ANALYSIS

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The OE-A roadmap for organic and printed electronics: creating a guidepost to complex interlinked technologies, applications and markets

Stephan Kirchmeyer

Management Consultant, Organic and Printed Electronics, Pastorskamp 16, 51381 Leverkusen, Germany

E-mail: sk@stephankirchmeyer.com

Starting from its early days about 10 years ago, the OE-A roadmap has constantly reported technical progress for organic and printed electronics. Based on data gathered from several expert groups, the OE-A biannually publishes an updated version. As a technology roadmap, it has been a strategic tool for OE-A members to synchronize efforts for research and development.

This article highlights the 6th edition of the OE-A roadmap and links its content to global trends and dynamics of existing markets. The 'organic growth path' stated by the OE-A roadmap required a complex roadmapping process to consider technology movements in established markets and the development of new markets.

Exemplified by selected applications, this article explains the complexity, challenges and benefits of the roadmapping process and links the real OE-A roadmap to roadmapping concepts.

Introduction

The vision of organic and printed electronics was simple: print electronic chips or, more generally speaking, print all kinds of electronic components and devices. The basic concept seemed quite clear: the use of printing will allow us to simplify the manufacturing process and use cheap materials. No material waste would be produced. Hence, the decreased manufacturing costs would make electronics available everywhere. Or in other words: make electronic intelligence omnipresent. Plastic substrates would allow us to provide large areas and flexible surfaces with electronic functions.

Print 'all kinds of electronics parts' was not quite specific and in the meantime this simple vision underwent several modifications, clarifications, and ascertainments. For example, OE-A members started to print inorganic materials as well, such as metal inks and metal oxide semiconductors, and employed vapor deposition besides printing. As a consequence, the scope of the OE-A roadmap gradually broadened. Today the OE-A, the Organic and Printed Electronics Association as a working group of the VDMA, defines in its vision statement 'emerging electronics' as 'flexible, printed electronics from organic, polymeric or inorganic materials beyond classical silicon' [1]. This more pragmatic statement allows, for example, lithography as a patterning step whenever necessary. However, with technology progress it is expected that the OE-A vision may also experience further adjustments. The European Commission as well as national and regional funding agencies started to fund research projects for organic and large area electronics (OLAE) in Europe [2]. With time, topics diversified and targets became more specific. Large area electronics, flexible electronics, smart textiles, organic photovoltaics, OLED (organic light emitting diode) displays, OLED lighting and many other topics become part of the organic and printed electronics roadmap.

The phrase 'market for printed electronics' implied by various market studies [3,4] is convenient but misleading. The multiple technologies representing organic and printed electronics target diverse consumer markets such as consumer electronics, automotives, energy, the medical sector and many more. Frequently, the target market turns out to be a so-called 'emerging market', a market which does not exist at present. Entrepreneurs who target emerging markets with new technologies work in a difficult environment as they invest in a technology that is still in its infancy, and need to envision future markets and products.

The Organic Electronics Association (OE-A) was founded in 2004. As an industry association it enables communication along the value chain and across technologies. Headquartered in Germany, it is an international association with a strong European membership base. The OE-A roadmap [5] was established in 2005 in analogy to

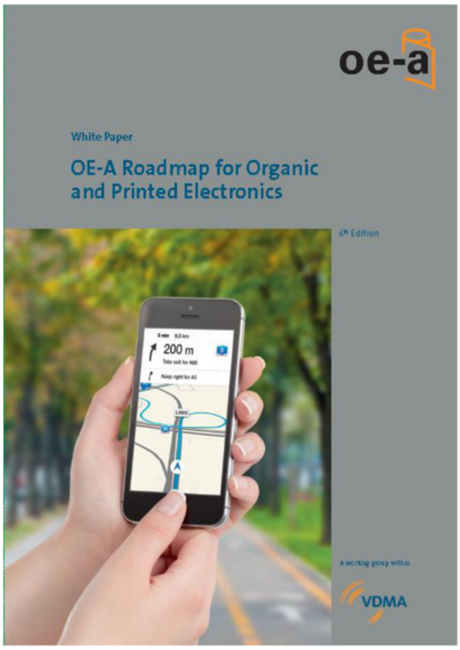

Figure 1. Cover page of the 6th edition of the OE-A roadmap for organic and printed electronics.

the ITRS roadmap for semiconductors [6]. As a strategic tool it serves to synchronize the efforts of OE-A members along the value chain. An update is published every two years. The 6th edition of the roadmap was published in early 2015 and has been the base for this article (figure 1).

In 2005 the research on technology roadmapping was still in an exploratory phase. In the meantime, and with increasing practical experience, roadmaps were widely established as a viable approach to align strategic objectives and technology management [7]. The task of this article was to critically review the implementation process of the OE-A roadmap, identify specific challenges in the roadmapping process, make suggestions to modify technology roadmap concepts, and to improve future OE-A roadmap editions.

1. How the OE-A roadmap evolves

Entrepreneurs active in organic and printed electronics face a high degree of uncertainty, market uncertainty and technology uncertainty as well. Technology roadmaps have been valued as promising and practical tools to assist in the entrepreneurial decision making process on innovation [8]. In general, technology roadmaps link markets to products and to technologies to allow an 'extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field' [9] (figure 2).

In a continuous process, the OE-A roadmap evolved and guided the community active in this field. It took over 10 years to achieve its current format and content. In frequent meetings OE-A experts contribute their specific knowledge to cluster groups, negotiate on data, technical targets, obstacles, and timelines. In return the members receive comprehensive information on the status of upstream and downstream technologies and can make sure that their specific technology is correctly represented in the final white paper. Based on the manifold of tables and documents produced by the expert groups, an editorial team creates the roadmap and publishes a white paper. The OE-A roadmap contains two sections, a first section on application areas and a second section on technology areas (figure 3). For each chapter the expert groups define and quantify product generations, key application parameters, key technology parameters, create a list of 'red brick walls', and perform a SWOT (strength, weakness, opportunity, threat) analysis. In general, the open communication process within the OE-A works well for technical data. Being aware that an open communication on commercial aspects may violate anti-trust laws, the OE-A had introduced an additional tool in 2013, the 'business climate survey'. The OE-A business climate survey is a semi-yearly questionnaire which anonymously gathers targeted applications, business developments and investments in R + D, personnel, and production. With the business climate survey, the OE-A has created a tool to overcome some of the restrictions of the OE-A roadmap. However, incorporation of the business climate survey into the OE-A roadmap is pending (table 1).

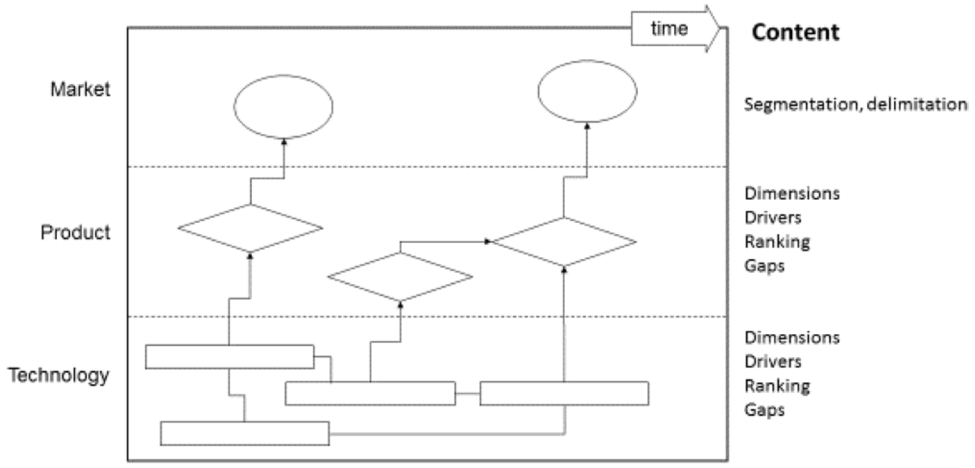

Figure 2. Common scheme of technology roadmap layers.

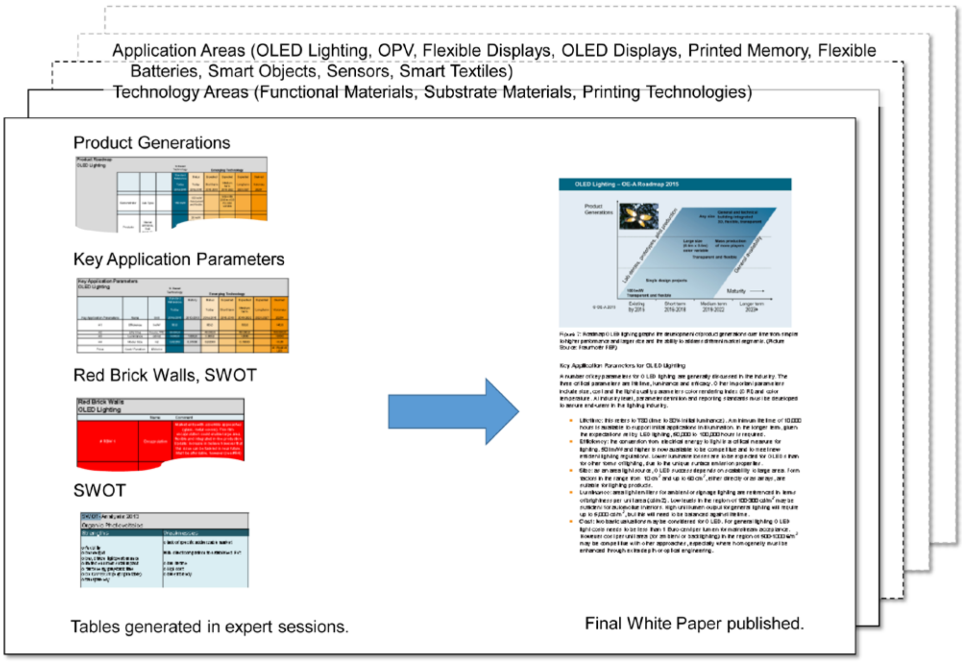

Figure 3. The OE-A roadmapping process.

Roadmapping is suggested to proceed in layers starting from markets via products to technologies. An important requirement for the market layer is a clear delimitation and segmentation and of the considered markets. To meet this requirement, the OE-A roadmap has implemented application areas:

- Organic LED (OLED) lighting,
- Printable, organic photovoltaics (OPV),
- Flexible and OLED displays,
- Electronics and components (printed memory and batteries, active components and passive components),
- Integrated smart systems or ISSs (including smart objects like RFID, sensors and smart textiles).

Application clusters such as 'electronics and components' and 'integrated smart systems' represent a compromise between completeness and manageability and tend to vary with editions. For example, the cluster 'electronics and components' comprises components such as batteries, which allow a detailed roadmap, and resistors, which cannot be skipped but do not have a clear roadmap.

To connect the market and product layer, a technology roadmap needs to define dimensions and drivers, rank them in accordance to their significance, and describe gaps. The OE-A roadmap dimensions with implicit ranking are found as 'key application parameters' and 'product generations'. Gaps are reflected in 'red brick walls' and within the SWOT analysis. 'Key technology parameters' connect the product with the technology layer.

Table 1. Conceptual roadmap layers and their implementation within the OE-A roadmap.

Conceptual roadmap layer	Content	OE-A roadmap sections	Content
Market	Segmentation Delimitation	Application area	• OLED lighting • Organic photovoltaics • Flexible displays • OLED displays • Printed memory • Flexible batteries • Smart objects • Sensors • Smart textiles
Product	Dimensions Drivers Ranking Gaps		• Key application parameters • Product generations • Red brick walls • SWOT analysis
Technology	Dimensions Drivers Ranking Gaps		• Key technology parameters • Red brick walls • SWOT analysis
Enabling technology		Technology area	• Functional materials ∗ Key application areas ∗ Key application parameters • Substrates ∗ Key material properties • Key printing processes • Red brick walls

The meaning of ‘technology’ found in roadmap concepts is slightly different from its meaning within the OE-A roadmap. Most roadmapping concepts consider a technology to be directly linked to the associated product. Technologies in this sense are an implicit part of the application section of the OE-A roadmap. ‘Technologies’ described in the OE-A roadmap technology section constitute ‘enabling technologies’, specifically functional materials, substrate materials and printing processes, which constitute their separate roadmaps.

Jointly for application and technology areas, product generations have been defined in relation to their maturity such as prototypes, pilot and mass products. This definition was chosen as the lowest common denominator.

Timelines were separated into the five categories which reflect the typical development periods in the electronics industry:

- today (accounting for already existing products)
- short term (1–3 years),
- medium term (4–7 years),
- long term (8–11 years), and
- visionary (12+ years).

Self-evidently, the OE-A roadmapping process faces constraints. The process involves people with specific but limited knowledge, and it has limited resources in terms of money and time. For each of the application and technology areas, expert teams need to meet in several expert sessions to generate the input data. With time, expert teams turn over in members. The final compilation of this information into a comprehensible text, the white paper, is a laborious process done by a small editorial team.

The following chapters will evaluate the actual roadmapping process of selected application areas and identify specific challenges which originate from target markets, technology interlinks and resource restrictions.

2. OLED lighting—benchmarked against LED

The IEEE (Institute of Electrical and Electronics Engineers) published a dedicated roadmap for OLED displays in 2004 [10]. Since then this roadmap has not been updated. The US Department of Energy published an OLED lighting roadmap in 2014 [11].

The OE-A roadmap section on OLED lighting has been continuously part of the OE-A roadmap since 2005. In terms of roadmapping this section reveals the importance of defining a relevant benchmark technology to avoid overoptimistic predictions.

The OE-A roadmap underlying scenario reflects a lighting market which is driven by light efficiency and cost, and impacted by governmental regulations. As in many countries governments phase out traditional light bulbs (incandescent lamps, halogen lamps) and have mid-term plans to phase out gas discharge lamps, the lighting market has now started to widely adopt LEDs for lighting purposes. Consequently, LED lighting was chosen as the benchmark technology for OLED lighting.

The key application parameters 'efficiency' and 'lifetime cost per function' serve to describe the demand to produce light in a cost efficient way. LEDs from commercial production have reached an efficiency of approximately 100 $\mathrm{lm\,W^{-1}}$ [12] and significantly dropped in price to less than 10 US$/60W equivalent [13]. OLEDs have reached the benchmark efficiency of 100 $\mathrm{lm\,W^{-1}}$ in laboratory devices. The roadmap projects a further efficiency increase, which will reach 190 $\mathrm{lm\,W^{-1}}$ in approximately 10 years. A similar value is projected for the efficiencies of LEDs [14].

The production scale will highly impact the production costs. Today, LEDs have been in mass production for many years, whereas OLED lighting elements are produced in the pilot scale. To predict a commercial breakthrough, the roadmap also needs to predict production costs as well. As a cost discussion is restricted by anti-trust laws, the roadmap team is currently limited to publically available commercial information such as public sales prices.

Within the last three years, prices for OLED lighting panels have decreased approximately by a factor of four. Recent news announced the availability of OLED lighting products in home supply stores in the US [15]. This is promising but does not hide the fact that OLEDs are still more than ten times more expensive than LEDs. This may change when the production of OLED lighting panels approaches the full scale, which is projected by the roadmap to happen in the medium-term. Nevertheless, public sale prices are not a direct measure for production costs and, therefore, are of limited value to predict commercial success in future.

As the prediction of productions costs hits practical barriers, technological indicators such as

- Processed substrate size
- Alternative substrate materials
- Alternative coating techniques

might allow a qualitative or even semi quantitative prediction with a higher precision than an 'educated guess'. This approach will be laborious but offers an option to further quantify the OE-A roadmap in light of the following discussion.

The production cost of OLED lighting elements decreases with larger substrate sizes. To use even larger substrates that at present, the manufacturing technology may need to shift away from the evaporation deposition. At present Gen 6 glass substrates (1500 mm by 1800 mm) can be handled, but OLED lighting elements are still manufactured on smaller substrates. There is some doubt that the precision of evaporation can be kept on larger than Gen 6 glass substrates. Once the evaporation technology hits its limits, an alternative deposition technology would be needed such as coating or printing. Glass substrates are difficult to process by printing, slot dye coating, and other wet processing techniques. In this regard polymer films are much easier to handle. The OE-A roadmap forecasts the adoption of plastic substrates instead of glass in a few years. In order to succeed, a red brick wall, the availability of barrier films in commercial quantities, needs to be overcome. Without suitable barrier films, OLED lighting panels, as well as OLED displays, will have an unacceptably low lifetime. Hence, barrier films are a critical component for OLED lighting elements. The 'lack of investment', listed as another red brick wall for the scale-up process, accounts for some hesitation to change from the currently well-managed evaporation process to a wet process with unidentified technical hurdles.

In summary, the OE-A section on OLED lighting elements revealed the necessity to benchmark the projected technology with existing technologies. It also revealed the difficulty that industrial expert groups have in predicting commercial success factors. Semi-quantitative, generic cost models may guide a way out of this dilemma. Such models may help to improve the quality of future OE-A roadmap editions, but they are not part of the current roadmapping process.

3. Organic photovoltaics—understanding the value chain

Organic photovoltaics [16] (OPV) is one of the emerging PV technologies based on organic semiconductors. A recent report to the European Commission claims that OPV should not be seen as replacement for current PV technologies but 'is a disruptive technology that opens access to completely new markets' [17]. The roadmapping processes of both organic photovoltaics (OPV) and OLED lighting products share similarities. The electricity and the lighting market follow similar rules: in both markets an energy/cost relationship is relevant for commercial success; both are impacted by governmental regulations. Strictly speaking this applies only to solar cells connected to the grid. Different key application parameters need to be considered when power will be supplied to places where no grid is available and solar cells enable new off-grid solutions.

Again, the definition of the closest existing technology as a benchmark for the emerging technology was essential for the quality of the roadmapping process. The OE-A roadmap benchmarks OPV to crystalline silicon and thin film cells. In contrast to OLEDs, OPV does not only compete with existing, but also with other emerging technologies. Crystalline silicon and thin film cells are manufactured by mass production. OPV is part of the so-called '3rd generation photovoltaics', which denotes several competing cell types such as organic photovoltaic cells (OPV), dye sensitized cells (DSC) and perovskite cells. All these emerging technologies strive to substitute the existing technologies, but vary in performance and maturity.

For the time being, the OE-A roadmap solely focuses on OPV. None of the 3rd generation photovoltaics technologies (including OPV) has gained full maturity yet, and mass products from any of these technologies are not likely to appear on the market within short term. For the 6th edition of the OE-A roadmap, crystalline silicon and thin film cells constitute valid benchmarks, but the window is open for all 3rd generation photovoltaics. A chapter comprising all 3rd generation photovoltaic technologies may be a valuable addition for the next roadmapping cycle.

The OE-A roadmap lists the following key application parameters for OPV:

- efficiency (the ratio of the electrical output of a solar cell to the incident energy in the form of sunlight)
- total power output per year
- lifetime per cost
- manufacturing status
- market price/production cost

OPV has been developed for many years and the technology has become somewhat mature. By intention the roadmap lists efficiencies separately for laboratory and mass production devices. Publically reported record efficiencies from small area laboratory cells have been criticized as not being relevant. The power of such cells is small and an extrapolation to larger cells is not possible as larger cells are commonly less efficient. However, it is fair to say that the efficiency of OPV is likely to remain inferior compared to the existing technologies. This subsequently leads to cost considerations.

Production cost-related key application parameters are reflected by 'lifetime per cost' and 'market price/production cost'. Like for OLEDs, the production costs for OPV are difficult to forecast as reliable, publically available information is missing. The comparison of sales prices (at present roughly 60 times higher than the existing solar cells) again might be misleading; existing solar cells originate from mass production, while OPV cells come from pilot lines.

Despite these obstacles, and in analogy to OLED lighting, a discussion of factors driving the production cost of emerging technologies may be a valuable tool. Already today, wet processing of OPV on polymeric substrates is a serious and practised option. Wet processing allows roll-to-roll production; today many of the functional materials are available as inks. Simultaneously, the use of plastic substrates is facilitated as the demand for barrier properties is roughly 100 times less than for OLEDs.

Several enterprises active in this field target solar products for areas with no grid. For such products the key application parameter 'efficiency' is of lower relevance. As existing PV cells can be used for such products too, the use of OPV will be limited to cases in which existing photovoltaic cells are not accepted, for example due to their rigidity. Examples of such target products are bags, bus stops, umbrellas, and tents equipped with photovoltaic cells (for examples see [18]). Such examples highlight the design aspect of the integration of PV into everyday goods, which is difficult to translate into a quantitative key application parameter. It is not fully clear to which extent these arguments also hold for IoT sensors (IoT: Internet of things). It is believed that a fraction of the IoT sensors will be driven by solar cells, among them OPV. In terms of roadmapping, products potentially evolving from the IoT need a better understanding. This refers to potential target markets and the technology requirements as well.

As explained, the key performance parameter 'efficiency' and its relevance depend on the cell size, but also the use case. Although adding another dimension of complexity the roadmap process, efficiencies in future roadmap editions might need to be listed separately for different use cases. The following discussion on building integrated photovoltaics (BIPV) may serve to illustrate this statement.

Under optimal conditions silicon solar cells are more efficient than OPV. This reverts under conditions of low illumination, in artificial light, and at low angles of incidence. The demand for zero-energy buildings is believed to increase, and silicon solar cells need to be placed on the rooftops of buildings, precisely aligned towards the sun. As the roof area is limited, walls may serve as additional area for solar cells. Walls are not suitable for silicon solar cells due to the unfavorable incidence angle. Under such conditions OPV cells and other 3rd generation solar cells integrated into outer walls or even transparent solar cells [19] integrated in windows may allow an extended building area to be equipped with solar cells [20].

This discussion reveals that for complex technologies a three-layer roadmap process with market, product and technology, may be too simple. In markets with extended value chains an upstream 'product' layer may constitute a downstream 'technology' layer. The solar market is an evident example of such a multi-level market which adds yet another dimension to the roadmapping process (figure 4).

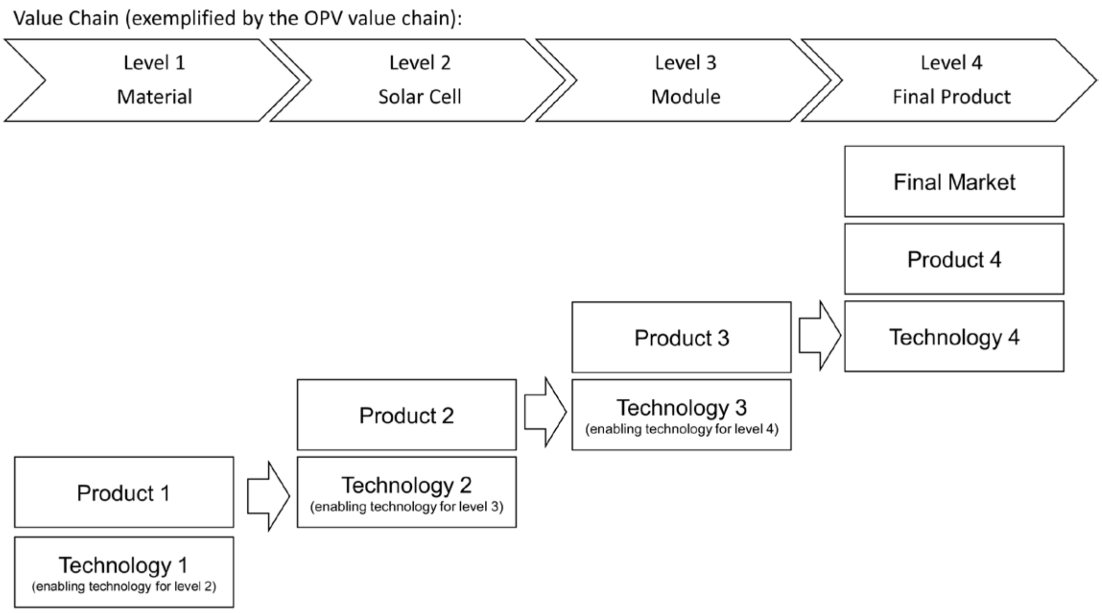

Figure 4. Roadmapping process for a complex value chain.

As a practical consequence of this insight, it will be necessary to identify the highest product level of the value chain during the roadmapping process. Such products are not always obvious and are case-dependent. However, it may not always be possible to deeply involve experts from downstream technologies into the roadmapping process. For example, in building integrated photovoltaics this would mean an involvement of architects, facade elements and window producers.

In summary the roadmapping process of OPV has revealed new lessons learned: the roadmapping process requires the ability:

- to track relevant existing as well as upcoming technologies as benchmarks, and
- to consider the whole (downstream) value chain to fully understand the market demand.

4. Foldable smart phones and wearables on the go

The creation of a display roadmap is facilitated by the fact that established display technologies serve an existing market of roughly of 150 billion US$ [21]. Viewed from a distance, the OE-A display roadmapping process may appear to become a straight forward product roadmapping process. Following the specific interest of OE-A members, the section on displays of the OE-A roadmap was focused on OLED and flexible displays and needed to consider a number of enabling technologies as well.

The first step, the definition of a set of suitable key application parameters and benchmark technologies for flexible displays, turned out to be extremely sensitive towards the final (consumer) product. The dominant existing display technologies are LCD (liquid crystal display), OLED and ED (electrophoretic displays). LCDs are used in TVs, laptops and smart phones, OLEDs serve predominantly smart phones, and EDs are mainly used for e-readers. With the exception of LCD all major display technologies may potentially become fully flexible. As a completely new display technology is not likely to become mature in the near term, the OE-A roadmap concentrated on solving the question of which existing display technology may be used in upcoming final consumer products.

One of the crucial key performance parameters, ‘flexibility’, was found to be not well defined and has been used to describe various functions of final products.

- TV sets and mobile phones with curved displays have been available for about two years. These are sometimes called ‘flexible displays’[1], but in general they are curved but rigid. Flexibility in the sense of the OE-A roadmap was defined as the ‘capability of being bent during use’ and therefore is not applicable for those devices.
- Rollable TV screens are clearly flexible but not likely to appear within the near future. They are part of the mid-term to long-term vision of the roadmap and critically depend on the availability of large size flexible displays as prerequisite.

[1] The OE-A roadmap calls curved rigid displays ‘flexible’. The correct technical term for curved or 3D shaped rigid displays is ‘conformable’.

Figure 5. Polyera's electronic bracelets Wove (Source: Polyera).

- Mobile phones with smaller flexible displays seem within reach. Smart phones tend to increase in display size from generation to generation, and consequently become too bulky. The concept of a foldable display requires displays that survive small bending radii, for example a bending radius of 3 mm. The short-term perspective of this approach is highlighted by Samsung's announcement of a foldable smart phone for January 2016 [22] and ITRI's launch of the spin-off 'FlexUp' in 2014 to commercialize its flexible display technology [23].
- 'Wearables' like smart watches and activity trackers may become another short to mid-term option for flexible displays, however it is not fully clear to what extent flexible displays will be adopted. Most existing activity trackers and smart watches use curved rigid displays, usually based on OLEDs. Products with fully flexible electrophoretic displays like Polyera's electronic bracelets Wove[2] are in a pilot stage (figure 5). As a long-term vision, wearables are predicted to adopt flexible displays, followed by electronics integrated into textiles ('smart textiles', figure 6).

This complex product scenario was the background when the roadmapping team defined and used the 'bending radius' as key application parameter for flexibility. Additional key application parameters were 'lifetime', 'resolution', 'update speed', 'transparency' and 'market price', which will not be discussed at this point. To predict technological progress, the OE-A roadmap on flexible displays needed to take several enabling technologies into account which are required to eliminate red brick walls of existing technologies. 'Flexible backplanes' illustrate such an enabling technology which is described in the following example.

All established display technologies (LCD, OLED and ED) need a backplane. Backplanes are usually made from rigid glass and carry the transistors controlling the pixels. Although being brittle, glass has the benefit of high temperature stability and excellent barrier properties. Transistors made from LTPS (low temperature polysilicon) or IGZO (indium gallium zinc oxide) [24] usually require process temperatures up to 350 °C. This is far beyond the stability of most common plastics and, with a few exceptions such as polyimides, eliminates most polymers as optional substrates for LTPS and IGZO transistors. Solution cast polyimides, on the other hand, are more expensive than common polymers such as PET (poly ethylene terephthalate).

Fully flexible 'all plastic backplanes' have been in the pipeline for many years. They use organic semiconductors which do not require high process temperatures. They have reached pilot manufacturing status in electrophoretic displays (figure 7).

Combining a flexible backplane with a suitable display technology, significant barriers exist for flexible LCD, as bending the display generates small distance changes between front- and backplane causing so-called 'clouding'. In contrast, the technology barriers to combine flexible backplanes with electrophoretic displays are considered to be low. However, these displays are slower and in general do not allow videos to be viewed. Therefore, OLEDs are seen as one of the serious options for flexible displays. The protection of the active materials contained in OLED displays continues to be the main challenge. These materials are highly sensitive to oxygen and humidity and require high-quality barrier properties. At present two substrate options are considered in parallel for flexible OLED, both having their pros and cons in performance and handling during production [25]: polyimide substrates with barrier films and flexible glass.

In summary, the roadmapping process for flexible displays faced the specific challenge that the team needed to consider several interlinked levels of the value chain leading to a manifold of competing technology options.

[2] www.wove.com for a product demonstration.

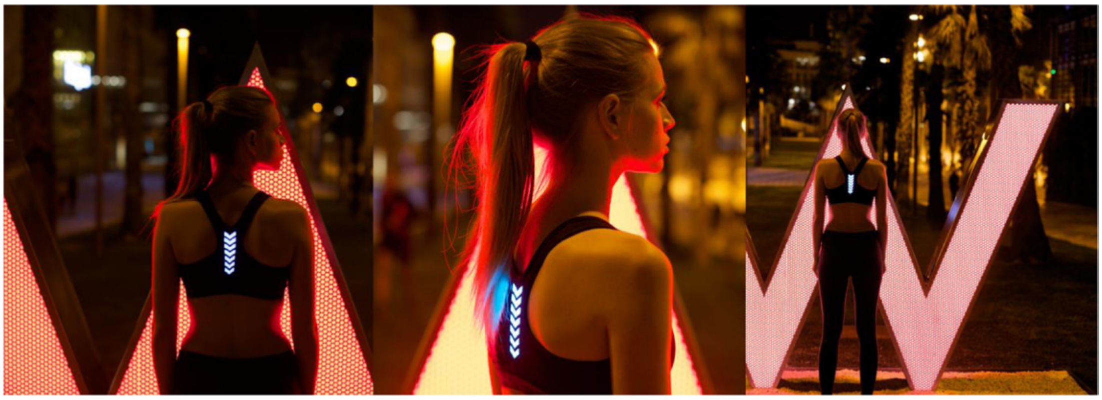

Figure 6. Printed active light incorporated in clothing, developed by Eurecat in collaboration with light-flex (source: Eurecat).

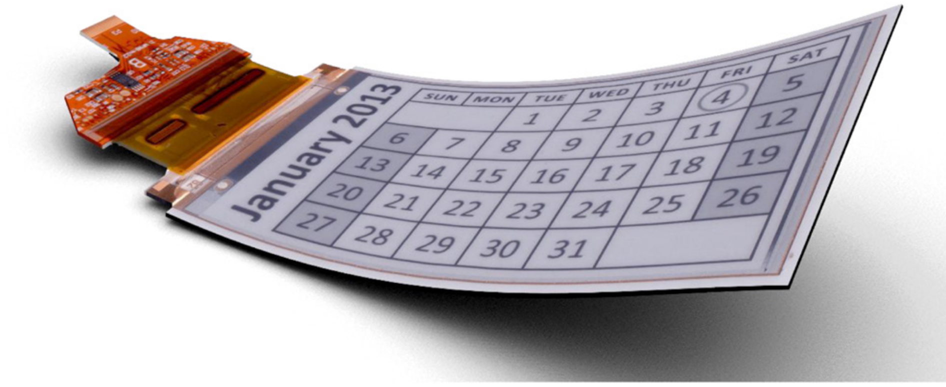

Figure 7. Flexible display Lectum™ of Plastic Logic (source: Plastic Logic).

Each level of the value chain, final consumer product, display, display component, and material, has a product and technology layer.

5. Barrier films—a future chapter for a critical component

As previously mentioned, the OE-A roadmap is structured into two sections: application and technology areas. Using the common roadmapping terminology, technologies described in OE-A roadmap technology section are better labeled as 'enabling technologies'.

The OE-A roadmap describes functional materials, substrate materials and printing technologies as enabling technologies. Emphasis has been put on a detailed forecast for functional materials such as organic and printable semiconductors and conductors. Despite their critical role for OLED displays, OLED lighting elements and OPV, flexible display barrier films have not been separately covered in the 6th edition of the OE-A roadmap. To account for the significance of barrier films as a technology enabler, a separate chapter is planned for coming editions of the OE-A roadmap.

The following highlights a general challenge for the roadmapping process. To make the roadmapping process manageable, markets and technologies and enabling technologies need to be delimited. This delimitation is a balance: without delimitation the roadmapping process becomes unmanageable, however in a worst case a delimitation might cause loss of information. There are trigger points when it becomes necessary to separately discuss an enabling technology and create a separate roadmap. Here it is suggested that such a trigger point is reached when an enabling technology becomes critical for a product with short-term market perspective. In this sense barrier films were triggered solely as critical component for flexible displays, despite their critical function in other application areas.

- Backplanes for flexible OLED displays based on polyimide plus barrier film are needed for foldable smart phones within the next 1–2 years.
- Present OLED lighting elements from pilot production employ glass substrates. Flexibility is projected only mid-term to long-term and makes barrier films less urgent for this application.

- OPV on flexible substrates has reached pilot production. OPV needs good barriers against oxygen and humidity. Flexible barrier films are less urgent as (a) the demand for barrier properties is roughly two orders of magnitude lower and (b) module technologies offer alternative ways to ensure proper encapsulation.

Hybrid systems (or 'hybrids'), photonic sintering and other technologies constitute other upcoming enabling technologies than may need future attention. 'Hybrids' covers systems combining printed components and classical silicon-based chips. Their significance is highlighted by the fact that in 2015 the European Commission started a funding program to develop a toolbox of integration processes, design and modelling of hybrid electronic systems. The US government has recently announced the investment of 75 million US$ into flexible hybrid electronics [26].

To summarize: the roadmapping process requires a careful decision which technologies and enabling technologies to cover and which to omit. Upcoming enabling technologies need to be closely monitored and might require a separate roadmapping section as they approach a trigger point. Such a trigger point can be defined as the point in time when an enabling technology becomes critical for a product with short-term market perspective.

6. Summary and conclusion

The task of the current work was to critically review the implementation process of a technology roadmap, the OE-A roadmap or organic and printed electronics, in view of conceptual considerations, identify specific challenges in the roadmapping process, and make suggestions to improve technology roadmap concepts and future OE-A roadmap editions.

It was found that the roadmapping process of the OE-A roadmap follows common roadmapping concepts. Not only for OE-A members, but also for others active in this community, the OE-A roadmap has become a meaningful tool, supporting their strategic planning process.

As a 'real world document' the OE-A roadmap has constraints and needs to overcome several challenges:

- The roadmapping of emerging technologies requires the definition of the closest existing technology as a benchmark. The choice of this benchmark is sensitive as an incorrect choice is likely to cause incorrect conclusions during the roadmapping process.
- Roadmaps usually consider technological progress to proceed independently on a separate level of the value chain. In the real world the technical progress on several levels of the value chain is interrelated. Roadmaps need to consider the progress of enabling technologies on upstream and downstream levels of the value chain.
- An ideal roadmapping process proceeds from markets via products to technologies, and the value chain is fully known in the selected field. Ideally the roadmapping process starts from the highest level of the value chain, for example from a consumer product. However, in reality this may need additional expertise from outside the roadmapping team and, if not available, may require workarounds.
- Although commercial information such as production cost and prices would be essential for the roadmapping process, this information is usually restricted by anti-trust laws. Semi-quantitative, generic cost models may guide a way out of this dilemma, but are not yet available.

Reviewing the OE-A roadmapping process was fruitful in two aspects, to perform a structured search for improvements of future editions of the OE-A roadmap and to match conceptual work on technology roadmaps with the reality faced during the creation of a real technology roadmap.

Acknowledgments

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Stephan Kirchmeyer, born in 1957, has a doctoral degree in organic chemistry. In his professional career with IBM, Bayer, H.C. Starck, and Heraeus he worked in various positions in research, technology, and business for electronic materials. In 2009 he became member of the OE-A board and chaired the OE-A from 2011 to 2015. Having 18 years of experience in this industry, he started his own business as management consultant for organic and printed electronics in 2016.