, in large part driven by the US Jet Propulsion Laboratory's Flat-Plate Solar Array project, which achieved a more than five-fold reduction in module production costs and which helped establish module designs not significantly different to those produced today. Following the emergence of these module designs, increased demonstration and deployment support activities helped to establish larger scale, more automated, lower cost manufacturing, helping to achieve the current sub-$1/Wp production cost which has made many reconsider the economics of PV.

This picture of PV development contrasts with the relatively straightforward learning curve analysis which (in its single-factor form) has equated a reasonably constant learning rate with each doubling of cumulative installed capacity. It indicates that at relatively early stages of technology development, intense and coordinated activity is required to achieve market-ready designs. Subsequent deployment support is then necessary to stimulate further scale-up and innovation in manufacturing, which could achieve equally if not more dramatic cost reductions in the technology. The challenge remains to identify when such a dominant design has emerged, in order that activity can shift from early design improvement to manufacturing cost reductions.

Acknowledgements

This paper benefited greatly from detailed conversations with Nigel Mason of PV Consulting Ltd and formerly of BP Solar, as well as input from Martin Green of UNSW, Jenny Nelson of Imperial College London, and Chiara Candelise of Imperial College London and FEEM. Opinions stated and any errors remain those of the authors alone.

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