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Review

Business, market and intellectual property analysis of polymer solar cells

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ABSTRACT

The business potential of polymer solar cells is reviewed and the market opportunities analyzed on the basis of the currently reported and projected performance and manufacturing cost of polymer solar cells. Possible new market areas are identified and described. An overview of the present patent and intellectual property situation is also given and a patent map of polymer solar cells is drawn in a European context. It is found that the business potential of polymer solar cells is large when taking the projections for future performance into account while the currently available performance and manufacturing cost leaves little room for competition on the thin film photovoltaic market. However, polymer solar cells do enable the competitive manufacture of low cost niche products and is viewed as financially viable in its currently available form in a large volume approximation. Finally, it is found that the polymer solar cell technology is very poorly protected in Europe with the central patents being valid in only France, Germany, the Netherlands and the United Kingdom. Several countries with a large potential for PV such as Portugal and Greece are completely open and have apparently no relevant patents. This is viewed as a great advantage for the possible commercialization of polymer solar cells in a European setting as the competition for the market will be based on the manufacturing performance rather than domination by a few patent stakeholders.

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1. Introduction

1.1. Polymer solar cells

Solar cells employing organic matter as the active layer converting a photon flow into an electron flow have been known and reported for quite some time [1–7], while the term polymer (or plastic) solar cell is relatively recent with a history that essentially span the first decade of the new millennia [8]. During this decade the field has seen a near exponential growth in the number of published scientific articles and citations with an annual publication and citation rate in year 2009 of, respectively, 900 and 22,000 (when searching the topic "polymer solar cells" in ISI web of science). Several other search terms can be employed and they all reflect the same pattern of steeply increasing annual rates. This can be attributed to two major factors: the larger availability of research funds due to increasing international focus on energy, environment and climate change and the fact that polymer solar cells are moving rapidly towards commercialization. It also shows that the field by no means has reached maturity or a stable commercial phase as the latter is normally preceded by a stagnation in the number of published scientific articles. The field has been reviewed in excess of one hundred times when viewed broadly with a representative set of reviews [9–40], several special issues dedicated to polymer solar cells [41–48], numerous book chapters and several textbooks and monographs have been published [49–53]. The reviews span from broad overviews of the field with more recent specific reviews dealing with subsets of the published overall data e.g. tandem cells [34,35], stability [26], processing [32,33], low band gap materials [13,21,28], hybrid solar cells [20,29,31,39] and novel concepts [40]. All this is indicative of a large potential and the massive body of information available and research activity warrant further analysis of the polymer solar cell as a technology in the context of business, market and intellectual property.

1.2. Companies and markets

In line with the observations of the scientific activity described above, recent years have also seen several companies with polymer solar cells being central to their business or intended business profile. Since there is no established market or documented revenue based on polymer solar cells the companies are all funded by venture capital or by larger companies that view the polymer solar cell as a business segment that is either in their current portfolio under a different name or one that very easily could be. In terms of the types of companies they range from large venture capital funded companies with the aim of developing and manufacturing the technology through companies that wish to develop plug-in technology for the manufacturing companies to materials suppliers of specific subcomponents and small enabling companies that address niche markets in the periphery of the polymer solar cell field. In terms of marketing and designing a business strategy it should be emphasized that the polymer solar cell technology is viewed as being easy to copy and this poses some challenges for someone wishing to enter the field with a commercial motivation. The aim of the large manufacturing companies is to make the polymer solar cell available as a product and they depend heavily on a large and complete patent portfolio that gives them freedom to manufacture a given version of the polymer solar cell technology without influence or dominance by others. The manufacturing company is the largest and most complex structure that necessarily will involve licensing and acquisition of patents that were not developed by the company itself and will involve some level of dominance to avoid competition from other companies that may have copied the technology. A prototypical example of such a company is Konarka [54] that has pioneered the commercialization of polymer solar cells at nearly all levels: they were first movers, they have presented the largest total investment, they possibly have the largest patent portfolio, they have presented an unflinching and constant loyalty to the field, they have been persistently marketing the technology and have fenced off strong criticism and proved critics wrong in some cases. Konarka made polymer solar cell modules commercially available in 2009. When a product is commercially available may be debatable. Commercially available, in this context, does not include the general public, but primarily designers, product developers and partners of Konarka that buy and apply the solar cells. Konarkas website offer detail on various product types and sales contact. There is currently no information available on the volume of modules sold. The companies that wish to provide plug-in technology does not rely on a large and complex patent portfolio but instead relies on primary patents such as composition of matter patents and will have to invest heavily in the development of their technology such that it provides the user with a competitive edge. An excellent example of such a company is Plextronics [55] that target the ink technology for polymer solar cells. They were relatively early and have several central composition of matter patents and commercially available ink technology. The large existing companies that have entered the polymer solar cell market segment have generally done so with specific components of the polymer solar cell such as substrates material, barrier foil or materials for one of the layers in the solar cell. Typically the material they provide is already a central part of their general portfolio and in some cases patents are not critical at all. Examples include Dupont Teijin films, Amcor Flexibles, Agfa and HC Starck. The small enabling companies are typically providing the field with chemicals, precursors, substrates and other peripheral components. Typically their customers are scientific groups that need to purchase substrates, polymers and materials for research and development. The small enabler has a relatively limited business which is highly dependent on public and governmental funding of their clients. Examples are Lumtec [56] and Osilla [57].

1.3. The freedom to operate

Central to all business endeavors and possible markets is the patent landscape and also the patent history. It must be remembered that an issued patent is only valid in specified countries and maintenance fees must be paid. As a document it enables the patent holder to prevent others from performing the inventions defined in the patent claims and exploring them commercially. Phrased crudely, it gives the patent holder the possibility to call someone that they suspect are violating their patent rights to a court of law based on physical evidence of infringement. The purpose of calling someone to a court of law upon suspicion of them violating ones patent rights is to stop the commercial activity on the other part, to settle a license agreement or to claim loss of revenue or accountability as a result of the other parts activities. For this reason the patent landscape and the freedom to operate is very important when wishing to explore an area such as polymer solar cells commercially. The importance transcends several levels including securing revenue, market shares, venture capital and start-up company foundation.

1.4. Motivation

In this work we will describe and review the business, market and patent situation for polymer solar cells and will take into consideration the currently available data for the state-of-the-art and the projected performance on a short 3–5 year horizon. We demonstrate how a patent analysis can be used as a tool to predict where business opportunities may be large in spite of dominant stakeholders in some regions and further demonstrate how this can be used to establish where new markets and market opportunities exist.

2. Business opportunities for polymer solar cells

As polymer solar cells are able to perform the same action as any other photovoltaic technology (conversion of light into an electrical current) it is natural to assume that they can replace existing photovoltaic technologies. Had this been the case the business opportunities would be enormous and easily identifiable as the market, typical applications and consumers would be known factors. This vision is also what has driven research and investment into polymer solar cells and with proper development this situation may become reality as foreseen by many. The current state-of-the-art for polymer solar cells is however falling somewhat short on several fronts and this naturally affects the business opportunities for the currently available version of the polymer solar cell. There are two possible courses of action that one can take in such a situation and one is to wait while calling for further development and the other is the commercial exploitation of the currently available technology with the aim of being ready to explore newly accessible markets as the technology matures and improves. We will assume the latter approach and the question in this case is what the current business opportunities are and how the pursuit should be positioned to best match the expected future developments.

2.1. Current boundary conditions

The polymer solar cell is most similar to current thin film photovoltaic solar cells such as amorphous silicon, CdTe and CIGS. The performance of these photovoltaic technologies ranges from 5% to 20%. Best confirmed amorphous silicon efficiency is $9.5\pm0.3\%$ (this does not include tandem cells, that typically provide higher efficiencies), but standard available amorphous silicon solar cells in the market average from 5% to 8% at a cost of around 1.2–2 US$ W_p^{-1}. Best confirmed CdTe efficiency is $16.7\pm0.5\%$. Available CdTe cells average from 9–11% at a cost in the range of 2.3–2.5 $ W_p^{-1} with cost potential estimates around or below the 1 $ W_p^{-1}. First Solar claim to be reaching 0.7 $ W_p^{-1} by 2012 and competitive 0.52–0.62 $ W_p^{-1} by 2014. Best confirmed CIGS efficiency is $19.4\pm0.6\%$, but commercially the technology provides around 14–16% on the module level, but closer to 12% in large scale production. Cost is in the range of 2 $ W_p^{-1} with a cost potential of 1–1.3 $ W_p^{-1} [58]. Best confirmed DSSC efficiency is 10.5%. The average PCE and cost cannot be established for the available DSSCs as the technology is barely commercial. G24I apparently shipped the first modules for bag integration in October 2009. A company such as Nanosolar that employ printable CIGS ink is capable of large scale optimized production and has recently established a new 640 MW plant in Germany to support the high output and increasing panel sales to the utility industry and the claimed 4 billion $ order book.

The cost of these technologies are well proven for amorphous silicon while both CIGS and CdTe are reasonably new to the market but have been demonstrated on pilot scale to potentially yield significantly below 1 € W_p^{-1}. The polymer solar cell has to compete with these technologies in terms of efficiency and cost. Commercially available polymer solar cells only originate from Konarka Technologies and while laboratory reports, including Solarmer [59] and Heliatek [60], hovers in the area of 5–8% power conversion efficiency, the estimated power conversion efficiency on a standard KT-20 panel from Konarka is maximally 3% with a module energy cost in the vicinity of 11–12 US$ W_p^{-1}. Such numbers makes it brutally hard to compete in the current technology field, not even bringing lifetime into the equation. Status quo is that polymer solar cells are not competitive in the current thin film solar cell market, a market that is flooding with competitors ($\sim$100 thin film related solar cell companies in 2009), all fighting for a two digit market share.

In terms of competition it is evident that funding for solar research not only reaches polymer solar cells, but to a very large extent reach all types of solar energy, subsidizing the continued development of more mature and thus "closer to or in market" solar cell technologies. By taking a single sided industry perspective that not openly takes existing and competing technologies into account there is a risk of not only greatly misjudging market and potential of a given technology but also the misleading of potential stakeholders. This pitfall is a natural consequence of the need to convince the external world about the superb quality of the polymer solar cell technology and this is most easily done if comparison to the general status quo is neglected or entirely avoided. The industry thus risk establishing an inflated image of the technology that in the public sphere sooner or later will be adjusted to the correct size by liquidation, technological setback or change of research focus and business area.

As a minimum polymer solar cells must improve significantly to compete in the solar module market together with other types of thin film. This is a significant challenge and bears with it a significant economic burden which can only be fuelled by venture capital and public funding—unless the industry is capable of utilizing submarket performing solar cells in previous uncharted market segments to create the necessary revenue.

2.2. Current small scale production cost

The potential for low cost polymer solar cells has been claimed to be as low as <1 € W_p^{-1} [36]. Many of the arguments in favour of this view are not founded in real data and are often proposed by the exponents of the technology. It is likely that polymer solar cells can offer very cheap electricity costs but it is almost certainly only realized once a very large scale manufacturing chain is operable. All aspects of the preparation from raw materials and components to manufacture have to be honed for the lowest achievable cost before a decrease below <1 € W_p^{-1} is possible. It is also problematic to compare the unit cost of electricity produced by a technology that is not stable in the long term perspective and from this point of view life cycle analysis is extremely important [61,62]. The correct unit cost of electricity cost used for comparing PV technologies is the levelized cost of electricity (LCOE) as this takes the operational lifetime of the device into account. There have been a few reports detailing the electricity cost based on available and projected data [63,64] and a few reports that rigidly details the actual manufacturing cost for polymer solar cells on the scale of the experiments including the real cost of materials and manufacturing labour thus enabling a better view of the capacity of the polymer solar cell technology in terms of cost [65,66]. The first example detailed the manufacture of a circular polymer solar cell module prepared entirely by screen printing of all the layers using existing industrial equipment where the capital investment in equipment is zero [65]. The purpose of the polymer solar cell was to charge a battery for a small FM radio. A second example detailed the manufacture of a reading lamp for the lighting Africa initiative [66] and was intended to provide inhabitants in developing countries a safe and sustainable source of light and replace kerosene lamps. Both demonstrations were fully public and enabled the establishment of the cost structure and analysis of how well the technology performs [65,66,68]. The intention was specifically to identify where investments in efforts to reduce the cost are best placed. In the case of the lamp made for the lighting Africa initiative that was based on the fully roll-to-roll manufacturable ProcessOne technology [67,68] the practical electricity cost initially reached was 35 € W_p^{-1}. This indium-tin-oxide based technology was further reduced in cost through moderate upscaling and better use of materials and process control as shown in the learning curve (Fig. 1). The lowest electricity cost reached with ProcessOne when using P3HT:PCBM and indium-tin-oxide as the bottom electrode is on scale of these experiments 8.1 € W_p^{-1}. It is based on this quite detailed data possible to estimate the lowest possible production of the ProcessOne technology to be ca. 5 € W_p^{-1}.

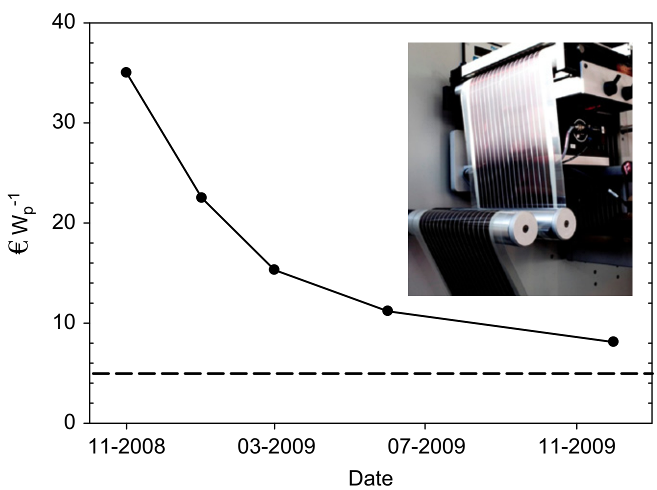

Fig. 1. Learning curve for the manufacturing cost in € W_p^{-1} for full roll-to-roll manufacture of polymer solar cells based on ProcessOne [67]. The lowest achievable cost with P3HT:PCBM and ITO using ProcessOne is estimated to be around 5 € W_p^{-1} shown as a broken line. A photograph during manufacture of ProcessOne [67] is shown to the right.

It should be noted that the investment in man power and processing time already contribute very little (< 20%) to the total cost which is essentially limited to the cost of materials. In order to reduce cost further one has to eliminate the most expensive components such as indium-tin-oxide. The PEDOT:PSS could perhaps be reduced in cost by less usage and optimization of the formulation. PEDOT:PSS is already manufactured on a large industrial scale. The cost for the active materials can possibly be reduced further through significant upscaling on the part of the supplier as demand increases. The processing speed may contribute to cost reduction if increased significantly by a factor of 10 or more. Finally, if one could print electrodes directly on the barrier material it is possible to eliminate one adhesive layer.

The actual costs for the lowest achieved cost of the ProcessOne technology is shown in Table 1. Other factors that can significantly lead to cost reduction are new high performing active materials that could enter Table 1 and give significantly lower cost in € W_p^{-1} provided that they have a similar or lower cost than the P3HT:PCBM composite. It should also be noted that the manufacturing cost shown in Table 1 excludes the cost associated with characterization of the final module. The manufacturing time for a module as shown in Table 1 is in the range of 90 s. This manufacturing time is the total manufacturing

Table 1
The cost structure in terms of materials usage and processing time for the manufacturing of polymer solar cell modules based on ProcessOne [67] after optimization. The calculations represent the actual cost for the manufacture of one 16 × 13 mm stripe module with an active area of 360 cm^2 and include associated materials losses. Power outputs for these modules are up to 660 mW (AM1.5G, 1000 W m^{-2}). The module is shown to the right of the table.

Material	*Materials cost (€)*	*Processing cost (€)*	*Total (€)*
PET-ITO	2.6077	0.21111	2.8188
ZnO	0.0582	0.16667	0.2249
P3HT–PCBM	0.4492	0.16667	0.6159
PEDOT:PSS (EL-P 5010)	0.2311	0.16667	0.3978
Silver (PV410)	0.4120	0.16667	0.5787
Barrier	0.4575	0.03173	0.4892
Pressure sensitive adhesive	0.1918	0.03173	0.2236
Total	**4.4078**	**0.9412**	**5.3491**

time starting from a polyethyleneterphthalate substrate fully covered with indium-tin-oxide. With the current operational lifetime for polymer solar cells the LCOE is not competitive as detailed above whereas the cost of electricity for freshly prepared cells is likely to be competitive with inorganic solar cells even on a small scale. This shows that low cost manufacture of polymer solar cells with a competitive performance is possible while work on improving the operational stability must be carried out to decrease the LCOE. For the module described in Table 1 the operational lifetime is highly temperature dependent with a typical T80 in the range of 500–1000 h under illumination (280 W m^{-2}, AM1.5G) at a temperature of $<45\,^{\circ}$C (T80 is the time it takes for the device to reach 80% of the maximum performance). Finally, it should be noted that throughout this review € W_p^{-1} is being used when comparing polymer solar cells with other types of solar cells. This is the simplest comparison, but may be challenged through the number of simplified assumptions that this includes. Shorter lifetimes, unknown difficulties with recycling and disposal, toxic emission during manufacture, etc. may all shift the actual cost of electricity towards higher values.

2.3. Current requirements for investment

The capital investment in equipment required to enable manufacture on the scale described here is outlined in Table 2. Generally the capital investment in manufacturing equipment for polymer solar cells is viewed as low and range as low as zero in cases where existing equipment can be used.

This was the case for the solar hat [65] that demonstrated manufacture using existing industrial equipment and infrastructure albeit with low performance. The machine cost and investment in infrastructure (in a Danish setting) are shown. The machine park described enables full R2R manufacture and characterization of polymer solar cell modules based on the ProcessOne technology [67,68]. The realistic production capacity on the machinery described with the processing speeds achieved is optimistically about 100 m day^{-1} (assuming one 8 h shift). The corresponding annual production capacity is around 20,000 m equivalent to 80,000 modules described in Table 2 or 50 kW_p assuming a technical yield of 95%. With the ~530 k€ investment in equipment shown in Table 2 it is unlikely that this is financially viable at an electricity cost of 8.1 € W_p^{-1} and it is almost certain that the polymer solar cell product would be offered at significantly higher cost to enable a stable business. This of course assumes that customers are available in a competitive and relatively small thin film PV market.

Table 2
Capital investment in equipment and infrastructure required to manufacture complete polymer solar cell modules based on ProcessOne [67] using a web width of 305 mm.

Equipment	*Machine cost (€)*	*Infrastructure (€)*	*Total (€)*
R2R Screen printer (Alraun)[a]	126,400	35,800	162,200
R2R Slot-die Coater (SCM)[b]	152,000	18,500	170,500
R2R Etching machine (Klemm)	42,500	9500	52,000
R2R Laminator (GM)	35,800	0	35,800
R2R Characterizer (Risø DTU)[c]	72,850	0	72,850
R2R Sheeter (GM)	28,900	0	28,900
Contactor (Prym)	8000	0	8000
Total	**466,450**	**63,800**	**530,250**

[a] Includes both hot air dryer and UV-curing oven.
[b] Includes edge guiding system, humidity sensors and corona treater.
[c] Includes solar simulator (KHS1200), source meter (Keithley 2400), power meter, control electronics and pneumatic control.

3. Market analysis and competition

3.1. The thin film market, leading polymer solar cells

Silicon photovoltaics have been a market for 35 years making solar electricity well recognized globally. The development of new and competitive – low cost, light weight – solar cell types has been spurred by a cocktail of growing market demand with an exponential market potential. The pursuit of cheaper solar cells is a result of focus on environment, climate, sustainable energy, political support through industry incentives and research grants. This has lead to an increasing interest from investors and venture capitalists. In this context the macroeconomic perspective becomes central. The market for thin film solar cells is driven by the need for cheaper solar energy and is the focus of large scale utility solar projects. Until a few years ago thin film solar cells were seen as immature but with a promising potential. Recent developments, solar startups and investments in thin film are now powering up capacity and installed capacity. The cost is the main driver and the closer costs gets to grid parity the more interesting thin film solar cell technologies become. This development may very well be the evolution that changes solar electric energy from a niche energy source to an energy source with a presence in total global electrical energy production. Thin film power conversion efficiencies have gone from low 1 digit to low 2 digit power conversion efficiencies and have through this rise been applied in various market segments. Segments like consumer electronics, remote off-grid power, military and emergency, residential building applications, commercial building applications and larger utility scale projects have been explored. These business areas have become the focus of thin film companies and in many ways they signal the ascent from low power conversion efficiency small area applications to higher power conversion efficiency and large area applications.

The trend in the CdTe, CIGS, a-Si thin film manufacturer segment indicate a surge for up-scaled manufacturing capacity in the pursuit of cost optimization. When added to the increase in efficiency, demand and the number of companies active in thin film photovoltaics it is not solar cells for calculators and small scale battery chargers that attract attention. Large scale thin film manufacturing equals large scale industrial and residential building installation and large scale utility projects and a maturing technology.

The thin film market size has gone from a curious few MW for small scale consumer electronics and mobile applications to a current buildup of a GW scale production capacity presumed to be online between 2010 and 2012—by companies like First Solar, Nanosolar, Solyndra and Global Solar. In the beginning of thin film technology development, the market was assumed to be consumer electronics, as low efficiency was understood not to be a limiting factor for market development in this segment. The market for small scale solar applications did grow, but not to a proportion sufficient to support a growing industry, thus continued funding and continued development was brought forward to develop thin film PV technology towards the energy segment. The potential market for small to medium solar chargers is on the order of hundreds of megawatts but has not established itself during the second generation thin film ascent to the energy market, see Table 4 [69]. Thus the question that can be raised is if polymer solar cells will be able to sustain the development of wide spread small scale solar applications. Cost may become low, but the market needs to be convinced of the prolific qualities to create a significant momentum to sustain the investments put into the technology field. The predominant factor that may spark a wide spread application of small scale solar energy, is cost, in the understanding that it is disposable and cheap. Can polymer solar cells reach the required lifetime, power conversion efficiency and cost in the quest to achieve what second generation thin film proved unable achieve?

In the future perspective – beyond the very small scale consumer solar charger market – lies the energy market. When taking a look at the political signals and the technological advances it is reasonable to think that a noticeable increase in market share and size is to be seen over the next decade. First Solar stands as a beacon and as a competitive adversary to the CIGS cells and will thrive in the light of continued incentives, the stimulus bill of the united states government combined with the European focus on solar energy, general green technology and climate. This development is also foreseen to propagate downwards into the ranks of small scale applications, portable and stand alone solar cells—for the boat, the cabin, the hiker, the biker and the recreational vehicle. Not as much with focus on the retail price, but possibly rather as a feel good commodity where the end user feels that he or she is doing something good for the environment.

The application of polymer solar cells is not difficult to envisage. Fig. 2 visualize the market segment development where each market in principle is a prerequisite for the next market segment as a result of the momentum of the technology development when increase in lifetime, power conversion efficiency, production capacity and subsequent reduction in cost allow for new market segments to be developed or entered.

The challenge lies in providing functional solar cells fitting the power conversion efficiency and lifetime requirements for the given application at the right cost. As polymer solar cells mature they will meet hard competition from other thin film technologies that perform better. Thin film solar cell costs are decreasing, quality and performance are increasing, and thus when polymer solar cells are ready for larger area markets, competition may already be there waiving newcomers from the area. In a natural order of evolution second generation would be overtaken by a third generation—better, lighter, cheaper. This is clearly the ambition of the polymer solar cell technology as the industry reflects itself in the second generation solar cell industry and identifies most of the possible market applications from what the thin film industry have realized or intend to realize as products. What is not already an obvious product idea may thus already have been foreseen by many as a possible product. The polymer solar cell industry has set out on a quest to compete with other

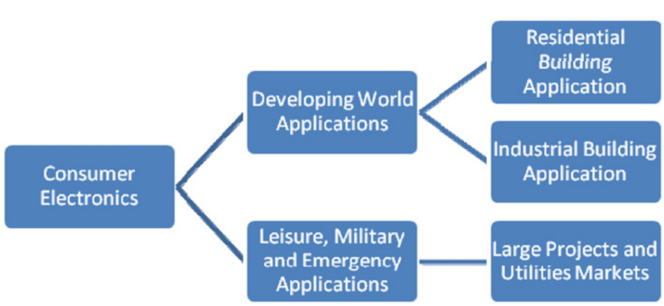

Fig. 2. Increasing solar cell performance leads to increasing market size. Each market segment represents a jump forward in technology maturity and market size increase with the addition of each market segment to the previous segments.

thin film manufacturers on their existing markets by rational choices of the technology selling points. Some examples include:

- Solar cell—third generation (therein lies improvements over second generation)
- Cheap (potentially)
- Flexible (good during production)
- Light weight (so the solar bag does not get too heavy)
- Transparent (because looking through a coloured solar cell is attractive in some applications)
- Colour variability (it matches the current fashion)
- Environmentally friendly (it is solar energy and recyclable materials)
- Portable solar energy (easy recharging of batteries).

In Section 2.1 we described how the CdTe, CIGS and a-Si costs were significantly competitive. Lifetime is at the same time significant. Turning the cost potential of polymer solar cells into a must of reaching significantly below 0.7 $ W_p^{-1}—to compete with the better lifetimes and power conversion efficiencies of the other technologies. What is most likely to happen is commoditization of the choice of solar cells offered to the markets. A stringent segmentation categorized by cost, performance, design for specific applications—indoor, outdoor, flexible, cheap, short life, long life, portable, stationary, power production, trickle charge, etc. On a general level other types of solar cells exhibit a downward trend in cost/performance (LCOE), though recession and increase of demand have resulted in cost fluctuation [70,71]. This positive development together with the expected significant increase in US investments in solar power will continuously decrease cost, maintain or increase demand and harden competition. There is no reason to believe, that polymer solar cells out of flexibility, ease of processing and potential low cost will receive any favors from the rest of the market. The next decade will be decisive for the emerging solar cell technologies as the speed at which development within first and second generation solar cells is occurring will create an intense competitive solar cell market.

3.2. *Market scope*

The polymer solar cell selling point is cheap and light weight solar cells. An important question to ask is how soon the customer will find a performing product. Table 3 presents the polymer solar cell development scenario, estimating the next 15 years of polymer solar cell development. The scenario is based on history, current status, assumptions and estimates and through current debate between market analysts, researchers and industry people. The phase division scenario assume that technology will develop, that investments will be made, that new companies will be founded, that market segments will be conquered as technology improves and production capacity expands.

By the start of 2010 phase 1 has just been entered. It is expected that lifetime will be a significant challenge towards phases 3 and 4, while phase 2 with the current technological maturity and laboratory results should be within reach. Indicated increase in the number of manufacturing companies is proposed to be due to the massive increase in research effort, published patent applications and publications emanating since 2007, which is expected to attract venture capital. With a phase two level maturity, materials knowledge and large scale processing should be mastered.

This could potentially drive a massive increase in production capacity as processing facilities are not extremely expensive to establish. Key elements will be that the cost/performance ratio must be competitive with competing solar cell technologies, if

Table 3
Polymer solar cell phase development scenario compiled from industry and academia conference presentations and discussions over the course of 2008 and 2009. As the cost/performance ratio of the solar cell develops, new market segments will become available. The indicated time is an estimate of when each of the phases is estimated to begin—overlap is intentional. Costs are indicated for large area modules for phases 3 and 4. Annual capacity is capacity and not amount of manufactured cells.

	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Phase implementation	2010–2013	2012–2015	2015–2018	2018–2025
Market segment categorization	Consumer Electronics	Beginning small scale stand alone equipment	Beginning residential building add on panels and medium scale stand alone systems	Beginning large scale implementation of polymer solar cells
Phase description Continuous lighting conditions lifetime	1–3% PCE 1–2 year lifetime 8–12 US$/W Small area modules T(80) 2500 h	3–4% PCE 1–3 year lifetime 2–4 US$/W Medium module size T(80) 5000 h	4–6% PCE 3–5 year lifetime 1 US$/W Large area module T(80) 12,000 h	6–9% PCE 5–7 year lifetime Below 0.5 $/W Large area modules T(80) 20,000 h
Cost/performance ratio	$2\% \times 2500/8 = 625$	$4\% \times 5000/2 = 100$	$6\% \times 12{,}000/1 = 720$	$9\% \times 20{,}000/0.5 = 3600$
Expected application	Portable chargers for consumer electronics, integration in toys, low power electronic equipment, smartcards and many electrical pieces of equipment in need of a low power source	Larger area chargers for leisure and camping activities, integration in tents, sunscreens, awnings, small scale lighting lamps for developing markets, military application and possibly early emergency and relief application	Solar panels for retrofitting on residential buildings, solar curtains for indoor use and the possibility of polymer solar cell film for windows. Massive application in developing countries with low power applications developed accordingly	Solar panels for large scale commercial building integration and potential successive development of polymer solar cell solar power plants if cost/performance ratio is competitive
Polymer solar cell companies	**5–10**	**10–15**	**12–18**	**18–30**
Annual capacity (GW)	**1**	**1.5**	**5**	**60**

Table 4
Organic and hybrid organic/inorganic photovoltaics revenue by application (Million US$). Market segments and their estimated development over time in US$ (2007). The table has been adapted from the original and added point 7, which was not included as a market potential in the original Nanomarket report [69] (this table is based and adapted from the Nanomarkets report, p. 77).

Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
(1) Large projects and utilities	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(2) Cormmercial and industrial building applications	0.0	0.0	0.1	0.5	2.0	5.6	14.7	31.5	63.3
(3) Residential building applications	0.0	0.0	0.2	0.7	2.5	8.1	23.5	57.1	126.6
(4) Consumer electronics	0.2	0.9	1.9	4.9	11.6	24.4	48.0	82.8	130.3
(5) Military and Emergency	0.0	0.0	0.1	0.3	0.9	2.6	6.9	15.8	33.5
(6) Other	0.0	0.0	0.1	0.3	0.9	2.1	4.9	9.9	18.6
(7) Developing countries	0.0	0.0	1.0	2.0	15	45	60	75	90
Total million US$	0.2	0.9	3.4	8.7	32.9	87.8	158.0	272.1	462.3
Total market size in megawatt	0.2	0.7	1.9	5.8	16.6	43.4	107.7	235.5	483.6

unsuccessful; the product will only obtain a niche market role, largely insufficient to sustain a large industry capacity.

3.3. Polymer solar cell market segments

The estimated market size according to market segment is illustrated in Table 4 which is an adaptation representation of the 2007 Nanomarket numbers [69]. The original market analysis estimated expected initial availability of polymer solar cells by 2007, but the estimates were not realized before 2009.

Therefore the liberty has been taken to shift the forecast from 2007 to 2009. This alteration provides a polymer solar cell market expected to grow from 0.2 million US$ in 2009 to 462.3 million US$ from 2009 to 2017 (and not from 2007 to 2015 as in the original table). Growth is in the range of ~5000%, as it has been estimated that the basis of the market has not changed significantly. The original table also covers DSSC cells making the market share of polymer solar cells less than what is stated in the table. In the following the polymer solar cell market share has been set to a high 100% in order not to underestimate the market size. Table 4 builds on the expected improvement of the technology bringing with it scale, lower cost and improved material performance. Only selected segments will be discussed below as the total projected market size is of higher relevance. For the military and humanitarian segment the search for an alternative to primary batteries brings attention to polymer solar cells. The cost of primary batteries can reach ~4000 USD for 1 kW, which is 80–90 times higher when compared to secondary rechargeable batteries [72,73]. Potential low cost, light weight and portable energy is behind the US defence to fund the leading US polymer solar cell companies. The consumer electronics segment is estimated to grow from 0.2 million US$ in 2010 to 130.2 US$ in 2017 with the assumption that close collaboration with consumer electronics manufacturers are established to push forward technology. An area like battery development may support polymer solar cells as a possible method of battery recharging. The early market introduction may provoke a slight consumer buzz but may die out as buzz turns to realization of the limited applicability of polymer solar cells. Residential and industrial building application prospect a 190 million US$ market in 2017. Large projects and utilities is at this point a scenario of a distant reality that lives with the potential and dies if significant improvement in performance is not mastered. Point 7 in the above table indicates that developing countries are a possible large market segment. This was until recently not a market segment in strong focus with the thin film manufacturers. It has been brought forward here as we find good opportunities for affordable solar energy among the low income inhabitants in the developing part of the world—under the assumption that OPV is able to lower costs significantly to allow for bottom of the pyramid consumers to buy OPV solar products. As an example the developing world might through solar energy find an alternative to kerosene lamps—a market based on old technology estimated by the World Bank to be around 38 billion US/$ annually [74]. Risø DTU recently demonstrated the functionality of OPV as a power source for LED based lighting. Based on this and a significant interest in such a solution, the developing world market segment has been included in the market segments for polymer solar cells. The size of point 7 is an estimate based on presumed capacity and cost reduction. The total annual estimated polymer solar cell market size is 462.3 million US$ in 2017, if summed, this gives a 2009–2017 period total of 1026.5 million US$. If the proposed market development is adapted to the current level of production capacity and cost, then it comes apparent, as described in Table 5, that the provided production capacity in the first years will be tremendously above capacity for the whole period, even with a status quo of 1 GW production capacity for the next 8 years. If this estimate balances it becomes obvious that Konarka, with their potential 1 GW production capacity can easily cover the total production capacity need for a decade. From the estimate, the unbalanced production capacity and market size indicate either that the market estimate is completely off target or that the production capacity is significantly above what can be sold in the market. In any case the estimate suggests that investments in polymer solar cells will take time to create a return.

The 1005 GW phase 1 production capacity is the production capacity of Konarka Technologies of which probably only a smaller 5 MW pilot scale process line is in commercial operation (in 2009). This clearly makes the phase 1 market too small to bring any significant turnover to manufacturers. Most likely any resemblance of a market size of 57 million US$ will not be met before 2015–2016. In other words Phases 2 and 3 must be reached to realize the mid-scale economic potential of the technology. In conjunction with the phase estimate, the polymer solar cell development history and expected increase in market size, it is unlikely that the technology can hope for a ketchup effect in development after a slow initiation of phase 1. Despite this, industry will be powering up production capacity to prepare for Phases 3 and 4. Volume goes up, price goes down, market goes up, but will the increase be enough to create a turnover that can justify investment costs in time to meet investor expectations? This may well become an issue within the industry. Betting on small scale chargers as base for an industry is unlikely to suffice.

Table 5
Current and projected market size and production capacity 2010–2018—estimated applied production capacity is based on the phase projection in Fig. 2 and the market estimate in Table 4. The maximum potential turnover is shown below each scenario. 11.5 US/W is the $ per W cost of the Konarka KT-20 module (when sold in small quantities ultimo 2009).

Estimate	2010	2014	2018
Market size million (US$)	0.2	87.9	462.3
Polymer solar cell cost (US$/W)	11.5	1–2	1–0.5
(1) Production capacity status quo (GW)	1005	1.005	1.005
Potential max turnover—billion US$	11.5	1.5–3	0.5–1
(2) Estimated applied production capacity (MW)	> 5	~44–88	462–924
Potential max turnover—million (US$)	> 57	88–176	462–924
(3) Production capacity projected (GW)	1	1.5	5
Potential max turnover—billion US$	11.5	1.5–3	2.5–5

3.4. Market discussion

To illustrate the market imbalance a couple of cases are established. As claims among polymer solar cell developers on production capacity are hard to verify, focus will be on the expected market size in terms of MW. The size in terms of MW of the current phase 1 and phase 2 markets are hard to verify and at best unclear. Navigant Consulting estimate an existing 40 MW market for consumer power and indoor applications as a reference point [75]. Some may set it higher others agree, the point remains that it is not the required 500 MW—but rather a small market. A 40 MW market in Phase 1 is not unrealistic as a starting platform. Market size will increase with phase development, but the starting point is quite low. As a first case we can take that Konarka Technologies 1.3 W KT-20 series [76] and extrapolate with the currently claimed 1 GW production capacity using the current cost of the panel. This implies that a total amount of 769 million KT-20 panels can be manufactured. It is clear that cost will drop down once the large scale 1500 mm roll width production facility is operational and will be able to provide market performing cells. But the total potential turnover from KT-20 panels at 7–15 US$ a piece is 5.38–11.58 billion US$ (in phase 1: 7 US$ being an estimated price when sold in large quantities and 15 US$ in small quantities, the latter is information from Konarka Technologies). When comparing market development phases in Table 3 with market size forecasts in Table 4 it is evident that a 1 GW capacity for an estimated 462 million US$ market with the estimated price development does not correspond. If Konarka takes 100% of the thin film solar cell market by 2017, 37,230,000 KT-20 panels equal to 1/3 of the current production capacity, will cover the market—if the phase 4 scenario is correct. In a product perspective the Neubers solar cell bag equals one KT-20 Konarka Technologies solar cell and 37 million bags covers the estimated total market in 2017. If the market is completely off—then where can a large market be found? Polymer solar cell powered LED lamps may be one of these market segments. 1% of the global kerosene for lighting market equals a 390 million US$ market potential. But industry will only get there if polymer solar cell cost is reduced dramatically. The potential is there, the art is to get there and back with a profit.

4. Patent and intellectual property analysis

4.1. The definition of intellectual property

The World Intellectual Property Organization defines intellectual property as follows: "Intellectual property (IP) refers to creations of the mind: inventions, literary and artistic works, and symbols, names, images, and designs used in commerce. Intellectual property is divided into two categories: industrial property, which includes inventions (patents), trademarks, industrial designs, and geographic indications of source; and Copyright, which includes literary and artistic works such as novels, poems and plays, films, musical works, artistic works such as drawings, paintings, photographs and sculptures, and architectural designs. Rights related to copyright include those of performing artists in their performances, producers of phonograms in their recordings, and those of broadcasters in their radio and television programs.'' [77].

Patent rights can be obtained upon application. The patent holder has an exclusive time-limited right to prevent others from carrying out the invention described in the claims of the given patent. A patent also gives the patent holder the right to prevent others from performing specific operations as described in the claims of the given patent. As an example a successful inventor might disclose the procedures for preparing a solar cell having very high power conversion efficiency in a patent. The inventor can then use the patent to prevent others from replicating the invention and make a profit from it. However, only to the extent that the invention is sufficiently well described in the patent. This naturally comes at a cost since the patent must be published so that everybody can see what the invention is. This naturally serves the purpose of clearly demonstrating what others cannot do but it may also inspire and give away the invention if it is not fully explored or exhaustively described. Before a patent on an invention is obtained three requirements must be met: (1) it must novel meaning that it may not have been publicly disclosed anywhere, (2) it must be inventive in the sense that it must be non-obvious for a so-called skilled person in view of the state of the art and (3) it must be possible to exploit the invention industrially. If a certain technology area is cluttered with many patents it is highly likely that licenses to other patents is necessary to be able to exploit the invention described in the patent. In that way patent holders can make money by licensing the technology or prohibit the use of the invention by disallowing licensing. Laws and rules and perceptions of patents vary from country to country/region. This is a result of nation states and their differing law and regulations and cultural interpretation of the patent idea. On a broad scale the national systems are undergoing revision to simplify the inherent complexity and bring it up to par with modern time as the evolution of the internet in many cases have caught various patent office's off-guard.

4.2. The administration of intellectual property

Four major patent authorities of relevance to polymer solar cells exist; The European Patent Office (EPO) [78], the United States Patent and Trademark Office (USPTO) [79], the Japanese Patent Office [80] and the World Intellectual Property Organization (WIPO) [81]. The latter does not itself issue patents, but provides for a centralized and preliminary patentability assessment. Patent applications filed under the Patent Cooperation Treaty (PCT) which is administered by WIPO, must be converted into national and/or regional patent applications in order to be issued as patents (this is described in further detail below). The State Intellectual Property Office of China (SIPO) and The Korean Intellectual Property Office (KIPO) should also be mentioned, but do not yet represent areas of high activity within polymer solar cell patents. It is possible to conduct searches in patent databases and establish an overview of the polymer solar cell patent landscape through the local patent offices. There are also a number of patent search engines [82–84] that are the most valuable tools that can be used to cross-reference searches made in several databases.

4.3. The protection that a patent grants

The patent is generally viewed as an important instrument for the world economy, and is essential when protecting high-tech investments. The patent system extends globally to nearly all countries in the world. More than 170 countries are members of the Paris Convention, and among these countries more than 140 have ratified the Patent Cooperation Treaty (PCT). Historically the introduction and development of a patent system has been motivated by the following:

- To reward the inventor (or inventors) with a time-limited monopoly to ensure that others are prohibited from commercially exploiting the invention. In this way, inventive contributions and developments in the Society are encouraged. In other words, patent protection is established in order to protect investments in research, product and technology development, and to encourage further development.
- To encourage disclosure of valuable information, that might otherwise have been kept secret. Thereby, the Society's general level of knowledge is increased, and the Society will be able to freely exploit the invention when the patent is no longer in force.

A patent may be seen as a legal document prohibiting unauthorized exploitation of the particular technical field in the particular country and for a limited period of time. It is interesting to consider the fact that a patent is drafted and prosecuted by the patent proprietor of the technology or his attorney. Thus, the patent proprietor controls the ''legislation'' in this particular technical field, which makes the patent system unique compared to any other intellectual property system. It should be stressed that it is important to distinguish between a 'patent application' and a 'patent'. The latter is an issued right which is enforceable in the state in which, or for which, it is granted. The former is only an application which might end up being abandoned, refused or granted with its original scope or with a restricted scope. Thus, when studying patent literature it is important to note whether the patent publication relates to an issued patent or a patent application. The patent process is often initiated by the filing of a so-called 'priority application'. Priority applications are applications which at a later stage – within one year at the latest – are used to claim priority from. When priority is claimed, the effective date of the later filed 'priority claiming application' is the filing date of the previously filed 'priority application'. However, only with respect to subject matter which is described in both applications. The principle behind the priority claiming was introduced in 1883 with the Paris Convention. At that time it was practically impossible to file patent applications for the same invention in a plurality of countries on the same date, as neither the fax machine nor the email had been invented. Moreover, the patent application texts typically had to be translated to each of the national languages. Thus, in order to be able to file identical patent applications relating to the same invention in a plurality of different countries and on the same date, the Paris Convention was introduced, whereby the applicant was provided with a one year period within which identical patent applications could be filed in other countries. This principle still exists today. When the first priority application is filed, the priority year is initiated. Within the priority year, the applicant is free to file as many priority applications as he/she wants. This opportunity is often used to file new priority applications which are based on the first filed priority application with addition of further subject matter. By the end of the priority year, a priority claiming application is filed which claims priority from all these applications. The date of filing of each priority application is called the priority date.

There are many routes to obtain a national patent since patent applications may be filed nationally, regionally, or as an international patent application. The route chosen depends on the overall strategy of the applicant of the patent application. A majority of companies choose one particular route called the 'PCT route' or the 'international route', as it includes the filing of an international patent application under the Patent Cooperation Treaty (PCT). The PCT route normally includes filing of one or more priority applications which within one year is followed by an international patent application—a PCT application. At a later stage, the international patent application is converted into a series of national and regional patent applications. The PCT route is described in detail in the following, however it shall be understood that alternative routes to a national or regional patents are in existence.

4.4. The PCT application and the national and regional phases

Within one year from the first priority date, a priority claiming application must be filed if the priority right is to be utilized. When the PCT route is chosen, the priority claiming application is an international patent application (a PCT application). In connection with the filing of the priority claiming application, priority from one or more priority applications is claimed. These applications may have different and overlapping subject matter, and the effective date of any subject matter in the priority claiming PCT application is the date on which this subject matter was described for the first time in either one of the priority applications or in the PCT application. Although the phrase 'international patent' or 'world patent' is often used in the media, no such thing as an international or world patent exist. Only international patent applications exist. An international patent application is only a patent application which at a later stage may be converted into a national or regional patent application. This process is called nationalization or regionalization of an international patent application. The international phase is the period from filing the PCT application until the time limit for nationalization/regionalization. This period terminates 30 months after the earliest effective date. Thus, if a PCT application is filed at the 12 month date (calculated from the filing date of the first priority application), the international phase terminates one and a half year after the filing of the PCT application. In the international phase, three major events occur. These events are: (1) the drawing up of the combined search report and patentability opinion, (2) the publication of the international patent application and (3) the preliminary examination of the international patent application. Where the two first are mandatory, the third is optional for the applicant. Upon receipt of the PCT application, the International Searching Authority starts to draw up a search report. The search report is used by the authority to examine whether the patent application relates to a patentable invention. The search report lists the most relevant patent literature which the searching authority was able to identify. Attached to the search report is a patentability opinion in which the authority states its opinion on the patentability of the invention in view of the cited patent literature. The patent application is published 18 months after the earliest priority date. If the search report has been drawn up, the search report is published with the application. If the applicant for the patent has requested and paid for a so-called 'Demand for preliminary Examination', the patentability of the invention is preliminarily assessed. As this assessment is preliminary, the national offices, before which the patent is nationalized or regionalized, are not bound by this patentability opinion.

The international phase terminates 30 months after the earliest priority date. Prior to the termination of the international phase, the patent application must be nationalized or regionalized. When a patent application is nationalized and regionalized, the international patent application is converted into corresponding national and/or regional patent applications. Some countries and regional patent systems allow the national/regional phase to take place after the 30 month time limit. One example is the European Patent Office before which the international patent application must be regionalized no later than 31 months after the earliest priority date. When the international patent application is filed, the application automatically designates all PCT member states or regions. This means that the applicant has the option of converting the international patent application into national or regional patent applications in all these countries before the time limit set by the respective national/regional patent office. However, if this is not done before the set time limit, the right to convert the international patent application into a national or regional patent application is lost. After the nationalization or regionalization, the examination of the patent application continues nationally. A clear description of each step of the European PCT application process can be found at EPO or WIPO [77,78,87] (see also Ref. [87, pp. 73 and 75]), the USPTO and WIPO guidelines can be found in comprehensive form on the respective websites [79,81].

4.5. Regionalization before the European Patent Organization (EPO)

The European Patent Office (EPO) covers not only the EU member states but also states like Norway, Iceland, Turkey and Switzerland. The European Patent Office grants patents under the European Patent Convention. When the international patent application has been regionalized before the EPO, the examination of the now European application continues until the application is granted, refused or abandoned. If the European patent application matures into a European patent, it has the effect as if a national patent was granted in each of the EPC contracting states. However, some of the EPC contracting states require that the patent proprietor must validate the patent in order for the European patent to have legal effect in that particular state. Validation implies that the patent proprietor must file a translation of the European patent, or in some instances simply the claims thereof, in a national language of that state. ***This must typically be done within 3 months after the grant of the European patent. If the patent is not validated in a state setting for such validation requirements, the European patent ceases to have effect for that state and cannot later be enforced in that state.*** The choice of states in which the patent is validated depends – among other factors – on the field of business. All states further require that annual fees are paid to the national offices in order to keep the national part of the European patent in force. Statistically, most European patents are kept in force in at least Germany, United Kingdom, France and Italy.

4.6. Publication of patent application and patents

In most countries and regions, the patent application is published shortly after 18 months from the earliest priority date, and again upon granting of the patent. The patent publication can be said to have three important functions:

- The patent publication defines the invention for which the applicant seeks protection. If the application actually matures into a patent, the patent provides to the patent proprietor the right to prohibit others from exploiting the technical field defined in the patent. In most countries, the legal system provides for relatively fast and efficient injunction where a patent is infringed. A patent is a prohibition right, and it is therefore important to understand that a patent does not grant the patent proprietor the right to exploit the patented technology, because in doing so, other patents might be infringed.

- The patent publication is normally a valuable communication of technical or scientific information. The patent literature is an important source of such information. A considerable proportion of the knowledge communicated through the patent literature is not communicated in any other way. Due to the disclosure requirements of the patent system (for the patent to be obtained and to be valid, the description must disclose the invention in a manner sufficiently clear and complete for it to be carried out by a person skilled in the art), information in patent publications is normally just as complete and reliable as in any other kind of literature. Monitoring of the patent literature is facilitated by the fact that the patent literature is classified in a highly systematic way.
- The patent publication is a bar to the later patenting, by competitors, of features disclosed therein. Although any piece of published literature will constitute a bar against later patenting of its disclosure, patent publications are normally written in such a manner (i.e. because of the disclosure requirements discussed above) that they are more effective citations than most other kinds of literature.

With respect to the first point, it is important to determine whether the patent or patent application is in force or pending, respectively. In the case of a patent, the patent ceases to be enforceable if renewal fees are not paid. In the case of a patent application, the application may have ceased to be pending e.g. due to a refusal by the patent authority or if the applicant has allowed the patent application to become abandoned. In the case of a pending patent application, it is important to note that the scope of the published patent application may be drastically reduced during examination thereof. In fact, patent applications are frequently published with clearly invalid main claims.

4.7. *The polymer solar cell patent field*

The nature of the polymer solar cell patent field makes it difficult to oversee without significant effort and technical insight. A complete patent analysis and the detailed understanding of where there is freedom to operate rests with the productive universities, research institutions and the companies involved in commercialization and their respective patent lawyers. For the purpose of determining the extent of the prohibition right referred to above, the information on the front page of a patent publication is an essential starting point. Initially, it must be determined whether the publication relates to a pending patent application or to a granted patent. For the interested third party, this information is highly important, because the prohibition right can only be enforced after the grant of the patent, namely from the date of publication of the mention of the grant of the patent. In the period between the publication of the patent application and the publication of the granted patent, the patent applicant is – under certain circumstances – offered a provisional protection. This provisional protection may only be activated if the patent eventually is granted, and only for the designated states wherein the European patent is kept in force upon validation (if necessary) and payment of annual fees has been maintained. It should be kept in mind that patent publications represent the information valid at the time of publication of the patent application shortly after 18 months from the priority date, or at the time of grant. The ownership may very well have changed since the date of publication, just as a granted European patent may only be validated and kept in force in a certain number of the designated states. Although the front page of the European patent publication offers a valuable starting point, updated information about the European patent (application) should be checked on the EPO online service, Epoline [85]. At Epoline, information about the change of ownership, amendment of the patent claims, and filing of oppositions, etc. is immediately available. After the patent is granted, reliable information about the actual status of the national parts of the European patent is generally only available at the national offices. As an example the patent application most often designate all contracting states and extension states upon filing. However, upon grant of the patent the patent is normally validated in fewer states. Often the granted patent is only validated in Germany (DE), France (FR) and Great Britain (GB). Hence most issued European patents only cover a few of the originally designated states and extension states.

4.8. *Polymer solar cell patent analysis*

A detailed overview of the polymer solar cell patent portfolio is hard to establish as the technology field relates to several other technology areas with a long history of patenting. These other technology areas include materials research related to conducting polymers, organic light emitting devices, organic field effect transistors, substrates, barrier layers, front and back electrodes, device architecture, processing and application among others. A rough and unsubstantiated estimate suggests that the polymer solar cell field as a technology touches upon 10,000–25,000 patents. Fig. 3 provides a conceptual overview of a polymer solar cell patent grouping in primary, secondary and peripheral patents. Primary patents are the hardest to establish as they build on the core concepts of the technology; the materials and the device structure. Examples are the A.J. Heeger and N.S. Saricifti patents that represent the very start and are fundamentally important. US Patent Nos. 5,331,183 and 5,454,880 defined the key concept of the polymer solar cell technology field.

In order to establish a composition of matter materials patent, one has to prepare a new material that is rethinking the concepts held within these two ground breaking patents. Secondary patents are not necessarily easier to establish or less valuable. Core concepts of coating and printing was established many years ago—and thus it is prior art in the public domain. One way of processing can also be exchanged with another way of processing. As an example, a 5 layered device with 5 layer forming techniques can be made in 3125 ways and thus processing patents may have a tendency to be less strong in defending its IP domain. Peripheral patents relates to patents that are not directly based within polymer solar cell technology, but still related to the technology field—examples are the knowledge of conducting polymers,

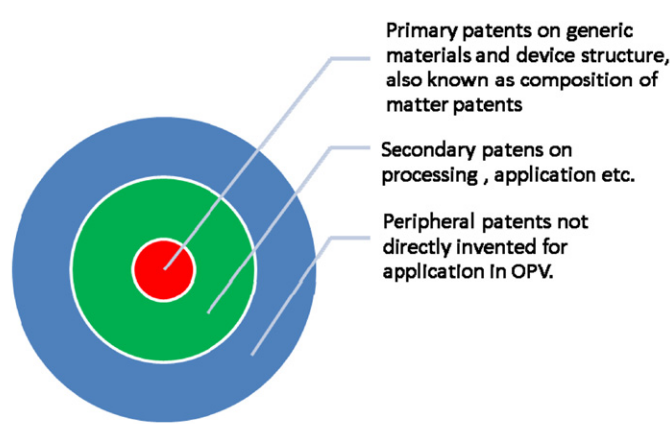

Fig. 3. Illustrates the three levels of patents encountered in the polymer solar cell technology field. The size of each ring does not correspond to the size of each patented area. If any correlation between the three patent categories, it is the hardship of making primary patents – composition of matter pattents – compared to secondary patents.

printing techniques, contacting solutions and materials that was invented for other purposes but can be applied in polymer solar cells. A structured approach is necessary to establish an overview of polymer solar cell patents. In the following the reference point will be the Cintelliq polymer solar cell patent dataset [86]. The patent search strategy is proprietary to Cintelliq and not available in detail. In general specific terminology is used, i.e. polymer solar cell, organic PV, flexible solar cell, company names, inventors, IPC codes and ECLA codes to identify the patents. This provides a large number of patents which is then sorted by software to decide if the patent is to be kept or rejected. This process narrows down the amount of patents to the relevant sum, and these patents are then classified through a semiautomatic process and a manual process. The data is then structured to a normalized standard level that makes the data searchable. This taxonomy has been refined and matured over 5 years and provides very good results and is continuously updated and currently contains over 2000 patents. To uncover the polymer solar cell patent landscape a search was performed in the Cintelliq database. The results are in the following visualized through tables and figures each described by a short text. The search contains small molecule, polymer organic photovoltaic devices and a few dye sensitized patents from 2003 until November 2008. An analysis of the polymer solar cell intellectual property landscape over a longer period of time may provide a different result with respect to assignees, invention focus, priority year and priority country. The polymer solar cell data presented here only provide parts of the results and the overall discussion of the material. Published patent applications used as part of the polymer solar cell dataset cover EP, JP, US and WO patents. Granted patents used as part of the polymer solar cell dataset cover the EP and the US patent offices. Patents filed after November 2008 were not available in the Cintelliq polymer solar cell Dataset at the time of writing this review.

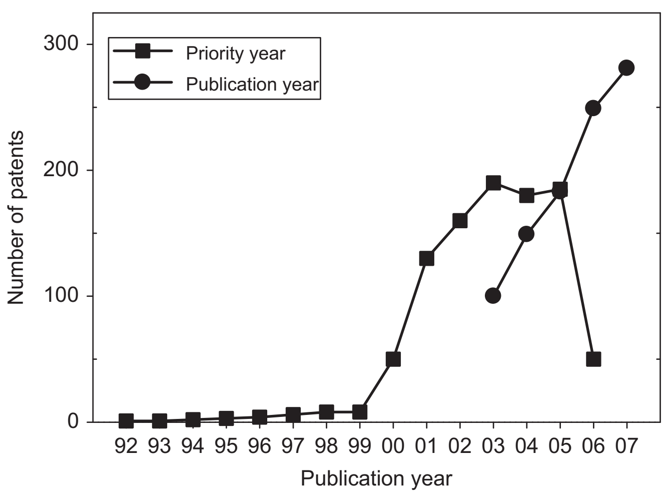

Fig. 4. A patents priority year provides the applicant with 12 months to file the patent in other countries. Thus a picture of a patent landscape will always provide uncertainty towards the latest filings. The priority year is the fixed time of the patent application to the patent authority. From 2003 until the end of 2007 a total of 962 patents were published. This displays an aggressive increase in annual publication of close to 300% in the period. The publication year is the fixed time of publication of the patent to the public sphere.

The 962 patents filed express the massive research effort and focus on polymer solar cell, again exemplifying the potential of the technology. The polymer solar cell patents with a publication date in the years 2003–2007 have varying priority dates that indicate when the initial innovation occurred, in this case from 2000 and onwards. In other words, an invention can be years old before it is published, as visualized in Fig. 4.

There is normally 18 months between priority date and publication date. An overall view of the 962 patents provides a clear idea of where and when polymer solar cell patents have priority from and in which country, as visualized in Table 6. The table lists countries, regions and registered patents by priority year and priority country from 1992 and until the end of 2006. It is clear that polymer solar cell patent applications published in 2003–2007 are dominated by US and Japanese filings as they represent 62% of the patents. The majority of the patents have been filed since 2001. The geographical distribution of the granted patents provides an indication of which countries that are the leading priority countries, often translated into the main markets for the invention. For granted polymer solar cell patents the US (38%) is the leading priority country, however taking GB, DE, EP and AT (47%) together presents European organizations as key innovators in polymer solar cell technology.

This is shown in Fig. 5 along with the distribution of these patents within different areas of focus. Materials and device structure patents are the main focus of innovation, this is a reflection of the maturity of the technology which is in its very early stage of commercialization or possibly still in a pre-commercial stage. Industry and academia is building the technology to a level where it can be brought into development in an industrial process. It is expected that as the technology moves into production there will be an increase in process related innovation. This may however be heavily influenced by existing processing technologies and prior art from other technologies

Table 6
The table lists countries, regions and registered patents by priority year and priority country from 1992 until end of 2006.

Year	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Total
US	1					1	4	1	7	24	64	61	66	84	25	338
JP							1	5	9	25	45	44	55	62	12	258
DE						2	1		6	39	19	26	18	12	6	129
EP						1		1	14	25	12	34	15	3	6	111
GB							1	1	2	7	17	10	5	5		48
KR											1	2	5	12	2	22
AT									11	4	4				2	21
FR												5	10	2		17
TW												1	1			2
FI													2			2
BE											2					2
CN														2		2
IL										1		1				2
CA												1	1			2
RoW										1		3	1	1		6
Total	1					4	7	8	49	126	164	188	179	183	53	962

with similar processing basis. When detailing granted and published patent applications a visible difference appears as shown in Fig. 6 where polymer solar cell patents (published patent applications and granted patents) for the period 2003–2007 are split almost evenly between the three priority regions EU (35%), JP (30%), and US (35%).

The almost equal share of patents between the regions underlines the strong focus on solar energy and the potential of polymer solar cells. An indication of a shift towards commercialization can be observed when examining the distribution amongst the categories for the patent applications and the granted patents as the granted patent group necessarily represent an earlier stage of development than the patent applications when taken as a whole. This is shown in Fig. 6 where it is evident that the innovation focus differs between granted and published patent applications with the granted patents being largely concentrated on materials the published patent applications have about equal focus on materials and device structure. The number of materials and device structure patents has grown rapidly over the period 2003–2007 and dominates the polymer solar cell IP landscape. This truly reflects the current state of the technology as being in a pre-commercial phase (or a very early commercialization phase). A distinct difference in the regional variations is the overall innovation focus which should first focus on materials, then device structure, and then fabrication.

However, the US and Far East organizations place slightly greater emphasis on device structure over materials as detailed in Table 7. Which of these two approaches will pay off in the long run is hard to say, but the US leads on points when it comes to polymer solar cell companies. When examining the assignees that are the individual, organization or company to who rights under the patent is transferred as shown in Table 8 one finds that Konarka Technologies is the top assignee with about 13% of patents for the period 2003–2007. Merck is while ranked 2nd actually leading when choosing only to look at the granted patents (about 22%). Konarka Technologies was originally part of Siemens and it is likely that many of the Siemens patents have been reassigned to Konarka Technologies and thereby increasing their overall position in the field. This underlines Konarka Technologies as a leader, but it cannot confirm the +350 patents claimed by the company, as the search base is too small.

When broken down into US, EU and Far East patents the distribution among assignees provide a regionalized and detailed look at who in industry as well as academia that are involved in polymer solar cells. In the US 72 assignees holds 338 patents, of which Konarka Technologies is top assignee with 21% of the patents with US priority as shown in Table 9. It may seem that the strong focus on device structure and materials has left little focus

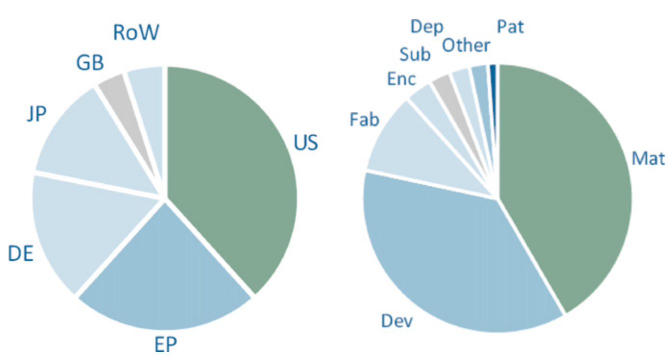

Fig. 5. A pie chart showing the distribution of the granted polymer solar cell patents according to the region is shown on the left (a total of 123 patents). On the right a pie chart of all patent applications and granted patents according to the focus of the invention. Materials and device structure – the layers in the polymer solar cell structure – accounts for 78% of all patents. This is truly expressive of a technology under development (Mat=materials, Dev=devices, Fab=fabrication, Enc=encapsulation, Sub=substrate, Dep=deposition, Pat=patterning).

Table 7
The innovation process varies from region to region. Materials are in strong focus for the EU, but Far East and USA is focused more on device structure. The numbers shown are in % of all patents.

Innovation	Far east	USA	Europe	RoW	Total
Device structure	44	40	28	40	37
Material	37	37	50	20	42
Fabrication	8	9	13	40	10
Encapsulation	2	6	2	0	3
Deposition	1	3	2	0	2
Patterning	0	1	1	0	2
Substrates	6	1	1	0	1
Other	2	3	3	0	3
Total	100	100	100	100	100

Table 8
An overview of assignees, granted patents, published patent applications and total patents assigned to the assignee. Konarka Technologies, Merck and Princeton University lead the field.

Assignee	Granted	Published	Total
Konarka	18	105	123
Merck	27	74	101
Universal Display Corp.	8	0	8
Princeton University	6	44	50
Siemens	0	34	34
General Electric	4	29	33
Matsushita Electric	0	23	23
University of California	0	22	22
Cambridge Display Technology	5	14	19
All other assignees	55	494	549
Total	123	839	962

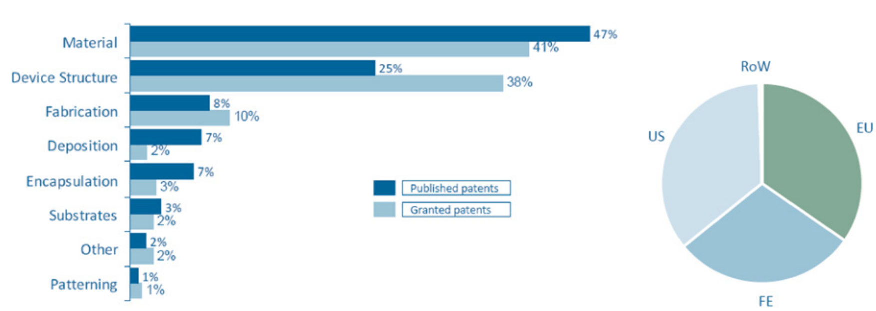

Fig. 6. The innovation focus between granted patents and patent applications as published patent applications. There is a clear shift between a materials focus towards device structure. The polymer solar cell patents are shared almost equally amongst the US, EU and Far East.

on fabrication and encapsulation—two central areas to conquer before large scale industrialization is possible. But it is more likely that the field of processing to some extent is prior art, that device structure and materials are prerequisites to processing and encapsulation and therefore not as developed. It is therefore likely that a number of processing and possibly barrier layer patents will be issued the next few years.

In the Far East 92 assignees holds 284 patents as shown in Table 10. The Far East has the highest number of independent assignees reflected by the top assignee only holding 23 patents compared to 71 in the US and 100 in EU as shown in Tables 9 and 11. Again there is a strong focus on materials and device structure with little focus on fabrication from essentially one assignee and no patents within barrier layers. One assignee, Fuji Photo Film, has several of the most cited key patents.

When reflecting on the implications of this it not only shows that the entire industry agrees on where effort is best placed but it also shows where the technology is and that it is equally well developed within all three regions. The fact that there is little on fabrication and nothing on encapsulation implies that very few have developed complete processes to competitive polymer solar cell modules as this would almost certainly require a series of patents in all fields. Also very few stakeholders branch all the patent categories which would be expected for an industry that is fully established in polymer solar cell manufacture.

In the EU 56 assignees holds a total of 333 patents. Merck is the top assignee with 30% of the patents with a European priority country. In second place is Konarka (GmbH/Inc.) with 50 patents (13%) as detailed in Table 11. The regional differences can be summarized as Europe being characterized by a few stakeholders that has the majority of patents, the US having several stakeholders with important shares and the Far East by having a large spread of stakeholders with only a small proportion of the overall patents. In terms of size the three regions are essentially equal and the differences can be ascribed to cultural differences and differences in how industry typically operates in those regions. Germany (DE) accounts for the majority of European patents with 39%. The top assignees are Siemens, Konarka Technologies and Merck. It is worth noting that Siemens may have reassigned their patents to Konarka Technologies. Merck patents are filed as DE and EP; similarly Konarka patents are filed as DE and AT. Academia makes a strong contribution to the polymer solar cell intellectual property landscape, increasing from 20% of the patents in 2003 to 35% of the accumulated polymer solar cell patents in 2007 suggesting that science discovery is still central to the evolution of polymer solar cell technology. The top two academic assignees are Princeton University (US) and University of California (US), Princeton University is also ranked 3rd overall. Overall, US academic assignees are responsible for about 50% of the patents from academic institutions in this survey. When looking at the regional variety it stands clear that the US Academic assignees account for the highest number of publications from the US. On the contrary the lowest number of publications and highest number of assignees come from the Far East. US academic assignees account for the largest number of polymer solar cell patents for the period 2003–2007, generating more patents per academic assignee than either EU or Far East academic assignees. The number of patents per assignee is, respectively, 5.17, 2.6 and 1.83 for the US, EU and the Far East. The number of assignees for each region is roughly the same, respectively, 24 (124), 25 (65) and 29 (53) for the US, EU and far east with the number in brackets being the total number of patents. When looking at the most frequently cited patents (Table 12) by polymer solar cell patent publications for the period 2003–2007 it becomes apparent that key research was conducted from 1992 to 1999. The older a key patent is the more citations it

Table 9
US assignees with patents on device structure (Dev), materials technology (Mat), fabrication (Fab) and encapsulation (Enc)—each asterisk indicating that the assignee has patents in the given area.

Assignee	Mat	Dev	Fab	Enc	Total
Konarka	*	*			71
Princeton University		*			50
General Electric	*	*	*		32
University of California	*	*			22
Dupont de Nemours	*			*	16
Universal Display Corp.				*	11
Plextronics	*				10
Nanosolar		*	*		6
University of Southern California	*				5
Midwest Research Institute		*			5
MIT	*				5
Kent State University	*				5
Subtotal (12 assignees)	*	*	*	*	237
Others (60 assignees)	*	*	*	*	101
Total	*	*	*	*	338

Table 10
Far East assignees with patents on device structure (Dev), materials technology (Mat) and fabrication (Fab)—each asterisk representing that the assignee has patents in the given area.

Assignee	Mat	Dev	Fab	Total
Matsushita Electric industries/works		*		23
Dai Nippon Printing		*		16
Sony Corporation	*	*		10
Nippon Oil		*	*	10
Nippon Kayaku	*	*		10
Toray Industries	*			9
Sharp	*	*		9
Samsung SDI		*		8
Samsung Electronics	*			8
Kyoto University	*			8
Ricoh	*			7
Hayashibara Biochemical Laboratory	*			7
Fuji Photo Film	*	*		7
Sumitomo Chemical	*			6
Semiconductor Energy Laboratory		*		6
Japan Science and Technology Agency	*			6
Subtotal (16 assignees)	*	*	*	150
Others (76 assignees)	*	*	*	134
Total	*	*	*	284

Table 11
EU assignees with patents on device structure (Dev), materials technology (Mat), fabrication (Fab) and patterning (Pat)—each asterisk representing that the assignee has patents in the given area.

Assignee	Mat	Dev	Fab	Pat	Total
Merck	*				100
Konarka		*	*		50
Siemens	*	*			34
Cambridge Display Technology	*	*			18
Sony International Europe		*			12
C.E.A.	*				11
Philips Electronics		*		*	8
Frauenhofer Gesellschaft		*			8
Agfa Gevaert	*				7
Osram Opto	*				5
Subtotal (10 assignees)	*	*	*	*	253
Others (60 assignees)	*	*	*	*	80
Total	*	*	*	*	333

will have. It is not expected that new patents will enter the most cited list due to two things:

(1) polymer solar cells as a technology is based on the concept of conjugated polymers that in substance have not changed significantly since early and highly generic patents—US Patent Nos. 5,331,183 and 5,454,880. These patents, together with the other most cited patents have created a technology base on which others have built their ideas. No generic patents have appeared since then in terms of materials and only patents that develop the original concepts have been applied for and issued.
(2) The polymer solar cell technology seems to be branching out into defined clusters that apply the original concepts with local variations. These clusters will be seemingly independent patent families that support a university and or a company in its quest for commercial application. This is clear with Konarka Technologies, Solarmer Energy and Plextronics Inc. that all have their particular method of applying the original concepts. Specifying academic assignees over the last 5 years prove that growth mainly comes from the US and further shows that from 2003 to 2006 the number of academic assignees trebles from 5 to 15; while patents merely doubled. This is founded in the spreading of polymer solar cells as an academic research discipline and the fact that the polymer solar cell field is inherently hard to break new and valuable patents from. Intensified research at Princeton University is behind the three-fold increase in publications from 2006 to 2007 (24 publications), at the same time University of California doubles their publications (to 10). In Europe, publication numbers also doubled from 2006 to 2007 and 10 of the 26 patents in 2007 came from CEA (France). The corresponding numbers from the Far East are incomplete as only 3 quarters of the JP data could be used (many JP publications tend to claim JP as priority country). The main contributors to patent growth have been Konarka and Merck out of 222 different assignees. Princeton has doubled their patent publications from 2006 to 2007 and is currently the third largest assignee. Summarizing the analysis of granted and published polymer solar cell patent applications for the period of 2003–2007 shows a total of 962 polymer solar cell patents identified, of these 123 are granted patents and 839 are published patent applications. The ratio between granted and published patent applications is 1:7. Top assignee overall is Konarka Technologies with 13% of the patents followed by top academic assignee Princeton University. Merck leads the list of granted, patents holding 22%.

Table 12
A list of the key patent numbers, assignee, number of citations and priority year—providing an overview of the key inventors, key players in industry and academia and patent content.

Patent	Assignee	Cited	Priority year
US5331183	University of California	17	1992
US6291763	Fuji Photo Film	17	1999
US5482570	Asulab SA	15	1992
US5454880	University of California	13	1992
US5986206	NanoGram Corporation	12	1997
US5525440	EPFL	12	1992
US5885368	Hoechst AG	11	1995
US6580027	Princeton University	11	2001
US6376765	Fuji Photo Film	11	1999
US6075203	DuPont	10	1998
US6239355	University of Columbia	10	1998
US6278056	AIST	10	1998
US6451415	Princeton University	9	1998
US5084365	EPFL	9	1988
US5441827	Asulab SA	9	1992
US6350946	Fuji Photo Film	9	1999

The complexity of the polymer solar cell technology establishes a wide platform to operate on so new materials, new device structures and new processing and barrier layers can be developed. It will be very hard for any one company to tie down the market by a strong IP portfolio—Konarka has been trying, but may have underestimated the competition. From a commercial point of view it comes down to who has the best performing proprietary technology that is scalable at the optimal price. One may have the best materials in theory and laboratory, but if they are not scalable at a competitive cost, they become obsolete—the same applies for improvements in power conversion efficiency and lifetime results from the laboratory, device structure, processing and barrier layers. The Cintelliq polymer solar cell patent dataset provides an understanding of who are active, where they are active and how many patents there are in existence. From this information it is possible to see in which countries the leading companies see a market opportunity—the patent protected core markets. US based assignees focus primarily on the US, EU based assignees focus primarily on EU and Far East based assignees focus primarily on the Far East. Konarka Technologies is based both in the US and EU and is thus represented in both regions.

4.9. Central composition of matter polymer solar cell patents and why Europe is unique

An analysis of generic polymer solar cell patents reveals that there is significant freedom to operate in large parts of Europe. Key findings from this small patent survey shows that inventors A.J. Heeger and N.S. Saricifti – made 2 fundamentally important – composition of matter patents – US Patent No. 5,331,183 (Filed August 17, 1992; issued July 19, 1994; expires October 2011), US Patent No. 5,454,880 (continuation of US Patent No. 5,331,183) (Filed January 12, 1994; issued October 3, 1995; expires October 2012). *Pending patent application in Japan*: JP-20006-080530A published March 23, 2006 and claiming priority from US application 07/930,161 and WO/1994/005045 (cf. above). Expire October 2013 (if issued). These are highly generic patents that describe: polymer–fullerene hetero-junctions, polymer–fullerene bulk hetero-junctions, polymer–polymer hetero-junctions and polymer–polymer bulk hetero-junctions, donor–acceptor concepts, etc. The current state of the art rests on the ideas held in these documents. University of California seems to be the sole owner of the US patents. No assignments to other parties have been recorded at the USPTO. Konarka Technologies has obtained a limited sole license in a specific field of use. According to the findings from analysis of the two key patents indicate that there is no protection in Europe: A PCT application (WO/1994/005045) claiming priority from US application 07/930,161 (now issued as US Patent No. 5,331,183) was filed August 17, 1993. Based on this PCT application, an EP patent application 93920199.2 was filed, but later deemed withdrawn (due to lack of paying filing and search fees) effective March 18, 1995. In a patent environment it is close to sensational, that such an important patent was not maintained in Europe. This means that solid work from Heeger and Saricifti, contained in the two patents, in principle is free to access in Europe in contrast to the US and Japan where these patents are issued and pending, respectively.

4.10. Freedom to operate in Europe

To detail this situation and bring it up to date by applying the Cintelliq polymer solar cell dataset, a patent and freedom to operate analysis of Europe was carried out as Europe is an easily identifiable market. The retrieved patents are grouped in Table 13 which shows that the core focus is on "general materials" subcategorized under terms like organic-, polymer- and small molecule-solar cells, but also the active layer and process are in focus. The largest group of patents is taken to indicate which area within the field of polymer solar cells that is the most sought. The organic/polymer solar cells are the most sought and essentially represent the same area but are categorized as two here because that is how they are marked out in the patents. The second most sought is the small molecule and the least sought is polymer hybrids. After reading through all of the patents it was established that 56 patents are issued of which 5 have expired as they have passed the lifetime for an issued patent—a patent can only be enforced once it is issued and during the patent life. Taking a closer look at the inventors of the 56 issued patents, a number of names arise. The 56 patents in Table 13 have 72 inventors, as there can be more than one inventor per patent. The top inventors are mainly connected to Merck. Nearly all of those issued patents have been published in Europe, the US and Japan. About half of them have been published in China and Korea while a few have been published in Australia and Taiwan. When looking at earliest publication date it becomes evident that after the increase in issued patents from 2001 to 2004 there is a significant drop in 2005–2007. This can be explained by the fact that each patent application takes at least 3 years to pass through the patent system.

This implies that in combination with the increasing research effort it is almost certain that the increase seen from 2001 to 2004 will continue through 2005–2007 once all the patents have been processed.

When the 56 patents are distributed geographically it is possible to see which markets are crowded with patents. The map of Europe shown in Fig. 7 illustrates the freedom to operate for polymer solar cell commercialization. The countries with digits indicate the number of polymer solar cell patents in the given area up to November 2008. It becomes very clear that Germany, France, Great Britain and to a certain extent Holland are the countries with the highest concentration of polymer solar cell patents. The leftover 13 patents are scattered out over Finland, Sweden, Spain, Belgium, Ireland, Switzerland and Italy. This observation leads to the conclusion that, as expected France, Germany and Great Britain are crowded with polymer solar cell patents, but the rest of Europe is seemingly free to operate in. What is more interesting is that aside from France only 4 patents cover the European Mediterranean coast where the potential for the use of solar energy is the highest in Europe. Countries such as Portugal, Greece, Turkey and all countries across the Balkan are totally free. The geographic polymer solar cell patent distribution

Table 13
The count of patents/publication numbers yield 56 issued patents in Europe as found from the Cintelliq polymer solar cell Dataset.

Type	Organic	Polymer	Polymer hybrid	Small molecule	Total
Active layer	0	2	1	4	7
Encapsulation	1	0	0	0	1
Material	1	23	0	11	35
Other layers	0	2	0	0	2
Process	2	6	0	2	10
Substrates	1	0	0	0	1
Total	5	33	1	17	56

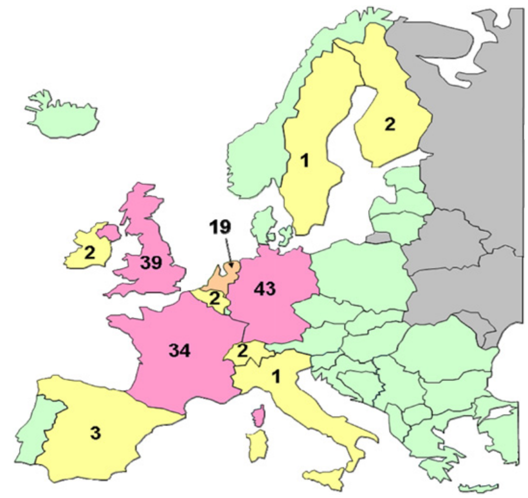

Fig. 7. An illustration of the freedom to operate in Europe for the 2004–2008 issued patents. Digits show the number of issued and active patents in that country. Countries coloured in green have no valid patents and grey areas were not included in the search.

is a result of the research effort in the 4 main countries, both in academic and industrial environments. So why are these patents not registered in other countries? There are three possible reasons for this:

(1) The capability of academic inventors of economically maintaining the cost of patents in several countries is very limited, thus they stick to their home market or the 2–3 traditionally large markets for technology solutions in Europe
(2) Industrial inventors, like Merck and others have a fixed market focus and this is again the large economies in Europe, thus it seems, that it is not where the sun is dominant which has been decisive for the patenting. This again comes down to the estimate of where the inventors are capable of utilizing the economic potential of the patents. Large chemical companies in Germany are traditionally close to their large near markets in Europe.
(3) The issued patent is often not validated in other regions than France, Germany and the UK within 3 months of issue of the European patent. The reason for this being that the patent requires translation into the given language and requires annual maintenance fees with each local authority.

This also underlines a significant difference between the European and the US patent system. Both regions are multistate regions that technically are on the same scale in terms of the number of member states and population (the US has more states but a smaller population). In the US one language suffices for all states whereas in the EU which is a multilingual region the cost of maintenance and translation is nearly a multiple of all the individual states. Enforcing and maintaining patents in the Europe is therefore notoriously known to be the most expensive and complex. Unless the patent holder is absolutely certain that a given patent will generate revenue then it is not maintained.

As a final observation, it is noted that the OPV patent landscape is indeed a merciless environment. The speed of PCE development has been impressive during the last 36 months. The improvements have been made through the best combination of existing or slightly improved primary and secondary patents combined with knowhow, which simply is being kept secret. During this process yesterdays PCE record was made obsolete with today's improvement, but further improvement will make these landmarks obsolete and this process will continue until the technology has stabilized at the optimum cost/performance ratio. Many patents have been published on polymer materials that will never have a market potential as development has caught up with them.

5. Polymer solar cells today and in the near future

The state-of-the-art for polymer solar cells in early 2010 is viewed as being in a pre-commercial or very early commercialization stage. The technology has been demonstrated to be scalable from the laboratory single device scale to fully industrial roll-to-roll processing. This should be viewed as a clear strength of the technology as it is demonstrated that it can be both made and use can be made of the technology in demonstration products. There is however still a considerable amount of development needed before a simple polymer solar cell module becomes commercially viable and it is most likely that the business opportunity today has the enormous ability for adaptation and integration of the technology rather than solar energy conversion itself. Since polymer solar cells compete poorly with all other thin film technologies it is unlikely to attract any useful market shares before the power conversion efficiency significantly approaches 10% for roll-to-roll-processed modules and the lifetime exceeds 3–5 years. One could view the polymer solar cell as a commercially fragile technology that perhaps is destined to failure due to poor performance in the competitive and small market that has to be conquered before that larger future markets can be reached. In addition the technology is dominated by possibly too few players that have to operate in a highly complex and dynamic patent field. There is however clear opportunities that emerge when examining the business opportunities, the markets and juxtapose this with the patent field as detailed above. Some of those opportunities are due to very particular events and patent procedures in particular regions. It is likely that the revenue from polymer solar cells will be extremely marginal since customers have a wide selection of thin film solar cell technologies and as such have no particular inclination towards polymer solar cells. The choice of PV technology is rationally based on the value of the technology in a given application. It had been different if the only available thin film PV technology was polymer solar cells. In a traditional SWOT analysis the weaknesses and threats are thus clearly identified as the poor performance, a competitive market, too few and too dominant patent stakeholders. The strengths and particularly the opportunities are less clearly identified and perhaps even misunderstood by many. It should be clear from the above that the large freedom to operate in Europe is one of the greatest opportunities for the technology and this may be what saves it in the end such that it can make it through to phases 3 and 4 (Table 3). An additional opportunity lies in the fact that one of the most performing material combinations P3HT–PCBM is free to exploit commercially in a polymer solar cell. There is no composition of matter patents on P3HT or PCBM. In many European countries (Fig. 7) it is thus possible to manufacture complete polymer solar cell modules based on P3HT–PCBM with the objective to create profit. This is a significant strength as a relatively small capital investment in manufacturing equipment is required and there are no extra cost associated with licensing patents or maintaining patents for a small company that would pursue such a business opportunity. This large freedom to operate implies that there will be little dominance in the field and competition between polymer solar cell manufactures will be ruled by the best product in terms of cost/performance ratio. The consumers will play a vital role here as they will be the ultimate judge of the polymer solar cell product. In terms of the patents that are in state in Europe many of them are likely to be difficult to enforce. As an example the operation of preparing and solvent annealing the P3HT–PCBM mixture from a particular solvent which is known to significantly influence the performance represents an important and truly proprietary operation. It is however very difficult from the patent holding company A to demonstrate (in a court of law) that some other polymer solar cell producing company B has made use of the operation described in and protected by the patent just by examining the polymer solar cells that company B produces. Company B is likely to state that they did not make use of the claims held in the patent and somehow company A must show how company B have violated their patent right which can be very difficult or impossible because all evidence of which solvent company B used is unlikely to be detectable in the final product. Company A may thus have much important proprietary knowledge protected through patents but not all of it may be useful in a court of law or in protecting others from copying the technology. This is why composition of matter patents are the strongest patents you can have as the violation of patent rights are obvious with the product at hand. A particular layer structure or particular use of materials in the product is something that can be verified and analyzed. Process patents are inherently weak and unlikely to be enforceable in many cases unless the process leaves traces that are unique fingerprints of that process. One example could be a process patent on the use of a particular film forming technique for a particular materials combination where the film forming techniques leaves some unique signs of it use. An example could be slot-die coating that may result in unique film thickness differences across a printed stripe due to the uneven drying properties of low viscosity solutions with a significant wet thickness. In such a case a unique trace is left in the final product. Most often however processing information is lost or erased in the final product.

6. The need for standards

There are currently no standards within the field of OPV and it should be considered mandatory that standards are developed as a quality assurance for the technology. As IP develops it is expected that technology specific standards for materials, processing, encapsulation, performance, stability and Balance of the system—including inverters, systems for application, etc. will develop concurrently. This is simply necessary to establish consumer trust in the technology, as the current trend is a branching towards numerous methods (from material to finished module) of manufacturing, which makes it hard to know what is what—even among industry insiders.

7. Future developments that can significantly alter the conclusions of this review

Due to the long time between initial filing of a patent and its final issue (up to 6+ years in Europe) it is complex to project the shape of a patent field and its influence on a non-proven market for a technology that essentially took off 10 years ago in terms of filed patents (see Fig. 4). This would in most cases make it impossible to make firm statements of a technology. The important freedom to operate in Europe, however makes it much more straightforward to define the boundary conditions for someone wishing to enter the field with a commercial goal as described above. There is however still some factors that can significantly influence the willingness of the polymer solar cell technology to respond well in a commercial sense. Firstly, the entire world is in a state of awareness with respect to the environment and this large focus which is very political may significantly influence the governmental investments in scientific projects related to polymer solar cells and other solar cell technologies. Political decisions to support a particular type of thin film PV technology firmly is likely and could thus significantly alter that the competition between different technologies in the field of thin film PV. Secondly, the use of indium-tin-oxide in roll-to-roll manufactured polymer solar cells available today is unlikely to be competitive in terms of cost even with significantly improved power conversion efficiency and the development of a printable and transparent electrode combination as an alternative to indium-tin-oxide may not only represent an important patent possibility but could also significantly improve the competitiveness of polymer solar cells with respect to other thin film PV materials. Thirdly, the appearance or disappearance of polymer solar cell companies can critically influence the belief in a polymer solar cell market in a very difficult period for the technology where required investments are large and the corresponding revenue is small or zero. The disappearance of one of the few large stakeholders would possibly spell commercial doom for the technology and could make the patent situation in the aftermath very difficult to overlook until all patents from that stakeholder are reassigned.

8. Conclusions

The business opportunities for polymer solar cells were analyzed and based on the current understanding of the technology, its capacity and estimated annual market that could be in the range of 500 million US$ by 2018. This market will be in competition with other thin film technologies and it was found that significant improvements in the polymer solar cell technology would be warranted. Power conversion efficiency, operational lifetime and cost would all need to be much better before a significant market share can be anticipated. The significant competition from other better performing and available technologies means that cost must be essentially reduced to attract any market shares. From this point of view commercialization looks dauntingly difficult. Polymer solar cells however also open up for new possible markets as for instance in very low unit cost products for third world countries and it may be that such markets can be conquered by polymer solar cells and thus avoid the hard competition of existing thin film photovoltaics. The patent field of polymer solar cells was mapped and it was found that there is a larger freedom to operate in most of the European countries. It was also found that aside from the EU, US and far east there are completely open fields such as South America, Africa, Middle East, Central Asia and Australia—in other words the world is open for polymer solar cells, and there is a significant chance that many academic and industry players will create small patent pockets. The cost/performance ratio will be a significant factor deciding which technology solutions prevails in the given market segment. This should be viewed as a strength of the technology as it places competition where it matters, namely on the overall performance of the technology and it prevents one or two players from dominating the commercial aspects of the technology. The settling of disputes concerning patent infringements between competing companies will thus be on the market through securing market shares and attraction of customers rather than in a court room. In the case of polymer solar cells this should be viewed as fortuitous as it is a marginal technology at the present stage of market entry and lack of competition and the possibility for one or two players to dominate the small polymer solar cell market could spell the end of the technology (however useful it may be).

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