



OLEDs and E-PAPER: Their disruptive potential for the European display industry

Author: Simon Forge and Colin Blackman

Editor: Sven Lindmark



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■ Preface

Information and Communication Technology (ICT) markets are exposed to a more rapid cycle of innovation and obsolescence than most other industries. In order to avoid losing market share to competitors in commodity markets, ICT companies have to sustain rapid innovation cycles. As a consequence, the competitiveness of the European industry in this sector must pay attention to emerging and potentially disruptive technologies.

In this context, the Directorate-General for Enterprise and Industry (DG ENTR) and the Institute for Prospective Technological Studies (JRC-IPTS)¹ have launched a series of studies to analyse prospects of success for European ICT industries in the face of technological and market innovations.² These studies, under the common acronym “COMPLETE”,³ aim to gain a better understanding of the ICT areas in which it would be important for the EU industry to remain, or become, competitive in the near future, and to assess the likely conditions for success.

Each of the “emerging” technologies (or families of technologies) selected for study are expected to have a potential disruptive impact on business models and market structures. By their nature, such characteristics generate a moving target whose definition, observation, measurement and assessment precludes the use of classical well-established methodologies. The prospective dimension of each study becomes an intrinsic challenge that is to be solved on a case-by-case basis using a mix of techniques to establish lead-market data through desk research, expert group discussions, company case analysis and market database construction. These are then combined with a strong reflection on ways and means to assess future competitiveness of the corresponding industries. At the same time these characteristics result in reports that are uniquely important for policy-makers.

The collection of COMPLETE studies illustrates, and each in their own right, that European companies are active on many fronts of emerging and disruptive ICT technologies and are active in the supply to the market with relevant products and services. Nevertheless, the studies also show that the creation and growth of high tech companies is still very complex and difficult in Europe, and too many economic opportunities seem to escape from European initiative and ownership. COMPLETE helps to illustrate some of the difficulties experienced in different segments of the ICT industry and some of the anguishes of growing global players from the ground up. Hopefully, COMPLETE will contribute to a better understanding of opportunities and help shape better market conditions (financial, labour and product markets) to sustain European competitiveness and economic growth.

The present report reflects the findings of the JRC-IPTS study related to Display Technologies (OLEDs and Electronic Paper). The report starts by introducing the technologies, their characteristics, early market diffusion and potential industrial impact, before moving to an analysis in terms of the contribution to the competitiveness of the European ICT industry.

1 IPTS is one of the seven research institutes of the European Commission's Joint Research Centre (JRC).

2 This report is one out of a series, part of the umbrella multiannual project COMPLETE, co-financed by DG ENTR and JRC/IPTS for the period 2007-2010 (Administrative Arrangement ref. 30667-2007-07//SI2.472632)

3 Competitiveness by Leveraging Emerging Technologies Economically

The report concludes that both OLEDs and ePaper are both potentially disruptive, thus offering opportunities for the European industry to strengthen its position in the growing displays market. European strengths include its capacity in R&D, bulk materials and process equipment. It is weak in however complete display and/or device production. Nevertheless, if the EU industry concentrates in participating in the value chain, not hoping to dominate it end-to-end, then it can be a significant player in those mentioned segments as well in content distribution and new product design for some ePaper applications.

Although it is not emphasised in this report, it is worth noting that public funded research has played a significant role in establishing a critical mass of experience and technological capacity in the course of developing these potentially disruptive technologies. Specific R&D funding to the area of OLAE (Organic & Large Area Electronics) amounts to some € 300-400 million over the past 5 years with some 60% contributed from national research programmes (most significant being from the UK and Germany) country1 and) and some 40% from EU (FP6 & FP7).

David Broster
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■ Executive Summary

Displays are an increasingly important segment of the ICT industry. In the early 1990s, the bulky cathode ray tube (CRT) began to be replaced by flat panel displays (FPDs) based predominantly on liquid crystal display (LCD) technology. Since then, the global display industry has grown dramatically, to over €100 billion. Moreover, development of flat panel technologies has enabled the creation of important new product segments, two of which are the dominant growth categories today in consumer electronic devices - laptop computers and mobile handsets.

Asian suppliers for thin film transistor liquid crystal displays (TFT LCD) have come to dominate the display industry. Now two new technologies may be on the verge of breaking into the market – organic light emitting diodes (OLEDs) and electronic paper (e-paper). The purpose of this report is to assess Europe's future competitive position in the display industry as a result of progress in these new technologies.

The study, on which this report is based, set out to assess whether these technologies have the potential to disrupt the current market in displays. Will these technologies substitute existing technologies? Will they also enable completely new applications and the creation of entirely new market segments? If so, what are the implications for the competitive position of the European ICT industry and, if there are new opportunities, how well placed are European firms to take advantage of them?

The study was comprised of two main steps:

- First, a techno-economic analysis was carried out of the potential for further development of the two technologies in question, their

possible applications, and their potential market success.

- Second, and building on the first step, an assessment was made of the competitiveness of the European ICT industry in these two technologies, by analysing the impacts of OLEDs and e-paper on leading markets, and then evaluating their position in the European ICT industry. This made it possible to assess the value chains for OLEDs and e-paper and which segments are most likely to offer opportunities for European players in the event of discontinuities arising from the new technologies.

Structure of the report

Chapter 1 sets the context for the study, explaining the study objectives, and highlighting relevant aspects of the current displays industry and the ICT sector more generally. It goes on to define the technologies with more precision, and concludes by summarising the state of the art in the various technologies, considering the advantages and disadvantages of OLEDs and e-paper in comparison with current technologies, as well as trends in manufacturing processes.

Chapter 2 examines the market for OLEDs and e-paper, drawing on published market analyses, forecasts and interviews with leading industry representatives to build a picture of market potential, globally and in Europe, for the main application areas. Interviews also helped in formulating the detailed value chains for OLEDs and e-paper, which are described in Chapter 3.

In Chapter 4, the European Union's competitiveness in ICT generally and, more

specifically, in display technologies is assessed. This is followed by an analysis of the strengths, weaknesses, opportunities and threats presented by these technologies in the European Union. All the findings are brought together in Chapter 5 to assess the disruptive potential of OLEDs and e-paper.

Finally, Chapter 6 summarises the key findings on the disruptive nature of these new technologies and looks at the opportunities for Europe and the strengths it can build upon.

Defining the technologies

The report points out that, strictly speaking, it is incorrect to describe OLEDs and e-paper as 'two technologies': OLEDs are really a family of technologies, and e-paper is an application that can be produced using a number of different technologies.⁴ Nevertheless, for convenience, the study refers to e-paper as 'a technology' throughout. The study defines OLEDs as polymers that emit light when a current is passed through them in one direction. In multi-pixel colour form, OLEDs can be used for displays for ICT, consumer goods and industrial applications. In the single-pixel form, OLEDs can be used as a new kind of lighting. E-paper, on the other hand, is a portable, reusable storage and display medium, which is thin and flexible. It is literally the electronic substitute for the printed page. Typically, it reproduces mainly static text, usually monochrome, on a screen which is highly flexible. In the future, it may even be possible to fold or roll these screens like traditional paper.

Theoretically, OLEDs have several advantages over LCDs. First, since they generate their own light, they do not require backlighting as LCDs

do, which means they can be made thinner and lighter. This also means they consume less power, which makes them attractive for applications such as laptops and mobile handsets. Additionally, the quality of OLEDs in terms of colour range, resolution, brightness, contrast, response time and viewing angle is impressive in comparison with LCDs. They could be manufactured using a simple continuous method at low temperature, rather than the batch processing in high temperature clean-room conditions necessary for LCDs. This means that a far lower cost base could be attainable for OLEDs in volume production, compared to LCD and plasma FPDs

On the downside, being organic, OLEDs suffer from degradation in the basic material which affects their lifespan. Longevity no doubt will improve, but early OLED TV screens have perhaps only one-third of the lifetime of an LCD. Moreover, OLEDs degrade in such a way that the red, green and blue colours deteriorate at different rates, adding to the complexity in producing them. These are serious drawbacks that will limit their application and may hamper the investment necessary for a volume of production which would allow their cost advantages to be realised.

E-paper, as already mentioned above, is an application that can use several alternative technologies, such as electrophoretic, cholesteric LCD, electrochromic and nematic bistable LCD. These different technologies bring different advantages and drawbacks in terms of their features and their manufacture. Like OLEDs, e-paper is light in weight and has even lower power requirements because images remain without having to be refreshed. The characteristics of ultra-thinness and flexibility really make e-paper different to current displays.

Though e-paper has been envisioned for decades, it has been slow to arrive because it requires the putting together of two entirely new technologies. The first is the 'electronic ink' that creates the actual printed display on the e-paper

4 Note that defining the technologies is not completely straight forward. Both can be regarded as being part of a larger family of plastic / large area electronics, where applications also include lighting, signage, organic photovoltaics, etc.

page, and the second is the flexible electronics required to generate the pattern of text and images on a flexible page. The challenge has been to produce low-cost, high-volume flexible display products using organic electronic materials that can be used at room temperature, allowing the circuitry to be mounted upon a flexible plastic substrate rather than glass.

Applications and market potential

The major existing markets where OLEDs could be a substitute are TV screens, IT monitors, and smaller screens for mobile handsets. The markets in the other application areas identified are typically smaller or more uncertain, the prime example being lighting. The global TV display market is valued at over \$40 billion, driven in recent years by demand for larger flat screens. Other significant markets are displays for laptops and for mobile handsets.

Clearly there are some significant market opportunities arising from the commercialisation of new display technologies. It seems likely that OLED TVs will gradually enter the market over the next few years as a premium product. The extent to which they could take market share from LCDs is unclear but will critically depend on the resolution of technical obstacles. If these can be overcome, mass produced OLED TVs could undercut LCD TVs in price while offering higher picture quality and thus dominate the market. However, LCD technology is still maturing and improving and there has also been substantial investment in production facilities that will not be cast aside in the short term.

OLED screens may well make significant inroads in the market for mobile handset screens, where their advantages will be most sought after. Similarly, desktop monitors, notebook screens, MP3 players and so on are likely to be significant markets.

The market for lighting is potentially enormous but more uncertain. OLED lighting seems likely to remain a niche product for the foreseeable future, owing to investment in existing incompatible infrastructure. Nevertheless, some of these market niches could well be significant and the potential for energy efficiency means that OLED lighting could be seen as highly desirable if energy costs soar. Also, there is the possibility that OLEDs could form the backlight for a TFT-LCD screen. Ordinary LEDs (inorganic) are appearing as backlights, for instance in the new Apple laptops, and are claimed to consume less power and have higher visibility.

The most visible result of e-paper developments – the e-reader – looks set to take off in the next few years, possibly in North America first. The e-reader could well have an effect similar to the iPod. Other e-paper applications are likely to take off more slowly, depending critically on achieving very low cost.

The disruptive potential of the two technologies

Both OLEDs and e-paper have the potential to disrupt the existing displays market, but it is still too soon to say with certainty whether this will occur and when. Success for OLEDs depends on two key technical advances: first, the operating lifetime, which is based on the stability of each colour (see Chapter 4, Section 4.2 on recent ageing tests); and second, the production process. If the latter can be developed for larger screen sizes, with consistent high quality at low cost by using low cost printing and room temperature processes, that combination could take unit costs well below those of LCD. However, TFT LCD is far from being a mature technology and incremental improvements will continue to be made, so the bar will get higher for OLEDs. Moreover, LCD FPD prices are also being driven down by the global recession. This could hasten the entry of OLEDs, if their production costs are

lower, as the LCD bulk buyers (TV manufacturers, laptop makers etc) are now demanding below-cost prices when purchasing LCD FPDs. In 2008, it was predicted that, due to the collapse in global demand, LCD FPD sales may even shrink for the first time in 2009 by 3% measured in unit sales.⁵ Also, it has recently come to light that some LCD FPD industry players have been engaged in price fixing, indicating there is a buffer zone in pricing for LCD FPD's which will further challenge OLEDs.⁶

The industry is quite divided on how this will play out over the next few years. It is in the interests of the large Asian TV suppliers to maintain the status quo, because they are only now reaping the rewards of their large investments in infrastructure to manufacture LCD. Unsurprisingly, those in favour of OLEDs are generally those whose fortunes are not tied to LCD success and they are probably being over optimistic in their view of the speed with which OLEDs will progress technically and in the marketplace. Nevertheless, it is notable that many of the big Asian display suppliers, such as Sony, Samsung and Sharp, are hedging their bets and positioning themselves to take advantage of any discontinuity. Taking all the study's findings into account, it is unlikely that we will see significant market share for OLED TVs until 2015-2020. However, they are likely to be available as premium products in the next few years, led by Sony's small TV, an 11-inch model initially costing US \$2,500. More likely is the take up of smaller OLED screens for devices with shorter lifetimes, such as laptops, mobile handsets and MP3 players and we could see this occurring in the next three to five years. OLED lighting products seem likely to remain a niche segment and are not likely to disrupt the lighting market in the short to medium term. Their use in pure ICT applications is restricted - perhaps to a more efficient backlight for LCD FPDs.

The situation for e-paper is somewhat different since it is not just a technology substitution but also an application that forms a new product category. In this sense, it is highly disruptive because it opens the door to new applications, largely text-based, not just in ICTs but also in consumer goods, pictures and advertising that can use its key properties. It could also displace display technologies that offer text-reading functions in ICT terminals such as tablet notebooks.

The industry applications in retail, advertising, industrial and vehicle display could occur as soon as robust technology is available. This would imply a timeframe of the next 3-5 years for major technology take-off, although the actual changeover may be piecemeal. The most visible form may be the e-reader, and there are signs that the market may be ready to take off, with Amazon's Kindle success in 2008 and other devices on the market such as Sony's e-reader now being relaunched.⁷ On the content side, the publishers have been preparing for this for at least 20 years. The question is whether the consumer is ready and here one senses that successive waves of ubiquitous diffusion of consumer electronic devices over the past 15 years, especially mobile phones and MP3 players, may well mean that consumers will soon be ready for the 'next big thing'. Everyone, of course, dreams of replicating Apple's iTunes model.

The opportunities for Europe

With regard to OLEDs, there are three discrete segments in the OLED value chain where any discontinuity could offer EU firms the opportunity to play a more significant part in the displays sector:

5 Kwong, R. (2008)

6 Jordan, LJ. (2008)

7 It was chosen as a contender for one of the 'gadgets of the year' in December 2008 in a popular UK TV show and is selling via bookshop chains in Europe.

- Original R&D and IPR for devices and for the manufacturing process and material supply/verification: innovation by the European Union in OLED technology is strong and growing in the basic OLED mechanisms, manufacturing and materials.
- Bulk materials for manufacture and glass: the European Union is potentially strong in this and has leading special organic compounds suppliers, but other global suppliers are also present.
- Process equipment: there are some strong European players but also major competition from Asia and USA.

Then, however, the question arises of whether suppliers in this segment would have enough of a critical mass to change the balance of industrial power in the whole display segment. With the European Union's fairly restricted access to finished goods production cycles, especially for TVs and laptops (i.e. screen dimensions of over 10 inches), this seems remote. Only in smaller screen sizes for mobile handsets could there perhaps be a possibility of entry by EU display screen suppliers.

For Europe, therefore, the real point of entry in OLED FPDs is most likely to be in the mass production of smaller FPDs for mobile handsets. With some 3 billion users globally, this is an enormous market which is still growing. The replacement and growth handset market volumes combined may be of the order of 1 billion FPD units per year, depending on global economic conditions and OLED handset pricing.

From the analysis of the e-paper value chain, we can see that the entry of EU suppliers is perhaps possible across other value chain segments than just OLEDs, specifically in:

- Original IPR and/or material supply/verification as innovation by the EU in e-paper technology is strong and growing in the basic OLED polymer photonic

mechanisms, as well as the key areas of manufacturing processes and production materials.

- Supply of bulk and refined materials – EU suppliers have a high profile and established reputation, so there is a medium to strong chance here, as the EU has one of the leading special organic compounds industries. However, other global suppliers are also present which are closer to the electronic manufacturing centres in Asia and the United States specialist chemical suppliers are also strong.
- As a process equipment supplier, there is a medium-level chance of success with the EU's advanced players and its presence in printing technology, but there is also strong global competition from the USA and Asia (Toppan, etc).
- The EU has some pilot plants for OEM e-paper film and/or screen manufacture, for instance in Germany, so there is a medium chance here for the few EU players. However, there is major competition from Asia and the USA.
- Branded application device and display manufacturers with retail device sales do exist in the EU (Polymer Vision, iRex, Endless Ideas, etc). Thus there is perhaps a medium-level possibility of success for the EU players.
- Europe has not yet reached the US level in product design and tied retail sales channels but preparations by the publishing industry in e-books are under way, so there is a medium-level chance. In other application areas, such as signage, the USA and Japan seem to lead but it is too early to estimate whether the EU could successfully compete on the global market.
- The EU is quite strong on content for e-readers –publishing e-books. Many established publishers in the EU are preparing titles for a nascent e-book market using open standards, which may possibly lead to global exports, as well as European sales in each national language, if e-readers take off.

Manner of market entry	Degree of EU strength	Value of strength factor
New players, formed for new technologies with an evolved industry structure	HIGH in certain value chain links – especially R&D, materials, production processes	High, despite the display value chain being close to the LCD/ semiconductor model today
IPR – Ownership and control	MEDIUM – EU has gained more expertise in applying IPR to production.	Low – value is in local skills acquired, not necessarily pure ownership of IPR. Relevant IPR is fairly globally owned so ownership may be useful for trading IPR
Competences and skills	HIGH - in some key segments – materials, printing, production equipment, original R&D and end-product design	High – possibly the key parameter for creation of industry in the EU
Industrial ecosystem or clusters with 'mini value-chain'	LOW - From original R&D, EU has built some eco-systems in materials, print production processes, the manufacturing equipment to end-product design	Medium – for the segments in which the EU may concentrate but not as crucial as for final assembly

- Overall, a concerted effort by EU suppliers could lead to a revision of the current state of play in consumer electronics in the e-paper/e-reader segment but this may occur in complete devices such as e-readers, rather than e-paper film.

Conclusions

Interestingly, although OLED is a pure technology and e-paper an application with many technologies, the market entry strategy has common features. A summary of how Europe could enter the display market with both OLEDs and e-paper is shown in the table below:

The above analysis implies that the European Union has a reasonable chance of re-entering the display industry. It is weak in the key area of complete FPD or device production, owing to its lack of eco-systems of components. Nevertheless, the EU could be a player in these segments, if European industry concentrates on participating in the value chain, and does not hope to dominate it end-to-end. Moreover, as regards certain e-paper devices such as e-readers, there is the possibility that the EU could enter the global export market via production in lower cost Eastern and Central Member States. As regards OLEDs, the EU might enter production for small screen sizes. However, this is a very important market in its own right, where mobile handsets are a major segment demanding high volume.

■ 1. The Potential for New Display Technologies

1.1. Context, objectives and approach to assessment

Since the 1960s, ICT markets have been exposed to ever more rapid cycles of innovation and obsolescence, compared with other industries. New products such as the mobile handset, and the product technologies they depend on, such as low-power non-volatile RAM, have often become commodities in a very short time, once take-off is established. Technology innovations like these may have a disruptive impact on business models and market structures and hence are of strategic importance to Europe. Within this context, display technologies have been identified by IPTS as one of several groups of technologies suitable for further analysis, and these technologies are the focus of this particular study. The study therefore takes place against the background of the competitiveness of the European ICT industry.

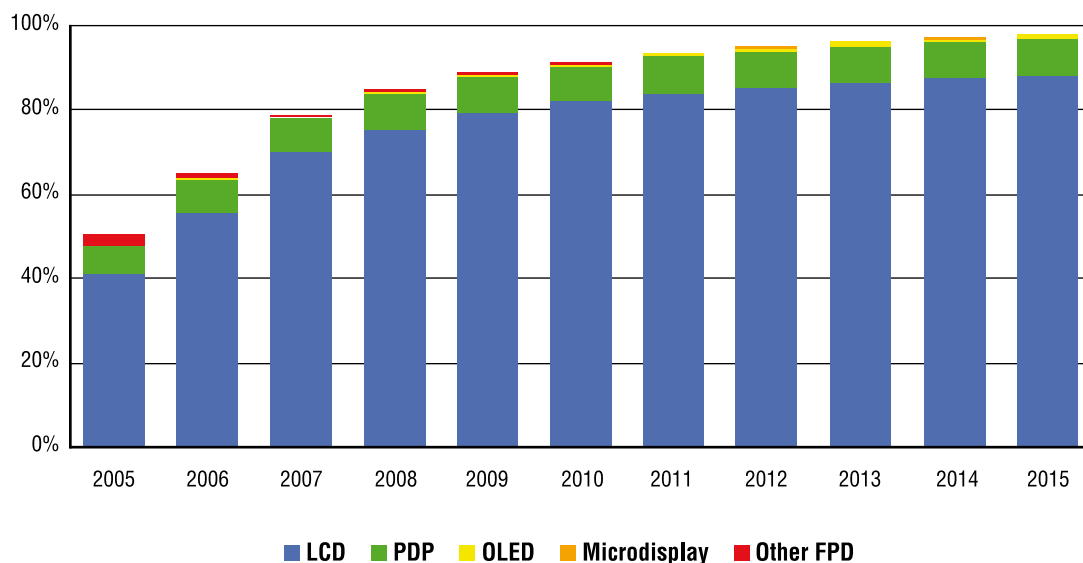
DG Enterprise has entrusted JRC/IPTS with the COMPLETE (Competitiveness by Leveraging Emerging Technologies Economically) study. Its findings should highlight those areas of Information and Communication Technology (ICT) where EU industry is likely to remain, or become, competitive in the future. So a major goal is to assess the probabilities of commercial success of EU ICT industry innovations. In consequence, this study for IPTS has the objective of analysing the prospects of success of the EU ICT industry in displays when faced with new market innovations in two specific display technologies – Organic Light Emitting Diodes (OLEDs) and electronic paper (e-paper).

In recent times, the display industry has been overwhelmingly dominated by the thin film transistor (TFT) LCD, while other technologies have been relegated to niches. Geo-politically the industry is dominated by Asian suppliers for TFT LCD. However, two new technologies are seen as potentially disruptive – OLEDs, and electronic paper or e-paper. OLEDs are beginning to be commercialised, in small simple screens such as MP3 players and mobile phones with larger TV screens promised in 2009; companies such as E-Ink are now introducing a new generation of colour e-paper, some using colour filters as in conventional LED displays, with reflected light from monochrome generation.

The study was divided into two steps. First we undertook a techno-economic analysis, much of which is given here and in Chapters 2 and 3. Our approach for this first step revolved around data gathering on the industry structure and possible value chains, main technologies, market growth and the potential in new applications, and especially for disruptive applications. Both products and production processes were explored regarding factors affecting take up, for instance the sustainability of the technology in terms of environmental impacts in both manufacturing and use, eg power consumption or use of hazardous substances, which could reflect on take-up.

To do this, our approach was to use a range of research sources for the issues of the techno-economic analysis, to cover definitions, state of the art, markets and scope for disruption, structured as:

Figure 1-1. Total display sales share by flat panel technology



Source: DisplaySearch, 2008.

- Suitable definitions of the technologies – possibly improving on those definitions initially suggested by IPTS
- Current state of the art – the key technologies and how they work
- Existing and potential new applications – capabilities and characteristics
- Future technological development – future trends, results and discontinuities
- The overall market potential and growth rates – market size today, trends now and in the future, with geographical markets
- Identification of the value chain and its key players
- The disruptive potential – where it may substitute and the related market impacts

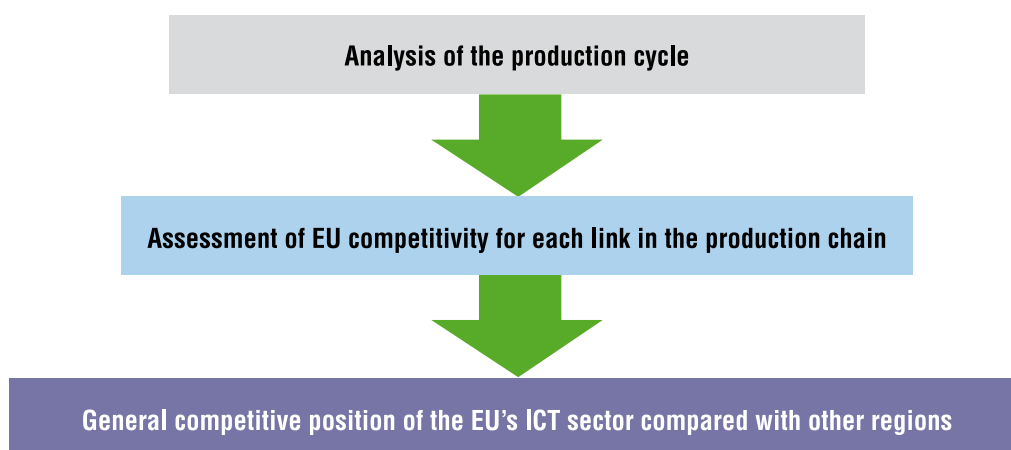
The techno-economic analysis acted as the basic input to the second Step, an assessment of the competitiveness of the EU's ICT industry, particularly with regard to display technologies. Thus we needed to construct a methodology to assess the position of the EU ICT industry and its competitiveness, as described below.

Market analysis data currently available certainly endorses this view of LCD dominance in the near term. For instance, DisplaySearch's forecast to 2015 in Figure 1-1 shows a highly marginal impact of OLEDs.

In addition, it is possible that other technologies may also appear to challenge OLEDs (e.g. FEDs, field emission displays and SEDs, surface conduction electron-emitter displays using carbon nanotubes⁸). Therefore it is crucial to provide a thorough and nuanced analysis of the future prospects of the two technologies, as a possible outcome of the analysis could be that they are not likely to be disruptive, which we attempt to do here.

8 SEDs have been set back some years by patent disputes, principally between Canon and Applied Nanotech, now perhaps resolved in December 2008. Canon claims it has production techniques that make SED displays comparable in cost with LCD and plasma and a rival to OLEDs. SED may not be launched by Canon yet, due to descending costs of other technologies (Harding, 2008).

Figure 1-2. Methodology to assess the EU position in novel display technologies



Informed by the techno-economic analysis, we chose a methodology that seemed to be appropriate to address the study's key questions on the disruptive qualities and Europe's position for the two new technologies. Our approach is multi-faceted because it is only by looking at Europe's position from a number of different perspectives that a more complete picture can be built up. It also takes into account likely difficulties in data availability, typically encountered in such studies. Hence, our analysis of the future competitive positioning of the EU's ICT sector with regard to OLED and e-paper technologies comprised a series of steps, followed in this report:

1.2. The technical context – a brief summary

Before examining the technology aspects of OLEDs and e-paper, we briefly consider the main current technologies, for background and context.⁹

9 We note that, although the study focuses on OLEDs and e-paper, there are other technologies that may have potential for flat panel display, including: Plasma addressed LCD (PALC); Cholesteric LCD; Bistable nematic LCD; LED arrays; Thin film electroluminescent (Tfel); Field emission display (FED); surface emission display (SED); Electrochromic; Electrophoretics; Vacuum fluorescent; Thermochromic; Organic luminescent; CMOS backplane micro-displays; MEMS – micro electromechanical systems, also termed MOEMs – micro optical mechanical systems. Several of these are examined in Appendix 1.

1.2.1. The current market dominator – liquid crystal displays (LCD)

LCD is the current dominant technology and is the earliest type of flat-screen solid-state display. It employs an electric field to alter the light-absorbing properties of each element in the display, each pixel. An LCD display panel rests on top of a backlight, and the individual display elements are addressed electronically, to either block this backlight's emission or allow it to pass, effectively acting as optical switches. Although the inherent technology is monochrome, filters can be used to colour the output from the individual elements, creating a full-colour image. The drive technology used to apply controlling voltages to the elements can be passive or active, but the active method is now the most common, since it gives a faster response and higher picture quality.

Such displays are manufactured using semiconductor process techniques with steps of masking for deposition in a lithography type process inside a clean room environment. This is capital intensive and in terms of sustainability is becoming more questionable, especially on a large scale.

The LCD market has grown to dominate the electronic displays market over the past decade, now accounting for about 85% of the value of the

total market of about \$125 billion. The dominant players in 2007 were in order – Samsung, (around 17%) then LG Electronics, followed by Sharp, Philips, NEC and Sony, with others taking 25% of the market. Some 60% of the LCD market goes by area to TVs and over 30% to PCs, desktops and laptops as the TV has overtaken the PC screen as the market driver. In the smaller plasma FPD market, the leaders are Matsushita-Panasonic, LG Electronics, Samsung, Pioneer, Hitachi and NEC with many others taking over 20% of the market (Murray, 2008). A more detailed description of the displays market and the position of LCDs is provided in Chapter 2.

1.2.2. The plasma display panel (PDP) – how it works, and its disadvantages

The plasma display video panel is fairly well established, being invented in the 1960s for a computer terminal device with a monochrome screen. The first monochrome PDPs did not use a phosphor coating on the front panel as in a CRT. The PDP was made in large production runs for consoles such as for the IBM 3290 display of 1983. In 1993, Fujitsu introduced a 21-inch colour TV by using phosphors. Pioneer and Matsushita/Panasonic also produced TV screens with ever-larger sizes, the largest TV in the world in 2008 being a 150 inch plasma screen from Panasonic, 11 feet wide and 6 feet high (3.35 m x 1.83 m). Until 2006, plasma dominated the TV market for larger screens above 40 inches but increasingly LCD can compete for these screen sizes.

The display works with inert gases, neon and xenon, in hundreds of thousands of cells sandwiched in a flat glass envelope of two plates which are charged. These excite the gas to ionise and form a plasma. In the colour screen version, the gas ions emit UV photons which excite the phosphor on the back plate to give off coloured light. Each pixel is composed of three sub-pixels (for red green blue) having the three different coloured phosphors, like a shadow-mask CRT.

Cells are selected by control circuitry to form the image.

Plasma TVs are expensive to produce but offer high resolution, response time and brightness, compared to LCD panels and so are favoured for HDTV and large size screens, as they also offer a thin form-factor. They are good for full motion colour video. However the colour PDP suffers from screen burn of the phosphor layer for images held for any period of time (e.g. a menu toolbar on a PC). Moreover, PDPs are weightier, more expensive and consume more power than LCDs, so the TFT form of LCD has overtaken plasma for TVs, laptops and PC monitor screens. According to DisplaySearch, the volume of sales of plasma TVs in 2007 was one eighth that of LCD TVs.¹⁰

1.3. Defining the technologies and their applications

Strictly speaking, OLEDs and e-paper are not two technologies at all. OLEDs are really a family of technologies rather than a single technology. E-paper isn't a technology at all but rather an application that can be produced using a number of different technologies, including, ultimately, OLEDs.¹¹ However, for ease of analysis, it is perhaps helpful to refer to OLEDs and e-paper as two separate technologies with the link being physical flexibility. First we examine definitions for the two basic technologies.

1.3.1. Definition of OLEDs

Organic Light Emitting Diodes (OLEDs) are a next-generation display technology comprising small dots of organic polymer that emit light when

10 Digital Home Canada, 'LCD televisions outsell plasma 8 to 1 worldwide', 21 May 2008, <http://www.digitalhome.ca/content/view/2538/206/>

11 Not that defining the technologies is not completely straight forward. Both of can be regarded as being part of a larger family of plastic / large area electronics, where applications also include lighting, signage, Organic Photovoltaics etc.

charged with electricity. Much of the first research was in Europe, especially in the Netherlands, Germany and the UK, although Kodak in the USA did some very early research. In percentage terms, OLEDs are the fastest growing flat panel display technology today, with Europe playing a key role as a technology developer.

As multi-pixel colour displays OLEDs have many ICT applications in consumer goods and industrial applications. In the single-pixel form, OLEDs are also a candidate for new forms of lighting so that lighting manufacturers in Europe, such as GE Osram and Philips, are working on new concepts using its unique flexible properties.

Setting OLEDs in the industry context of the leading technology, i.e. various types of LCD, can be viewed as generating a taxonomy of the FPD industry, through the technical attributes of each, as shown below:

1.3.2. Definition of e-paper

E-paper is a portable, reusable storage and display medium, typically thin and flexible. It is literally the electronic substitution for the printed page. Typically it reproduces mainly static text, usually monochrome, with high flexibility of the whole screen so ultimately it may even be folded or rolled like traditional paper. This implies being produced as a thin film, rather than as a panel, like LCD or plasma FPDs. There are several technologies that offer e-paper properties.

Some other display technologies are also appearing which are of a flexible nature, but these may not be considered by many as e-paper, more as upgrades on inflexible technologies improved in their ability to be shaped as required. One instance is the flexible forms of the current TFT-LCD with bendable substrates in plastic or even stainless steel. Such displays are not e-paper, where we look for the qualities of paper – good

Figure 1-3. A taxonomy of current and future flat panel display technologies

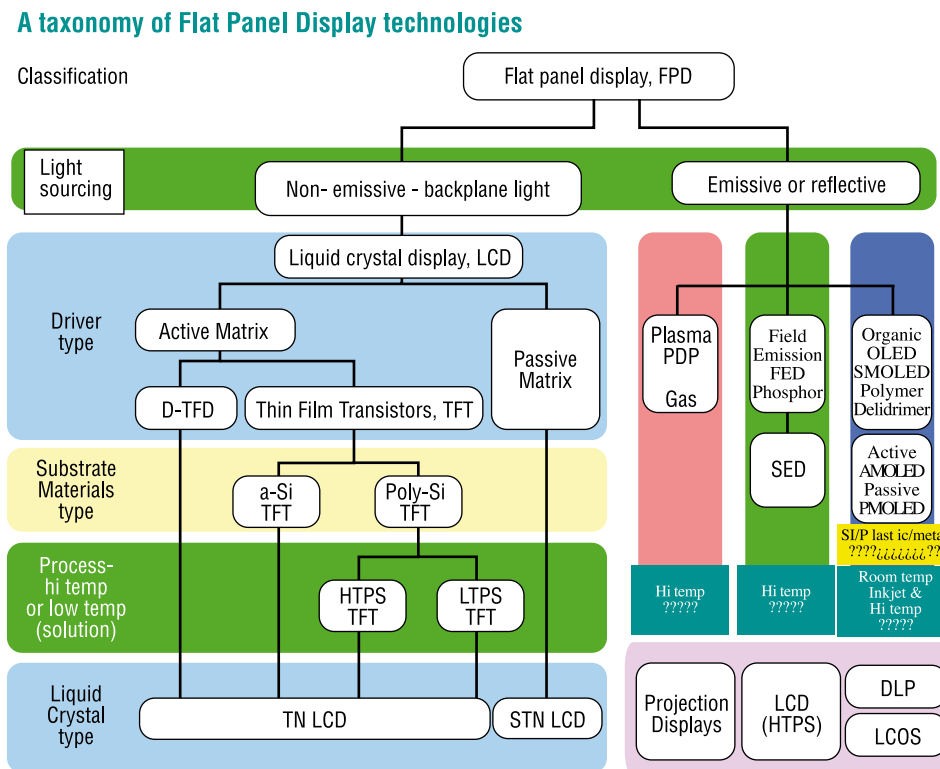
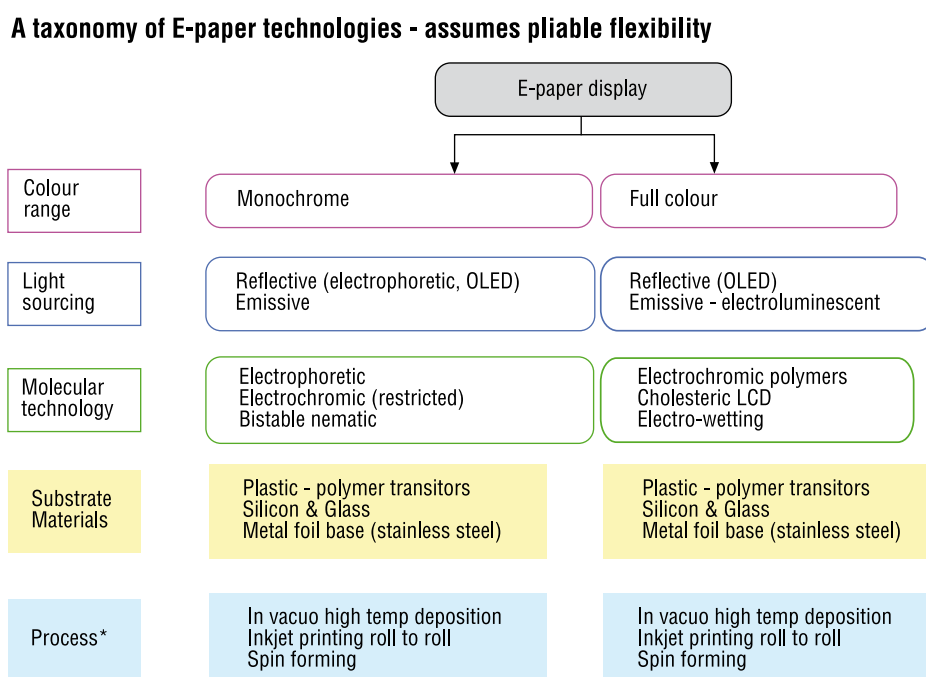


Figure 1-4. A taxonomy of e-paper technologies



* Each technology has its own process - range of types only is shown

for text, thin and flexible like a page of paper. E-paper technologies also offer a further key property of paper, in that ambient lighting may be used for reading, via its reflective properties, in which characters appear as black or a dark colour on white in a flexible substrate. Like paper, the image may remain in place without power, with duration depending on the technology – from minutes to hours.

Thus essentially the primary use today for its displayed images are text and simple graphics – with an image which is static, and has readable print quality resolution (typically 100-150 dpi) usually monochrome with a simple bi-stable mode (on/off) without refresh like a CRT or LCD. But unlike ordinary paper, the screen may be updated with the next page when reading. This may take as long as a second, but newer technologies may be faster, even with full motion video rates.

E-paper products are largely centred on electrophoretic technologies,¹² with E-Ink (USA, with links to MIT) being a major supplier for the technology and basic materials. Other players include Polymer Vision (the Netherlands) and Plastic Logic (UK), while PVI (Taiwan) has a volume production of electrophoretics in a silicon TFT fabrication facility and SiPix (USA) has flexible electrophoretics for smart cards (Gurski and Quach, 2005). Bridgestone (Japan) has its own electrophoretic technology. NTERA (Ireland) has an alternative technology for high colour, small flexible displays at very low cost. E-paper offers relatively simple manufacturing for the basic monochrome electrophoretic

¹² An electrophoretic display is an information display that forms visible images by rearranging charged pigment particles using an applied electric field.

Table 1-1. Flexible display technologies - comparison of OLED with E-paper and flexible LCD

Technology	Market pricing	Response time	Ease of entry – technology required	Contrast	Roll to roll, Ink-jet, Low-temp	Colours
Flexible OLED	High/ Med, descending	<1ms	High/ medium	>10,000:1	Yes	>16Mn
E-paper, Electrophoretic	Low, descending	<500ms	Medium, descending	>10:1	Yes	Monochrome, future >4096
Flexible LCD (Cholesteric)	Low/ medium	<2ms	Low/ medium	>250:1	Yes (future)	>4096

Sources – various industry sources including Display Technology Centre/ITRI, Taiwan, NCTU/Display Institute, Taiwan, 2007, 2008 and other sources

Table 1-2. Comparison of current dominant technology, LCD, with competing emerging display technologies

Display Technology	Need for backlight and its power	Power consumption	Thickness	Weight	Sustainability (lifetime)	Readability in daylight	Brightness	Response time	Flexibility of format/ screen size
LCD	Yes	+	+	+	+	+	+	+	+
OLED	No	++	++	++	-	++	0	++	++
E-paper	No	++	++	++	0	++	-	-	++
Plasma	No	-	0	0	++	-	0	++	++
LED	No	+	0	0	0	0	+	-	-
CRT	No	-	-	-	0	-	0	0	-
SED/FED	No	0	0	0	0	0	0	0	0

++ better performance than LCD ; 0 same as LCD; - poorer than LCD; + LCD performance level for comparison

Sources: Various industry sources

effect. A basic taxonomy is shown below of e-paper types.¹³

1.3.3. Comparing OLEDs, e-paper and LCD

OLED technologies and e-paper have different characteristics that make them suitable for different applications. Where they coincide is in the concept of flexible displays based on OLED technologies, which is not that far fetched for the future. It is perhaps helpful to compare them on a number of key parameters as to their position in the display market with the leading technology,

LCD, which is available in a limited flexible form using hollow flexible supports, see table below:

Sharp (the current LCD FPD leader with a new \$4 billion factory in Japan) favour LCDs although recently (July 2008) they have joined an OLED TV consortium. Their comparison of the two key technologies with other technologies already on the market gives the following table, where it is especially interesting is to compare OLEDs against the market leader today, LCDs, even if the view could be seen as coming from one of LCD's major producers:

OLEDs and e-paper are light in weight and have low power requirements. Typically they are more physically flexible than LCDs. In volume production they could be competitors to LCDs in some applications and, at the right price point, could be strong contenders for market leadership.

13 As an interesting footnote, Sony and LG Philips LCD demonstrated flexible OLED sheets at the Society for Information Displays (SID) conference in May 2007, which could work as a form of e-paper. See <http://www.presentationtek.com/2007/05/14/flexible-color-e-paper-a4-size-developed-by-lgphilips-lcd/>

Moreover, they should align with the strong move to sustainable technologies, processes, materials and recyclable application devices.

Overall, we can also define the two technologies in terms of their technical features and characteristics, as shown in the table below:

Table 1-3. Defining the two technologies by key operating parameters for displays

Parameter	OLEDs	E-paper
<i>Cost</i>	Lower than LCD in the future (projected costs)	Medium today, projected to be very low cost for future
<i>Resolution</i>	High	Medium/low (100-150dpi)
<i>Size possible</i>	Large – very large – wall size	Very large (wall size)
<i>Brightness</i>	Medium/high (emissive)	Medium/high (reflective)
<i>Contrast</i>	High	Very high
<i>Sunlight readability</i>	Medium/poor	Good
<i>Darkness readability</i>	Good	Poor
<i>Colour range</i>	Wide – millions	Monochrome today, colour soon – thousands
<i>Response time</i>	Fast – full motion video compatible	May be slow, depends on technology - e.g. some electrochromics may be fast
<i>Sustainability(recycling capability, use of hazardous materials and processes, etc)</i>	Yet to be proven – should be better than LCD	Yet to be proven –should be better than LCD
<i>Ease of production</i>	Good – water soluble inkjet	Reasonable – future is continuous rather than batch
<i>Weight</i>	Light	Light
<i>Geometry</i>	Any	Any
<i>Text suitability</i>	Medium/high	High –prime function
<i>Full motion video suitability</i>	Good	Not for first generation monochrome
<i>Power consumption</i>	Low of LCD (can be 1/100 th) for TV, may be 40% of LCD	Very Low (can be 1/1000 th of LCD)
<i>Need for power to maintain image</i>	Yes, currently	No – image stays; no refresh needed
<i>Flexibility/Pliability/foldability</i>	Will be made to be flexible	High
<i>Operational life</i>	Varies with colour (blue shortest)	Monochrome long; variable for colour
<i>Robustness</i>	High except if water entrance	Fair to good
<i>Viewing angle</i>	Wide	Wide
<i>3D capability</i>	Yes	Not with first generation monochrome
<i>Nearness to market</i>	First volume production 2009	Applications in e-readers 2007/2008

1.4. Current state-of-the-art of the two technologies

In this section we examine the two major technologies of this study – first OLEDs and then e-paper.

1.4.1. OLEDs

OLED displays promise much over the current LCD technology. They are brighter, may be much thinner, offer more contrast, yet can give wider viewing angles. Most importantly, they can consume far less power (Putman, 2002; Ortiz, Jr, 2003). These are all areas where LCDs fall short (Gurski and Quach, 2005), although LCD technology continues to advance. On the downside, OLEDs currently suffer from some technical problems - notably their lifespan - and only time will tell whether these will be resolved.

As already mentioned, there are different kinds of OLED technology, including:

- Small Molecule Organic Light Emitting Diodes (SMOLEDs),
- Polymer Light Emitting Diodes (PLEDs) based on light emitting polymers (LEPs) or long molecules,
- Dendrimer technology, repeatedly branched molecules with electroluminescent properties that use a solution-based production process, useful with inkjet printing and can emit the elusive blue light (Markham, 2004).

OLED types are differentiated by their electroluminescent component substances, ie the basic molecules that emit light when excited by an electric current.

Research into OLED display technology is being conducted in over 80 companies and universities, with major players including Samsung SDI, CDT, GE/Osram, Universal Display Corporation, Sony, Novald, LG Electronics, Philips, Dow Chemical, Kodak-Sanyo, Pioneer, Sharp, DuPont, eMagin,

Three-Five Systems and others. OLED displays have already entered the market in the form of digital cameras, cell phone screens, radio displays, and handheld games. Research is also underway for highly flexible OLED display panels on plastic substrates. CDT has combined dendrimer with polymer OLED technology as both are solution-based, with CDT buying the IPR for the technology from Opsys of Oxford in 2002.

OLED technology advantages

OLEDs, being emissive displays (i.e. self luminescent, generating their own light) require no backlighting, as for LCD FPDs. Another significant advantage is that OLED displays have high switching speeds and so may handle fast refresh rates required for full-motion video. OLEDs' simple and thin structure for the emissive component and excellent display qualities make them ideal for use in flat panel displays. Their polymer basis and the simplicity of construction should lead to lower materials and production costs. They can be made very thin – Sony's first production XEL-1 has a screen 3mm deep and Sony have now made a 0.3 mm thick screen. As organic polymers, displays can in theory be made to be "rolled up" much like real paper or possibly for televisions hung like pictures or attached to walls using adhesive. The self-luminescence enables more accurate natural colours with better brightness and contrast. They offer 'true black' which LCD cannot and contrast ratios that are far higher – one million to one in the Sony XEL-1 (Conti, 2008). As such, OLEDs may compete strongly with LCD technology. As more progress is made with OLED displays, the technology could match or surpass the current popularity of LCD displays due to the emissive direct view imaging, high switching speeds, low operating voltage, high quality of imaging, and potential for larger screen size at lower cost (Putman, 2002; Ortiz, Jr, 2003).

OLED technology problems

OLEDs, being organic polymers, suffer from degradation of the basic material, affecting the lifespan of displays. Such degradation

occurs through chemical processes, especially oxidation, so OLEDs slowly lose their light-emitting properties. The current materials used are expected to last between 10,000 and 14,000 hours although this is expected to improve. Some would say this is long enough as it implies a screen usage of 5.5 years for a 7 hour per day usage (Conti, 2008) although this falls far short of current LCD lifespan at 50,000-60,000 hours.

While OLEDs can produce full colour images using the RGB matrix just like current LCD FPDs, the three OLED chemicals producing the red, green and blue colours have different aging rates and brightness gains with age. In order to keep the display colour unchanged during their lifetime, compensation algorithms are required. Thus a key element is the signal-processing unit. Moreover, if an active TFT matrix is used for an AMOLED, it is often based on amorphous silicon, like an LCD. But with AMOLED technology, the light emitted is produced by the backplane itself and not through a separate backlight. The increased use of the TFT introduces further aging issues – the more a pixel is used, the less efficient is the pixel-driving transistor. Thus, automatic compensation is also required to achieve a constant level of brightness over the matrix.

Moreover, although printing is seen as the future for inexpensive organic electronics, there is still some way to go in developing both the materials and the processes. More specifically, some of the most widely used organic electronics materials – those based on small molecules (SMOLEDs) – do not lend themselves to solution processing. Thus, today, perhaps 90 % of the printed OLEDs are still created using vapour deposition of small molecules.

Trends in manufacturing processes for OLEDs

The current state of the art is the move from prototyping and first volume production in batch mode. Early techniques have followed semiconductor processes of deposition of semiconductor materials on a rigid or flexible substrate to lay down the transistorised substrate

for control, with shadow masking and the OLED layer attached on top either preformed or via deposition in a similar manner, in sterile *in vacuo* conditions. The vast majority of OLEDs so far have been produced in this way, as most are SMOLEDs.

However the industry is moving towards materials and processes for process flow, if possible at closer to room temperatures with the OLED layer being in water soluble form for printing or coating attachment processes, in a roll-to-roll mode. This involves preparing solutions of the various organic materials for solution-processing techniques (spin coating or inkjet printing) onto the substrate. Solution-processing methods – inkjet printing in particular has the potential to be a lower cost approach, scalable to large area displays.

These often demand large-scale research projects with several partners across the value chain. For instance, over the past few years, Universal Display Corporation (UDC) has researched Printable Phosphorescent OLEDs (P2OLEDs) under joint development agreements with Seiko Epson, also collaborating with Mitsubishi Chemical Corporation to develop novel materials for P2OLEDs. In December 2007, UDC in collaboration with Seiko Epson, announced inkjet printing advances for P2OLEDs production with enhanced material lifetimes. However, today the industry is still in need of new and better inks for use in functional printing, or other high-yield coating processes (e.g. spin coating). It is perhaps thus interesting to review two specific commercial processes under development by UDC in the USA:

Organic Vapour Phase Deposition (OVPD):

The standard approach for manufacturing a SMOLED or PHOLED is based on a vacuum thermal evaporation, or VTE, process. With VTE, the thin layers of organic material in an OLED are deposited in a high-vacuum environment. In contrast, the OVPD process uses a carrier gas stream in a hot walled reactor in a low-pressure environment to deposit the layers of

organic material in an OLED. The OVPD process improves on the VTE process having more efficient materials utilisation and enhanced deposition control. UDC has partnered for this with Aixtron AG (Germany) which is a leading manufacturer of metal-organic chemical vapour deposition equipment, to develop and qualify equipment for the fabrication of OLED displays.

Organic Vapour Jet Printing (OVJP): OVJP technology is another direct printing method for the manufacture of OLEDs. OVJP technology potentially offers high deposition rates for any size or shaped OLED. In addition, OVJP technology avoids the OLED material wastage associated with use of a shadow mask (i.e. the waste of material that deposits on the shadow mask itself when fabricating an OLED). By comparison to inkjet printing, an OVJP process does not use solvents and therefore the OLED materials used are not limited by their viscosity or solvent solubility. UDC is working in collaboration on developing this proprietary technology with the University of Michigan and is currently qualifying a prototype OVJP tool to build prototype white PHOLED lighting panels.

Another solution-based process, spin coating, has also been used in circuits fabrication with organic materials by Polymer Vision, TFE and MED for example.

Clearly a number of trends are shaping the currently emerging printed electronics industry, trends which are equally true for e-paper as for OLEDs:

- A growing number of materials are being turned into inks and thus bringing the advantages of printing to more segment of the display industry. Inks made from silicon, and innovative hybrid materials such as silver-plated copper, or dye sensitive photovoltaic materials will be important in the new manufacturing processes, with carbon nanotubes.
- Five key segments are appearing in the printed electronics materials business: printed

organic materials, printed silicon, inks that use nanomaterials, substrate materials inks and conductive metallic inks (Nanomarkets, 2008). Commercialisation of both printed silicon and printed electronics on paper is imminent. There are, however, some barriers implied for some these printed electronic materials such as the high price of silver.

- Silicon inks are emerging as a viable way to create thin-film transistors, while transfer printing opens up new roads to fabricate sophisticated silicon devices on flexible substrates. Printed silicon is a challenge to the organic electronics concepts, but also an inspiration as technology developers borrow concepts such as CMOS and materials sets from the silicon world and transfer them to organic electronics. Here, the printed electronics industry is learning from the established semiconductor industry.
- Nanomaterials are beginning to establish themselves as a base component of printed electronics in various ways. Inks using metallic nano-particles promise higher conductivities and lower curing temperatures. Carbon nanotube inks open up interesting new possibilities for substrate replacements, lighting and emissive displays. Overall, nano-silicon inks may prove the best route to printed silicon.

Over the next few years, printed electronics will evolve rapidly for commercial products and will therefore require ever more sophisticated inks, for improved and new processes, and made available in commercial quantities. This is certainly an opportunity for Europe.

1.4.2. E-paper displays

E-paper is based on an active matrix display using “electronic ink”, in the sense of an electrically controlled pigment resembling the ink used in traditional printing. Thus they may become a technology to challenge or even replace paper. By using a suitable technology (typically a reflective type) an e-paper’s display

content can be viewed in full daylight, anywhere that ordinary print on paper can be viewed, using a simple bi-stable (on/off) mode without refresh.

As already mentioned, e-paper is an application that can use several alternative technologies, the main ones being electrophoretic, cholesteric LCD, electrochromic and nematic bistable LCD.

The key challenge: low temperature manufacturing for plastic substrates

Although prototypes appeared first in 1974, it has taken over 30 years to create commercially practical and reliable electronic paper in volume production because two entirely new technologies have to be put together. The first is the 'electronic ink' that will create the actual printed display on the e-paper page, and the second is the flexible electronics required to generate the pattern of text and images on the bendable/foldable page of electronic ink – maintaining the flexibility and thinness is a major challenge if it is to compete with traditional paper.

Looking at current display technologies we may observe that most flat panel displays, such as LCDs, consist of two main elements:

- a backplane to select which pixels on the display matrix of cells turn on and off
- a frontplane that either emits light, or acts as a shutter controlling the light coming from another source, at those pixel locations determined by the backplane.

An 'active matrix' display is the basis of most of today's modern flat panel displays. The backplane provides an electronic switch under each pixel, so that the pixel can be turned on and off, without affecting its neighbours. Older displays did not have this 'switch', just a matrix of connections. These 'passive matrix' displays have poorer visual performance as the length of the conductor that links the driving circuit and the pixel delays and distorts the precise signal needed to generate sharp, rapidly refreshed

images. They are often too slow and smeary for modern applications, e.g. full motion video.

Conventionally, fabrication of the transistors, which form the backplane switches, is by deposition of a thin layer of silicon on to a glass substrate, followed by standard semiconductor manufacturing techniques to create the transistors and associated circuitry. However these processes require high temperatures, and perhaps in-vacuo techniques of masked deposition, making such backplanes expensive to manufacture while precluding use of a low melting point substrate such as a plastic. The answer is to use a semiconductor other than silicon to fabricate the transistors, one that can be formed into the appropriate circuitry at room temperature. Recent technology for organic semiconductors is the solution and has been pursued by several suppliers such as NTERA, Philips/Polymer Vision and Plastic Logic.

Such suppliers have developed organic electronic materials that are soluble, and can thus be used at room temperature allowing the circuitry to be mounted upon a flexible plastic substrate. Another advantage of organic semiconductors is that the circuitry can be created using conventional screen printing and inkjet technologies. Manufacturing such displays becomes far cheaper as investment in fabrication capital equipment may eventually be reduced by over 95% (Hampshire, 2005). A modern LCD plant producing two million 2-metre substrates for the LCD TV market costs upwards of \$4 billion, whereas an organic electronics display plant may cost as little as \$10-20 million. Thus in volume production, the cost of an A4 150 dpi flexible organic electronic display is likely to be much cheaper than a comparable LCD display five years on from the start of volume manufacturing, perhaps 2010-12.

Darren Bischoff, senior marketing Manager of E-Ink, the leading suppliers of e-paper technology so far, has noted:

"With the expectation that the materials and processes used in the manufacture of flexible displays will advance in the next five years, there is the possibility for a new paradigm in display manufacturing that could produce low-cost, high-volume flexible display products. Assuming current display component pricing trends continue on their downward trend, this could signal the potential for highly rugged displays that are one third the cost of today's fragile, glass-based displays".

Developing a frontplane for a flexible display presents new and different challenges compared developing the technology for the rigid TFT LCD panels. In a conventional LCD display, the frontplane is also made of a rigid piece of glass, like the backplane, in order to ensure that the cell gap between it and the backplane are precisely maintained. Minor variations in the gap produce image distortions. Now maintaining such a precise gap in a rollable or bendable display is very difficult. Research by Philips and also Hewlett Packard has demonstrated prototype solutions.

Currently, for flexible, fairly high-resolution displays, the leading alternative to a liquid crystal frontplane is an electrophoretic one. It is flexible and uses reflected light, as opposed to conventional transmitted light (through the screen from a backlight as in LCDs) or emitted light (as in the phosphors of CRTs). Thus electrophoretic displays are close to paper in readability, being viewable in ambient light, have a high contrast ratio, with a wide viewing angle and require minimal or even no power to maintain the static text image.

The main e-paper technology types

There are several types of e-paper technology. The oldest is the electrophoretic already mentioned – in which particles move in a charged field. Newer technologies are electrochromics from suppliers such as NTERA, in which organic nanomaterials change colour in an electrical

field. E-Ink, with their patented electrophoretic 'electronic ink', claim that their displays need only 1/1000th the power of a similar LCD display. This is because an e-paper display can preserve its contents even when switched off, and most importantly does not need a backlight (Gurski and Quach, 2005). Organic thin film backplanes feature in manufacture to give the bendable property of paper and low cost so this is a field still in development. For instance, in November 2008 Samsung of Korea in collaboration with Unidym showed off a prototype carbon nanotube (CNT) active matrix electrophoretic e-paper display in A4 size (Deviceguru, 2008).

New fabrication techniques

New fabrication techniques are the core driver for both technologies. These are currently being developed and are based on continuous, roll-to-roll processing in normal factory conditions at room temperature rather than the batch processing in sterile conditions typical of semiconductor fabrication.

OLEDs in spreadable form as a liquid, are being researched by Sumitomo Chemical, announced in May 2008. The basic concept is of a liquid containing OLED and solar cell molecules and is currently in research. Real implementation would appear to be in an advanced industrial process, spraying a 100 nm coating on top of a pixel matrix control layer, also in plastic perhaps for flexibility, robustness and weight. Improvements on roll-to-roll techniques are being heavily investigated worldwide, including in various industrial consortia:

- In Japan, a government orchestrated consortium started in June 2008, with Sony, Sumitomo Chemical, and others – now including Sharp despite its previous support for LCD only.
- In July 2008, another consortium for production was started in Germany by three Fraunhofer research centres – FEP, IPMS and COMEDD – who are building a new coating plant in Dresden for low temperature processes.

- GE Global Research in the USA is investigating similar roll-to-roll processes on the scale of newspaper printing, but aimed at OLEDs for lighting, with introduction for 2010.

Note that roll-to-roll technology is already in use for mass production of solar cell photovoltaic laminates, e.g. by United Solar Ovonic of the USA and others. Plextronic, (Pittsburgh, USA), a spin-off company from Carnegie Mellon University, is also researching new printing technology.

Carbon nanotubes are now being explored for new production processes. The technology is largely in the research phase today, for instance in laboratory projects in the University of Southern California, Berkeley (Zhang, 2006) which has applied for patents.

Solvent processed nanotube composites are being developed for composite organics for both the transparent electrodes and light emitting layers of OLED FPDs. These are the two basic elements used in OLED displays. This new class of conductive polymers is also applicable in organic photovoltaics and OLEDs for lighting. The process for conductive polymer production is to uniformly suspend and disperse carbon nanotubes, enabling

them to function as high efficiency charge injectors in the electrodes and light emitting layers of OLEDs and organic solar cells.

Currently, OLED cathodes are often produced by thermal vacuum evaporation, owing to the use of reactive metals for electron injection. Use of calcium or lithium requires air-impenetrable packaging. In contrast, devices made using air-stable cathode materials can be manufactured by solvent processes, applied using inkjet printing or spin coating. Packaging is also easier. Other advantages of the technique include more efficient charge injection and higher conductivity than conventional conducting polymers, a film which is transparent, reduced drive voltage and compatibility with flexible substrates. Moreover they are solvent processed and so inkjet printable, yet have longer material lifetimes than devices made with active metal. Problems to overcome are overall lighting efficiency and maintaining the carbon nanotubes in suspension for the lifetime of the display screen (possibly 5-7 years).

1.4.3. The key e-paper applications

The major e-paper industry applications can be viewed as:

Table 1-4. E-paper application segments

Application segment	Applications	Rate of emergence
Signage	Outdoor displays Indoor information and advertising displays Smart shelves – electronic shelf labelling and POS displays	Rapid emergence, already happening for smart shelving (e.g. from Fujitsu)
ICT components	E-books or e-readers (consumer and military) Mobile handsets Other handheld devices Laptops Desktop PCs Computer and telecommunications peripherals Wearable electronics (consumer and military)	Still just emerging – e-readers leading and market expected to expand in 2009/2010, especially as content widens. Other applications are further away
Disposable electronics	Smartcards Smart packaging	Slowly emerging
Consumer electronics	Clocks and watches White and brown FMCG	Imminent in low cost applications
Cars and other transport	Instrument dashboards Navigation screens Avionic displays	Slow emergence and various problems of robustness in harsh environments to be overcome

1.5. The longer term outlook – a cyclical industry

One point about FPD production in general is that this is a boom and bust cycle market, with a cycle stretching usually over three quarters to a year. Traditionally, there is a shortage then oversupply. At each point, new technology is entering and being absorbed which changes the price point in the industry. Materials are exactly the same – shortages, new investment, new capacity, over-supply then new technology and/or cut back on capacity. This has been the story in plasma, LCD and we may now expect OLED and e-paper to enter exactly the same cyclical business model.

The price point is everything – as prices descend from today, at around €2,500 for an OLED laptop or TV, they begin to become affordable. Assuming that problems with longevity can be solved, if the price were to fall to less than €500, an OLED FPD TV would sell

in huge quantities, wiping out the LCD TV and also increasing the number of TVs in every home – perhaps one in nearly every room. This would drive sales, and so drive production capacity.

Also the cyclical nature of the market means that players tend to constantly enter and exit depending on their returns and their views of the market, as Osram has exited lighting production in Malaya in 2007 using P-OLEDs, Dow Corning also exited from P-OLEDs with the remnants forming Sumation, a 50/50 venture with CDT and Sumitomo Chemical, before Sumitomo Chemical bought CDT in 2007.

We should also note that claims and counter claims are being made about rival technologies. For instance Katsuji Fujita, former CEO of Toshiba Matsushita Display Technology stated that above 76 cm screen size OLEDs consumed more power than LCD (Conti, 2008). Moreover the technical performance of LCDs is a moving target as it is rapidly developing.

■ 2. The Market for OLEDs and e-Paper

In this chapter, we seek to understand the market for the main application areas arising from OLEDs and e-paper. In section 2.1, we assess for each main application area the current value of the market, growth trends and forecasts for the medium term future to identify the potential of the key markets.

are typically smaller or more uncertain, the prime example being lighting. The total, global electronic display market is now estimated to be worth over \$125 billion (see Figure 2-1) and moreover, potential affects of a global recession could make figures for later years optimistic.

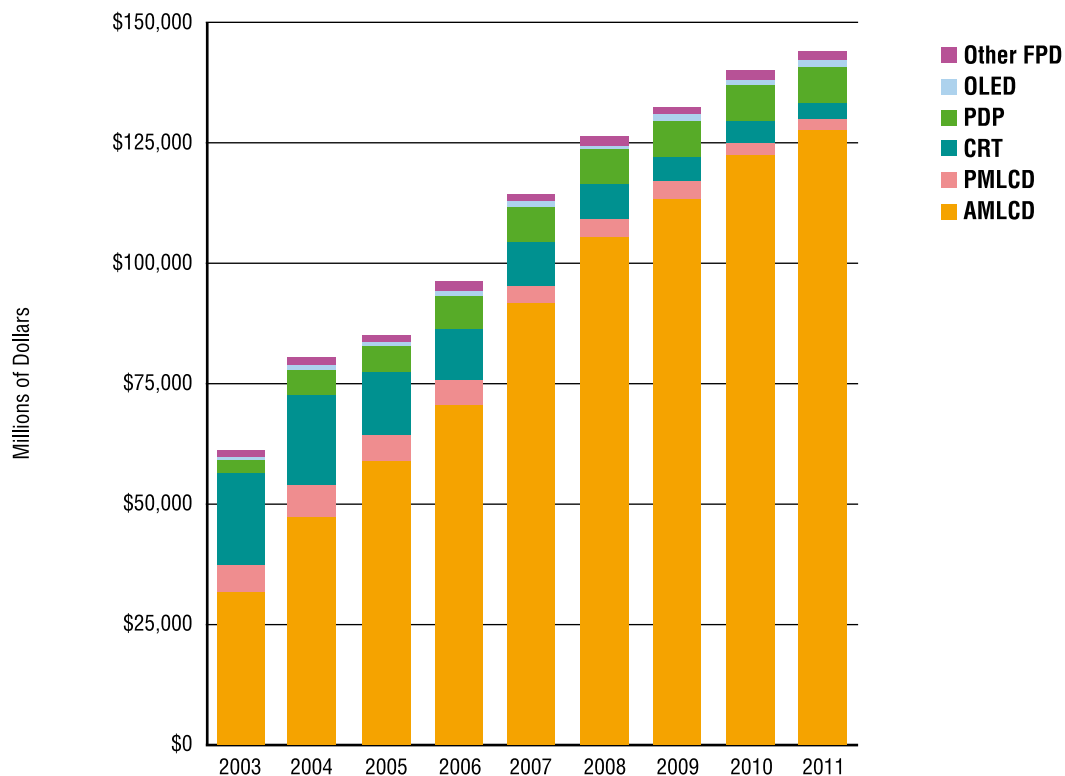
2.1. Market forecasts for major application areas

As shown in the Figure 2-2, TFT-LCD technology currently dominates the global display market representing 84% of the total market (i.e. some \$100 billion). OLEDs currently represent a tiny proportion of this market and most industry analysts expect little change to this segmentation in the next few years. The figure below shows the key application areas for LCD and the current value of these markets. The key market areas are TV screens, desktop and portable computers, mobile handsets and portable media players.

2.1.1. Introduction

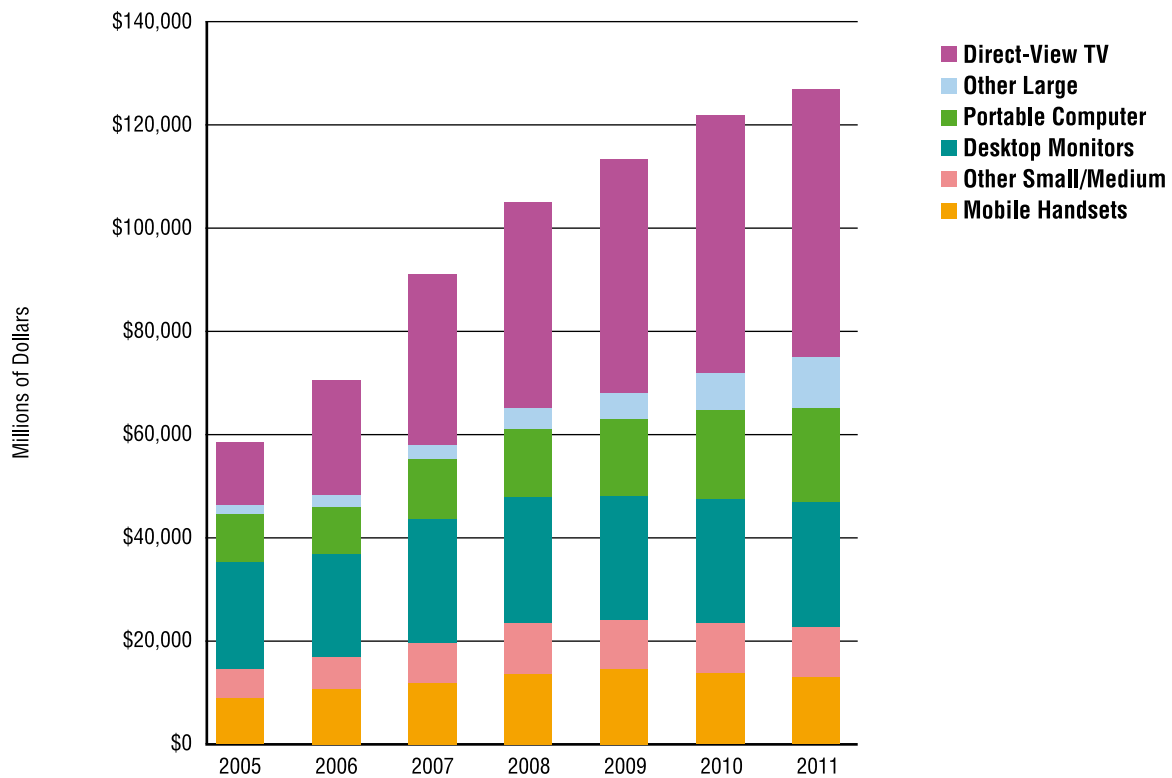
The major existing markets for which OLEDs might substitute are TV screens, IT monitors, and smaller screens for mobile handsets. The markets in the other application areas identified

■ Figure 2-1. Total global electronic display market



Source: iSuppli, Display Market Outlook, 2008.

Figure 2-2. Global TFT-LCD market and applications



Source: iSuppli, Display Market Outlook, 2008.

While current shipments of OLEDs are small, significant growth in their use. According to iSuppli, the OLED industry will experience rapid growth of 36% annual growth rate over the 2007-2013 period, with the most advanced OLED technology, active matrix (AMOLEDs) making up the majority.

It is believed that global shipments of AMOLEDs for applications including TVs, mobile handsets and portable media players will nearly quadruple in 2008, rising to 10.2 million units, up 294.2% from 2.6 million units in 2007. AMOLED revenue in 2008 will rise by 237% to reach \$225 million, up from \$67 million in 2006. By 2013, global AMOLED shipments and revenue are expected rise to 132.4 million units and \$2.8 billion.¹⁴

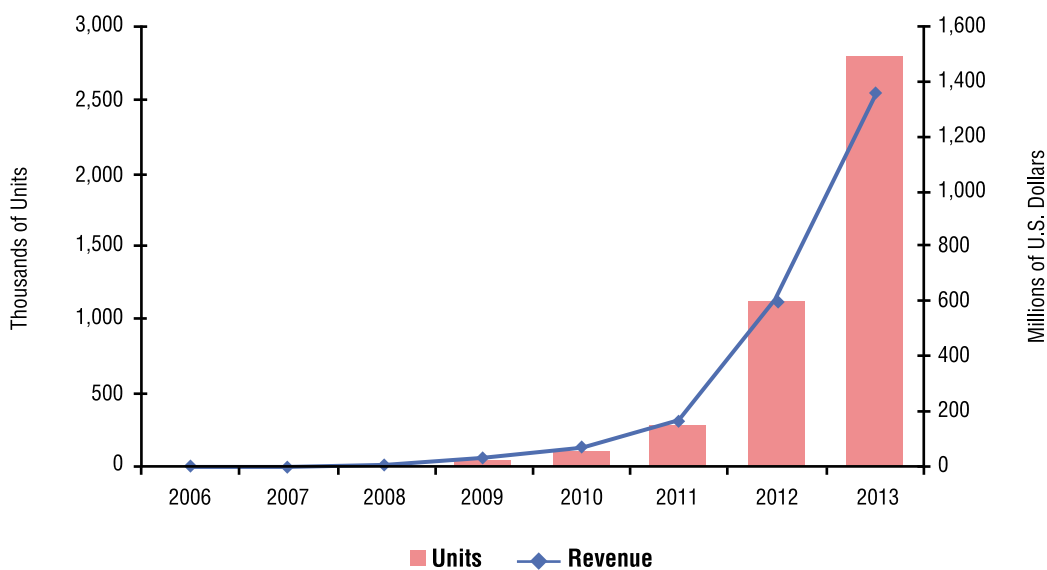
2.1.2. Television screens

Television sets are one of the most widespread and important electronic display applications. In 2006 190 million units were sold worldwide. In recent years the market has been given a boost by with the availability of lower cost flat screen LCD displays. The global market for LCD TV is estimated to have grown to about \$40 billion in 2008 (iSuppli, 2008), thanks to the fast growth in demand for flat panel TVs and a move to wider screens and larger screen sizes. Older technologies, such as CRT, are in rapid decline.

The prospects for growth in OLED TVs are promising, although forecasts are highly influenced by an industry that currently is seeking to reap the benefits of its investments in LCD manufacturing. In 2008, IDTechEx forecast that OLED TV sets will account for around half of all

14 <http://www.techradar.com/news/television/oled-prospects-on-the-up-370010>

Figure 2-3. Global OLED TV market forecast



Source: iSuppli, 2007, as reported by Designline.¹⁷

revenue for OLED panels in 2012, growing rapidly from just \$150 million in 2011 to \$1.5 billion in 2013.¹⁵ iSuppli's similarly forecasts the global OLED TV market will reach 2.8 million units by 2013, managing a compound annual growth rate (CAGR) of 212.3% from just 3,000 units in 2007. In terms of global revenue, OLED TV will hit \$1.4 billion by 2013, increasing at a CAGR of 206.8% from \$2 million in 2007.¹⁶

The arrival of Sony's XEL-1 OLED TV in late 2007 spurred development and market forecasts, as it was the first relatively large-screen OLED display (11") launched into the market, although the price was high compared to LCD (\$2500). Not to be outdone, Samsung unveiled a prototype 31" TV in March 2008. Other manufacturers, such as LG, Toshiba and Panasonic, quickly announced plans for commercial rollout of 30" and larger

screens, typically by 2011. In July 2008, Sony said that they were 'awfully close' to selling a 27" OLED version commercially.¹⁸

However, industry analysts' views cooled somewhat when it became apparent that there were still significant problems with the longevity of the display,¹⁹ and also as the financial and economic crisis began to deepen in the summer and autumn of 2008. In October 2008, David Barnes, DisplaySearch strategic analysis VP, said, "Concerns over contracting consumer demand over the near term may grab headlines today, but slower growth may be a long-term trend in the flat-panel market". Even so, Barnes thought that, "While less than 40 thousand OLED units for TV applications may ship this year, DisplaySearch foresees potential for 126% compound annual

15 <http://www.idtechex.com/products/en/articles/00000934.asp>

16 Is there room for OLED technology in the TV market? <http://www.digitimes.com/displays/a20071211PR200.html>

17 Dennis P. Barker, "Is the room for OLED technology in the television market?" Design line, 11 December 2007, <http://www.powermanagementdesignline.com/news/204801558>

18 http://www.oled-info.com/sony/sony_we_are_awfully_close_to_selling_27_oled_tvs

19 Display Search, *OLED Characterization Report: Sony XEL-1*, http://www.displaysearch.com/cps/rde/xchg/displaysearch/hs.xsl/oled_characterization_report_sony_xel-1.asp

growth in OLED TV panel demand over the next seven years".²⁰

In summary, TV screens, of all types including LCD and CRT, are the largest display market segment, worth about \$40 billion globally each year. Growth has been strong over the past decade but may slow in the medium term as a result of a global economic downturn. There is undoubtedly an opportunity for OLEDs to take a significant proportion of this market but this will only transpire if costs come down as a result of investment in mass production. This is unlikely in the short term while doubts over the longevity of OLEDs and other technical difficulties remain.

Opinions differ strongly on the market prospects for OLED TVs depending on whether they come from proponents of the LCD

manufacturers or those with an interest in OLEDs. The blog entry below neatly encapsulates the contrasting views.

Even then, it is likely that any transition to OLEDs will be managed carefully by the key industry players to ensure that margins for OLED TVs remain high in the short to medium term. OLED TVs will be a premium product over the next few years while maximum value is extracted from the investment in LCD manufacturing capacity. It is not in any of the players' interests for OLED TVs to become highly commoditised in the short term. Sharp, for instance, publicly holds the position that LCD is not yet a mature technology and that it will be another decade before it is threatened by OLEDs.²¹ Sharp, perhaps, has most to lose by rapid take up of OLED TVs because of its huge investment in LCD manufacturing.

Contrasting views from the blogs

Our friend at the DisplayBlog, Jin, has written an interesting view on OLEDs. Basically he says that by the time OLEDs are available (around 2010, hopefully) LCD/PDP TVs might have better contrast, be just as thin and with the same colour gamut - and obviously they will be cheaper when OLEDs first arrive. In fact he thinks that a 30" OLED will cost about as much as a 60" LCD - and he's probably right at that - I'm not sure however that everyone will want such huge TVs!

My take is a bit different. First of all, I believe that OLEDs will improve at a faster rate than LCD/PDP. It's true that much more money is invested in the older, more proven techs, but being a new technology OLEDs can enjoy a much faster rate of improvement (it's always like that with new tech). Second, I believe that because OLEDs are inherently simpler, and do not require a back light, they will always enjoy a better contrast ratio (blacks will only be real blacks when you do not use a backlight) and they will be smaller too. Actually being so much more simple means that OLEDs will eventually be cheaper to make than other types of TVs. Another thing that Jin forgot to mention is refresh rate where OLEDs fare a lot better than LCD/PDP in this regard!

In fact, let me say this - LCD and PDP TVs simply do not look good. I have seen several new models, and on all of them the picture is always 'smeared'. My old CRT (yeah...) has a picture quality that is better! So while the new TVs are flat and thin and big and shiny - I personally think we have lost something in the picture quality.

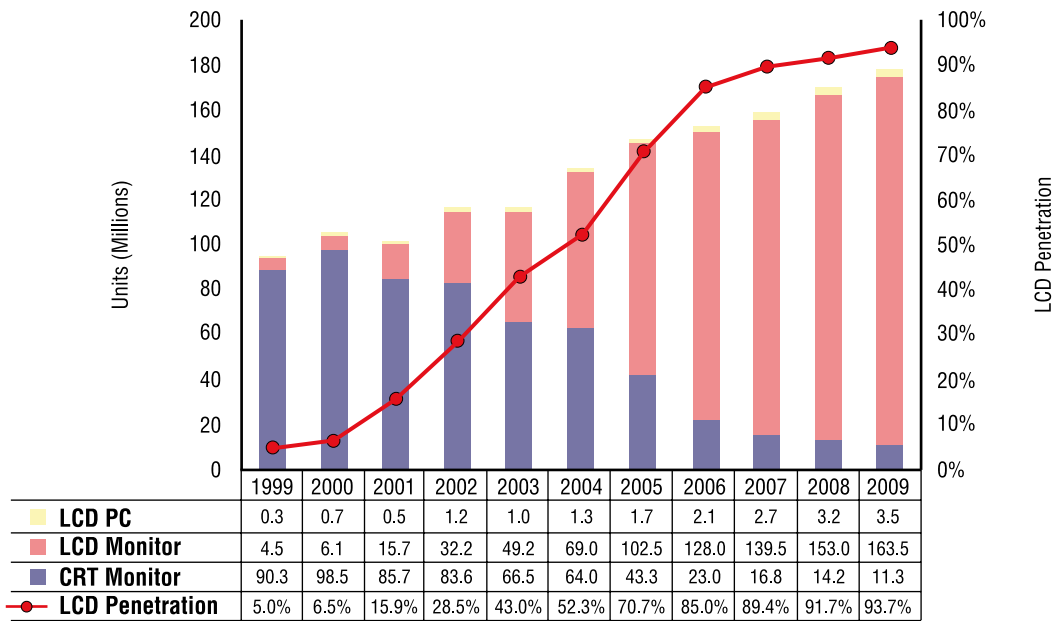
My last argument is that OLEDs are also more power efficient - I think this is an important point. As we move towards a more environmental-oriented way of life, I believe this will be a major factor.

Submitted by oled on 21/10/2008 to www.oled-info.com

²⁰ <http://www.oled-display.net/displaysearch-oled-tv-market-growth-126-every-year-until-2015>

²¹ http://www.techradar.com/news/computing/pc/exclusive-sharp-reveals-big-plans-for-lcd-tv-398394?artc_pg=1

Figure 2-4. Global desktop monitor market forecast



Source: Hsteh, 2005.

2.1.3. IT Monitors

After TVs, LCD monitors are the second biggest segment of the display industry with revenues of about \$24 billion in 2007 (DisplaySearch, 2008). iSuppli estimate the combined market for desktop and portable PC screens to be worth over \$35 billion in 2008 (iSuppli, 2008). In terms of unit volumes, more desktop monitors were sold in 2007 than either LCD TVs or notebook PCs. DisplaySearch forecasts that the desktop monitor market is poised for growth at least until 2015, with LCD monitors continuing to dominate. The current trends are towards notebooks and laptops substituting for desktops and a move towards wider and larger screen sizes. CRT monitor shipments, still available as an entry-level display technology in emerging markets, will continue to shrink.

Of the three major trends driving desktop monitor growth, organic growth in emerging markets such as China, Latin America and Asia Pacific is the most noteworthy. Green IT initiatives and transitions in monitor sizes and resolutions are also important.

China is forecast to grow rapidly over the next five years and will overtake the North American market to become the world's second largest market for desktop flat panel LCD monitors by 2011. The EMEA region with Europe will remain the world's largest market for such products.

2.1.4. E-paper: e-publishing, e-books and e-readers

The widespread diffusion of e-paper could impact the traditional paper industry, making the reams of paper used today for newspapers, books, manuals, catalogues shrink enormously.

E-paper will seed new markets for new devices. The original technology is taken to market through its packaging, i.e. the e-reader, such as Amazon's Kindle, while seeding a new content market. Key applications are thus expected to be e-books, e-magazines, tablet PCs, etc, as well as outside advertising such as billboards, etc and diverse consumer uses.

Being a new market, it all hinges on consumer acceptance. Industry observers are therefore

watching closely to see how well Amazon's Kindle is selling. Launched late in 2007, Amazon has been guarded about figures. But according to *Digitimes*, Prime View International, which manufactures the Kindle's 6-inch electrophoretic display (EPD), is shipping 60,000-80,000 of them monthly of which 60% of those displays go to Amazon. That would imply annual sales in its first year of the order of half a million units, initially at \$399 (later reduced to \$359) with a value of \$200 million (Garofoli, 2008). An unnamed source claimed in August 2008 that Amazon had shipped 240,000 Kindles in the previous nine months.²² Other commentators have speculated that sales of the Kindle and Sony's Reader could be around one million units in 2008.²³ Some estimates are that by 2012, Kindle sales may total \$2.5 billion.

According to a report on e-paper displays published in 2005, in 2010 flexible displays will account for about 40% of the annual global production of 3.5 million square metres of flat panel displays (Hampshire, 2005). The total global market for such flexible displays is expected to be worth about \$7.8 billion. The report predicts that the largest proportion of this market will initially go to signage products (e.g. shelving displays in supermarkets) with e-readers only starting to take off after about 2008. The report also predicts that commercial A4 size e-readers using digital paper will be on sale in 2010 at around \$100 and will support a range of PDA-type functions. Compared to the size of the paper and printer market, the size of the e-paper display market in 2010 is considered small, and so suppliers of paper-printing and related products, like Xerox and HP, will not be expecting competition from e-paper at this stage.

Meanwhile iSuppli predicts worldwide e-book display shipments will rise to 18.3 million units in 2012, increasing at a rapid 161% compound annual growth rate (CAGR) from 150,000 units in 2007. Global e-book display revenue is forecast to reach \$291.2 million by 2012, rising at a CAGR of 143% from \$3.5 million in 2007.²⁴

This, of course, is just for the hardware and does not include e-content sales. Amazon CEO Jeff Bezos said in June 2008 that e-book sales in the Kindle store had hit 6% of book unit sales. This has led to speculation that the value of e-books sold by Amazon in 2008 could be in the region of \$60 million.

Publishers of all varieties are in a good position to exploit any new opportunities since nearly all content is available in digital form. Whether e-readers will actually boost consumption of digital content or simply replace paper consumption is not known. A prediction in 2005, that is backed by Lynne Brindley, the British Library's chief executive, is that the switch from print to digital will be mainly complete by 2020, with only 10% of new material remaining as traditional print only.

2.1.5. Mobile handsets

The potential volume for OLED displays in mobile handsets is enormous. The global market for all handset segments is about three billion users. New unit sales are expected to rise continually at over one billion units per year, despite the economic slowdown with the credit crunch and commodities inflation. A strong expansion in larger screen mobile handsets is at hand, particularly with touch sensitive features. It is estimated that the current market for mobile handset displays is worth about \$15 billion.

22 Erick Schonfeld, 'We Know How Many Kindles Amazon Has Sold: 240,000', 1 August 2008, <http://www.techcrunch.com/2008/08/01/we-know-how-many-kindles-amazon-has-sold-240000/>

23 <http://blog.oup.com/2008/06/ebooks-2/>

24 <http://www.digitimes.com/displays/a20080724PR201.html>

Investment in production of OLED screens for mobile handsets is accelerating. In June 2008, Samsung announced a \$55 million investment for 2" OLED screen production facilities, upping output six fold to 9 million screens a month (Conti, 2008). This is a key market for OLEDs, which is very well suited to the OLED's attractive image, low power consumption and thin profile.

2.1.6. Lighting

Of all the applications and potential applications for OLEDs, lighting is perhaps the most difficult to quantify with any certainty. Clearly there is potential but there are obstacles as has been mentioned in previous chapters.

OLED lighting will probably find easier entry points where the application exploits its nature as an area, not a point, source of light. Point-source ILEDs may always be a better solution for car headlights, for example, and area-source OLEDs for general illumination, although this is not a hard and fast rule.

There seems to be consensus that "flat-panel lighting" is likely to emulate flat-panel displays by starting out with products of modest capabilities (backlighting for cell phones and consumer electronics, for example), then evolving performance over time to capture more demanding applications.

Emerging Markets for OLED and Printed Lighting predicts that OLEDs will break EL's stranglehold on the backlighting market in 2008. The entire backlighting market is expected to grow to around \$2 billion in 2014. From a 0% market share in 2007, OLEDs will grow to a dominant 88% share in 2014. In vehicular applications – long dominated by EL lighting, OLEDs will intrude initially accounting for \$4.7 million or so of a \$43.9 million market. OLED use will grow, however, reaching near parity with EL in this application in 2011 and spiking significantly at several stages of the projection

period. NanoMarkets predicts that by in 2014, OLEDs will account for \$172.3 million of a \$207.3 million market for printed vehicular lighting—achieving a commanding 83% share.

NanoMarkets predicts that from zero in 2008, the general purpose market for printed lighting will grow to about \$119 million in 2010 and to over \$1.5 billion in 2014, consisting mainly of OLEDs.²⁵

In its most recent report in October 2008, NanoMarkets continued to be optimistic about lighting as the major market for OLEDs. According to the report,²⁶ OLED lighting has surpassed the efficiency of fluorescent lamps in laboratory tests, giving a new era of power-saving solid-state lighting. As the world becomes more energy conservation-oriented and concerned about energy costs, NanoMarkets think it will drive rapid growth for the OLED lighting industry and the demand for OLED materials so that as much as 90% of OLED materials by volume will be used by lighting applications by 2015.

2.1.7. Road vehicles

The global potential display market for motor vehicles of all kinds is of the order of 60 million new registrations worldwide with the EU representing some 33%. In value, the global road vehicles display market is projected to be worth \$1.6 billion in 2008 and \$1.8 billion in 2009 (Adria Roadmap, 2007) with some 130,000 units being shipped in 2009, with 4% CAGR in unit numbers and 9% CAGR in value. The vast majority of current and expected units (some 95%) to 2012 are expected to be LCD with passive LCD being dominant over active LCD by around a 3 to 1 ratio to 2012. However these projected figures do not take account of the credit crisis nor the rise in oil prices which

25 <http://www.nanomarkets.net/resources/oledwp.pdf>

26 http://www.eetasia.com/ART_8800549913_480700_NT_76c80b85.HTM

have reduced registrations of passenger vehicles by between 10% and over 20% in the major car consuming countries in 2008; the future may hold deeper cuts. This is a small but growing part of the total display market and is likely to remain so for longer than some have expected for these reasons and others given below.

Social trends driving cars should be looked at in judging the market. While the manufacturer sees its goals in its design as being to add value and churn the market, social trends are guided by quite different goals, of lifetime costs of vehicles against disposable income, also by safety, sustainability and a resistance to unreliability. These point to longer lifetimes for cars, since the key benchmark for new vehicle buyers in the EU is increasingly reliability against total cost of ownership, as highlighted now by a large number of surveys (JD Power, etc) as consumers become more sophisticated in an era of high fuel costs and awareness of sustainability issues.

Price sensitivity and reliability are closely linked from the consumer perspective. This has major impacts on the car producers, who have suffered in the past from unreliable car electronics. Thus displays will have to conform to market forces, not a techno-centric wish-list. Moreover, although rarely mentioned, the experience of the largest European car manufacturers in 2000-2003 with warranty claims over electronics (in engine management systems) has had some strong counter effects, as it took balance sheets deeply into the red.

2.1.8. Medical

The medical imaging market in Europe is growing quickly, being worth an estimated \$110 million in 2005 and some \$290 million in 2012 (Adria Roadmap, 2007). Greater use of image exchange between care centres is supported by PACS (picture archiving and communications systems) for diagnosis, referral, patient consultation and surgical planning. Mass produced monitors

can meet much of the need, perhaps with lower electro-magnetic interference, special mounts, touch screens etc. However advanced imaging systems for diagnosis, image guided surgical interventions, simulation and surgical training typically require better resolution and contrast.

2.1.9. Advertising and public displays, permanent and exhibition

This is a growth segment, with market analysts iSuppli predicting global sales for 2007 of \$10 billion rising to \$14 billion in 2012 (Murray, 2008) with the European market leading the world to 2012 as customer for such displays. LCD is expected to be the dominant digital signage technology to 2012, with front projection second (together taking over 70% of sales between 2007 and 2012). This is where OLEDs and forms of e-paper could become important with large roll-to-roll manufacture, at lower cost. For specialised applications, other technologies dominate – for instance, LED video is now dominant in outside displays at sports events and theme parks. For indoor venues (auditoriums, theatre, cinema, stadiums, etc) LCD screens are dominant, as LCD brightness advances, while front projection – especially in cinemas – is second. The hotel TV market also comes in here, again dominated by LCD FPDs. E-paper also appears here as a substitute technology for LCD or LED information displays or even paper signage, as used in airports, vehicles, public buildings, hotels, hospitals, universities, etc. Colour is not so important in these applications and the low power of e-paper means that in some of the applications, displays can be powered with batteries for portability. This is useful in trade shows, and anywhere electrical outlets are not easily found.

2.1.10. Retail and banking

The market for the disparate set of applications in this area – tags, electronic shelf labels (ESL), point of sale (PoS) displays, smart cards, catalogues, animated packaging,

promotional displays – is quite significant but difficult to quantify.

From the e-paper industry point of view, the volume of ESL displays would be large. If we take a large EU Member State such as the UK as an example, the three biggest supermarket chains have about 400 stores each, and each would probably have around 20,000 products displayed. That would mean a potential for about 25 million ESLs for these stores alone. Currently a small ESL would cost about €5 each but the large potential market only opens up if the price falls dramatically through lower cost technologies that might arise with OLEDs and e-paper.

2.1.11. Military

Not surprisingly, public information about the market for military applications of OLEDs is limited. Nevertheless, the market for applications in the defence and military sector could be significant. OLEDs offer a number of features that are of great interest. For instance, OLEDs bring both a wider temperature range to military displays, and also a wider field of view. Moreover, flexibility is attractive in military applications, which typically also equates with greater ruggedness, i.e. the display is less likely to break. The military is also less sensitive to cost than consumer markets, which means they are more receptive to new technologies with technical advantages but higher costs.

Consequently low-power OLED displays are starting to be used in a growing numbers of military applications supporting soldiers and commanders in situational awareness, thermal imaging, simulation and training. Two types of OLED applications are currently at various phases of maturity – the near-eye microdisplays, developed by eMagin and Flexible OLED developed by Universal Display Corporation (UDC).

Applications of interest to the military include wrist-mounted, very light and rugged

PDA's and wearable electronic displays such as "display sleeves". Other applications could be conformed, high-contrast automotive instrument panels, windshield displays and visor mounted displays to be used by pilots, drivers and divers. More futuristic applications include camouflage systems, "smart" light emitting windows and shades.

The military OLED market is starting to take off in 2008. Universal Display Corporation announced in April 2008 the successful development and delivery of a novel OLED display prototype to the US Army. The prototype demonstrates the world's first flexible OLED display that incorporates both visible green emission for daytime operation and infrared (IR) emission for use in dark environments.²⁷ While it is possible to see niche markets developing for such applications, it is difficult to quantify the market opportunity.

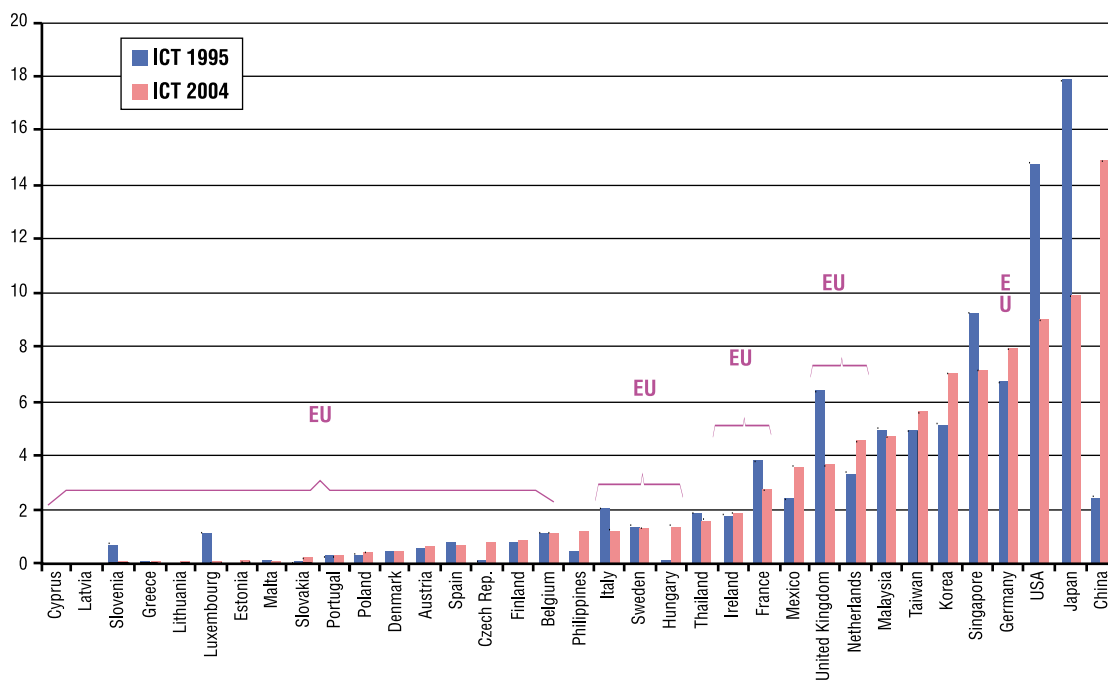
2.2. The display sector from a geographical perspective

From a geographical perspective, the displays sector follows closely the position in ICT overall. On the supply side, the past decade or so has seen the rise of China as the world's ICT manufacturing powerhouse, largely at the expense of Japan and the USA (see figure below). Korea has also been on the rise but in 2004 Germany was still a larger exporter than Korea or Taiwan.

Although Asia now represents over half of world electronics production, Europe and North America are still important producers, see Figure 2-5.

²⁷ <http://www.oled-display.net/universal-display-corporation-delivers-flexible-oled-prototype-with-novel-capabilities-for-u-s-army>

Figure 2-5. Export shares in ICT manufacturing industries 1995 and 2004 (%).



Source: European Competitiveness Report, 2006.

Europe is home to some significant suppliers in the ICT sector – Alcatel-Lucent, Siemens, Philips, Ericsson, and notably Nokia as a manufacturer of mobile handsets – but is generally weak in terms of manufacturing of electronic devices including displays. With the rise of Asia and especially China, Europe is likely to find it increasingly difficult to maintain production facilities for ICTs generally and any display manufacturing. What we are witnessing is quite a dramatic change in the supply chain for electronic equipment. As electronic devices become commoditised, China is inexorably becoming the dominant supplier of what can be characterised as old-style mass-production. Broadly speaking Europe will not be able to compete because of economies of scale and the availability of semi-skilled workers at low cost.

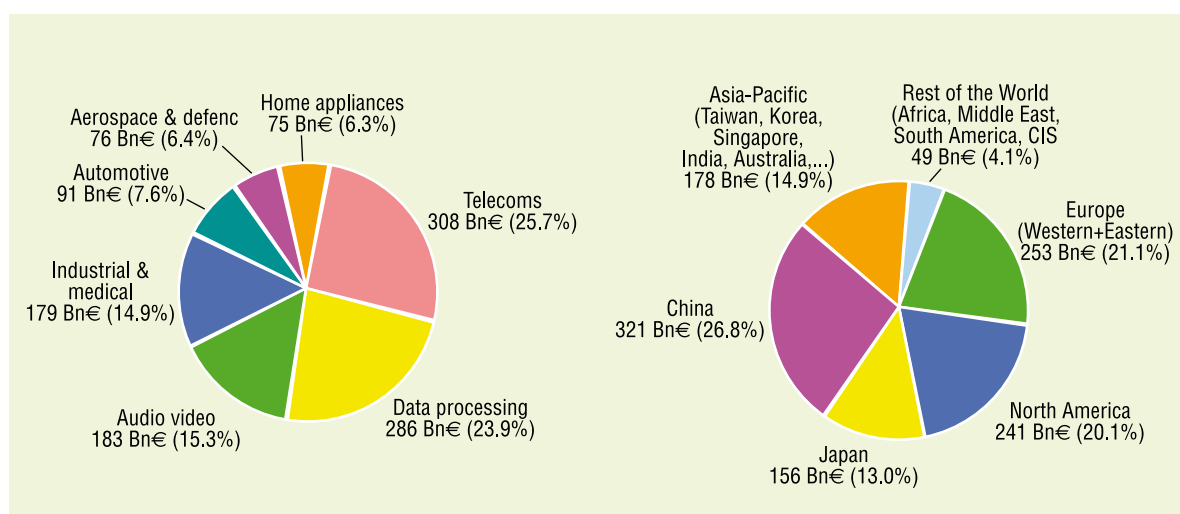
The broad picture from a geographical perspective that emerges from analysing current markets and the supply and demand for displays of all kinds is very clear. Nearly all TFT FPDs are manufactured in Asia, initially with Japan leading the way in R&D and manufacturing but with a shift

over time towards Korea and Taiwan, and more recently towards China. The strongest demand for the largest market segments is from Europe (see table below). Europe is the largest market for TVs, desktop monitors and mobile handsets.

The introduction of OLEDs could, however, lead to some changes to the industry clustering that has grown up around current technologies. In terms of production capability, China is not well placed because it lacks the ability to produce the substrates necessary to produce OLEDs. Europe, because of its quite strong position in R&D and IPR may find an opportunity to develop manufacturing capacity. For instance, relatively small European firms may prefer to develop small-scale production in Eastern Europe rather than ship expensive materials to China for assembly.

Turning to the consumption of electronic displays, the table below indicates the relative size of the main market segments by region. Here the EU is shown to be the major market for LCD and PDP TVs and, for IT monitors and mobile phone displays.

Figure 2-6. The World Electronics Industries in 2007, production per application sector and region



Source: Rospide (2007).

Table 2-1. Consumption of displays by region

	2005	2008	Consumption Regional Share in 2005						Total
			USA	Japan	EU	China	Asia	Row	
NB PC	57M	85M	34.5%	13.4%	30.5%	2%	12.6%	7%	100%
TV	182M	213M	16.8%	5.1%	20%	19.2%	18.9%	20%	100%
LCD TV	20M	60M	27%	25.2%	38.1%	4.5%	3%	2.2%	100%
PDP TV	5M	12M	33%	11%	35%	10%	5%	6%	100%
MD-RPTV*	3M	7.1M	81%	0%	4%	4%	5%	5%	100%
Mobile Phone	660M	844M	12.1%	7.4%	24.6%	18.1%	20%	17.9%	100%
LCD Monitor	97M	144M	34.2%	7.5%	39.6%	8.6%	8.2%	1.9%	100%
CRT Monitor	47M	23M	20.3%	0.38%	23.75%	22.88%	16.2%	16.6%	100%

* MD-RPTV = Micro-Display Rear Projection TV, including DLP, LCOS, LCD Projection

Source: Hsieh, 2005.

2.3. The overall market potential

In summary, there are clearly some significant market opportunities arising from the commercialisation of these new display technologies. Most obviously, it seems likely that OLED TVs will gradually enter the market over the next few years initially as a premium product. The extent to which they take market share from LCDs is as unclear but will critically depend on the resolution of technical obstacles. If these can be overcome, mass production could see them undercutting LCD in price while offering higher picture quality leading to them dominating the

market. However, LCD technology is still maturing and there is substantial investment in production facilities that will not be cast aside in the short term. It is unlikely that we will see significant market share for OLED TVs until 2015-2020.

Before that, however, OLED screens are likely to make significant in-roads in the market for mobile handset screens, where their advantages will be most sought after. Similarly, desktop monitors, notebook screens, MP3 players and so on are likely to be significant markets and could become dominated by OLEDs within ten years.

The market for lighting is potentially enormous but more uncertain and OLED lighting seems likely to become a niche product in the foreseeable future. Nevertheless, some of these market niches could well be significant and the potential for energy efficiency means that OLED lighting could be seen as highly desirable if energy costs soar.

The most visible result of e-paper – the e-reader – looks set to take off in the next few years, first in North America. The e-reader could well have an effect similar to the iPod. Other e-paper applications are likely to take off more slowly, depending critically on very low cost.

■ 3. Value Chains for OLEDs and e-Paper

3.1. The OLED value chain

3.1.1. Introduction

The value chain for OLED production in outline is shown below, with just the major stages from the generation of the IPR up to integration of an OLED display in a product to end of lifecycle, with return and recycling.

The key production technology is printing. The market is really one for low cost production and this implies some form of printing technology, increasingly inkjet. The only truly all-printable displays use plastic technologies. However the future industry will most likely favour a range of production techniques being used, as printed electronics with plastic/silver is not always less

expensive than photolithography. Note that the EU is strong in printing technologies and can export them.

The above figure gives a simplified overview – there are more branches to this value chain for base materials, production equipment and display screen assembly so that a fuller picture is that shown below.

With R&D at three stages, this is quite complex as a value chain, namely for:

- Original OLED chemistry and circuit principles
- Production process for OLED film – likely to be inkjet
- Application R&D including display screen development.

■ Figure 3-1. Simplified value chain for OLED production

The basic OLED Value Chain - 6 stages

1 Basic R&D with IPR licensing

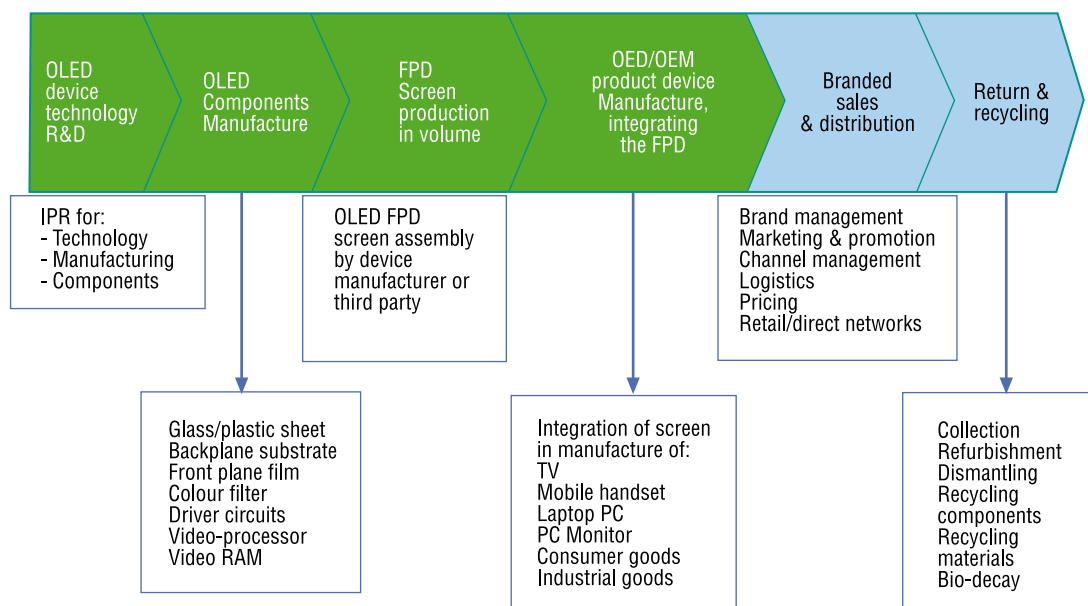


Figure 3-2. The complete OLED value chain

OLED Value Chain - the complete 18 stages

1 Basic R&D for IPR licensing

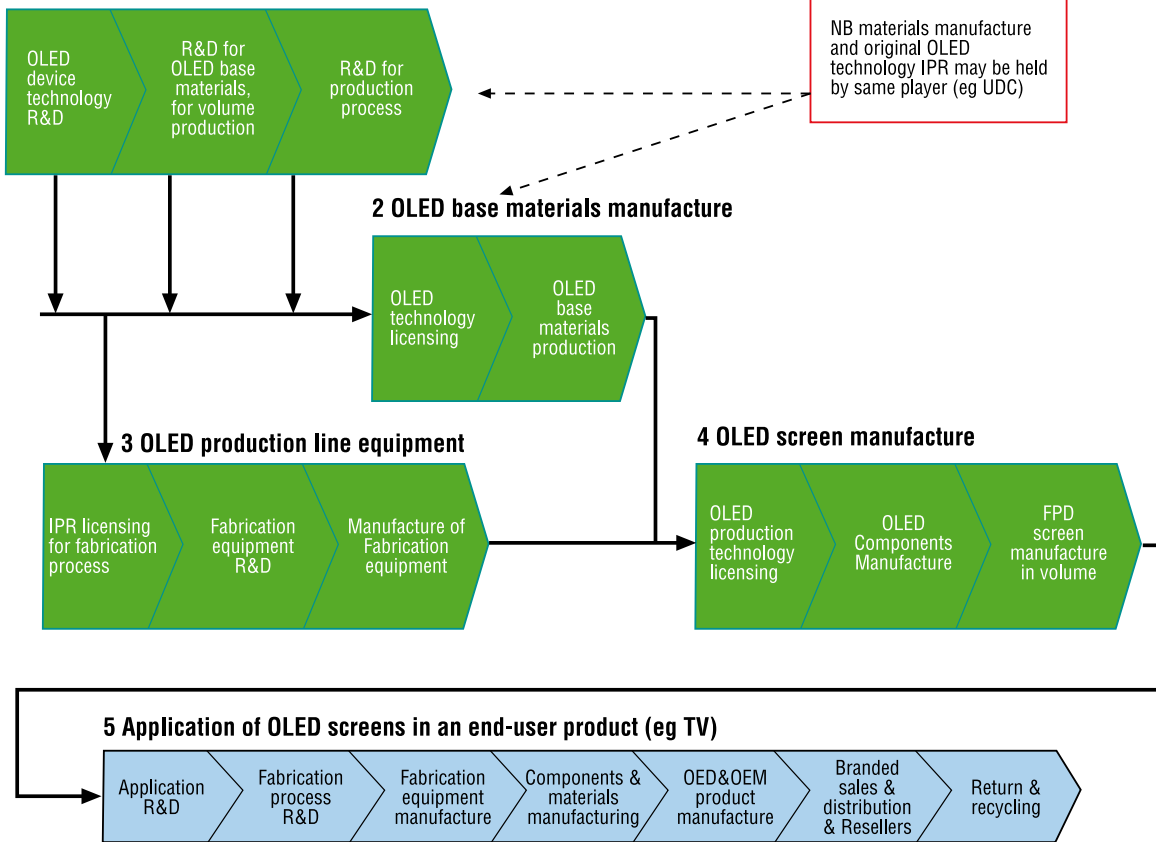


Table 3-1. Marginal value of the value chain elements

Link in value chain	R&D (IPR)	Materials	Production equipment	Components For display	Flat Panel Display production	Device/ product
Margin	Hi	Hi	Lo	Hi, 45%	Hi/Med, 20%+	Consumer market margins*
First approximate relative size of value added as % retail cost of FPD ready for device	5	20	5	40	30	(Value of device less screen= 50-90%) depending on position in life-cycle
Player example	UDC, CDT	UDC, CDT, Merck, 3M, Sumitomo	ULVAC	Maekawa, Japan	Samsung, Sony	Samsung, Matsushita

*Consumer market margins follow lifecycle of product – high early on; often <5% at end of cycle.

Our estimate of the approximate margin levels of the various elements in the value chain, based on interviews with industry players, is shown in Table 3-1.

Perhaps surprisingly we see that materials and components have higher margins than the production equipment or the finished products – display screens and complete devices – perhaps

as competition is more intense in those final segments. In fact, being early on in the value chain may be advantageous.

As a percentage of total value-added at each stage, drawn from interviews and industry research, we estimated the above proportions - but we note that these can only be a first approximation to actual production figures. In reality these could vary enormously in some value chain segments – especially in materials, components and production of screen costs. For instance, display screen production cost may be much higher at the start of production, when yields are lower so it could be 80% of screen costs is yields are below 30%. Sony has already indicated as such. A worldwide over-production, or else a famine, of basic screen materials is also possible, again challenging these proportions.

3.1.2. The OLED industry structure

Types of player and who they are

The structure of the OLED industry and its types of players are closely related to the value chain. The major types of player are shown in the table below, with examples in each of the categories. This is a non-exhaustive list but does shows many major players, based on selecting well-known names, i.e. strong contenders, in each category as far as possible following industry research.

In reality there are characteristics of plying several key links at once to form hybrid business models by entering the value chain at several points – e.g. for IPR and for production, and especially for IPR in devices and in their manufacturing process, including the equipment for production.

Clusters, groupings and relationships

At each stage of the value chain, we also see either established trading relations or closer technology and development partnerships which tend to follow along the value chain.

In the OLED display industry, production is structured by products' characteristics as such as screen size, and segmented by screen sourcing – OEM or branded end-product suppliers.

OLED display screens are further segmented by function of the end device which dictates its size – small screens for mobile handset (1.5 to 6 cm diagonal, up to 10 cm+ for iPhone types), laptop and desktop PC (11 to 22 inches), medium size and medium to large for TVs (11 to 42 inches+).

For most product segments, except TVs, OEM sourced screens are integrated into the end-user product by the branded product supplier. For instance, Samsung is aiming to be one of the largest mobile screen (2 inches) suppliers for an OEM market, investing in larger facilities for a six-fold increase in capacity. Thus we may see 'co-opetition' – the same group may be a supplier for OEM screen products and competitor for finished branded devices.

The overall OLED industry structure is illustrated in Figure 3-3.

As well as display screens, a second major product segment for OLEDs is lighting. The problems of lighting fixtures and forms of the OLED lighting unit, as a flat screen, promise to curtail early optimism about the future of this second segment, however. The power supply required is usually one or more DC supplies, as opposed to the domestic and commercial norm of 240V AC, requiring a transformer and solid state DC supply. The market is segmented by lighting shape into bespoke fittings for architects' requirements for specific buildings and standard panels for a wider market.

Materials supply, components, screen and device design and manufacturing and sales for OLED displays exhibit a global flow between the various centres for each, shown in Figure 3-4.

Note that the USA offers largely the same flows as Europe – IPR from R&D, materials supply

Table 3-2. OLED industry players defined by basic value chain link and location globally

Major types of player	USA	EU	Japan	Korea	Taiwan	China
Original IPR for devices and for manufacture process + material supply/ verification	UDC; Kodak; Add-Vision; Magin; Plextronics; Organic Lighting Technologies; GE; 3M Innovation	CDT (Sumitomo Chemical) (UK); Novald (G); Fraunhofer IPMS (G); OLED-T (UK); OTB (ND); MicroEmissive Displays (UK)	Seiko-Epson; Matsushita; Sony; Sumitomo Chemical; Sharp; TM Display; Konica –Minolta; Sanyo; Toppoly; Lumiotec; Canon; Toshiba	Samsung; LG Phillips LCD; Neo View; Doosan DND	AU Optoelectronics (AUO); Univision; Toppoly; Tetrahedron; Chi Mei Optoelectronics	
Bulk materials and glass suppliers	PPG; 3M; Dow Corning	Merck Materials (G); BASF (G); CDT (UK); Degussa/ Evonik (G); HC Starck (G); Sensient Imaging Technologies (G); Goodfellow Metals (UK); Novald (G)	Sumitomo Chemical; Mitsubishi Chemical			Syndychem (Shenyang Syndy Chemistry Institute)
Components – driver ccts., packaging etc	Corning; Rockwell Collins	ST Microelectronics (It, Fr); Infineon (G)	Maekawa; Matsushita; Toppoly;	Dae Joo Electrncs	AUO; Richtek Technologies; Lightsonic; Univision; Wintek	Innocom Technologies Shenzhen; RIT Display
OEM OLED FPD screen manufacturer & resellers	eMagin; US Micro Products	Densitron Technologies (UK); MicroEmissive Displays (MED) (UK); Pacer International Distributors (UK reseller)	Seiko-Epson; Sharp; Sumitomo Chemical; Lumiotec; TMDisplay; Sanyo	Samsung SDI; Orion OLED; NeoView KOLON; Hyundai LCD	AUO; Chi Mei EL (CMEL); Univision Technology; Evervision Electronics; RiTDisplay; TPO Display	Visionix; Smartdisplays; Universal Display Technologies (Jilin); Varitronix (HK); Blaze Display Technologies
Branded application device or/and FPD screen manufacturer with retail device sales	OSD	Nokia; Sony-Ericsson	Sony; Matsushita; Hitachi; Toshiba; Imase	Samsung; LG Philips		
OLED lighting branded suppliers and R&D	GE	Thorn EMI (UK); OSRAM (G); Siemens (G)	Sumitomo Chemical			

and end-product design. Much of the original research was centred in the USA, by Eastman Kodak and UDC, as well as in Europe, for instance at the Cavendish Laboratory in Cambridge, UK.

The centre for display panel production in OEM fashion is in Asia, in Taiwan as well as Japan. The OLED film is also mass produced in Asia. Branded product manufacture in TVs, laptops, etc, incorporating OLED screens is concentrated

in Asia, specifically in Korea, as well as in Japan while assembly also takes place in China. We see clusters occurring in the USA for materials supply as well as for R&D. Similarly for the EU, this is the current situation. We will examine its evolution in the following chapters.

A full analysis of clustering in display technologies is beyond the scope of this particular study. However, in Europe we highlight the

Figure 3-3. OLED display industry structure by product and supply source

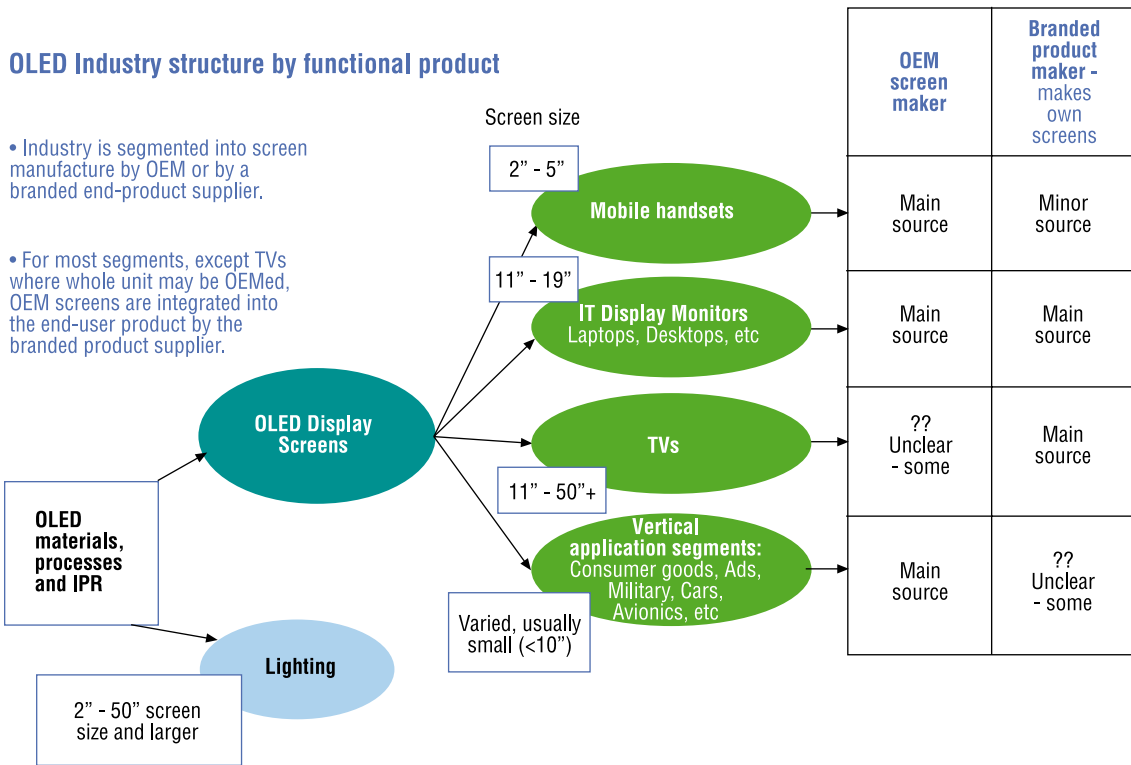


Figure 3-4. Formation of clusters in the global production industry for OLEDs

OLED production industry structure at initial stages today– trading consortia and technology partnerships – expect change

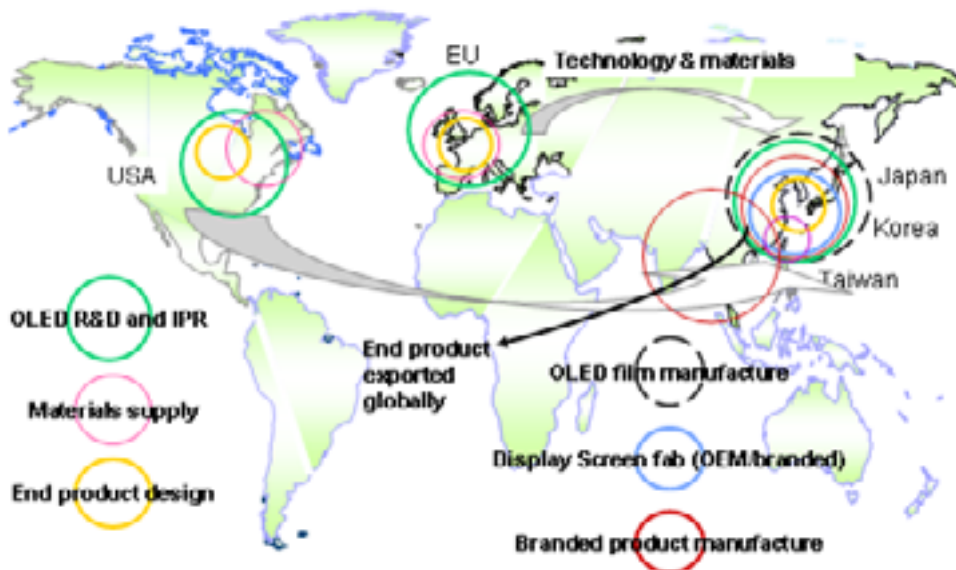


Table 3-3. Clustering in display technologies in the EU

Region	Companies/institutes	Activities
Cambridge, UK	Cavendish Laboratory CDT Conductive Inkjet Technology IDTechEx Kodak Novalia Plastic Logic Printed Electronics Pulsar Light Screen Technology	OLEDs, e-paper, printed electronics
Dublin, Ireland	Ntera University College Dublin	e-paper
Dresden, Germany	Fraunhofer Institute IPMS (Institute for Photonic Microsystems) Novaled Plastic Logic	e-paper, OLED lighting, manufacturing
Eindhoven, Netherlands	OTB Display Polymer Vision iRex Liquavista Philips (previously – sold off IPR)	OLEDs R&D e-paper R&D e-paper film production e-reader device R&D and production

clustering of relevant companies and institutions with activities in OLEDs and/or e-paper, i.e. R&D, and pilot or small scale manufacturing in three locations, as shown in Table 3-3.

3.2. E-paper value chain

3.2.1. Introduction

Below we outline a somewhat different value chain for e-paper and its end-user device:

Figure 3-5. Simplified e-paper value chain

The basic E-paper Value Chain - 7 stages

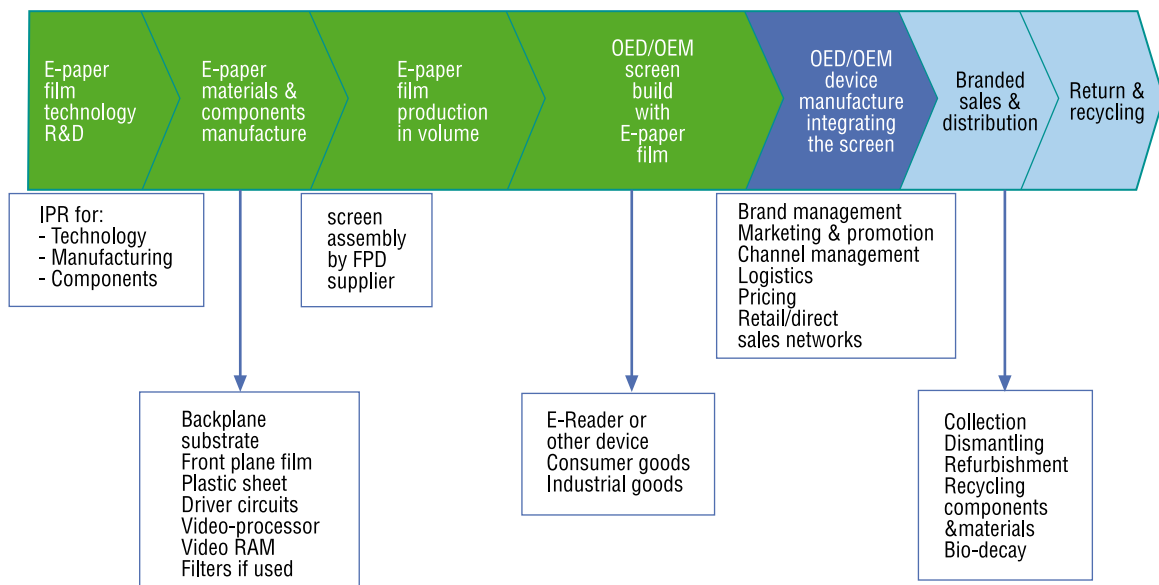
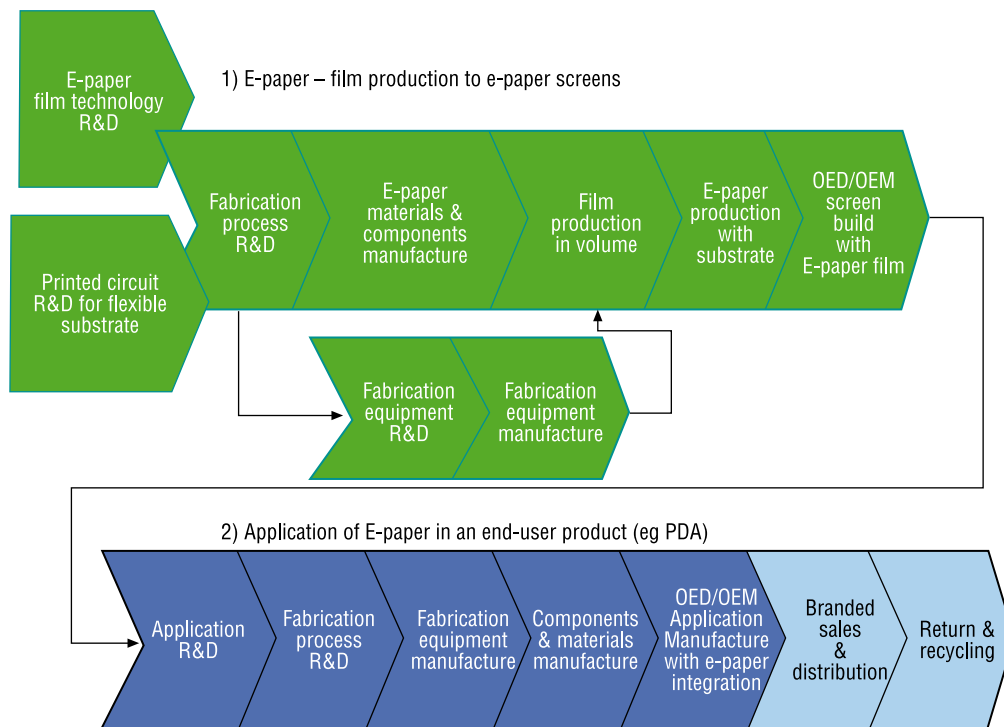


Figure 3-6. Complete e-paper value chain

E-paper Value Chain in detail with application



In more detail, each major path of the value chain can be broken down further (see Figure 3-6).

Again, as for OLEDs, the key production technology is likely to be inkjet printing for low cost e-paper, as the e-paper applications market demands low costs of production.

Here the EU also stands out with suitable printing technologies for e-paper which can be exported. Although inkjet is the way the industry currently moving, with printed layers on plastic technologies, overall we would expect a range of production techniques being used, such as spin coating and others (as printed electronics for e-paper with plastic/silver is not *always less expensive than photolithography*).

E-publishing

The e-paper display market is somewhat different to a general technology such as OLEDs.

It is an application that cannot stand alone. It needs content – e-books, manuals and electronic documents, newspapers and magazines. The industry structure for e-publishing and its value chain is illustrated in Figure 3-7.

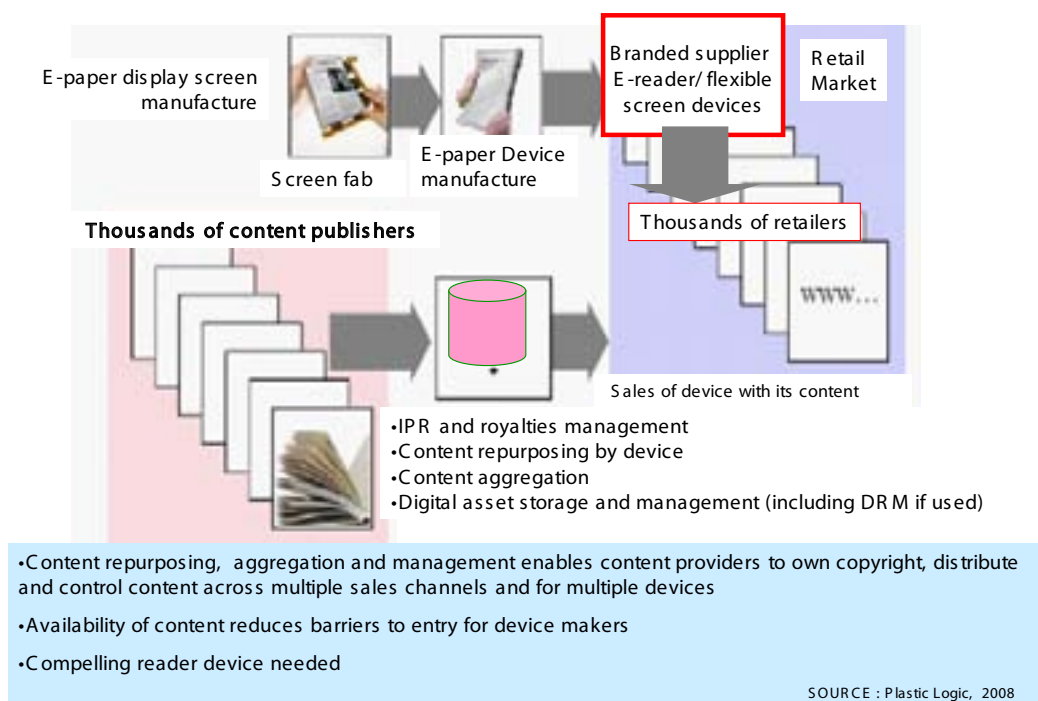
Various players and consortia are entering the e-book field with different e-book standards of document formats. Amazon has proprietary standard, .mobi, from Mobipocket of France, a company which it acquired in 2005. Other standards include:

- ‘Open’ or industry standards, principally that from the International Digital Publishing Forum (IDPF), .epub,
- Adobe portable document format, .pdf, a proprietary but widely used general standard,
- Microsoft.Lit, a proprietary standard.

These standards may be implemented by the content publishers before ingest, or in the

Figure 3-7. Content publishing forms an extra part of the value chain for e-paper

The value chain for e-paper is now extending into digital content



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stage of preparation of content, specifically the management as digital assets for storage and download with content aggregation.

In all there are around 25 different document formats that could be used for e-books, including the Chinese character based SSReader format, .pdg, but, so far, Apple has been silent on such standards. Standards vary on characteristics such as layout separate from content, reflow with flexible scaling and aspect ratios to match display screen format, published specification of standard, built-in DRM, text graphics and fonts in one file, etc.

The key interest in the format standard is the business model, as a restricted proprietary enables an iTunes type of business model, of a large number of titles available for download in a single proprietary format providing lock-in of users and market dominance. This is what Amazon has done with the Kindle, having some

90,000 titles available for download via a wireless link at time of launch in November 2007. Some large publishers in Europe, such as Hachette – Filipacchi of France are backing the IDPF format for an increasing range of e-books. Interestingly on the mobile cellular front, Google’s Android mobile operating system environment may use IDPF’s .epub too. Most of these standards incorporate a DRM capability so that they restrict access to one e-reader, ensuring that e-books cannot be passed on to others.

Naturally this nascent-market situation indicates a period of digital wars over content formats and also content rights, as in the free music download conflicts. This is likely to be quite fierce as the big names in publishing enter, from relatively small, quality publishers such as Random House with 6,500 titles currently to Barnes and Noble – large booksellers – who in this case may launch their own low-cost e-reader soon. As a sign of potential e-book demand, note

that, some BitTorrent free music sites are already stocked with books in .pdf.doc and .txt formats for free downloads.

Such activity indicates a growing interest and above all a rapid education of the mass market, by the informal marketing methods that are a characteristic of the Internet. The main point is that this is likely to drive the e-book and e-reader market and promote take-off of e-paper over the next 3 to 5 years.

3.2.2. E-paper industry structure

The types of player and who they are

The Table 3-4 gives an indication of some of the most significant players in the various segments of the e-paper value chain.

Clusters, groupings and relationships

We see an Asian cluster in final production, especially around film and display screen producers who may offer also product integration

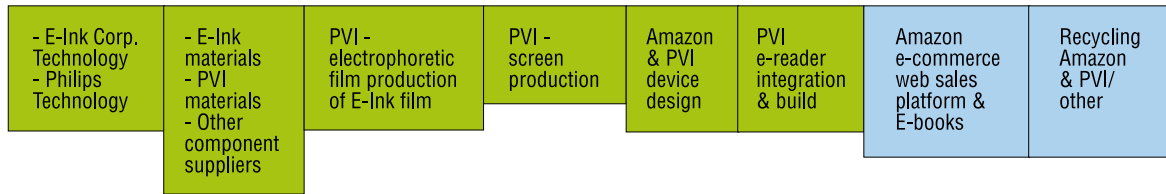
Table 3-4. Companies in the e-paper market by country

Segments in the e-paper value chain	Significant players by country/region
Original IPR and/or material supply/ verification	USA: E-ink; Kodak; Xerox; Kent Display; Unidym EU: Plastic Logic; Polymer Vision; NTERA; Philips/ Liquavista; Acreo; Barco. Japan: Fujitsu; Fuji-Xerox; Bridgestone; Hitachi; Seiko Epson; Toppan Printing Korea: Samsung; LG.Philips Taiwan: PVI; IEK; ITRI
Supplier of bulk and refined materials	USA: 3M; Dow; PPG EU: CDT; CIBA Speciality; BASF; Saint-Gobain Glass, Conductive Inkjet Technology Japan: Sumitomo Chemical; Mitsubishi Chemical
Process equipment supplier	EU: EV Group Japan : Dainippon SScreen
OEM e-paper film or/and screen manufacturer	USA: Kodak; Kent Display; SiPix Imaging; Aveso EU: Plastic Logic; Polymer; Vision; CP Films; Gebr. Schmid; KSG Leiterplatten; Nemoptic; UPM Kymmene; NTERA; Philips Liquavista; Siemens; ZBD Displays; Varitronix Int Japan: Fujitsu; Fuji-Xerox; Bridgestone; Hitachi; Seiko Epson; Toppan Printing; Dai-Nippon Printing Korea: Samsung; LG.Philips Taiwan: PVI; Industrial Economics and Knowledge Center (IEK); Industrial Technology Research Institute (ITRI) China: Displaytech HK
Electronic components, driver circuits, video display processors, video RAM	USA: Intel; Texas Instrument EU: ST Micro-electronics Japan: NEC; Toshiba; Hitachi; Fujitsu; Sony Korea: Samsung LGE
OEM White label application device manufacturer	Taiwan: PVI
Branded application device /display manufacturer with retail device sales and also resellers	USA: Magink Display Technologies EU: Polymer Vision; iRex Technologies; Plastic Logic Japan: Sony; Fujitsu; Matsushita; Seiko Epson China: JINKE Electronics; eREAD
Product design and retail sales channel	USA: Amazon EU: Polymer Vision; iRex Technologies Japan: Sony
Content for e-readers – e-book publishers	USA: Amazon; Hearst Interactive Media; Barnes & Noble; Random House EU: Penguin Books; Hachette; Reed Elsevier; Bertelsmann; Axel Springer Japan: Sony China: Shanghai Daily

From the above table we can see that the EU is stronger than might perhaps be expected in almost all areas, especially in R&D and the IPR created, also production of e-paper films, supply of base materials, as well as the complete branded e-reader products or display panels. Gaps are in retail sales channels

Figure 3-8. Strategic relationships in the value chain, the case of the Amazon Kindle

Example – Amazon Kindle e-reader production chain following value chain



in white label fashion, e.g., PVI (Taiwan). Looking at strategic relationships and technology partnerships, the pattern is of two types.

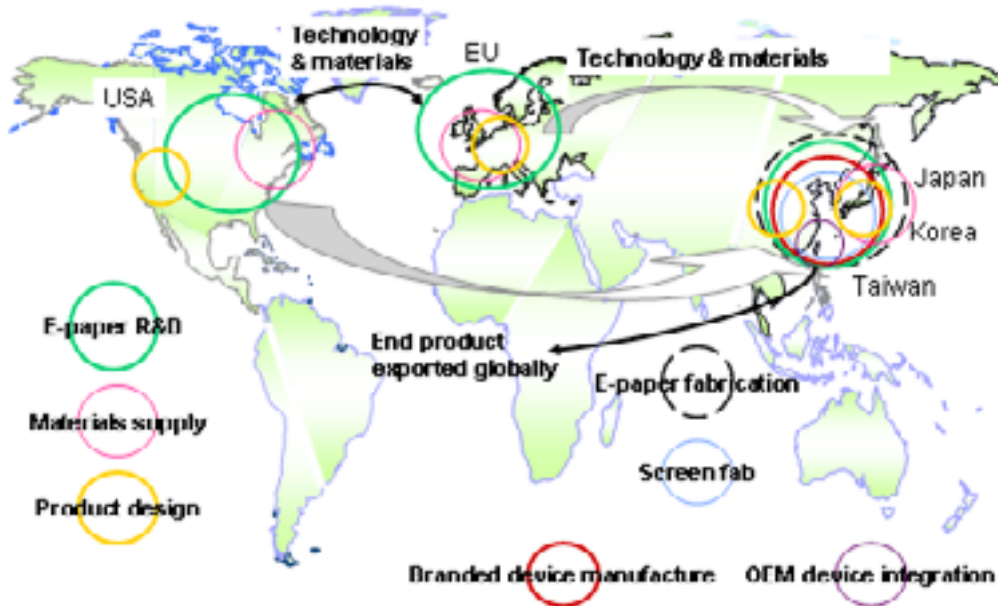
Firstly are those that ‘do it all’ to a large extent in-house from the technology IPR to e-paper production to the end-user device, such as an e-reader or a shelving display unit, for instance, such as Fujitsu. This is the Asian model for Japan and Korea; large consumer electronic suppliers such as Sony follow this.

Secondly is the EU/USA model for dividing up device design and production, best illustrated by an actual example (figure 3-8), one that is typical for products originating in the EU and the USA.

In this model, Asia forms the production end. USA and Europe dominate in materials, which have higher margins than the display screen and its integration. In materials, the major companies that dominate supply include US and EU players such as Merck (Germany, for base materials), 3M (USA, for base materials) and Corning (USA,

Figure 3-9. Current strategic relationships form global supply chain for e-paper

E-paper Industry structure at initial stages today – trading consortia and technology partnerships – expect change



materials including glass). Thus the value chain for e-paper must incorporate non-Asian players for technology, device design and the base materials, who may be from EU and USA.

The EU has perhaps one of largest range of the new technologies – such as Plastic Logic, NTERA and AVESO (for electrochromics), ACREO of Sweden, and Polymer Vision, iRex, and Liquavista (electrowetting) also linked to Philips. Production technology for these displays is aimed at all being printable. Thus many of the materials come from the EU, and the USA, as well as the IPR and product design, although they are applied in Asia. The value chain may be even more complex than this, e.g. one Irish player is selling materials to a USA company who then process these for final delivery to a German manufacturer of materials. Moreover USA IPR and technology may be used in the EU.

Increasingly, these exchanges are a moving target – it may even be that some displays will be made in the USA again with this new technology.

One example of the types of player we see appearing in the EU is NTERA (Ireland). The company makes printable electrochromic materials, driving electronics and related technologies for e-paper type applications in consumer bank cards, smart labels – ie for low cost applications. Our research revealed that NTERA has a *hybrid* business model with two main revenue streams – firstly licensing its IPR and secondly providing materials for production of screens and some of the driver electronic components. In consequence, it signed an agreement in 2006 with Seiko Epson for technology licensing for full colour video applications. This hybrid model is common in the e-paper segment (and in OLEDs) with Plastic Logic, E-Ink Corporation and others following this pattern more or less. Note that the key player in the USA, E-Ink Corporation, is also supplying European players with materials, e.g. for the iRex Technologies iLiad e-reader based in the Netherlands, as well as for Japan's Sony for its e-reader. Future applications for e-paper technology include mass-volume, low-cost consumer displays such as credit cards with a 'one time pass-code', given for each transaction, displays for USB storage devices, etc –large markets.

■ 4. The Disruptive Potential of OLEDs and e-Paper

4.1. The disruptive potential

4.1.1. The state of the display industry today

As noted, the global display industry is large, of the order of \$125 billion and so forms some 15-20% of total ICT sales. It is also growing due to the computerisation of consumer goods, the spread of mobile handsets and sales of ICT devices of all kinds, all products which continue to grow in sales despite economic downturns. Generally the high technology segment expects more displays to be added to products, often with animated colour. The major trends overall in the global display market are towards increased sales of displays in unit terms, but not necessarily of total revenues.

Today the flat panel display (FPD) industry is dominated by LCD technologies for TVs, IT monitors for laptops and desktop PCs, mobile phones, as well as diverse applications for small screens (<3") from washing machines to in-car instruments and now for large outdoor animated display advertising, currently being installed widely, e.g. in London's metro system. Plasma screens have also found a place in the TV market and in large-scale public displays.

Production processes in each case are akin to integrated circuit semiconductor manufacture. Today these tend to use fairly high temperature vacuum techniques with various forms of masking for deposition, with steps of lithographic and photographic processes, often in batch modes of production. In these processes, the circuits and display pixels are built up on rigid substrates, usually glass with some form of silicon, perhaps amorphous or polycrystalline. Thus the industry has become dominated by large FPD fabrication plants, backed by enormous R&D funding aimed

at improving the production processes for larger area displays and better visual characteristics with higher yield.

Capital investment is intensive. Over the past five years, a new plant's capital investment has increased from \$2 billion to \$4 billion as screen sizes (especially for TVs) have grown. The workforce must be highly skilled and production techniques of constant improvement, as practised in Japanese manufacturing, are the key to profits, through higher yield (Jackson, 1997). This has led to concentration of the display industry production in Japan firstly, followed by Korea. It is notable that although there are offshore FPD fabs in China, both Japan and Korea have their largest facilities in their own countries. Sharp, a major LCD player, is now building its new facility in Japan again, at a cost of some \$4 billion.

4.1.2. A potentially disruptive phase in displays

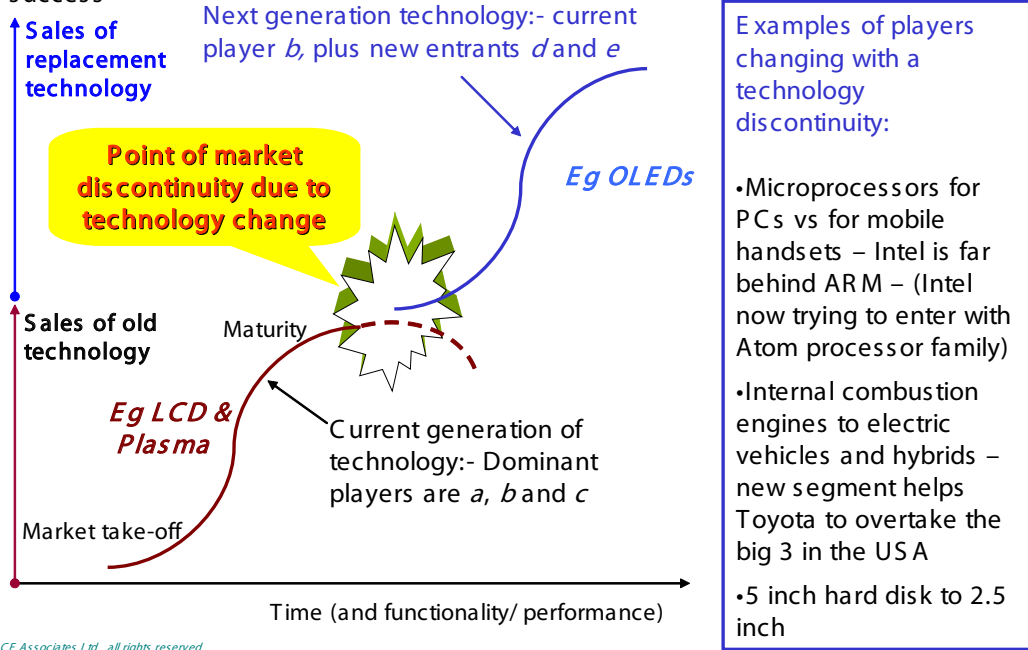
At this point we have sufficient indications to analyse the disruptive potential of the technologies of OLEDs and e-paper. In particular we should like to assess the probability of whether the discontinuities will enable EU players to enter potential global markets.

If there is some reasonable chance of success, we should also like to assess at what points in the value chain they could enter, with some estimate of the chances of success, due to the two technologies and their effects in existing display markets.

In general, a discontinuity may be viewed as an entry mechanism for new players, as shown in Figure 4.1.

Figure 4-1. Technology discontinuity offers an opportunity for new players

A new technology is a point of discontinuity where new players may enter as existing players have major impediments due to inertia of plant investments, skills, processes, marketing and above all, mental models based on prior success



We need to understand the disruptive potential of these technologies – either where they may substitute for an existing technology, or, where they may open up completely new applications or even a whole new industry segment, as mobile phones did for microprocessors. Microprocessors from Advanced RISC Machines, ARM, with some three billion in use, are now the most common microprocessors on the planet in numbers of units, far outpacing Intel and its Pentium range with its extensions. Note that this is a different business model to that of Intel, in that ARM acts as an original equipment designer (OED), in which its revenue stream comes from royalties on licensing its designs. It is not an original equipment manufacturer, OEM, with fabrication plants to sell in large wholesale volumes to equipment assemblers. Instead chip suppliers such as Samsung produce the ARM designed chipsets. Even Intel licences some design IPR from ARM.

The pure substitution case is more for OLEDs. An E-paper discontinuity (where many technologies may succeed) is firstly about generating a new product category with its application segment, i.e. firstly the e-reader market. Then it may perhaps be followed by applications in advertising and signage, retail distribution, packaging, etc, which are a mix of substitution and new categories, in that paper is substituted for especially in books and newspapers.

4.1.3. State of display technologies tomorrow – a route map for OLEDs

In looking at the disruptive potential, it is helpful to try to foresee what could be the positive path for the technology and its manufacturing process development. We have drawn up a tentative route map of potential progress, shown in Figure 5.2. Developments identified here are based on our findings from the wide variety of

sources consulted in the course of this study, but they are speculative, dependent on adequate progress in R&D for each technology. The actual path could turn out to be quite different. We expect that market share would advance through the series of stages for an innovation technology with phased market situations of being:

1. First as a niche technology or application, with take-up being quite limited
2. Second comes a phase of consumer and vertical industry acceptance in which the market becomes educated about the technology or application
3. Finally we enter the commodity phase; here we envisage this as perhaps after 2016 or so for OLEDs, when fewer technical advances are made and fewer new applications are brought into a mass-market environment, but volume scales up by orders of magnitude.

For e-paper this point could well be much earlier.

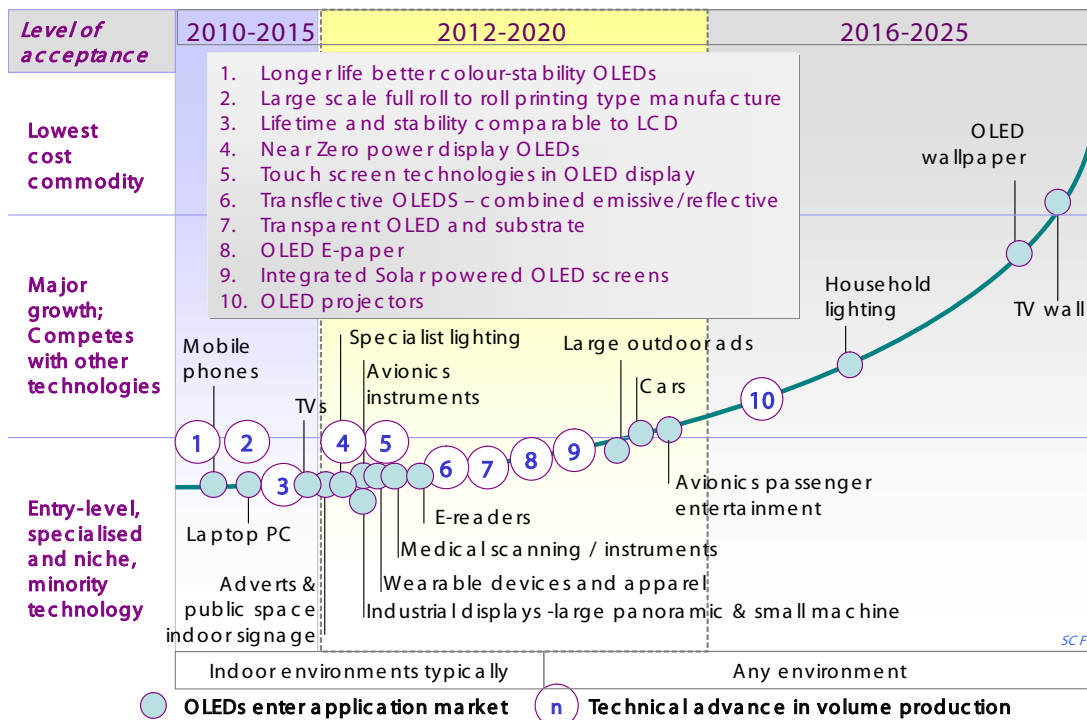
The OLED route map below anticipates a quite slow take-off – with the second phase of industry and consumer acceptance not really occurring until well after 2012, perhaps with major growth after that but possibly only becoming a lowest cost commodity beyond 2020. This may be pessimistic but could be a pragmatic view of the probability of continuous improvement and perfection of TFT-LCD base technology for at least another five years, perhaps to around 2014 and so maintaining market dominance.

Success for OLEDs depends on two key technical advances: first, the operating lifetime, which is based on stability of each colour, i.e. of the basic polymer technology; and second, the production process. If the latter can be developed for larger screen sizes, with consistent high quality at low cost, perhaps in a roll-to-roll mode

Figure 4-2. OLED route map to 2025

Routemap Estimate: development to 2020 for OLEDs, technology and applications

The three Epochs are general indicators and so overlap



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(whereby the production processes are based on passing an e-paper base film between continuous rolls for depositing the active e-paper strata, to create a low cost printing technology with room temperature processes, as in inkjet printing) that combination could take unit costs per FPD below those of TFT-LCD. To displace TFT-LCD may well require further incremental progress in production techniques for consistent high yield and high quality at lower cost.

There are, unsurprisingly, quite contrasting comments from market players on a future development path for OLEDs, especially against TFT-LCD. Most notable is Sony, which produces both types and has to defend its large revenue stream in LCD. It has publicly positioned OLEDs as the display technology for entirely new devices²⁸ and product categories (eg net-tops, small laptops usually with screen diagonal below 10 inches, mobile devices for web services, Apple-iPhone like, and further iPod-like Apple TVs for Sony's Blu-Ray video media player - and perhaps far into the future, wall-size TVs). Sony then positions LCD as being for the larger sizes of current TVs, which are also becoming both thinner and lighter. The Executive President of the Sony TV Business Group has noted that production of large TVs using OLEDs is currently difficult for Sony. This supplier currently has an 11 inch OLED production model (launched January 2008) and has shown (August 2008) a 27 inch prototype. However he also noted that commercialisation of OLEDs must be carried out without delay as they are the next generation of displays for colour, contrast and thinness (down to 3mm).

4.1.4. State of display technologies tomorrow - a route map for e-paper

For e-paper we see a rather different technology and production route map, in that we have an application with new devices and uses, perhaps never seen before. However there are similarities, especially in the development of low-cost production technology with inkjet printing for high yield and quality.

Rapid take-up depends on education of the e-reader market, already started by Amazon's Kindle. With others entering the market in volume over the next two years ranging from Polymer Vision, iRex Technology, Fujitsu, Endless Ideas BV, perhaps Plastic Logic, Hachette, Barnes and Noble, as well as relaunches by Sony and others, we may expect market expansion, if the content is there.

However the mainstream applications of e-paper in the future are also in e-readers for straight business documents, plus:

- Extending use of changeable text and moving images advertising and signage
- Substituting for displays in laptops, mobile handsets further into the future, and subsequently in perhaps new ways of using displays in medical and industrial applications when the reliability and lifetime of the technology has been proved. Larger handset screens (with touch screen properties) are being driven by the Apple iPhone phenomenon, used for social networking on Facebook, MySpace, etc.²⁹
- Long-term: more exotic applications in whole-wall displays for TV and wall paper perhaps

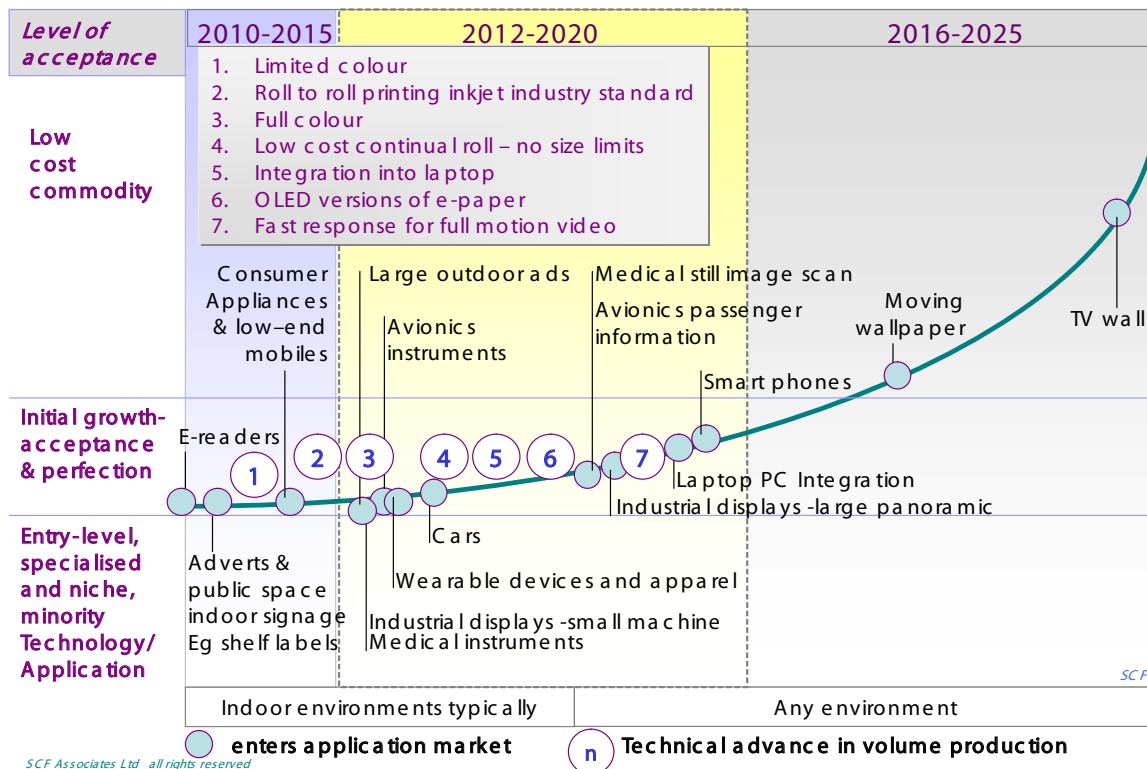
28 Takashi Fukuda, Executive President Sony TV Business Group, speech at FPD International 2007, 24 October 2007, http://technonnikkeibp.co.jp/english/NEWS_EN/20071029/141429/; M. Oonishi, Nikkei Microdevices, 'OLEDs position is different from LCDs', 29 October 2007, FPD International.

29 This trend to larger screens for social networking is now being picked up in the first Google phone, the G-1 with its Android operating system, from white label OEM/OED, HTC of Taiwan, sold through T-Mobile, while Motorola is also launching a similar larger screen Android packed device for late 2009 using Open Handset Alliance standards, FierceMobileContent, 20 October 2008.

Figure 4-3. E-paper route map to 2025

Routemap Estimate: development to 2020 for E-Paper applications & technology

The three Epochs are general indicators and so overlap



A possible development path with milestones is illustrated in Figure 5.3, with the market creation phases ranging from entry-level niche to low cost commodity.

4.2. Why OLEDs might be disruptive

Having seen the possible trajectory of technology advance and new product introduction for OLEDs we may examine the potential disruptive power of OLEDs in the display markets by firstly looking at the dominant technologies. Currently the two leading display technologies, of TFT-LCD and plasma, are characterised by:

- Limits in brilliance, resolution and colour ranges due to their inherent structures and physical processes of displaying images.

- Power requirements that are difficult to reduce further, owing to the need for a backlight for LCD, despite the move to large LEDs, or physical discharge for plasma.
- Weights that are difficult to reduce further because of the need for complex substrates and backlighting planes.
- Production facilities that demand semiconductor clean-room conditions and are unlikely to be replaced by low temperature, non-clean room environments. They are expensive, and the machines must be able to maintain vacuums at high temperatures, making production yields subject to minute changes to physical conditions, adding to costs and limiting production yield.
- Sizes that are constrained by their technologies, especially the yields – the basic technologies do not scale well without non-linear cost increases as the fault rate

goes up in a square law with *area* size and thus the yield comes down, making those perfect screens more expensive. This is linked to the capital expenditure nature of the production facilities outlined above, which also constrains size – moving to larger size display can mean replacing the whole production line.

- The mainstream technologies in LCD and plasma do not produce flexible types of displays. However a new LCD technology, cholesteric LCD, as proposed by Fujitsu and others for e-paper may offer a new avenue for flexible displays. But the mainstream remains with rigid substrates and so confines the applications.

In comparison, OLEDs are therefore quite disruptive to the current industry in that:

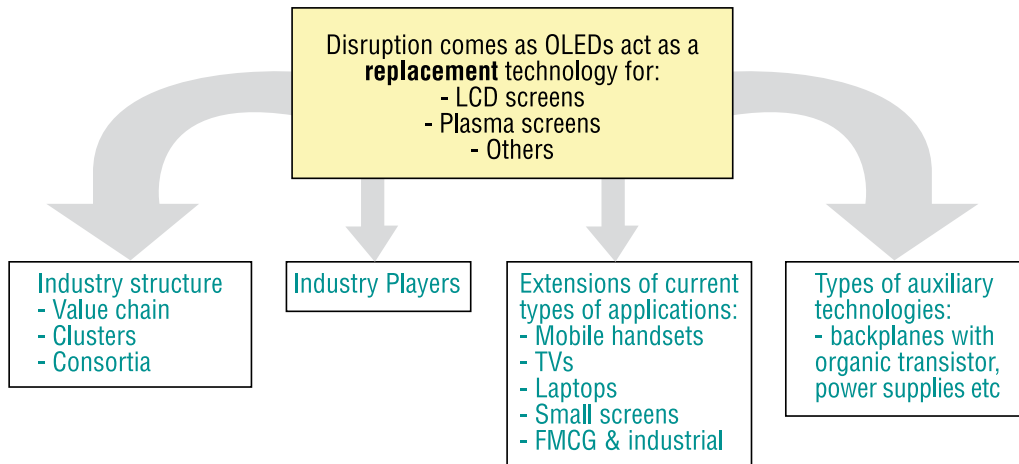
- They are based on plastic technologies of polymers, lending themselves to low temperature techniques of production that do not require vacuum conditions and so can scale quickly in theory. Thus the production techniques may be the lower cost processes, of inkjet printing or spin coating resulting in lower capital investments. Note that Samsung's investment of \$550 million for a new fabrication plant for OLED 2" screens, producing 9 million units per year (Soble, 2008) is an eighth of the Sharp investment in a new LCD FPD fab, although production volumes from the new LCD plant are not yet known for comparison and screen sizes are likely to be for TVs and thus far larger.
- The above point tends to indicate unit prices of OLED displays could eventually be much lower than LCD and plasma, perhaps as low as 10-20% of LCD cost when large-scale volume production is achieved with high yields.
- Inherent physical properties of polymers enable flexible displays to be made and this widens the applications base enormously.
- Power and luminescent efficiency are higher as OLEDs do not use light from a backplane

backlight (the transmissive mode) but from the polymer (emissive mode). This means that the power demands can be lower – a key asset for mobile phones and laptops. For many LCD laptops, 80% of the power consumed can be in the display backlight. In total the effect would be to cut the power demanded by ICT devices of all kinds by up to 80%. It is certainly significant in global terms of the recharging power required for the largest range of ICT devices on the planet, around 3 billion mobile handsets. Thus Japan's New Energy and Industrial Technology Development Organisation (NEDO) is promoting OLEDs in the hope of achieving TVs that run at under 40 watts, rather than the 200 watts on average for LCD and plasma screen TVs today.

- The display's weight can be lower as there is no backlight and the whole unit can also be made thinner, of the order of a few millimetres thick.
- Thus, OLEDs are a far more sustainable technology – both in energy required to manufacture and to operate. This is a perhaps a key driver and should not be underestimated. The EC ROHS (Restrictions on Hazardous Substances) Directive is far less likely to be contravened either in production or for the finished product. For recycling, as glass may well be absent, while the polymers can be recycled or broken down, the screen may be well advanced over LCD. Biodegradable properties could be imagined, by adding triggers (thermal, chemical, frequencies) for reprocessing/unwinding the polymer.
- Size impacts on production yields could have less effect, especially on a roll-to-roll type production line.
- Although this is a moving target, OLED suppliers claim the technology offers far more colours, brightness and contrast with less motion blur than LCD, especially against cheaper LCD models.

Figure 4-4. The disruptive potential of OLEDs

The disruptive potential of OLEDs: the key types of impacts



- Production equipment needed for large-scale manufacture of OLEDs is now appearing from companies such as Aixtron AG in Germany, Applied Films in the USA and Doosan in Korea, a sign of industry interest and confidence in the technology.

What we see here is a disruptive effect by substitution or replacement, specifically for the above reasons of production cost, power and quality. The various impacts of the disruptive qualities of OLEDs are summarised in Figure 4.4.

However, we should not forget that the substitution effect may be offset by several factors:

- Industry trends to replace the base technology slowly, in order to recoup current LCD capital investments. In the absence of a 'badly behaved' large competitor, or pressures from a major customer, such as the mobile handset suppliers, this wilful tardiness could be significant, as has happened in many other technology industries dominated by those with an existing technology to harvest.
- The lifetime of OLEDs is currently significantly less than LCDs. In May 2008, the first mass

production OLED TV on sale, Sony's XEL-1 was reported in a 1000 hour test by DisplaySearch to have aged twice as fast as claimed by Sony. Service life on average usage was projected to be reduced from 10 years to 5 years, or finished after 17,000 hours in service, rather than the 30,000 claimed by Sony.³⁰ However the same research noted that other OLED displays, for instance the Samsung small OLED display for mobile phones, do last far longer than Sony's OLED screen.

- A more specific version of the above problem is perfection of individual colour lifetimes of OLEDs – particularly blue, rather than general aging across all colours. This research delay holds back more general major market launches, as currently the display panel lifetime is too short for applications requiring many years of service.³¹

30 Oled-Display, 08 May 2008, at www.oled-display.net/sony-xe1-oled-tv-lifetime-only-17-000-hours

31 In a test in 2004 on a Kodak AMOLED small display for a camera, DisplaySearch, found that normalised luminance after 1000 hours for red green and blue was 62%, 69% and 38% respectively: from Summary of report: Is OLED Display in Sony's XEL-1 OLED TV as good as it looks?, DisplaySearch bulletin, May 2008.

- Problems in practice with OLEDs in everyday use, particularly with water resistance and oxidising which also affect lifetime length
- Problems in perfecting the production techniques for high yield and low unit cost. As production in volume of OLED FPDs is not yet perfected, rejection rates are high, so OLED TVs are expensive, e.g. In January 2008, \$2500 for the Sony XEL-1, somewhat expensive for an 11 inch screen.
- Problems in scaling OLED FPDs beyond small screen sizes – released in late 2007, Sony's OLED TV was only 11 inch in size, although others have unveiled prototype OLED TVs with larger sizes, e.g. Samsung's 31 inch screen.
- There is also the question of the competitive reply from the LCD FPD makers in terms of price and quality, as they are not standing still on basic display technology. Moreover, LCD FPD prices are being driven down by the global recession. Due to the collapse in global demand, LCD sales may perhaps shrink for the first time,³² predicted as a 3% drop, measured in unit sales in 2009. Indeed the global TV market is a picture of gloom so that LCD FPD factories in Taiwan cut production by 40% in late 2008. Also, it has recently come to light that some LCD FPD industry players have been engaged in price fixing, indicating there is a buffer zone in pricing for LCD FPD's which will further challenge OLEDs.³³ However, in some ways this might hasten the entry of OLEDs, if OLED problems are solved to some extent and if its production costs are truly lower, as the bulk LCD buyers (TV manufacturers,

laptop makers etc) are now demanding below-cost prices when purchasing LCD FPDs to meet the new consumer thresholds for buying the end product.

To resolve these technical OLED issues, much industry and academic effort is under way, most importantly at the phase of industrial development prior to large-scale manufacturing. The development of various consortia with centres of expertise and academic projects is shown below in the table of industrial collaboration projects and centres of excellence, as indicated as being notable from industry research (see Table 4.1).

4.3. When could a discontinuity occur due to OLEDs?

The prognostications for OLEDs to become dominant in the display market are very different. There are two major views which we now examine.

4.3.1. The current display (LCD) industry view

Sharp, Toshiba and Matsushita Panasonic are all partners in Japan's New Energy and Industrial Technology Development Organisation (NEDO). But they do not expect large OLED TV displays until the second half of the next decade, i.e. not before 2015 (Soble, 2008). To try to understand this dilemma of investing in OLED development while predicting a long-term gestation of the technology, we therefore spoke to the European president of one of these major Japanese suppliers, perhaps the largest supplier of TFT-LCD panels globally. He was categorical: OLEDs will take at least a decade to come to market because of the problems of lifetimes for the different colours, blue and violet being the major problems.

Also, he noted that an advance in the lifetime of blue often led to a reduction of the red tones' duration. Thus in this analysis, OLEDs

32 Kwong, R., and Pilling, D. (2008). An LCD FPD market contraction is expected in 2009 as demand has evaporated in November and December 2008. The price of a 32 inch panel in December 2008 has halved since December 2007. For the flat panel TV market, major LCD factories in Taiwan have been running at 60% of full capacity since June 2008 – Kwong, R. (2008).

33 LCD manufacturers Sharp, LG Display and Chungwha Picture Tube Ltd paid a total of US\$585 million in fines in November 2008, following a USA Department of Justice prosecution, admitting to conspiring between 2001 and 2006 to drive up FPD prices, Jordan, LJ, (2008).

Table 4-1. OLED Industrial collaborative projects, and centres of excellence

Name	Location	Subject area	Partners	Organiser/ funding
<i>NEDO (New Energy & Industrial Technology Development Organisation)</i>	Japan	OLED display technology over 40" for TV industry largely, for low power 40W TV	Sony, Sharp Panasonic & the Chemical / component suppliers	Japanese government, \$32m seed fund
<i>Fast2Light</i>	Europe	OLED lighting – polymer foil production	14 organisations (companies, Univs, etc)	EC
<i>OLLA</i>	Europe	OLED lighting	20+ organisations	EU/EC/FP6
<i>ComboLED</i>	Europe: Germany, France, Spain, Italy	OLED lighting – cost effective supply chain from substrate to device manufacture to application	7 members – Osram, Siemens & 5 others	EC FP7, €7 m, 01 Jan 2008, 3 years
<i>Lumiotec</i>	Japan	Organic Electroluminescence (OEL)	Mitsubishi, Rohm, Toppan printing, Mitsui	Commercial, to sell panels from 2009
<i>Topless, Thin Organic Polymeric, Light emitting semiconductor surfaces</i>	UK	OLED lighting: Polymer-OLEDs at 20lumen/watt, single large pixel devices	3 partners: Thorn Lighting, Univ. of Durham, Sumation	UK govt. £3.3m, June 2008
<i>US Display Consortium (public /private partnership)</i>	USA founded 1994	FPD manufacturing supply chain with tech. programmes	Around 150 members from USA industry	USA commercial & govt: DARPA, US Army (\$220m since 1994)
<i>Flexible Display Center, FDC, Univ. of Arizona</i>	USA	FOLEDs, Flexible displays, e-readers /e-ink	UDC, Applied Materials, US govt. depts, others	US Army and govt- depts / Academia/USA industry
<i>UK Displays and lighting knowledge transfer network</i>	UK	Lighting technology	Over 30: Merck, Sharp, Corning, Qiniteq, Kodak, Univs et al	UK DTI
<i>Rollex project</i>	Germany	Large industrial scale roll-to-roll production of OLEDs, for displays and solar cells; factory Dresden.	Fraunhofer Institute departments –IPMS, FEP, COMEDD	German Ministry of education and research (BMBF)
<i>MIT Media Lab</i>	USA	E-paper, OLEDs, display tech	E-Ink, others	MIT, US government
<i>Cavendish Lab</i>	UK	Polymer science	Various	Government & industry
<i>Center for Photochemical Sciences, Bowling Green SU</i>	USA	Photochemistry	Various	Industry & university

might be viewed as a *niche* technology, rather than a mainstream technology, at least for the near future. The niches are in segments with rapid product cycles, i.e. certain consumer goods, specifically those with low cost and a more 'disposable' profile such as MP3 players and low-end mobile handsets. Where the product lifetime is expected to be less than two years, as it is likely to be lost or replaced on those timescales, then OLEDs could be a successful contender. Also this implies a low-cost product category.

OLEDs are thus ruled out in the near future for white and brown consumer goods of 3-5 year

lifecycles, cars, or industrial applications. He also noted that TFT-LCD is the only current technology (including e-paper) that could scale from 1-100 inches. For these reasons, currently the CRT and LCD display technologies occupy 90% of the display market – all other technologies are in the range of a single-digit percentage of market share, even plasma displays. On the geometry side of a thin form factor, the latest TFT-LCD displays are of the order of 9 mm thick, i.e. as thin as OLED panels, but can have much larger screen sizes.

On the power side, lower consumption backlights are in development for LCD panels,

Table 4-2. 1000 hour test of % OLED luminescence decay

Colour luminescence degrade test over 1000 hours	Red, % of start luminescence	Green	Blue
2004, Kodak small on-camera OLED screen	62%	69%	38%
2008, Sony TV XEL-1	93%	92%	88%
<i>Improvement over 3.5 years</i>	540%	388%	517%

Source: OLED-DISPLAY.NET, May 2008³⁴

using arrays or large single cell LEDs (light emitting diode) perhaps. These LCD suppliers see that there is much hype around OLEDs, with some market analysts predicting growth rates of thousands of percent early on where as the truth is that in the next five years, OLEDs may take 5% of the display market at most. However, it was also noted that all LCD panel suppliers are also investigating OLEDs as a protective move.

4.3.2. The view of the EU OLED suppliers

In sharp contrast, others in the display industry, particularly those in Europe whose main revenue stream is OLED technology, position OLEDs as taking off earlier, perhaps even in the next year and certainly becoming well established by 2010. They see this as especially valid in perhaps what is the largest market, of small screens of 2 to 5 inches for mobile handsets where operational and production efficiency is easier to achieve.

Some in the OLED industry foresee the possibility of a slow take-off being engineered by the LCD technology manufacturers. The latter may fear loss of market dominance, and might wish to avoid the risk and investment in a new technology where they may have little competitive advantage. Furthermore, their existing capital investments in LCD plants, and intellectual capital could depreciate in commercial value far faster if OLEDs are taken up widely. However, the real customers for the

OEM volume producers are the large players, who use the FPDs as one component, such as Nokia. They are unlikely to allow the display fabricators to stand still on OLEDs in order to (over) extend their LCD revenue streams. In such a situation, the major producers of the smaller OLED panels would be forced to accelerate delivery of robust OLED technologies to market, following demands for lower cost, less power and higher brilliance and colour range. Their failure to do so could be an opportunity for a smaller player – possibly even a European one. This would certainly be a disruptive play. Moreover the smaller suppliers also see the technical differences being overcome as OLED research accelerates, as shown in the table below of OLED screen luminescence decay measured for 1000 hours of operation, for two tests of OLED technologies, about three and a half years apart (see Table 4-2).

4.3.3. Timing the discontinuity for OLEDs

The question of timing is perhaps best answered by looking at the industrial situation, specifically the behaviour of several key groups – first, the largest scale producers of consumer goods using displays, and second, those manufacturing screens for integration by others and also the materials suppliers, as well as the hand of industrial policy.

Here we see in the first group that large scale investment has been made in OLEDs over the past three years by Asian suppliers of consumer goods – Samsung, LG Philips, Sony, Matsushita (Panasonic brand), Seiko Epson in both R&D

34 <http://www.oled-display.net/sonys-xel-1-oled-tv-lifetime-only-17-000-hours>

and pilot consumer models of TVs and laptops. Most notable perhaps is the production of display screens for integration by others, including Taiwan suppliers such as PVI and CMEL. Despite its new investment in LCD, and its strong promotion as recently as April 2008 of LCD over OLED, Sharp has recently changed tack and hedged its bets by joining a Japanese consortium to progress OLED products, perhaps indicating the need to take OLEDs more seriously. The material suppliers such as Mitsubishi Chemical, Sumitomo Chemical in Japan as well as Merck, BASF, Solvay, CIBA in Europe and 3M, Du Pont, PPG, Dow Corning in the USA are all investing in materials supply for both OLEDs and e-paper.

When we turn to industrial policy we note that the Japanese Ministry of Economy, Trade and Industry announced in June 2008 support for the formation of an OLED development consortium of TV suppliers such as Toshiba, Sony and Matsushita. The aim is to develop key technologies to produce large-size next-generation display panels and cut development costs.³⁵ Increasing formation of industrial development consortia such as Lumiotec, in May 2008 in Japan, to form OLED lighting panels with Matsushita and others, also points to a point of discontinuity.

Taking the two opposing views above of the TFT-LCD manufacturers against the OLED suppliers, it seems probable that time to OLED mainstream take-off may be longer than the optimists predict. However, whether it will be more than a decade is also open to question. The momentum behind OLED technology has accelerated over the past five years to production scale delivery today at Samsung SDI, CDT/Sumitomo Chemical and others. The recent advances made would indicate that small screen applications in the fast product cycle items such as toys, MP3 and MP4 players and above all low-

end mobile phones could challenge, and perhaps even dominate, LCDs in five years, unless the backlight and cost disadvantages of TFT-LCD are overcome.

The conclusion on all this activity is that the point of discontinuity for OLEDs is not before 2009/2010, with major product launches over the following decade. This implies that with the timescales for mass production and payback for leading applications, production facility building for pilots has already started or been completed (e.g. for Samsung). Serious players are now entering volume production, aiming to replace LCD for TVs and laptops in price terms over the next two to three years. Such facilities are expected to have paybacks over the product cycle, of three to five years, at which point a new industrial process (and possibly plant) will be expected, if the current one cannot be incrementally improved.

4.4. Why e-paper could be disruptive

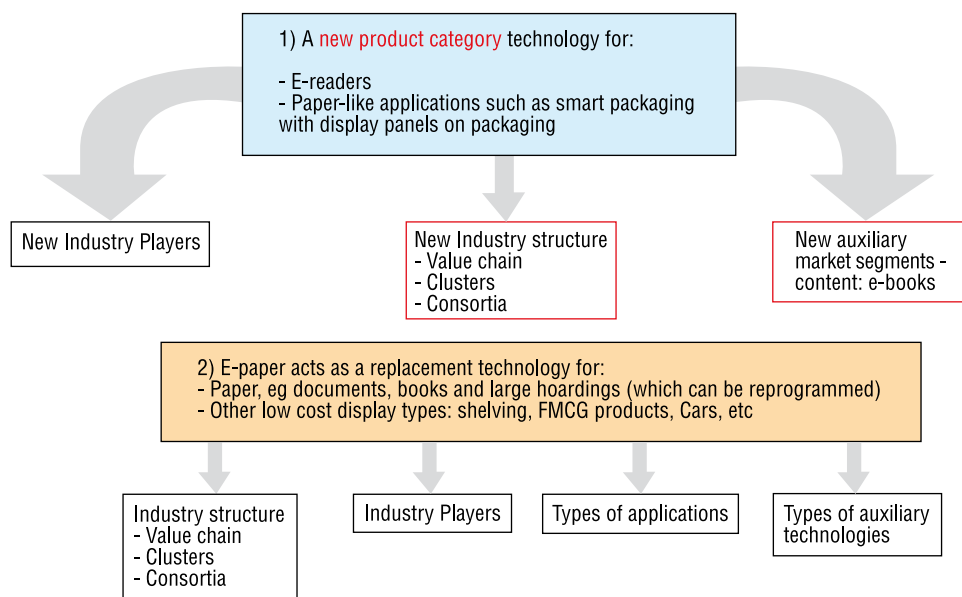
E-paper is not just a technology substitution. It is an application that forms a whole new product category. In this sense it is highly disruptive in that it:

- 1) Opens the door to new applications, largely text based, not just in ICTs but in consumer goods, pictures and advertising that can use its key properties:
 - Display of text, perhaps without power, until text is changed
 - Flexible physical properties due to its plastic base materials
 - Promise of ultra low cost
 - Reflective properties, not requiring light sources – although this limits use at night
- 2) Tends to displace display technologies (LCD largely) offering text reading functions today in ICT terminals such as tablet notebooks.

35 <http://www.reuters.com/article/rbssConsumerElectronics/idUST10184720080709>

Figure 4-5. The disruptive potential of e-paper

The disruptive potential of e-paper



However, we should not forget that this new product category has yet to really take off and, moreover, that the concept has been around since the 1970s, with major resurgences each decade. The last one was in the mid-1990s with displays from the likes of Roger Fidler at the Knight-Ridder laboratory in Boulder, Colorado, who aimed at newspapers, rather than books or business documents.

Such history indicates that this new product category could be held back by several factors. The first is that demand for the whole concept remains a niche market, restricted to techno-enthusiasts and the appeal fails to become more general. Current popular devices such as laptops and perhaps larger screen mobile handsets could progress to be document readers for those that need them, with LCD screens. Further more the trend may be emphasised by the global slow-down in technology evolution generally, as the economic recession starting in 2008 stretches out and becomes far deeper, which could be accompanied by severe restrictions on new spending by consumers and also business for

new devices and embedded displays in current devices/appliances. Yet again the e-reader product category might fail to crystallise.

In its second mode of discontinuity, substitution for paper in advertising, public signage notices, advertising and smart packaging, e-paper may fail to take off for either technical reasons, or the expected global slow-down in the economy, halting innovation, or a combination of technical and economic factors.

4.5. When could a discontinuity occur due to e-paper?

For e-paper, the timeframe is quite different to OLEDs and varies by application. The industry applications in retail, advertising, industrial and vehicle display could occur as soon as robust technology is available. This would imply a timeframe of the next 3-5 years for major technology take-off, although the actual changeover may not be evident but piecemeal.

As noted, e-readers using e-paper have been a long time coming. However, e-readers are a consumer item and consumer education is the first step, as the Kindle has done for some consumers in the USA. But in the EU, and Asia, the education process is yet to happen. Thus, e-paper is coming to market with the appearance of finished e-reader products which exploit its position as an application but in largely uneducated markets except perhaps for the USA to some extent and possibly France. The Amazon Kindle led the way in 2007 and sales are ramping up to 40,000 per month with price cuts and bundled wireless services for e-book downloads. Products from Polymer Vision, Fujitsu, Sony, iRex, and others are now hitting the market to form the new product category. Thus e-reader take-off could be in the 2008 to 2010 timeframe. Hence, the finished product side of the value chain is far more developed than for OLEDs with the full-scale production supply chain being in place for the first, electrophoretic, generation of products.

But simply having the e-reader is not enough. What will drive the market is the availability of

content and here the publishing industry is quite well prepared. Amazon has a large range of titles, possibly not enough, but the e-reader market will also take off with current digital document formats especially PDF and word processes formatted as well as e-mail. Book publishers in Europe and the USA are now preparing.

Note that e-readers are only the first product – and somewhat of a niche market. Take-off of other e-paper applications in signage, retail, military applications and even clothing indicate a progressive and slower take-off than that for a substitution technology such as OLEDs, with many technologies and branches in different directions being involved. E-paper has a much larger application category than OLEDs.

With prowess in IPR, printing technology and materials, Europe is quite well placed to be part of this slower take-off in new applications. Whether this is a discontinuity or a gradual new market segment creation is the question – overhyped at first but under-estimated for the longer term may be the real pattern of its diffusion.

■ 5. EU Competitiveness in Display Technology

5.1. The competitive position of the EU's ICT sector

In this chapter, we make an assessment of the EU's competitive position with regard to display technologies to identify the strengths and weaknesses of the EU's position. Our assessment in section 5.2 builds on the value chain analysis in Chapter 3 with an appreciation of the relative EU position for each step in the value chains for OLEDs and e-paper. Europe's ability to capitalise on the opportunities afforded by new display technologies depends on a variety of different factors. These include factors such as the availability of skilled workers, investment in R&D, availability of venture capital and so on. Thus our analysis begins by a brief assessment of the EU's general innovative capacity, and its competitive position in the ICT market as a whole.

5.1.1. The EU's innovative capability

The EU's innovative potential is indicated by the European Innovation Scorecard,³⁶ which measures innovation performance according to 25 indicators grouped into five dimensions:

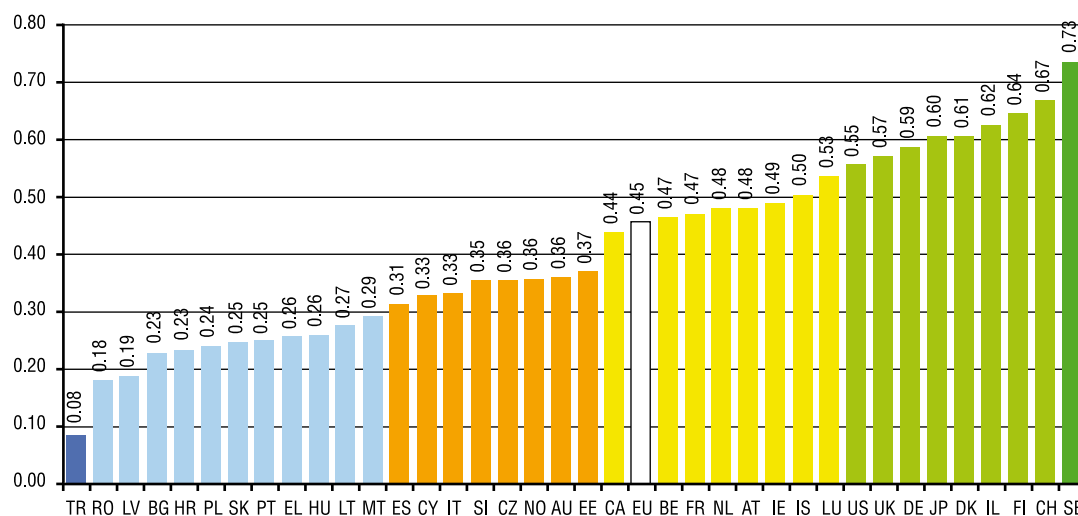
- Innovation drivers
- Knowledge creation
- Innovation and entrepreneurship
- Applications, and
- Intellectual property.

The Summary Innovation Index (SII) for 2007 is shown in Figure 5.1 and gives an overview of aggregate national innovation performance.

Overall, we draw two main conclusions from this analysis of innovative capability. First, there

36 <http://www.proinno-europe.eu/index.cfm?fuseaction=page.display&topicID=275&parentID=51>

■ Figure 5-1. The 2007 Summary Innovation Index (SII)



is a gap between the EU and the USA and Japan, but this is closing albeit very slowly with regard to Japan. Second, some of Europe's most advanced Member States, e.g. Sweden, are at the leading edge of innovation but there is a wide variation and some of Europe's Member States score very poorly indeed (e.g. Romania).

5.1.2. Europe's competitive position in ICT

Turning more specifically to ICT, in 2003 the ICT sector represented 3% of total EU-25 employment and 4% of GDP (European Commission, 2006). ICT services account for about 70% of total EU-25 ICT sector employment, 80% of value added and for about 90% of its enterprises. Indirectly, ICT impacts on the rest of the economy through investment, production and use. ICT uptake is one of the major drivers enabling firms in the rest of the economy to increase their productivity and competitiveness.

In terms of Europe's strengths, these lie in producing sophisticated and high-quality ICT products such as scientific instruments, electronic components and telecommunication equipment. Europe is particularly strong in chip design, software development and ICT services. A key strength is the quality of Europe's human capital, which partly explains why more strategic R&D is performed in the EU while less knowledge-intensive market oriented R&D is located in South-east Asia.

Europe's weaknesses are apparent from its ICT manufacturing trade deficit, which grew to €55 billion in 2004. Significant parts of ICT hardware production and software coding have been relocated to South-East Asia. Other weaknesses include:

- The ICT uptake in parts of Europe's economy is slower than in USA and Japan.
- Lower investment growth than in emerging economies threatens lower value added activities in the EU.

- Lower R&D intensity than US or Japan, R&D concentrated in larger companies.

It seems inevitable that ICT manufacturing will continue to shift to low-cost producers in China and other Asian countries. With Europe struggling to compete in mass production, except perhaps for locations in Eastern Europe, its future strategy would seem to depend on moving up the quality ladder, with focus on future technologies and services. That means that investment in R&D and ensuring the availability of skilled labour will be of critical importance for future competitiveness.

5.2. EU competitiveness in the display technology production chain

Here make a qualitative assessment of EU competitiveness for each link in the value chain for OLEDs an e-paper, as described in Chapter 3. This entails evaluating the position of the EU in terms of the specific capabilities required to be successful at each stage of the value chain, with the focus on techno-economic leadership. Analysis is based on the facts thrown up by our industry research and the opinions of the interviewees from the industry players. The key capabilities we concentrate on revolve around techno-economic leadership. We then assess where EU companies stand technically and strategically, as measured by the attributes needed for each element. These include:

- 1) Market presence, strengths, weaknesses and strategic behaviour of EU players in the (disruptable) markets/technologies/applications affected by the two technologies.
- 2) The level of R&D is invested in these technologies.

- 3) The extent of key patents held.³⁷
- 4) The likelihood that R&D will be continued in successor generations.
- 5) Experience in moving innovative technologies into a consumer/ business market.
- 6) Capabilities/competences in manufacturing either base materials, components, FPD screens and complete devices, etc.
- 7) Branding and distribution, wholesale and retail.
- 8) Existence and strategic behaviour of non-EU competitors in the two markets.
- 9) Other 'adjacent' factors, e.g. the ability to supply content for e-readers.

The qualitative assessment of these factors is based on extensive research and draws on a wide variety of sources including academic papers, analyst reports, interviews with industry experts, newspaper and magazine articles and blogs. It should be noted that accurate and detailed data at the level of granularity of specific technologies such as OLEDs is not typically available. However, by making a qualitative assessment on the above parameters based on the very wide variety of sources available, it is possible to build up an aggregate picture of the EU's overall competitive positioning with regard to the two technologies.

³⁷ This requires gathering as much data as possible on patents held and papers published in a bibliographic search for each link in the value chain. However, we have some reservations on this approach for a study of this size. Key patents are not obvious and crucial advances in process operations may not be patented, to keep them confidential where they give competitive edge. According to those we interviewed, patents in this field may not be indicative of true commercial standing. We would thus flag this step as possibly achieving an incomplete result, both in performing it completely and in assigning a reliable value, other than in a fairly general and approximate way.

5.2.1. Analysis of the production cycle for OLEDs

Here we examine the complete production cycle, in terms of the value chains (see Figures 3.1 and 3.5) for the main applications, for both OLED display and e-paper products. The aim is to determine the existence and strategic behaviour of EU suppliers and the other region-dominant suppliers globally for each of the two main technologies, along their entire value-added chains.

OLED R&D for basic device technologies and their engineering

The production cycle begins with the creation of IPR in R&D, whether it is explicitly published as patents, or not. Much of the intellectual capital is not published for two reasons in this industry:

- first to keep any knowledge from competitors, even via patents where only in theory is it protected, and
- second to build up a body of restricted expert knowledge, some of which cannot be patented but which can be resold however in the form of consulting and technology support.

Important players here from Europe include CDT of the UK (now owned by Sumitomo Chemical, of Japan), also Novaled in Germany, and Fraunhofer IPMS, and several others of its units in Germany. In relative terms, Europe is well placed in this industry segment, with early research coming from Cambridge University's Cavendish Laboratory (UK) as well as publicly funded research, e.g. Framework programs. We can summarise the EU position globally in this value chain link by a scorecard. This can be considered as rating the position in general terms, assessed from the industry research, as three levels with the assessment of what each means being follows:

High – EU is in the top rating but others may also be present if they are rated as highly. So US, Japan and parts of Asia could also come out as high. So in comparison to those at a medium and a low level, the EU is high.

Medium – the EU compares well but is not in the top tier. Whether, in the future it could progress upwards, depends on the conditions in the particular value chain segment. For instance, in know-how on manufacturing processes, moving up in global terms would require both R&D progress and experience gained from operating actual processes, which may be less likely to be available for European industry as its is weak in manufacturing.

Low - the EU lags behind. Its weakness is such is that it is unlikely to become a global leader in this segment of the value chain.

In consequence we may construct the scorecard 5-1.

Creation and ownership of the basic IPR for OLED production and testing processes and equipment

Actually producing OLED film in mass production requires a new set of R&D and intellectual capital, as well as the original device technology. The EU is strong in printing for substrate layering, especially inkjet and low temperature processes for deposition and in materials and process R&D (e.g. Merck). Much of the IPR in Europe for the manufacturing process is centred in Germany, especially around Dresden (e.g. Novaled) and in the spin-off enterprises around research institutes such as Fraunhofer. (Scorecard 5-2)

Supply of key raw and intermediate refined materials for OLEDs

Europe is a centre for production of materials for process manufacture with leading refined chemical processors offering a range of materials as well as services and know-how. There are some large firms, mostly in Germany – BASF,

Scorecard 5-1

EU Scorecard for	OLED R&D and IPR creation
Relative global competitiveness of EU in this link	High – many key players in device R&D (e.g. CDT, Novaled)
Chance of long-term leadership/survival in this segment	Reasonable, i.e. Medium /High High/reasonable
Support clustering and skills environment	Strong – academic and industrial R&D base with clusters in Cambridge and Dresden
Problems/ barriers/ constraints/threats	May need funding injections to continue long term, eg CDT bought by Sumitomo Chemical. Competitors in Taiwan as well as Japan and Korea are building portfolios of IPR while the USA has a strong presence from the research of Eastman Kodak, etc.

Scorecard 5-2

EU Scorecard for	Know-how on manufacturing processes to produce film, displays, components, applications, etc
Relative global competitiveness of EU	Medium to high
Chance of long-term leadership/survival in this segment	Reasonable/High
Support clustering and skills environment	EU has much experience in printing. Forms of fabrication by printing are highly applicable to OLEDs and are the key to lowering the cost of the new technology. Knowledge from this area may be important for inkjet processes at low temperatures, as opposed to vacuum deposition techniques in LCD and plasma panels' production. Materials know-how is also strong in the EU, especially Germany.
Problems/ barriers/ constraints/threats	Major production likely to be in Asia, so manufacturing skills/know-how likely to centre there

Merck Materials, Degussa/Evonik – and much smaller specialist materials suppliers such as Sensient Imaging Technologies of Germany and Goodfellow Metals of the UK. (Scorecard 5-3)

Supply of components for OLED screens and whole devices

Here, there is a distinct lack of EU presence compared to Asia for semiconductor device production, and with it, circuit design. The decline of semiconductor device manufacture in the EU, means that there is no large pool of associated skills with a supporting ecosystem for components production, comparable to Japan or Korea, only pockets of specialism. These do include some OED (original equipment design) centres of excellence for design of complex circuits such as addressing drivers and signal processors. Thus it is possible that Europe could maintain a foothold in the OED space for high-end components. (Scorecard 5-4)

Supply of manufacturing plant, machines and process lines for OLED display screens and other devices

The processing of OLED materials is becoming quite sophisticated. In addition to manufacturing process lines and machines from EU suppliers are design tools such as those from OLED simulation software company Sim4tec GmbH of Dresden, formed in 2007 to commercialise proprietary OLED design tools at the level of electric fields, charges, doping and excitons. There are already some major EU players in the OLED segment (e.g. Aixtron AG of Germany). However, as integrated circuit manufacture slowly migrated into Asia from the late 1970s, so much production of the machinery for process plant went with it. Firms in Asia and the USA that have established credentials in clean room machines and engineering may tend to dominate, although their forte is usually in a high temperature vacuum environment. The chance for Europe is that there are EU skills from

Scorecard 5-3

EU Scorecard for	Supply of key raw and intermediate refined materials for OLEDs
Relative global competitiveness of EU	Medium to high
Chance of long-term leadership/survival in this segment	Medium/ Good
Support clustering and skills environment	The EU has an established global presence in specialist chemicals and has a long history of chemical production. It thus has a pool of associated skills with a supporting ecosystem.
Problems/ barriers/ constraints/threats	Strong competition from Asia, including China, as well as Japan, the major competitor, with the leading chemical companies (Sumitomo and Mitsubishi Chemical) already supplying OLED materials and being long-established in the electronics industry

Scorecard 5-4

EU Scorecard for	Supply of components for screens and whole devices
Relative global competitiveness of EU	Low
Chance of long-term leadership/survival in this segment	Low/ Low
Support clustering and skills environment	in the OED space, for high-end components, the EU has skills in some clusters such as Cambridge and Dresden as well as a few global players such as ST Microelectronics.
Problems/ barriers/ constraints/threats	No real ecosystem, or strong industrial presence, especially as production of lower-value components has moved to Asia.

process manufacturing technology and printing processes that are relevant for the new types of room temperature atmospheric OLED process lines. (Scorecard 5-5)

OEM OLED FPD screen manufacturers and resellers

Dominance of Asia in low cost display screen manufacture and end-user device design and assembly for OLED products from TVs to mobile handsets seems to be unchallengeable, especially as the brand names can act as both OEMs for screens and white label suppliers to other brands for complete devices. There are some smaller European OEM suppliers of OLED FPDs as well as reseller-distributors sourcing other's brands. Manufacturers include Densitron Technologies (UK) and MicroEmissive Displays (UK) while Pacer International Distributors (UK) distributes. So production of the complete OLED panel and the application device could well continue to be centred in Asia, following on from the currently

ubiquitous TFT-LCD technology production. However, one EU industry player (although in e-paper) when speaking of the complete device noted that with rising costs of Asian manufacture and the delay in delivery, the difficulties in control of quality and functionality, Eastern/Central Europe became attractive. Now this could equally apply to OLEDs, for both complete devices and display screens as business costs of shipping containers from Asia are significant, manifested in increased capital in stock while in transit and stagnant cash flow. (Scorecard 5-6)

Branded application device and/or OLED FPD screen manufacturer with retail device sales

Production of branded appliances such as TVs and devices such as mobile handsets has migrated away from Europe to lower cost manufacturing zones in Asia and also South America. For all electronics goods manufacturing, in 2007, Asia-Pacific without China (Taiwan, Korea, Singapore,

Scorecard 5-5

EU Scorecard for	Supply of manufacturing plant, machines and process lines for OLED display screens and other devices
Relative global competitiveness of EU	Reasonable to Low, depending on process type (high temperature vacuum v low temperature atmospheric).
Chance of long-term leadership/survival in this segment	Medium/ Reasonable
Support clustering and skills environment	Some EU players and a supporting ecosystem. There are skills from printing processes and process manufacturing technology that might be relevant for new types of process lines using printing or spin coating.
Problems/ barriers/ constraints/ threats	The EU has some firms in this segment but competition from Asia – Japan, eg ULVAC, and Korea, e.g. Doosan, and even China soon, is strong, as well as the USA. These firms have established a dominant clean room presence, working for the major suppliers of LCD and plasma displays, and semiconductors in general.

Scorecard 5-6

EU Scorecard for	OEM screen manufacturer & resellers for OLED FPDs
Relative global competitiveness of EU	Low
Chance of long-term leadership/survival in this segment	Low/ Low
Support clustering and skills environment	The EU is not strong in OEM manufacturing of OLED FPDs. Central/ Eastern EU might be a viable future alternative to Asia, possibly, but would require a new ecosystem based on a semiconductor and electronic components community for OEM manufacture to thrive.
Problems/ barriers/ constraints/ threats	No real ecosystem, or strong industrial presence, exists in Europe especially as production of OEM FPDs is mostly in Asia, with firms such as Taiwan's RiTDisplay, AUO, and Chi Mei EL, etc.

India, etc) had a production value of some €178 billion (15% of global total) while China had €321 billion (27%) and Japan €156 billion (13%), with total electronic equipment production of some €1,198 billion.³⁸ North America had €241 billion (20%) and Western and Eastern Europe some €253 billion (21%). Thus changes in screen technology seem unlikely to bring back mass-market manufacture and assembly, especially with China growing at 9.9% in the electronic sector in 2006-2010.³⁹ There may be some low-volume high-end or custom manufacture, perhaps for niche markets such as test instruments or medical equipment. For the mass market, brand and channel management with distribution to retail level would follow existing supply chains and stay in the current mass producers' hands (Scorecard 5-7).

OLED lighting branded suppliers and R&D

Here, certainly Europe has made some leading advances, both in original device research and harvesting of IPR, and in manufacturing expertise. The main question is whether the market will become significant. Despite some major technical performance advantages, the home context may limit sales, i.e. the nature of power supply principally, but also the form factor. This year has seen a rising interest in the use of white flat panel OLEDs as the backlight for transmissive TFT-LCD display panels. But the pure lighting market appears to have been under re-examination by Osram and Siemens in Germany, and possibly by Thorn EMI (UK), while Philips seems to have retired⁴⁰ and GE in the USA is considering its position. European, UK, USA and Japanese manufacturers seem still to be interested by ideas of development in consortia projects including CombOLED (Europe), OLLA (Europe), Lumiotec (Japan), Fast2Light (Europe) and Topless (UK) (Scorecard 5-8).

38 Jean-Philippe Dauvin, 'Market forecast and industry trends', DECISION Etudes, Gixel, Deauville, 6-7 December 2007.

39 Jean-Philippe Dauvin, Ibid.

40 Some sources claim that Philips is still pushing hard on OLED lighting. We have not been able verify their position at the time of writing this report.

Scorecard 5-7

EU Scorecard for	Branded application device or/and FPD screen manufacturer with retail device sales
Relative global competitiveness of EU	Low
Chance of long-term leadership/survival in this segment	Low/Low
Support clustering and skills environment	No major clusters for supporting mass market assembly operations, so relevant manufacturing skills/know-how likely to centre in Asia.
Problems/ barriers/ constraints/threats	EU cost base too high for major production of appliances and consumer devices.

Scorecard 5-8

EU Scorecard for	OLED lighting branded suppliers and R&D
Relative global competitiveness of EU	Medium in rating on global market terms.
Chance of long-term leadership/survival in this segment	Medium/Low
Support clustering and skills environment	European lighting industry with R&D in UK, Germany and Netherlands.
Problems/ barriers/ constraints/threats	Mass market demand for consumer devices may not appear – so major production unlikely.

5.2.2. Analysis of the production cycle for the e-paper value chain

We now examine the links in the value chain for the e-paper sector. Again we use the same three level rating scale and assess the position of Europe from comparisons made from our industry research. In each case the rating refers to a global comparison of the position of Europe against the producers in other geographies.

E-paper R&D, IPR for basic technologies

Europe has a strong position in this segment, with a high research effort originating IPR (and holding patents) in the e-paper technology mechanism, in the thin film production in continuous roll to roll mode, the materials used in manufacture and in the end-user devices, principally in e-readers. Leaders with IPR include Polymer Vision, Philips and Liquavista all of the Netherlands, Plastic Logic (UK and Germany), NTERA (Ireland), while key IPR players outside Europe are in the USA (Eastman Kodak and Electronic Ink) and in Japan (Fujitsu, Fuji-Xerox, Bridgestone, Hitachi, Seiko Epson and Toppan

Printing). Where USA and Japanese competitors hold basic IPR for some device technology (e.g. electrophoretics) cross-licensing or using alternative technologies provides an avenue for progress. Note that this role of originating IPR may also include verification of materials with testing certification, using the accumulated IPR, and may become the key to material supply. (Scorecard 5-9)

E-paper bulk materials – supply of key raw and intermediate refined materials

Although the basic early e-paper technologies were based on forms of electrophoretics technologies, developed in the USA, basic materials suppliers are often European, especially in the specialist chemical arms of the larger conglomerates in materials such as Saint-Gobain Glass (France), BASF (Germany) as well as smaller suppliers, such as CIBA Speciality now part of BASF. Opportunities may lie with the spread of diverse alternative technologies, especially for colour, which use an evolving range of materials and processes. Margins are fairly high in this segment, encouraging innovation. (Scorecard 5-10)

Scorecard 5-9

EU Scorecard for	E-Paper R&D with collection of IPR for basic technologies, testing and production engineering and components
Relative global competitiveness of EU	Medium/ High – although USA and Japanese researchers hold some key IPR (eg Electronic Ink Corp, USA)
Chance of long-term leadership/survival in this segment	Medium/ High
Support clustering and skills environment	The EU is well established in R&D in the e-paper technologies and has an ecosystem based on chemistry, printing and semi-conductor technologies enabling the segment to thrive.
Problems/ barriers/ constraints/threats	USA and Japanese competitors hold basic IPR for some device technology (e.g. electrophoretics) but it is possible to cross-licence or use alternative technologies.

Scorecard 5-10

EU Scorecard for	E-Paper bulk materials – supply of key raw and intermediate refined materials
Relative global competitiveness of EU	Medium/ High – although USA and Japanese suppliers are well established and also hold patents, they may also have to licence the materials IPR from others, such as Electronic Ink.
Chance of long-term leadership/survival in this segment	Medium/ High
Support clustering and skills environment	The EU is strong in this segment and has the size and innovative resources to thrive.
Problems/ barriers/ constraints/threats	Strength of the USA and Japanese suppliers is challenging but European chemical materials suppliers are able to compete effectively.

E-paper process equipment: supply of manufacturing plant, machines and process lines for display screens and e-paper devices

Process equipment is available from the traditional semiconductor suppliers for the older techniques but the hope for Europe is that print technologies can be used as Europe has experience and a track record here. Those in Europe researching the basic technologies such as Polymer Vision⁴¹ and Plastic Logic are most interested in roll-to-roll inkjet printing technologies. Materials suppliers for printed electronics more generally such as Merck in Germany are also interested. Naturally the company that perhaps leads the world in this technology, HP of the USA, is investigating possibilities; Seiko-Epson and Canon in Japan, as well as LG Philips and Samsung in Korea⁴² are also developing processes and equipment. HP in Europe and the USA is investing in extensions of its inkjet print technology for manufacture and has developed roll-to-roll manufacturing using self-aligned imprint lithography⁴³ to solve the alignment problems for flexible substrates. Interestingly, there is overlap here with manufacturing techniques for high volume production of OLEDs, where European companies such as NTERA, Philips of the Netherlands,

Novaled of Germany lead, as well as Sony, etc. Related segments with technology for volume production of printed electronics which may prove fruitful are RFID and photovoltaics for solar panels, and ‘smart paper’ for packaging. (Scorecard 5-11)

OEM e-paper film or/and screen manufacturer

Film and e-paper display units are being delivered today in Europe, from companies such as Plastic Logic, Polymer Vision, Philips and lesser-known smaller suppliers especially of firms such as CP (Coated Precision) Films (UK), Gebr. Schmid GmbH and KSG Leiterplatten GmbH (Germany), Nemoptic (France), UPM Kymmene (Finland), NTERA (Ireland), and Liquavista (Netherlands). Naturally there are major industrial producers in volume in Asia and the USA for the film manufacture in high volume and they have the industrial scale to lead in mass production. They include the usual Japanese firms in printing as well as electronics – Dai-Nippon Printing, Toppan Printing, Fujitsu, Fuji-Xerox, Bridgestone, Hitachi, Seiko Epson, etc and the major Korean and manufacturers such as Samsung and LG Philips as well as PVI in Taiwan. The electronics manufacturers in each case assemble the display screen and perhaps the whole device, as PVI does in Taiwan, using E-Ink Corp. technology for the screen. Note that Asian players generally already have enormous capacity for low-cost manufacture, often based on their tied Chinese operations for mass consumer scale when that market segment takes off. European operations attempting the same kind of outsourcing to China for final assembly have faced problems of control

41 Nick van Earle, ‘Rollable display development for mobile devices based on organic electronics’, Printed Electronics Europe, Dresden, 2008.
 42 Bonwon Koo, ‘Active matrix e-paper using printed TFT array’, Printed Electronics Europe, Dresden, 2008.
 43 Carl Taussig, ‘Roll-to-roll manufacturing of electronics on flexible substrates using self-aligned imprint lithography’, Printed Electronics Europe, 2008, Dresden.

Scorecard 5-11

EU Scorecard for	E-Paper process equipment supplier
Relative global competitiveness of EU	Medium
Chance of long-term leadership/survival in this segment	Medium
Support clustering and skills environment	The EU is fairly well positioned for the segment to thrive in R&D and printing plant manufacture.
Problems/ barriers/ constraints/threats	Competition from Asia and USA in equipment and process lines especially in inkjet printing for printed electronics, not necessarily for e-paper initially

of quality and delay in delivery when trying to attempt the same manufacture at lower cost. However the hope is that eastern and central Europe (Hungary, Slovakia and perhaps Romania and eastern Germany) could form a replacement, where there is already lower cost assembly of high technology devices, with the skilled labour force and even partial eco-systems for components. This move could return some device manufacture into Europe (Scorecard 5-12).

Supply of components for screens and whole devices for e-paper

Europe is less well placed to supply the electronic components – e.g. thin film driver circuits, thin film video display processors, video RAM in the substrate and complementary components, e.g. (flexible) PCBs, cabling, power supplies, casings, keyboards, buttons etc. (Scorecard 5-13).

Supply of ‘white label’ manufacturing of devices

The e-paper segment exhibits OEM white label manufacturers for the application device and for display screens, as well as branded suppliers. The largest white label e-paper screen

supplier and device assembler is perhaps the Taiwanese screen OEM, PVI.

A business model that relies on such white label suppliers usually follows the pattern of R&D for technology and device design coming from a brand supplier who will also take care of marketing, distribution and retail sales, the classic case being the Kindle mentioned above, with Amazon being the distributor and original IPR and technology from E-Ink of the USA.

Dominance of Asia in low-cost end-user device design and assembly seems to be unchallengeable, so production of the complete device application could continue there. However, one EU industry player noted that for both complete devices and display screens, the costs of manufacture and the delay in delivery, the difficulties in control of quality and functionality with an outsourcer made Eastern/Central Europe an attractive location. The costs of a container full of devices being 4-8 weeks in transit from China meant that too much capital is frozen while cash flow suffers (Scorecard 5-14).

Scorecard 5-12

EU Scorecard for	OEM e-paper film or/and screen manufacturer
Relative global competitiveness of EU	Low/medium
Chance of long-term leadership/survival in this segment	Low/medium
Support clustering and skills environment	The EU is fairly well positioned using the low cost manufacturing MS so the segment might possibly thrive.
Problems/ barriers/ constraints/threats	Competition from Asian dominance in low cost volume process manufacture and device assembly Lack of eco-systems for components and skills

Scorecard 5-13

EU Scorecard for	Supply of Components for screens and whole devices for e-paper
Relative global competitiveness of EU	Weak
Chance of long-term leadership/survival in this segment	Low
Support clustering and skills environment	The EU is less well positioned and it will be difficult for the segment to thrive
Problems/ barriers/ constraints/threats	Competition from the large semiconductor and passive device manufacturers in Asia (especially in China) and advanced circuits from the USA

Scorecard 5-14

EU Scorecard for Supply of White label manufacturing of devices – sub-contracted/ outsourced manufacturing of displays screens and 2nd source suppliers	
Relative global competitiveness of EU	Low
Chance of long-term leadership/survival in this segment	Low/ Low
Support clustering and skills environment	The EU is largely absent from white label manufacturing. Central/ Eastern EU might be a viable alternative, possibly, but would require a new ecosystem based on a semi-conductor and electronic components community being built up for a white label assembly segment to thrive.
Problems/ barriers/ constraints/ threats	No real ecosystem, or strong industrial presence, especially as production of white label devices has moved to Asia, with firms such as Taiwan's PVI being a leading example.

Branded application device/display manufacturer

Europe is fairly well placed for branded e-reader devices, from manufacturers with products from Polymer Vision and others already on the market. However e-reader models are already available from Sony, Fujitsu, Chinese suppliers, and of course in the USA, led by Amazon's Kindle – see e-publishing business segment below. It is unlikely that a European e-reader manufacturer will dominate the segment, but a tie-up with a publisher or retailer, could extend sales, as this would provide the reseller channel. Document standards and multi-format interfacing software would be an important component for this to happen, to accommodate any e-title. An alternative document market is outside the publishing industry and e-books, the general business documents market, downloading via mobile broadband link or short-range radio technology (Scorecard 5-15).

Product design and retail sales channel with end-user device design, incorporating screen for e-paper

For this segment, as publishing and retailing blur, control of the channel to market can become control of the end-user's device. Hence it makes sense for the retailer or publisher to have its own design of content format and its tied e-reader device with titles based on its proprietary format that only the closed e-reader can display, in order to lock in the customer. This kind of 'walled garden' model follows the software industry, where applications will only run on certain hardware and software. It is the Microsoft and Apple iTunes operating systems and document format model. Note that both these players are likely to move into this market: Microsoft already has its .Lit document format. Several open document publication formats are appearing but different players have different advantages in open and closed formats (eg Amazon has its

Scorecard 5-15

EU Scorecard for Supply of branded application device /displays with retail device sales, retail distribution and resellers	
Relative global competitiveness of EU	Medium
Chance of long-term leadership/survival in this segment	Medium in Europe, rather than worldwide
Support clustering and skills environment	The EU is fairly well placed for the segment to thrive with small branded suppliers (e.g. Polymer Vision) and also publishers and retail chains could enter with e-readers from smaller EU manufacturers.
Problems/ barriers/ constraints/threats	Competition especially from Japan, the USA and soon China and Korea in branded e-readers.

proprietary .mobi format from Mobipocket of France). This Amazon business model for retail is equally applicable in Europe. As mentioned, the publishing houses such as Hachette, and others in France especially, are eyeing virtual book shops, or e-bookshops, connected directly via wireless link to the purchasing reader/customer. This business model could go direct from publisher to reader, cutting out the retail bookseller and wholesale distribution chain, with its retail price maintenance protective safeguards in some countries which can keep book prices higher than deregulated markets. For a publisher, it may be of advantage to be compatible with all types of e-reader, so an open format may be best; the new e-reader expected from Barnes and Noble might be more open. The next industry step is likely to be more open platforms with multi-format acceptance. However, digital content wars can be expected. In this area the EU is on an equal footing and has originated e-book document formats early. It should also lead to new business models for writers, who only have a download website, perhaps with a payment channel so they

cut out both the publisher and the bookseller and move into e-publishing themselves. Naturally the retail booksellers are already aware of this disintermediation threat, the reason for them to take a first mover position (i.e. Amazon, Barnes and Noble). Thus there could be a shake-up, as in the music industry. Also, the same kind of copyright issues may arise from pirated books downloaded for free, which might actually tend to drive the e-book market, despite protests from the publishers and retailers and the free download sites are already prepared (Scorecard 5-16).

The content segment for e-readers

In the e-publishing industry, Europe is well placed. Both retail chains and publishers are dominant and are fairly well prepared if the e-book market does take off. Moreover publishers have an obvious lead in local language books for each national market in the EU. Some device suppliers such as Endless Ideas BV (Netherlands) with its BeBook have a website with 20,000 titles for customer downloads (Scorecard 5-17).

Scorecard 5-16

EU Scorecard for	Product design and retail sales channel with end-user device design, incorporating screen for e-paper
Relative global competitiveness of EU	Medium
Chance of long-term leadership/survival in this segment	Medium
Support clustering and skills environment	The EU is fairly well placed and the segment may thrive with well prepared publishers and retail distribution chains. Europe can originate the software and contribute open e-book standards.
Problems/ barriers/ constraints/threats	Competition especially from Japan, the USA and soon China and Korea in branded e-readers tied to e-title selections. Sony is strong here.

Scorecard 5-17

EU Scorecard for	Content for e-readers – e-book publishers of e-books
Relative global competitiveness of EU	High
Chance of long-term leadership/survival in this segment	High
Support clustering and skills environment	The EU is well placed to dominate the segment as it has the strongest market presence locally and a strong global publishing presence.
Problems/ barriers/ constraints/threats	Asia and USA may enter with local language titles (e.g. Sony) but are unlikely to dominate.

5.2.3. Summary of the factors for each technology

We now examine the general position of EU companies technically and strategically, as measured by the attributes needed for each link. We observe that market presence and strength overall in each link across the value chain is quite variable.

Overall assessment of European position in OLEDs

The Table 5-1 explores the overall strategic position of EU players on the key OLED segments.

Overall assessment of European position in e-paper

Here we summarise the EU competitiveness in e-paper for each link in the value chain (see Table 5-2).

Table 5-1. OLED value chain – the strong and weak links

Link in OLED value chain	Strength of presence of EU industry
Original IPR for devices and for manufacturing processes + material supply/ verification	HIGH – Innovation by the EU in OLED technology is strong and growing in the basic OLED mechanisms, manufacturing and materials
Bulk materials for manufacture and glass	HIGH / Medium – Strong as EU has leading special organic compounds suppliers but also other global suppliers are present
Components– driver circuits, packaging, etc.	WEAK – Few players and weak presence
Process equipment	MEDIUM – Some strong players but major competition from Asia and USA
OEM OLED FPD screen manufacturer & resellers	WEAK – Not at levels of Asia, Taiwan for instance
Branded application device or/and FPD screen manufacturer with retail device sales	WEAK – Not at manufacturing levels of Korea (Samsung) or Japan (Sony)
OLED lighting branded suppliers and R&D	MEDIUM – But future of segment uncertain

Table 5-2. E-paper value chain – the strong and weak links

Link in e-paper value chain	Strength of presence of EU industry
Original IPR and/or material supply/ verification	HIGH – Innovation by the EU in e-paper technology is strong and growing in the basic mechanisms, manufacturing and materials
Supplier of bulk and refined materials	HIGH / Medium – Strong as EU has leading special organic compounds suppliers but also other global suppliers are present
Process equipment supplier	MEDIUM – Some advanced players and presence, from printing technology, but strong global competition from USA as well as Asia
OEM e-paper film or/and screen manufacturer	MEDIUM – A few strong players but major competition from Asia and USA
Electronic components , driver circuits, video display processors, video RAM	WEAK – Not at levels of China, Korea, Taiwan, Japan for instance
OEM White label application device manufacturer	WEAK – Not at manufacturing levels of Taiwan (PVI)
Branded application device /display manufacturer with retail device sales and also resellers	MEDIUM – Some strong market offerings (Polymer Vision, iRex)
Product design and retail sales channel	MEDIUM - Not yet at level of Amazon, Barnes & Noble etc but preparations by the publishing industry in e-books are under way
Content for e-readers – e-book publishers	HIGH- Many established publishers in EU preparing titles for e-book market using open standards

5.3. SWOT analysis of the EU position for the two technologies

Following the above analysis, we now gather the findings in a SWOT analysis on the position of the EU for each link of the value chains for OLEDs and e-paper, compared against other regions/countries. The aim is to assess the strength of the EU across the value chains. This should also incorporate expected competitive behaviour.

5.3.1. Global comparisons and competitive behaviour for OLEDs

The competitive behaviour of the major players, both globally and in the EU market may be centred on two tenets which are somewhat opposing – obtaining a first mover position while guarding existing advantages in the market for consumer electronics and ICT goods. Typical players who are trying both strategies at once are Sony and Samsung. Both of these have strong presence across the value chain, not just in finished TVs and mobile handsets but also in the original R&D and in the manufacturing processes. Moreover they have ‘conglomerate’ position in consumer and business electronics, able to finance loss-making product lines for up to decade if required, in order to achieve an ultimately dominant position with its attendant payback of long-term investments. They are not short-term players. This twin strategy may well establish their future ascendancy in these segments, as successors to the LCD display industry. Where the EU may be able to gain a foothold and then expand its presence is only in the areas identified above in the value chain analysis, i.e. in R&D and materials, perhaps process equipment especially if it is based on print technologies.

Use of IPR protection will be important but its impacts are likely to be mitigated through cross-licensing agreements, so the important point is not necessarily to have all the patent protection for complete manufacture, but to have

some IPR resources in order to trade to get the full set required. From our research, specifically interviews with major players and other desk research comparing the global market in original technology IPR, materials and processes, we found that Europe has a relatively strong position through players like CDT (although owned by Sumitomo Chemical), Merck, BASF, etc as well as centres of research in clusters such as Cambridge and Dresden.

On the demand side, identification of real applications with real consumer/business-led demand for OLEDs has already been made. If the technology can be made robust at low cost, it will trigger new application areas, perhaps, but the three leading markets – mobile handsets, TVs and laptops - will take all production initially.

In the value chain segments where it competes, the EU has a good probability of export market success. This could be driven further by the likelihood of further technical innovation in its core areas of expertise, which is good. Moreover the technical problems of OLEDs ensure there is great space for improvement in the two key areas – fundamental technology, especially polymer chemistry and volume processing techniques. These are the domains that count in solving its colour and aging problems. However the capability of bringing these innovations to market is possibly difficult for the EU. That may well be left to the large Asian suppliers, although the advances in volume processes such as printing are likely to be incorporated into the manufacturing equipment produced in the EU.

5.3.2. A methodology for assessing the global position of the EU in OLEDs

To analyse the competitive position globally of countries and regions we may visualise their position using two basic metrics, which, from our research we see as being at the core of display technology R&D, production and distribution.

These two parameters are the effective metrics of competitive performance. They are chosen as they effectively summarise the value chain, characterising the expected industry position of the various geographic players in terms of capability, capacity and competitive position across the value chain and also the future market power expected:

- Production capability, including R&D, with a global comparison across countries and regions.
- Industrial Infrastructure, i.e. the support environment for the production capability for the particular display technologies in question.

Each of these two main metrics can be analysed in terms of finer, more specific variables to form the dimensions of a 'competitive parameter space'. Using our industry research they are amenable to being broadly gauged (i.e. as high/medium/low), especially from rating performance in each of the major value chain segments:

Production capability globally - We can visualise the competitive position of the EU's OLED device production capability measured by the four key variables of:

- Capability in original IPR from R&D, with patents and process knowledge,
- Materials production,
- OLED film production,
- Capability to manufacture complete screens and devices in volume.

We then use the variables to form a type of presentation that provides a graphic visual comparison. For each variable we compare the industry position of the players:

- If we take the first variable, *capability in IPR with original R&D*, using the prior analysis, especially the EU value chain analysis

summarised in Table 5.1, we find the EU is strong, but so are the USA and Japan while Korea and Taiwan have a medium presence; China is weaker here.

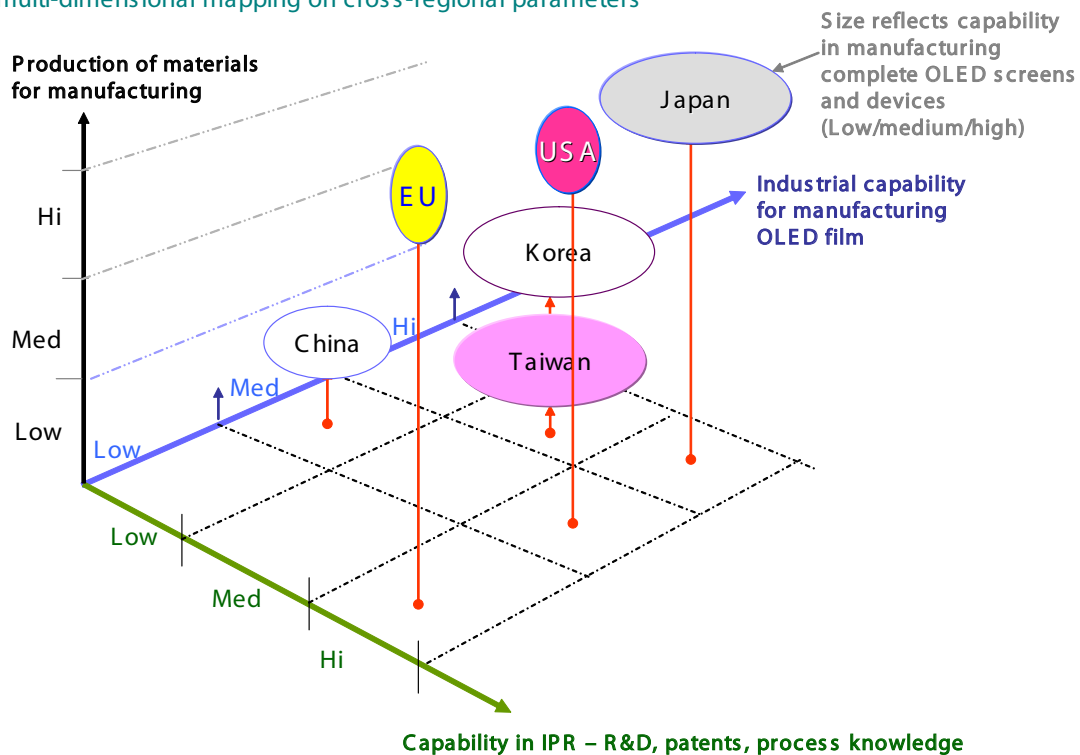
- Again using Table 5.1 and the preceding findings, we discover that *in production of the materials for manufacturing*, the EU is strong, but so are the USA and Japan while Korea has a medium presence; China and Taiwan are weaker here.
- From research findings and the summary for the EU in Table 5.1, we find that in industrial capability for OLED film production, the EU is weak, as is the USA, with lower factory capacity and workforce capability, and also volume production know-how, compared with the strong players – Japan, Taiwan and Korea - while China has a medium position so far, despite its low-wage advantages.
- For *volume production in manufacture of complete screens and devices assembled in volume*, using a supporting eco-system of component suppliers, three players stand out – Korea, Taiwan and Japan. Interestingly they have largely maintained their lead within their own countries so far, in terms of production equipment and know-how, so that China is at a medium level in OLED production line capability here. The EU has forfeited its industrial capacity of this type to lower cost suppliers in Asia but the USA still has some manufacturing capability.

The visualised comparison of this is shown in Figure 5-2.

From this visualisation we can see that the optimal position is to be in the top segment on all axes with a large capability, as expressed by size in the fourth variable, as shown above in the position of Japan. An alternative view however is to look at the margins in each segment of the value chain (Table 3.1) and aim for a strong position only for those – i.e. capability in IPR, materials, and final FPD production and perhaps in some FPD components.

■ Figure 5-2. Competitive global comparison for OLED production

Competitive global comparison for production of OLEDs – multi-dimensional mapping on cross-regional parameters



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The second main parameter is *Industrial Infrastructure*, i.e. the support environment for the production capability above for the particular display technologies in question. Competing OLED industrial infrastructures are centred on four main variables:

- Capability of moving innovations to market
- Industrial ecosystems of surrounding suppliers and the skills base,
- Brand strength, especially in consumer electronics,
- Capabilities in white label engineering complete FPDs and devices.

Again, we use these variables to form a graphic visual comparison, for each of the players:

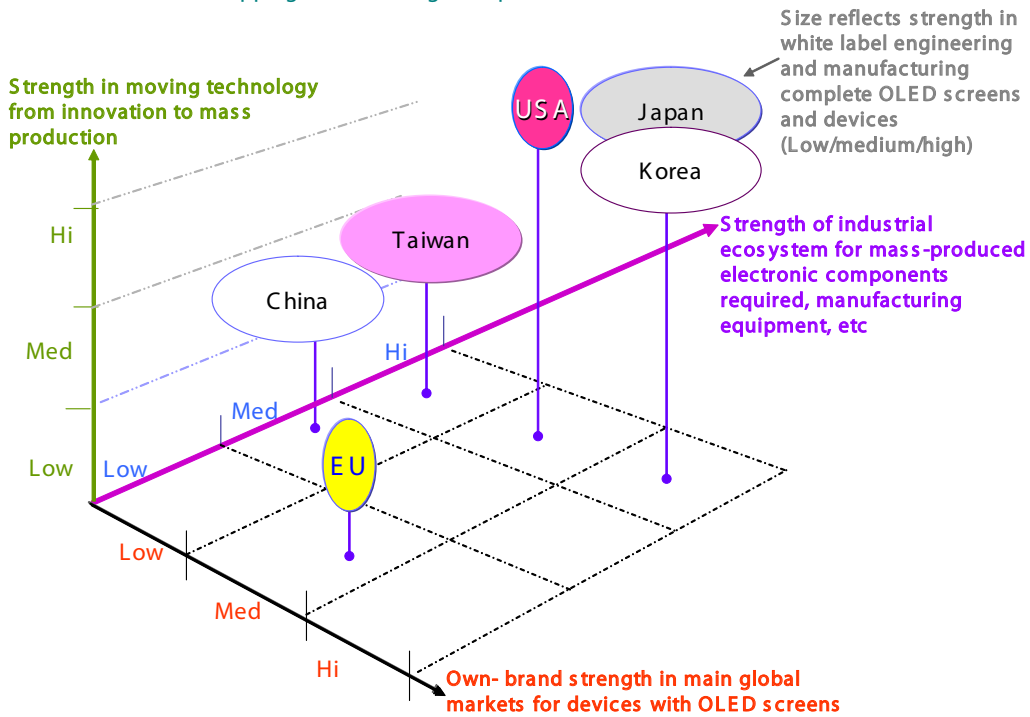
- For *capability in moving innovations to market, and into mass production* using the

prior value chain analysis and also Table 5.1, we find that the EU is weak for basic technologies such as OLEDs. But the USA, Japan and Korea are strong while Taiwan and China have a medium presence only here, as production dominates.

- On the *industrial ecosystems of surrounding suppliers and the skills base for components and other auxiliary support and equipment*, we find that China is only medium for OLED requirements, while Taiwan, Korea, and Japan are strong, as is the USA; the EU is weaker, despite some capabilities, e.g. in test and process equipment.
- From research we see that in *brand strength* (especially in consumer electronics containing displays) the EU has a medium position with a few major players such as Nokia and Sony-Ericsson in mobile but no global brands in laptops, desktops or TVs,

Figure 5-3. Competitive positions on the industrial infrastructure for OLEDs

Competitive global comparison of industrial infrastructure for OLED products
 – multi-dimensional mapping on cross-regional parameters



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while the USA has some in PCs (HP, Dell, Apple, IBM) while the strong global device and appliance brands are Korean (Samsung, LG), Japanese (Sony, Panasonic) with a few Taiwanese (Acer, HTC) as, like China, it produces more for other global brands.

- For *white label engineering of complete FPDs and devices*, using a supporting eco-system of component suppliers, one player stands out –Taiwan – but also Japan (e.g. Sony and Canon have made Apple products) and Korea. China is at the same level in white label capability. Again this is a segment where the EU has forfeited its industrial capacity to lower cost suppliers in Asia over the last two decades, as has the USA.

Thus the global comparative analysis for these variables can be illustrated, as below:

In general for productive capability, we see that Asian producers eclipse the EU and the USA in production of OLED film and in the end devices, with Japan equal in base materials with the EU and the USA while Korea is a medium player here. So far China lags in all areas. Whether this lag will remain in five years time is doubtful, in that if OLEDs move into mass market products, China’s capability, already past nascent, will emerge more fully, probably aided by a know-how transfusion for volume production by OEMs, most likely from Taiwan. Moreover established positions in the existing display technologies, especially LCDs, could further entrench the current display manufacturers, so a new technology has less chance of success, or could be held off longer, strangling attempts of new players to enter with competing innovative technologies.

When we come to the clustering of specialist suppliers and skills, again Japan and Korea lead. The EU is perhaps farthest behind, having lost much of its capacity and accompanying 'eco-system' for volume electronics manufacturing over two decades ago to Asia. Europe has fewer strong consumer electronics brands now and generally is weaker at moving innovations to market, specifically in consumer electronics and household appliances. In white label engineering and manufacture at low cost, Taiwan and China excel, whereas the EU and USA lag far behind. The only possible alternative view here is if volume low-cost electronics manufacture returns to the EU in central and eastern Member States so that a new eco-system may arrive over the next five years. The probability of this occurring depends on policy initiatives to attract foreign direct investment, as is happening with some success around Dresden in printed electronic generally, as well as the aggressiveness of competitive profile of the Asian electronics manufacturers.

5.3.3. OLED SWOT summary

From this we may summarise the strengths, weaknesses, opportunities and threats for EU in OLEDs as being outlined in the Figure 5-4.

5.3.4. Global comparisons and competitive behaviour for e-paper

For e-paper, despite a 30-year history of development in the USA by Kodak and Xerox, the supply side is quite fragmented across the globe. New entrants appear every few months so competitive behaviour of traditional major players tends to be reactive, expecting a shake-out eventually, but harnessing the IPR and patents of much smaller innovative companies on an opportunistic basis. Use of IPR as protection has been mitigated through agreements, such as those of PVI of Taiwan with Electronic Ink of the USA and also purchases, such as that of PVI of the Philips patents set.

We can now repeat the comparative exercise for e-paper, with the main pair of parameters being chosen as before, to summarise the value chain, to characterise industry positions of the various players in terms of capability, capacity and competitive position across the and expected future market power:

- Production capability, including R&D, with a global comparison across countries and regions,
- Industrial Infrastructure, i.e. the support environment for the production capability for the particular display technologies in question.

Figure 5-4. SWOT analysis – summary of positioning of the EU in OLEDs

<p>Strengths</p> <ul style="list-style-type: none"> • Capability for innovation • Production of base materials for OLED manufacture • Process equipment manufacture 	<p>Weaknesses</p> <ul style="list-style-type: none"> • Lack of industrial productive capacity or eco-system to support low-cost volume production • Capability to bring innovations to market – i.e. probability of export market success • Lack of branded consumer goods suppliers apart from mobile handsets – e.g. Nokia
<p>Opportunities</p> <ul style="list-style-type: none"> • Possible renaissance in manufacturing at low-cost, perhaps in Eastern Europe • Use of IPR – with mitigations through agreements • Expansion in base materials supply and process equipment manufacture for low temperatures 	<p>Threats</p> <ul style="list-style-type: none"> • Older technologies – TFT-LCDs which improve technically – become cheaper, flexible, lower power demands and better colour/contrast, scale up larger, etc, make existing (LCD) players far stronger • Strong competitive position and behaviour of current major players both globally and in the EU market make market entry difficult or increasingly impossible

We use the same variables to give the dimensions of each 'competitive parameter space' using the industry research and rating performance in each of the major value chain segments:

Production capability globally - We can visualise the competitive position of the EU's e-paper device production capability measured by the four key variables of:

- Capability in original IPR from R&D, with patents and process knowledge,
- Materials production,
- E-paper production (ideally in roll to roll rather than batch mode),
- Capability to manufacture complete e-paper displays and whole devices in volume.

The industry position of the players for each variable is as follows:

- For the first variable, *capability in IPR with original R&D*, we find the EU is strong, but so are the USA and Japan while China and Taiwan have a low rating on IPR generation; Korea is a medium player here, based on the prior analysis, especially the EU value chain analysis summarised in Table 5.2.
- We find that in *production of the materials for manufacturing*, again using Table 5.2 and other results, the EU is a strong player as a global supplier, as are the USA and Japan. Korea has a medium presence but China and Taiwan are weak here, buying in these materials.
- In *industrial capability for e-paper film production*, the EU is weaker than Japan, Korea and Taiwan but is producing some e-paper in production quantities (e.g. Plastic Logic in Dresden), and so has a medium rating. This capability might expand in Eastern Europe. China has a medium position so far in this new market.
- Japan, Korea and Taiwan are the major players in *manufacturing complete-paper*

screens and devices, assembled in volume so far, using a supporting eco-system of contributing suppliers of components and technologies (e.g. Samsung uses Unidym for the flexible electrodes for its electrophoretic e-paper [Deviceguru, 2008]). The EU has not completely forfeited its industrial capacity for manufacture of e-reader devices to lower cost suppliers in Asia (e.g. iRex, Polymer Vision, Plastic Logic) and the USA still has some manufacturing capability for such devices, so both have a medium position, as does China.

The visualisation of this is shown in Figure 5-5.

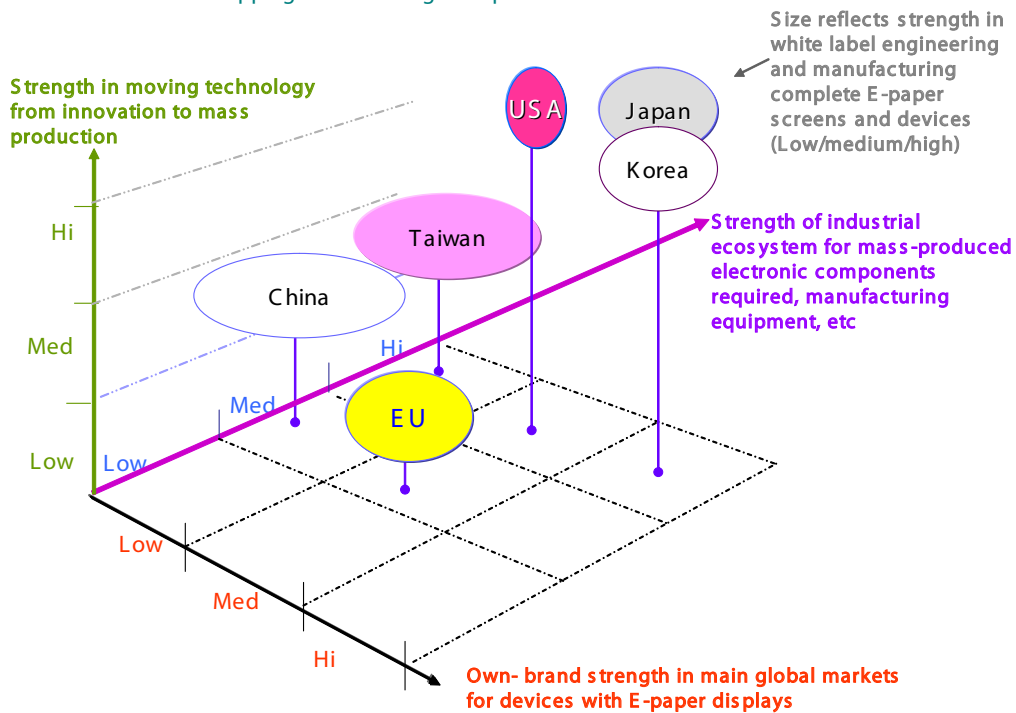
Production capabilities considered in the dimensioning variables above are based on competing industrial infrastructures. As before, the EU tends to lag competing countries, especially the leaders that have established clusters and eco-systems for low-cost mass produced electronics and can easily turn that productive resource to supporting the manufacture of any new display device such as e-paper and its first big application in e-readers.

The second main parameter is Industrial Infrastructure, i.e. the support environment for the production capability above for the particular display technologies in question. Competing e-paper industrial infrastructures are centred on the same four main variables, again used to form a graphic visual comparison, for each player:

- *For capability in moving innovations to market*, using the prior value chain analysis and also Table 5.1, we find that for applications such as e-paper the EU does possess some capability, already proven with its various e-readers (from Polymer Vision, iRex etc). The USA, Japan and Korea are stronger. Taiwan and China have a medium position only here, as production dominates in their economies, although PVI of Taiwan has figured substantially in production of the Kindle e-reader, but with the venture

Figure 5-6. Competitive position on industrial infrastructure for e-paper

Competitive global comparison of industrial infrastructure for E-paper products
– multi-dimensional mapping on cross-regional parameters



production. The EU has forfeited most of its industrial capacity to the lower cost suppliers in Asia over the last two decades, as has the USA. However, the costs of transport from Asia, direct control of quality and the possibility of local assembly at low cost in Eastern Europe has suggested the EU as a manufacturing possibility for some European players we interviewed. This indicates a medium rating for the EU.

Thus the global comparative analysis for these variables can be illustrated, as in Figure 5-6.

At the distribution end of the value chain, the European publishing industry, and its interest in e-readers as tied devices to access its stocks of titles, may be better at branding and exporting than the somewhat weakened EU consumer electronics industry. Thus the major publishing houses may design, promote and sell e-readers, using white label screen builders and device

designer/assemblers. There is a possibility that the early production for this could also be in Europe, for the e-paper film, assembly of display screens and assembly of complete e-reader devices. This could tend to rebuild the position of the EU in production of consumer electronics to some extent, but in a limited segment, e-paper and its devices.

Identification of real applications with real consumer/business-led demand is still in flux with the potential killer application – e-readers – still emerging. Other display areas have yet to be clarified as the demand, e.g. outdoor advertising or smart packaging, is unclear, although in niche segments such as smart shelving, e-paper displays are already appearing strongly (e.g. from Fujitsu).

The probability of export market success is linked to the specific segments of the value chain where the EU has a global parity – mainly materials and R&D for the fundamental

technology and IPR in production processes. However, in e-paper devices, the EU capability for innovation is fairly well developed and from the players we spoke with, the EU does appear to have recovered some of its capability to bring innovations to market. For the content side, with the iTunes type model, the EU is well placed,

owing to its publishing industry being well versed and prepared for e-books.

5.3.5. E-paper SWOT summary

Using the above analysis we can summarise the EU position on a SWOT diagram:

Figure 5-7. SWOT – summary of the position of the EU in e-paper

<p>Strengths</p> <ul style="list-style-type: none"> • Capability for innovation and IPR creation • Content production and stock of titles for e-books • Production of basic materials for e-paper manufacture • Printing technology know-how 	<p>Weaknesses</p> <ul style="list-style-type: none"> • Ability to move from innovation to mass production and weakness in ecosystems • Probability of export market success for finished devices against large Asian branded suppliers with diminished industrial base in consumer electronics
<p>Opportunities</p> <ul style="list-style-type: none"> • May build be possible to establish a slight first mover advantage if industrial base reinforced • Production of e-paper, display screens and e-readers in Europe, driven by the publishing industry 	<p>Threats</p> <ul style="list-style-type: none"> • Strong competitive behaviour of major players, large and small, from the USA as well as Asia both globally and in the EU market • Entry of China in e-readers and e-paper

■ 6. Opportunities for the EU ICT Sector

Finally we summarise the resulting position in competitiveness of the EU industry in novel display technologies. We also briefly examine possible European strategy options.

6.1. The potential for disruption by OLEDs and e-paper

The overall potential of these two ‘technologies’ could be profound. But the impacts may not be seen clearly, ‘at a stroke’.

For OLEDs, the substitution battle with current technologies is carried on at the FPD manufacturing end. The final sections of the value chain – the production of finished consumer and industrial devices with displays integrated could accept the technology tomorrow, especially if it were offered for mobile phones and TVs, the two largest market segments. The consumer would just see it as a ‘greener’ product owing to lower electric power demands, with better qualities of display in thinner, larger sizes if required. If the key factor of purchase price is also lower and OLEDs have the same robustness in service as LCD FPDs, there is no question OLED displays would take the market.

This thinking follows the double ‘S-Curve’ shown in Figure 4.1 and importantly implies a new potential set of players in the value chain. Thus there is the possibility that in the early segments of the OLED value chain, EU players may enter to participate in the OLED market, although the end product/device manufacturers are most likely to be the same. And it is these final stage players who will largely and effectively set the pace of change to OLEDs, unless a product manufacturer, such as a mobile handset producer, forces an earlier substitution.

For e-paper, the situation is rather different. End-user acceptance of new product categories must be established. This might take 3-10 years. For instance the large consumer category is e-readers, which are a consumer item and depend on consumer awareness, through market education, followed by take-up. On the content side, the publishers are perhaps further on in their ‘acceptance curve’ than the general consumer is with e-readers. The book, magazine and newspaper industry have been preparing for this for at least 20 years. The question is whether the consumer is ready and here one senses that successive waves of ubiquitous diffusion of consumer electronic devices over the past 15 years, especially mobile phones and MP3 players, may well mean that consumers will be ready for the ‘next big thing’. Everyone, of course, dreams of replicating Apple’s iTunes model.

However, many e-paper applications, other than e-readers, are not determined by ordinary consumer acceptance. Large-scale advertising, indoor, outdoor, on trains, etc will have to be accepted by an industry, and one that is used to printed paper. For retail, in shelving labels and in-store displays, or small read-outs on RFID tags, all are really just a substitution for low cost LCD and other technologies. In retail, there is perhaps no new product category to get accepted.

6.2. The opportunity for Europe

6.2.1. *Points in the OLED value chain for entry by European suppliers*

As analysed in Chapter 4, there are three discrete segments in the OLED value chain where any discontinuity could offer EU firms the opportunity to play a more significant part in the displays sector:

- Original R&D and IPR for devices and for the manufacturing process and material supply/verification: innovation by the EU in OLED technology is strong and growing in the basic OLED mechanisms, manufacturing and materials.
- Bulk materials for manufacture and glass: the EU is potentially strong in this and has leading special organic compounds suppliers, but other global suppliers are also present.
- Process equipment: there are some strong EU players but also major competition from Asia and USA.

Evidently, it would be optimal if these early value chain segments were pursued into the potential new market. However the question arises then of whether they are of a critical mass to change the balance of industrial power in the display industry. The answer may be that the EU could become a global player as long as it excels in quality and volume in these three specific segments.

On the question of entry to the assembled FPD market, this seems remote with the EU's fairly restricted capability in the finished goods end of the production cycle, especially TVs and laptops, ie screen dimensions of over 10 inches. Only in smaller screen sizes, eg for mobile handsets, could there perhaps be a possibility of entry by EU display screen suppliers, and also perhaps complete device manufacturers.

Thus if we take the view that it is possible for EU FPD to enter the market and also device manufacturers (e.g. Nokia and others) using OLED FPDs, then Europe does have a possible point of entry in the OLED FPD market. It is most likely to be in the mass production of small FPDs, e.g. for mobile handsets. The latter is an enormous market, with some 3 billion users globally and still growing. The replacement and growth handset market volume combined would be of the order of 1 billion FPD units per year,

depending on global economic conditions and OLED handset pricing.

6.2.2. Points in the e-paper value chain for entry by European suppliers

From the analysis of the e-paper value chain, we can see that the entry of EU suppliers is perhaps possible across more value chain segments than for OLEDs, specifically in:

- Original IPR and/or material supply/verification as innovation by the EU in e-paper technology is strong and growing in the basic OLED polymer photonic mechanisms, as well as the key areas of manufacturing processes and production materials.
- Supply of bulk and refined materials – the EU suppliers have a high profile and established reputation, so there is a medium to strong chance here, as the EU has one of the leading special organic compounds industries. But other global suppliers are also present closer to the electronic manufacturing centres in Asia while the USA specialist chemical suppliers are also strong.
- As a process equipment supplier, there is a medium level chance of success with the EU's advanced players and its presence in printing technology, but there is also strong global competition from USA as well as Asia (Toppan, etc).
- The EU does have some pilot plants for OEM e-paper film and/or screen manufacture, for instance in Germany, so there is a medium chance here with a few EU players but major competition from Asia and USA. This could spill over into other applications, for packaging and signage.
- Branded application device and display manufacturers with retail device sales do exist in the EU (Polymer Vision, iRex, Endless Ideas, etc) and there is a strong resellers element so there is perhaps a medium level possibility of success for the EU players.

- Europe is not yet at the level of the USA in product design and tied retail sales channels yet but preparations by the publishing industry in e-books are under way and so there is a medium level chance. In other application areas, such as signage the USA and Japan seems to lead but it is too early to estimate whether the EU could successfully compete globally on this market.
- The EU is quite strong on content for e-readers –publishing e-books- many established publishers in the EU are preparing titles for a nascent e-book market using open standards, which may possible lead to global exports as well as European sales in each national language, if e-readers take off.
- Overall, a concerted effort by EU suppliers could lead a revision of the current state of play in consumer electronics in the e-paper/ e-reader segment but it may in complete devices such as e-readers rather than the e-paper film.

6.3. European strengths to play on

6.3.1. Foundations of future EU industrial strength in displays

From the above one might ask on what such potential can rest for the display market in general, covering both OLEDs and e-paper. Five major foundations can perhaps be identified:

- European capacity in research and development – both at an individual company/research centre level and at a publicly funded consortium level, for instance the series of EC Framework Programmes, there is a core of world-class R&D which is generating IPR, be it formalised as patents, or, as was emphasised as being just as important, in know-how and expertise that is held within one organisation
- European strengths in industrial organisation (in terms of managerial and technical competences,

key skills, transport and power infrastructures, support services, national and EC support for industry and R&D) although the industrial eco-systems in components are much weaker than Asia and to some extent those in the USA, base materials and process equipment is available for what is, for both OLEDs and e-paper, a printed electronics industry. Clusters in the UK, Germany and the Netherlands are especially important but pockets of expertise exist in many Member States, from France to Ireland.

- Those at the leading edge in these fields in the EU are usually very small firms. This can be an advantage for Europe in that they can move far more quickly than larger companies and have highly focussed R&D generation, both being essential to exploit technology discontinuities. However, one theme that emerged in interviews is the issue of supporting small companies move into production (and not just in R&D with framework programmes). It is the key in moving innovations into the world market. Smaller innovative companies saw little help from R&D consortia but wished for better support pre-production and to move into production, as they see in Korea and to some extent in Japan and China. These R&D consortia seem more appropriate for large firms and are burdensome rather than supportive of small firms.
- Although there are differences between Member States, regional development is a potential strength of the EU. Industrial policy support was seen as most important, being used to satisfy the preceding need, for set-up funding, to move from R&D into production. Such support for eastern Germany was recognised as the force behind the Dresden cluster in electronics manufacturing processes at substrate level.
- The promise of east and central Europe in low-cost volume production is a strength for a future EU electronics industry in displays and could be a major factor. As the distance from Asia, with its attendant problems of

lack of management control, delays in transit and transport costs become more important, while differentials in wage levels between the two regions are shrinking. So Eastern Europe could possibly become a lively manufacturing and assembly centre in a future display industry.

6.3.2. *Could this become a discontinuity opportunity for Europe?*

Even if there is a chance of market entry with new technologies and products with OLEDs and e-paper, the question has to be asked – how and why will this enable the entry of EU suppliers, as each of the value chains resemble the existing ones, dominated by Asia?

In reply, the pragmatic strategy for EU entry may be to be a *competing participant in certain segments*, supplying some elements of the production chain to other players who perform final assembly rather than being a dominant player, end to end. Such a strategy gives reasonable credence to the notion of a potentially disruptive phase with several avenues for market entry into the supply chain. (see Table 6-1)

The above analysis implies that the EU position gives a reasonable chance to re-enter the display industry. It is weak in the key area of complete FPD or device production, owing to its

lack of eco-systems of components. Nevertheless, if the EU industry concentrates in participating in the value chain, not hoping to dominate it end-to-end, then it can be a player in those segments. Moreover there is the possibility in e-paper that for certain devices such as e-readers, it could enter the global export market via production in lower cost Eastern and Central Member States.

6.4. The resulting state of the display industry

The display industry would change fairly fundamentally if the centres of R&D and some of the other segments move largely or partly to include the EU, and also new devices are designed, especially in the e-paper segment. Supplies of the basic materials and the components would become more widely sourced if the EU can maintain and expand its position.

However, today's dominant suppliers in Japan, Taiwan and Korea of these same value chain segments will also tend to maintain their place in the industry. The final conclusion on the position of the EU is that success lies in specific segments of the value chain, as outlined above. Perhaps the EU may even become a dominator in a few of those segments but it is unlikely to dominate the entire value chain.

Table 6-1. *Disruptive times: how Europe can enter the display market with OLEDs and e-paper*

Manner of market entry	Degree of EU strength	Value of strength factor
New players, formed for new technologies with an evolved industry structure	HIGH in certain value chain links – especially R&D, materials, production processes High, despite the display value chain being close to the LCD/ semiconductor model today	
IPR – Ownership and control	MEDIUM – EU has gained more expertise in applying IPR to production.	Low – value is in local skills acquired, not necessarily pure ownership of IPR. Relevant IPR is fairly globally owned so ownership may be useful for trading IPR
Exploiting existing competences and skills in key technologies for R&D and process manufacture	HIGH in some key segments – materials, printing, production equipment, original R&D and end-product design	High – possibly the key parameter for creation of a display industry in the EU
Industrial ecosystem or clusters with 'mini value-chain'	LOW From original R&D, EU has built some eco-systems in materials, print production processes, the manufacturing equipment to end-product design	Medium – for the segments in which the EU may concentrate but not as crucial as for final assembly

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■ Glossary

AMOLED	Active Matrix OLEDs
CNT	Carbon nanotube
COMPLETE	Competitiveness by Leveraging Emerging Technologies Economically
CRT	Cathode Ray Tube
Electrophosphorescent	Light is emitted on passing current through material
Electrophoretics	Particles in a dielectric fluid are attracted to the top of a cell
Electrochromics	Polymers which change colour in an electric field
Emissive	Generate light rather than reflect it or re-emits it
FED	Field Emission Display
FLAMOLED	Flexible active matrix OLED
FPD	Flat Panel Display
LCD	Liquid Crystal Display
OLED	Organic Light Emitting Diode – emits light when current passed in one direction
OED	Original Equipment Designer
OEM	Original Equipment Manufacturer
PDP	Plasma Panel Display
PHOLED	Phosphorescent OLED
PMOLED	Passive Matrix OLED
P2OLED	Printable Phosphorescent OLED
RAM	Random Access Memory
Reflective	Display image formed by reflection of ambient light – useful in sunlight
SED	Surface Emitting Display
SMOLED	Small Molecule OLED
SWOT	Strengths Weaknesses Opportunities Threats (analysis)
TFT	Thin Film Transistor

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Abstract

DG ENTR and JRC/IPTS of the European Commission have launched a series of studies to analyse prospects of success for European ICT industries with respect to emerging technologies. This report concerns display technologies (Organic Light Emitting Diodes and Electronic Paper - or OLEDs and e-paper for short). It assesses whether these technologies could be disruptive, and how well placed EU firms would be to take advantage of this disruption

In general, displays are an increasingly important segment of the ICT sector. Since the 1990s and following the introduction of flat panel displays (FPDs), the global display industry has grown dramatically. The market is now (2009) worth about € 100 billion. Geo-politically, the industry is dominated by Asian suppliers, with European companies relegated to a few vertical niches and parts of the value chain (e.g. research, supply of material and equipment). However, a number of new technologies are entering the market, e.g. OLEDs and electronic paper. Such emerging technologies may provide an opportunity for European enterprises to (re-)enter or strengthen their competitive position.

OLEDs are composed of polymers that emit light when a current is passed through them. E-paper, on the other hand, is a portable, reusable storage and display medium, typically thin and flexible. Both OLEDs and e-paper have the potential to disrupt the existing displays market, but it is still too soon to say with certainty whether this will occur and when. Success for OLEDs depends on two key technical advances: first, the operating lifetime, and second, the production process. E-paper has a highly disruptive potential since it opens the door to new applications, largely text-based, not just in ICTs but also in consumer goods, pictures and advertising that could use its key properties. It could also displace display technologies that offer text-reading functions in ICT terminals such as tablet notebooks.

There are three discrete segments in the OLED value chain where any discontinuity could offer EU firms the opportunity to play a more significant part in the displays sector: (1) original R&D and IPR for devices and for the manufacturing process and material supply/verification; (2) bulk materials for manufacture and glass; and (3) process equipment. For the e-paper value chain, we can see that the entry of EU suppliers is perhaps possible across more value chain segments than for OLEDs. Apart from the ones mentioned for OLEDs, there are opportunities to enter into complete devices and content provision. In terms of vertical segments, the point of entry in OLED FPDs for Europe is most likely to be in the mass production of smaller FPDs for mobile handsets.

In conclusion, OLEDs and e-paper have the potential to disrupt current displays market and in so doing they may enable EU companies to enter at selected points in the value chain to compete with the Asian ICT industry.

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