The liquid-crystal display (LCD) market is over $100 billion, so the emerging technologies that can compete with LCDs have the opportunity to become serious opportunities. Electrophoretics, through their use in e-readers, demonstrated the potential of a technology that can exploit the limitations of LCDs. Judging from our component materials and manufacturing cost analysis, organic light-emitting diodes (OLEDs) will decrease from their current $3,000/m² for small-area displays to be cost competitive with LCDs by 2016, leading to an overall OLED market of nearly $11 billion in 2017. Reflective displays will also undergo significant change over the next five years, as the market for e-readers declines and digital signage becomes the dominant market of the overall $1.6 billion non-segmented reflective display market in 2017. While electrophoretics will continue to be the largest player in this area, alternative reflective displays like microelectromechanical systems (MEMS), electrowetting, and cholesteric LCDs will have an increasing share of this market.
**Executive Summary**

The emergence of flat-panel displays (FPDs) has enabled a transformation in the way electronics are used. Previously, cathode ray tubes (CRTs) were the prevailing display technology, but the emergence of FPDs – in particular, liquid crystal displays (LCDs) – ushered in the era of the portable electronics, enabling devices such as laptop computers, smartphones, digital cameras, and tablets. As the LCD opened opportunity in new markets, it also matured to where it could compete directly with CRTs in stationary applications as well – now, more than $100 billion worth of LCDs are sold annually, and CRTs are increasingly antiques.

However, LCDs also have their drawbacks, and a number of emerging technologies are rising to challenge them, such as organic light-emitting diode (OLED) displays, which have found a home in smartphones, and electrophoretic displays, which have seen impressive growth in e-readers. These examples show that emerging display technologies can take advantage of limitations in LCD performance to quickly grow into a serious market.

- Small-area OLEDs cost some $3,000/m² today, approximately 50% higher than LCDs, but will become cost competitive with LCDs by 2016. Currently, the capital costs that go into manufacturing OLED displays contribute approximately 60% of the overall display cost. However, unlike LCDs, which get cheaper per unit area as size increases, OLEDs get more expensive with increased size, primarily due to the difficulty scaling the fine metal mask (FMM) deposition process.

- As e-readers have become a serious market, electrophoretics have installed themselves as the incumbent technology for non-segmented, reflective displays. Now, however, a new set of technologies chases electrophoretics for the reflective market – microelectromechanical systems (MEMS), cholesteric LCDs, and electrowetting. Due to its maturity level, electrophoretics ranks as one of the lower cost reflective technologies, but it has limited color and video properties. As a result, emerging technologies like electrowetting, which can offer strong color and video properties in addition to low power, offer a compelling alternative.

- We evaluated the markets for OLEDs in small-area displays (smartphones, digital cameras, picture frames, music players, and handheld video games), medium-size displays (tablets, laptops, and desktop computer monitors), and large-area displays (televisions). In total, these markets add up to approximately $11 billion in 2017, up from $1.9 billion in 2011, a 34% CAGR. In total, over one-third of all smartphones in 2017 will have an OLED screen, corresponding to a $9.5 billion market in 2017 for OLED displays. However, despite receiving significant attention, lifetime and cost issues will limit OLED TVs to a $325 million 2017 market.

- Currently, e-readers dominate the non-segmented reflective display market. However, the e-reader market will peak in 2013 due to market saturation and competition from alternative devices like tablets. As a result, digital signage will become the primary application in the overall $1.6 billion 2017 reflective display market.

- Some of the promise of the emerging display technologies is the ability to make flexible displays, which can enable new form factors and create more robust versions of already existing devices. We found that flexible displays will reach $140 million in 2017. While OLEDs can also be made flexible, 85% of the flexible display market will come from reflective displays due to the many materials and manufacturing challenges to resolve for flexible OLED manufacture.
Landscape

OLED displays, already a significant player in smartphones, will compete with LCDs directly, while reflective displays rely on power and viewing in sunlight and chase different markets.

Displays Have Changed the Electronics Landscape Before – and Will Do So Again

The emergence of flat-panel displays (FPDs) has enabled a transformation in the way electronics are used. Prior to FPDs—in particular, liquid crystal displays (LCDs)—cathode ray tube (CRT) displays were the prevailing display technology. However, CRTs need to be very thick, which limited them to stationary applications like televisions and desktop computer monitors. LCDs' emergence ushered in the era of the portable display, enabling devices such as laptop computers, smartphones, digital cameras, and tablets. As the LCD opened opportunity in new markets, it also matured to where it could compete directly with CRTs in stationary applications, as well: In 2007, LCD captured over half of the television market, and quickly surpassed CRT to become the dominant display technology—now, more than $100 billion worth of LCDs are sold annually.

However, LCDs also have their limitations; they are interestingly hampering the growth of portable applications that LCDs once enabled. LCDs require a backlight to produce an image, adding cost, size, and weight to the display—and since the backlight is always on, it means the display drains the battery more than any other component in a device. In addition, the LCD structure employs two polarizer films, which require a fixed gap between the films—limiting how thin they can be, and meaning that they are not well-suited for flexible displays. Despite improvements, LCDs are still difficult to view in direct sunlight, making them awkward to use outdoors.

Due to these drawbacks, a number of emerging technologies are rising to challenge (see the report “Sorting Hype From Reality in Printed, Organic, and Flexible Display Technologies”), and some have started to have started to see some success. Organic light-emitting diode (OLED) displays have found a home in smartphones, and are rapidly gaining market share in that segment, increasing from 49 million units shipped in 2010 to 90 million in 2011. Electrophoretic displays have seen impressive growth in e-readers such as the Amazon Kindle, leading to an overall sales increase from approximately 1 million units in 2008 to nearly 30 million in 2011. That said, these displays still can’t fully compete with LCDs—OLEDs suffer from shorter lifetimes and higher costs, especially for large displays, and electrophoretics can’t match LCDs for color or video performance. Nonetheless, they do show that emerging display technologies can take advantage of limitations in LCD performance to quickly grow into a serious market.

Printed Flexible and Organic Displays Are Well-Suited for Portable Applications

Between smartphones, laptops, e-readers, music players, and tablets, it is common for a single person to carrying at least one display—if not several—with them at all times. As these devices and displays become ingrained into everyday life, there are particular opportunities that printed, flexible, and organic displays can present to ease the burden of carrying and using all these devices. To wit:

- **Printed and organic displays enable flexibility.** Printed and organic display technologies are well-suited to make devices more portable through the use of flexible substrates. Flexible displays can enable portability in several ways—robustness, weight, size, and bendability. Replacing glass substrates with flexible substrates like plastic films, even when packaged in rigid form factors, makes the display less prone to shattering upon impact, a particularly important attribute with the high cost of portable electronic devices. As devices with larger screens, like tablets and e-readers, come into vogue, reducing weight and thickness is important to the users who need to carry them; flexible substrates are typically thinner and lighter than standard glass. Similarly, bendable displays can enable a device to take on a more compact form factor when not in use, allowing it to be more easily stowed and transported.
• **Potential for lower cost.** Printed, flexible, and organic displays have the opportunity to be lower cost than incumbent technologies. The materials cost of these displays can be lower due to the lack of rare and expensive metals, while flexible substrates offer the potential for lower cost than glass counterparts. In addition, printing is an additive process, leading to higher material utilization rates than vacuum based processing. What’s more, these technologies can also lower manufacturing cost through high-throughput roll-to-roll processing. There’s even an opportunity for reducing secondary costs, since the lower weight and small size can lower shipping costs.

However, even with all of the potential to lower cost, in the near-term, printed, flexible, and organic displays will be higher in cost than their rigid, glass-based counterparts, since the technologies are less mature. While the materials are potentially lower-cost, they can be quite expensive today due to the early stage of development, lack of process optimization, and small scale of manufacturing. In addition, these technologies can’t yet benefit from the cost reductions throughout the factory and throughout the supply chain that come from the economies of LCDs’ massive scale.

**Displays Fall into Two Major Categories – Emissive and Reflective**

In our analysis of printed, flexible, and organic display technologies, we categorize emerging displays as either emissive or reflective. Emissive displays, as the name implies, generates light internally – the light striking the viewer’s eye and forming the image is produced in the display itself. While LCD is an emissive technology, OLEDs are the only technology we consider likely to compete with LCDs for a significant share of the emissive market before 2017. Other emissive technologies, such as quantum dot light-emitting diodes (QLEDs), are a longer-term proposition.

Reflective displays do not produce light, but instead reflect ambient light from the display to produce the image. Electrophoretic displays like those E Ink produces for e-readers, are the dominant reflective displays for non-segmented applications, but alternative approaches – cholesteric LCD, microelectromechanical systems (MEMS), and electrowetting – have been undergoing rapid development. ¹

**Emissive OLED Displays Face High Material and Manufacturing Hurdles**

OLEDs operate by passing a current through an organic molecule, which converts the electrical energy into light; different molecules provide different specific colors of light.² To get a uniform current, the emissive layers are surrounded by other organic layers, including layers for positive- and negative-charge injection and transport. While OLEDs can produce a vibrant image with a wide color gamut and faster switching speeds than LCDs, materials and manufacturing challenges still remain. We studied OLED’s materials usage, manufacturing process, and cost structure closely, and found that:

• **TFT requirements add cost and limit substrates.** Current OLED displays use a low-temperature polycrystalline silicon (LTPS) backplane, which has a mobility of 100 cm²/V·s – compared to 0.8 cm²/V·s for amorphous silicon (a-Si) – to support the higher currents that OLED pixels require (since light is generated at each pixel, not from a backlight). However, this higher performance comes at a higher cost because LTPS requires extra processing equipment. While it starts with the plasma-enhanced chemical vapor deposition (PECVD) similar to that used for a-Si, LTPS requires an additional laser annealing step; this process can reach temperatures up to 600 °C, which also inhibits the use of polymer substrates. In the future, OLEDs may use metal oxide TFTs – typically made of indium-gallium-zinc-oxide (IGZO), which can be produced in one processing step, typically with sputtering. However, metal oxide TFTs have lower mobility (around 10 cm²/V·s) and are less stable than LTPS TFTs.

• **Atmospheric sensitivity creates material challenges.** Operating an OLED places considerable stress on the organic components of the device, and OLEDs are extremely sensitive to water and oxygen. In OLEDs deposited on glass, device manufactures use reactive metal oxide materials called getters in the display in order to catch water and oxygen before it can degrade the organic materials. However, this sensitivity also creates additional challenges for flexible OLEDs, since flexible, polymer substrates are much more permeable to water and oxygen than glass is. Flexible OLEDs require additional barrier films, typically comprised of
alternating polymer and metal layers, to get below the $10^{-6}$ g/m²/day permeability metric required for stable OLEDs. However, uniformity is still a challenge, as pinholes will lead to local degradation of the display, and the costs of these films—or of more stable organic compounds with similar performance—remains high.

**Manufacturing wastes expensive materials.** To create OLED pixels, it’s necessary to arrange the organic material very precisely on the device substrate. Currently, device makers use a fine metal mask (FMM) process, vaporizing the organic materials and deposited onto the substrate through a patterned mask. While this process is capable of the high-resolution displays (greater than 250 ppi) required for mobile applications, it is not without its limitations. The use of vapor deposition, combined with the mask, means material utilization rates can be as low as 20%, adding significantly to the overall material cost. In addition, the process can only pattern material over a limited area, meaning that for larger displays it’s necessary to combine series of smaller panels to create the display.

While FMM deposition works well for small-area OLED displays, alternative processes like the Samsung’s laser-induced thermal imaging (LITI) transfer printing process, DuPont’s nozzle-printing, and Kateeva’s vapor deposition process are under development for larger area displays. However, these processes are still immature and still have significant yield and scaling challenges to overcome before they are ready to be used in mass manufacturing.

**OLEDs don’t last long enough for many applications.** OLED lifetime is not discussed in a consistent way—they are reported as an LX value, which is the amount of time before the output in lumens decreases to X% of the original output (for example, an L70 value corresponds to the time before the display drops to 70% of the original output). While the L95 for most OLED materials is in the hundreds of hours, the L50 is often over 30,000 hours. However, since the degradation it not uniform for each color, the generated image alters over time. The appropriate LX value to determine lifetime will vary based on the application, but since a primary advantage of OLEDs for many applications is the quality of the image generated, consumers will be unlikely to accept a rapid decrease in display quality over the life of the device.

**Energy saving is content-dependant.** OLEDs can require lower power than LCDs, while is particularly important for mobile applications where battery life and size are critical parameters—and where an LCD can account for nearly 50% of power consumption. However, comparing the energy consumption between LCDs and OLEDs is not straightforward. LCDs have a backlight that is turned on no matter the display being shown, so their power usage is essentially constant regardless of the image. However, OLED power can vary significantly depending on the image: A white image requires the most power—as much or more than that used by a LCD—while black images don’t use any power at all. As a result, devices with OLED displays will arrange to have more black in the content—which the Windows WP7 operating system for mobile phones enables—in order to maximize the power performance and extend battery life.

**OLED Costs Are Falling, but Still High**

Whatever their performance advantages, to continue taking market share from LCDs and to break into new markets, OLEDs must be able to compete on cost. To assess the cost of OLED and other emerging display technologies, we analyzed the bulk cost, amount used, utilization, and yield for each material component of an OLED display and how each material’s cost will change over time. In addition, we evaluated the cost, yield, throughput, operating cost, and substrate size for the equipment required to manufacture the displays. We found that:

**For small-area displays, costs are coming into line with LCDs.** Our analysis shows that while the overall cost of a small-area OLED is nearly $3,000/m² today—approximately 50% higher than LCDs, it will become cost competitive with LCDs in 2015 or 2016 as more OLED display manufacturing equipment comes online and ramps production. Currently, the capital costs that go into manufacturing OLED displays contribute approximately 60% of the overall display cost due to the high capital equipment required for production, including those for the FMM and TFT (see Figure 1). These costs are positioned to fall with scale, driving most of the reduction in OLED cost.
While capex is high, materials will be more significant in the future. Currently, the materials only comprise 21% of the overall cost of the display – a relatively low percentage, considering that materials utilization is still low. Among all materials, the hole-transport layer is the highest cost, in part due to it being one of the thickest layers in the stack. As capital costs fall, the proportion of the cost from materials will rise to 28%, placing a greater premium on material cost reduction and on more efficient use of materials.

Cost goes up for OLED with size. Unlike LCDs, which get cheaper per unit area as size increases – due in large part to the cost savings of making TFTs at larger scale and on large substrates – OLEDs get more expensive with increased size. While OLEDs can also benefit from TFT size and scale, other parts of the manufacturing process for OLEDs, particularly the FMM deposition, don’t scale well, affecting the throughput and yield. We determined the cost for three different sizes of OLED displays – 4-inch, 8-inch, and 42-inch diagonals, representing typical sizes for smartphones, tablets, and televisions. While the 4-inch display costs approximately $3,000/m², the 42-inch display costs nearly $12,000/m² – leaving larger displays far more expensive than LCDs, which cost approximately $400/m² for a 42-inch display (see Figure 2).

Several Reflective Technologies Chase Electrophoretics for Non-Segmented Applications

As e-readers have become a serious market in the past five years, electrophoretics have installed themselves as the incumbent technology for non-segmented, reflective displays, but now a new group of reflective technologies chases electrophoretics for the reflective market – MEMS, cholesteric LCDs, and electrowetting. These reflective technologies generally require lower power and perform better in direct sunlight than their emissive counterparts. In addition, these reflective technologies are “voltage-driven,” meaning that switching a pixel requires only a change in applied voltage (as opposed to current-driven OLEDs, which require a certain volume of electrical current), so they can use lower-performance TFTs. In addition, unlike OLEDs, these technologies are not water and oxygen sensitive, so high-cost barrier films are not required to make flexible versions. However, they generally lag OLEDs and LCDs in color and image quality, as well as refresh rate and, hence, video performance.

We also analyzed the reflective display technologies closely and built detailed cost models for the four major variations. Each of these technologies performs well in some ways, while being limited in others.
*Electrophoretics are the leading approach.* Electrophoretics through their use in e-readers have become a $600 million market. E Ink is currently the leading developer of electrophoretic displays, but other companies such as SiPix and Bridgestone also look to take a share of the electrophoretic market. The displays operate thorough the control of charged particles in a fluid with an applied voltage (for more information see the report “Sorting Hype From Reality in Printed, Organic, and Flexible Display Technologies”). The base technology only produces monochrome displays; it’s possible to make color displays using a red-green-blue-white (RGBW) color filter.

Electrophoretics do very well on power performance, as they are bistable, requiring power only to change the image. What’s more, due to its maturity level, electrophoretics ranks as one of the lower cost reflective technologies (see Figure 3). However, they do not perform well for video displays, due to slow switching speeds – and have high power requirements for video due to the constant image switching needed. The color performance of electrophoretics falls well short of emissive technologies.

*MEMS has video, but color lags and costs are still high.* MEMS displays operate with two plates for each colored sub-pixel (see Figure 4). The color reflected corresponds to the distance between the two plates, but with an applied voltage, the plates are attracted to one another, causing the sub-pixel to turn black. Telecom giant Qualcomm is the primary developer of MEMS displays, which it calls its Mirasol technology, and is in the process to transitioning from its pilot manufacturing facility to a larger volume manufacturing facility, which cost more than $1 billion. At the end of 2011, Qualcomm debuted the technology in its first commercial product, the Kyobo e-reader with a 5.7-inch diagonal display, which was released in South Korea. While a 30-frames-per-second (fps) refresh rate allows for good video performance, the color of the displays is underwhelming. In addition, MEMS is the highest cost reflective display that we investigated, due to the complex architecture, yield challenges, and high capital cost of manufacturing (see Figure 3).

*Cholesteric LCDs offer similar performance and cost as electrophoretics.* While there are several varieties of reflective LCDs, cholesteric LCDs are the most prevalent. Similar to conventional LCDs, the cholesteric LCDs operate by changing their orientation of liquid crystals to either pass or block light at each pixel, but the difference is reflective LCDs do not use a backlight. All cholesteric LCDs are low-power, and some, such as those from Kent Displays, are bistable. Due to their slow switching speeds, cholesteric LCDs are not capable of video, and are only capable of monochrome images. However, cholesteric LCDs are the only...
reflective technology that we surveyed that can compete with electrophoretics on cost (see Figure 3).

- **Electrowetting offers color and video, but at higher cost than some alternatives.** Electrowetting (and the closely related electrofluidic) is the only reflective technology that offers good color and video performance, with a refresh rate of 30 fps. Electrowetting displays work through the control of the dispersion of colored oil across a polymer surface with an applied voltage (for more information see the report “Sorting Hype From Reality in Printed, Organic, and Flexible Display Technologies”). These displays are low-power and some architectures enable bistable displays as well. Samsung acquired electrowetting developer Liquavista in late 2010, and smaller companies such as electrofluidic developer Gamma Dynamics are developing related technology. At a current cost of approximately $2,200/m², electrowetting is higher cost than electrophoretics due to its stage of maturity, but lower cost than MEMS (see Figure 3), the only other reflective technology capable of video. However, its color performance, while good, still doesn’t match that of LCDs or OLED, and remains higher cost than electrophoretics and cholesteric LCD due to its maturity level.