Electrowetting displays

Allow billboards anywhere!

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Electro-wetting display technology creates the opportunity for digital displays to become as abundant as "paper"

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Abstract
Advertisement on digital out of home displays becomes financially more and more attractive. Light pollution and energy consumption prohibit that LED displays become as abundant as "paper". Electro-wetting displays can fulfill that role, because of their highly reflective performance. Etulipa Carbon is the first electro-wetting product going to market that successfully passes all perception tests on readability under all outdoor conditions.

Digital out of home display market

Advertisement has long been a uni-directional communication between advertiser and consumer. Internet and social media, have created the opportunity for advertisers to communicate directly with targeted groups and to create a two-way communication thereby increasing the intimacy with its potential customers.

Total revenue in advertisement is strongly related to the GDP of a country. For example in the USA the advertisement business is on average 1.29% of the total GDP [ref 1]. Advertisement revenues can be expected to be shared according to exposure to audience size. The trend of the world population to urbanization leads to more time spent outdoors, and thus the outdoor audience increases at the cost of more traditional audience groups. Therefore Out Of Home (OOH) advertisement revenues are increasing yearly as a percentage of the total advertisement revenues and are becoming more and more relevant every year [ref 2]. In 2015 worldwide outdoor advertisement spending was estimated to be $37.1 BUSD, an increase of 6.6 % compared to 2014 [ref 3], much higher than the increase of the worlds GDP.

OOH advertisers follow the trend to increased intimacy with its audience by building digital out of home (DOOH) platforms which can be updated any time of the day. For example, momentarily the amount of digital billboards in the USA is roughly 4% of the total amount of billboards and the quantity of digital billboards grows approximately 15% per year [ref 4] as illustrated in Fig 1.

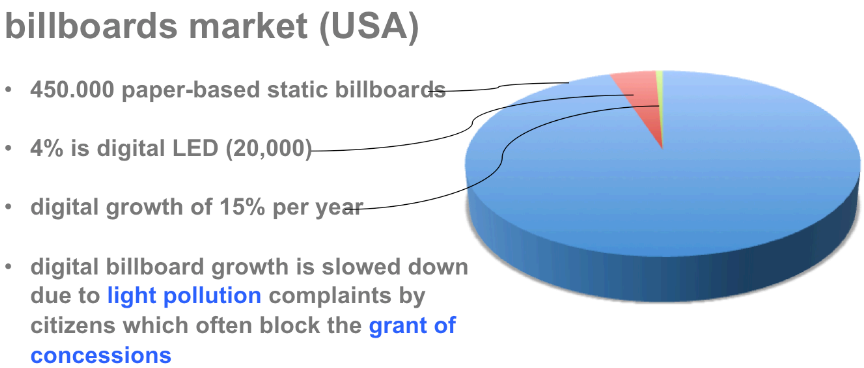

Fig1. Overview of billboard market in USA

Technical challenges
As of this moment almost all DOOH displays are made using LED display screens. Outdoor LED display screens consist of a high number of LED's mounted with a pitch of a few mm up to approximately 24 mm, depending on the average observation distance. Content is created by switching of the individual LED's. Companies and institutions experience often difficulty with installment of such LED display outdoors. LED displays emit light which is experienced as very intense and uncomfortable, especially in evening and night time. Therefore issues or worries about such light pollution can uphold the permits to to build an outdoor digital screen. An example is of such a discussion is given in [ref 5].

Secondly, LED billboards consume a large amount of energy. Each LED uses electrical power to emit light. The LED has to over-shine the ambient light which is especially challenging when the sun shines. In fact, when the sun shines directly on an LED billboard, the content often can not even be recognized. This necessity to over-shine the day-light leads to high energy usage. Average consumption over 24 hours is typically 200 – 400 Watt / m2. Considering that billboards can be as large as 14 foot x 48 foot this implies that power usage can easily reach over 20 kWatt! This has a considerable impact on the total cost of ownership of such a screen.

In addition, communities that encourage environmental stewardship often use the Leadership in Energy and Environmental Design (LEED) developed by the US Green Building Council (USGBC) [ref 6] as a guideline for concessions. Such guidelines force the implementation of low energy consuming solutions.

Quest for non-emitting low energy displays
Low energy consumption and elimination of light emission by displays are the key characteristics of e-readers. Hence OOH display makers are extremely interested in application of e-reader display technologies into their market. An excellent overview of the different e-reader display technologies is given by Jason Heikenfeld et al [ref 7].

The perceived quality of a reflective display is dependent on the three prime parameters defining a color. These are:

- Lightness, also referred to as "value".
- Hue, also referred to as "color".
- Saturation, also referred to as "chroma".

Together these define the color gamut, quantified by CIE 1976 with the parameters L*, a* and b*. Munsel described the color space with an orb where the north pole corresponds with white, the south pole with black and the north-south axis with grey scales from white to black as shown in fig 2. The equator represents all the full saturated colors. Bradley [ref 8] for example explains lightness, hue and saturation using this orb.

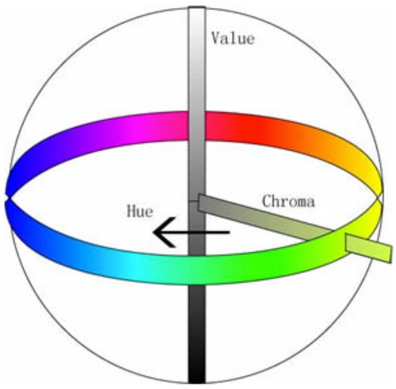

Fig 2: Munsel representation of the color space

Customers for DOOH displays require high contrast, full color and video capability. In emissive displays this can be achieved by enhancing the emissive power for a specific area, or pixels of a display. Non-light-emitting displays use the ambient light to reflect from the display, therefore they are also called "reflective displays". That means that available ambient light has to fall onto the display surface and reflect back to the eye of the observer. What does it mean to have high contrast and full color? Differently phrased, what does it mean to have a quality level of lightness, hue and saturation for a reflective display?

Lightness
Lightness is the perceived white or black level by the human eye. A high contrast in an image requests a large difference between the perceived white and black level in that image. Lightness is different from reflection. Lightness is related to human perception, reflection is related to the number of photons reflected from a surface.
The graph in fig 3 explains the relation.

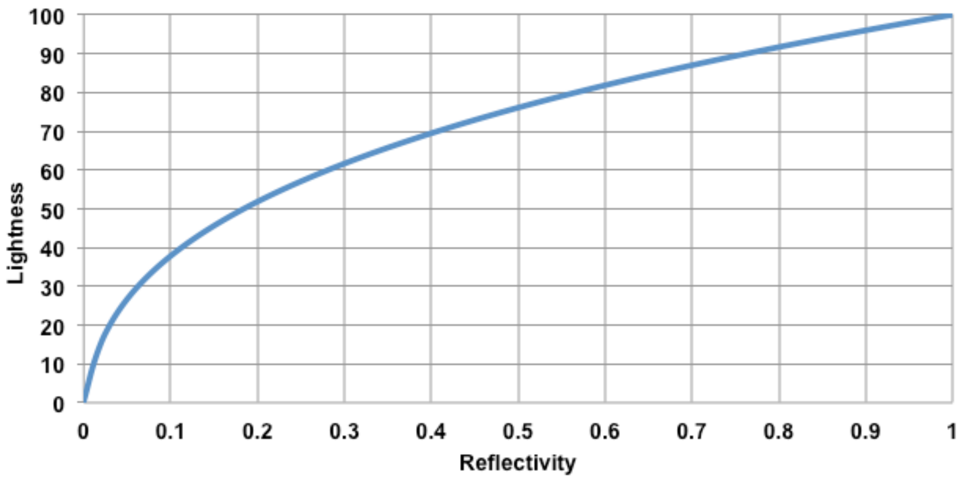

Fig 3: Relation between Lightness and Reflectivity

Two standards, SNAP and SWOP, specify when a reflecting surface can be referred to as "white". SNAP (specifications for newsprint advertising production) requires for white a Lightness of 80% and for black a Lightness of 36%, which correlates with a reflection of approximately 57% and 8% respectively, as can be seen in fig 3. [ref 10,11] Clearly any approach using polarizers that eliminate 50% of the light cannot fulfil the SNAP white requirements. In addition, below it is explained that any RGB approach cannot create the required white level. For reference, SWOP has even more stringent requirements than SNAP.

Color
In displays there are two principal approaches to create color: RGB and CMY. RGB is an additive approach. Pixels have Red, Green or Blue color filters, and a specific color is created by mixing a specific amount of light that passed through the specific color filters. CMY is a subtractive approach. Light is emitted through pixels which have each a Cyan, a Magenta and a Yellow filter. A specific color is created by tuning the filter of the C, M and Y to a specific level. Both approaches, RGB and CMY, can be used to generate any color in a reflective display. However, the perception of the quality of the specific color is much better when using of CMY.

Saturation
To create color with RGB is based on using color filters, pixels are set to white (reflect) or black (not reflect). If the pixel does reflect, the color filter determines the appropriate color. The red filter filters out the green and blue components of the light, the green filter filters out the red and blue components and the blue filter filters out

the red and green components of the light. Thus each color filter lets maximally 1/3 of the passing light through, which leads to a maximum total reflection of 1/3 of white light in an RGB system, as shown in Fig 4a.
Similarly, in the RGB approach every created color has a very low saturation. For example to make red, in the RGB approach the R pixel reflects light, but the other pixels have to be “off” or on black, which leads to only 1/3 of the available red light being reflected. This situation is shown in Fig 4b.

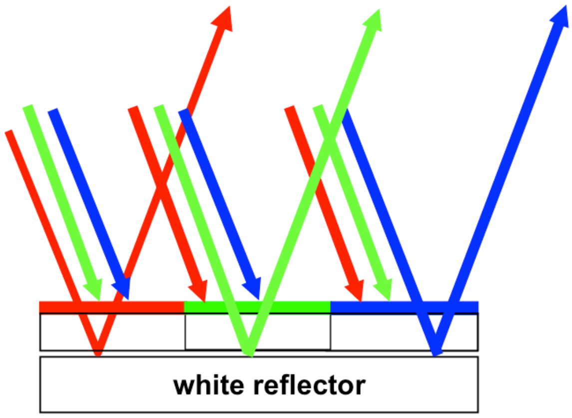

Fig 4a: Creation of white with Red, Green and Blue color filters. 1/3 of reflected light is transmitted.

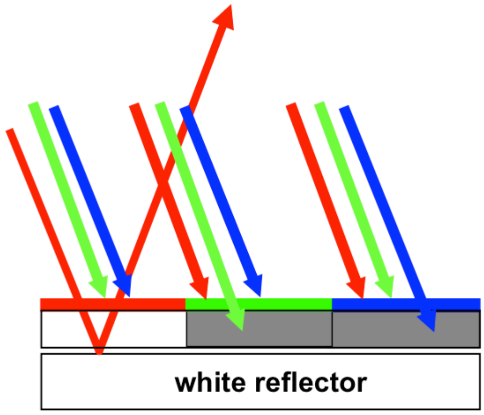

Fig 4b: Creation of red with Red, Green and Blue color filters. 1/3 of surface area reflects light.

Much better performance is realized with the CMY color approach, similarly to printing. In CMY the color selection is performed by three layers behind each other. Each specific color is created by reflection of the whole pixel surface. Thus the reflection from a surface with area 1 can get close to 100% by opening the cyan, magenta and yellow filter, as shown in Fig 5a. Highly saturated colors are achieved because the whole surface area reflects the appropriate component of the light. For example, Fig 5b shows creation of red, which is fully saturated because the complete incoming light is filtered over the whole area.

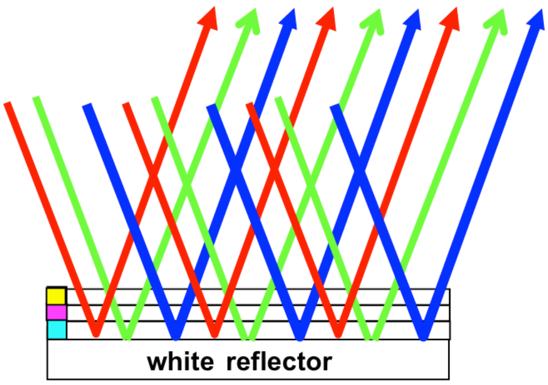

Fig 5a: Creation of white with Cyan, Magenta Yellow color filters. 100% of the reflected light is transmitted.

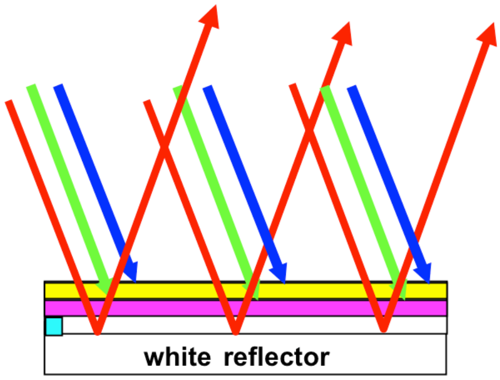

Fig 5b: Creation of red with Cyan, Magenta Yellow color filters. 100% of surface area reflects red light.

Electro-wetting displays

Electro-wetting displays have the capability to combine excellent contrast with highly saturated colors. A visualization of the electro-wetting effect is shown in Fig 6. In Fig 6a a droplet of water is shown on a hydrophobic surface, for example on a teflon surface, with an electrode placed into this water droplet. The water droplet tends not to wet the surface because of its hydrophobic characteristics. When a voltage difference is applied between the water droplet and a conducting surface below the hydrophobic layer, the water does wet the hydrophobic surface, as shown in Fig 6b. This wetting is caused by the fact that in presence of an electric field the total surface energy of the system can be lowered by creating a capacitor and storing energy in the capacitor.

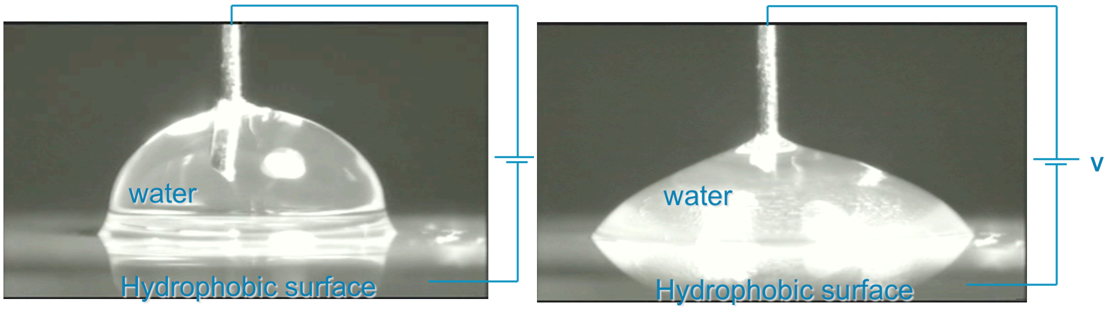

Fig 6: (a, left) A droplet of water on a hydrophobic surface does not wet the surface unless (b, right) a voltage is applied between the water and the electrode below the hydrophobic surface.

Etulipa makes use of this electro-wetting principle to build displays using its patented architecture: Sub millimeter area's, called electro-wetting cells, are created between two glass plates. Each glass plate has a conducting ITO layer and the electro-wetting cells are filled with a colorless electrolyte and a small amount of a colored oil. One of the ITO layers is covered with an electric barrier which has hydrophobic characteristics, as shown in Fig 7.

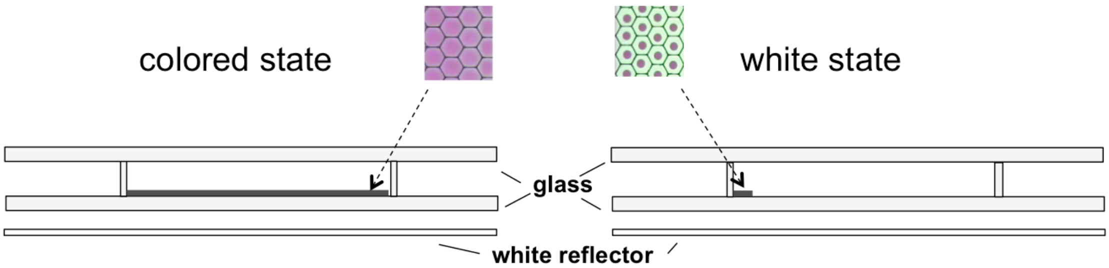

Fig 7: (a, left) A droplet of oil on a hydrophobic surface wets the surface unless (b, right) a voltage is applied between the electrolyte and the electrode below the hydrophobic surface, which results in the oil contracting into a little droplet.

The oil wets this hydrophobic surface, creating a colored layer, as shown in Fig 7a. In presence of an electric field the electrolyte wets the hydrophobic surface and consequently, the oil layer in each cell will change into a small droplet, indicated in Fig 7b. The viewer can now see through the system. When a white reflector is mounted behind the electro-wetting cells the ambient light reflects from this reflector and the observer sees a white surface. In Fig 8 an example of a section of a magenta display is shown in closed and open state. Either the colored layer absorbs the light, or the colored layer is broken up into little droplets, and the system becomes transparent. In this particular example the

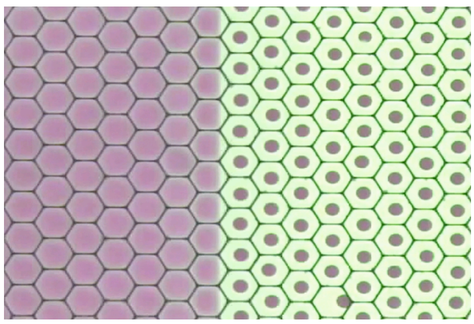

Fig 8: Electrowetting display partly in closed state (left) and partly in open state (right).

chosen color is magenta, but it could have been black, cyan, yellow or any other color. Fig 9 shows how a combination of three optically coupled electro-wetting cells can create any color. The full color space is created by switching the cyan, magenta and yellow filters to partly open using an electrical modulation approach.

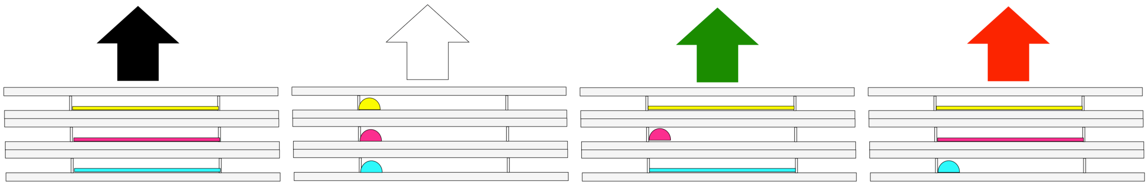

Fig 9. Three optically coupled electro-wetting-display bipanes can create any color. As example: From left to right all closed (all light aborbed) leads to black; all open (all light reflected) leads to white; magenta open and cyan and yellow closed leads to reflection of green; and cyan open and magenta and yellow closed, leads to reflection of red.

Etulipa has demonstrated very high reflectivity in the open state, and very low light reflection in the colored state, compatible with the SNAP requirements. In addition etulipa has demonstrated an excellent color gamut. Figure 10 shows a still from a movie [ref 12] where etulipa prototypes are shown in an outdoor environment. Striking are the contrast between the black and white and the high quality saturated colors.

Fig 10. Still [ref 12] demonstrating high contrast in the demo in the top right, and full saturated colors in the demo in the center under extreme sunny weather conditions.

Electrowetting and video speed
To enable high quality video messages it is required that the display technology has the intrinsic capability for high speed video. Etulipa standardly measures switch speeds as fast as 10ms, thereby enabling the possiblity for high speed video. Also others have shown video speed switching of electrowetting devices, as demonstrated for example by Liquavista in an interview with IEEE Spectrum [ref 13].

Additional requirements

I. Seamless displays

An out of home screen build up from individual displays naturally leads to a tiled approach, which generates seams between the tiles. It is clear that a digital image or advertisement on a display with a grating in front is not attractive. Etulipa has developed a patented front optics that creates the perception of a seamless display. Figure 11 shows two screens, one build up from individual tiles and below that a second screen build up from the same individual tiles, but including the patented seamless front optics. Both screens display the same image. Clearly the front optics create an image of one large seamless display, proving that etulipa's patented solution makes it possible to build high quality seamless reflective displays.

Fig 11: Demonstration of seams in a tiled screen (top) and etulipa's seamless solution using etulipa's patented front optics to hide the seams (bottom).

II. Operation in outdoor conditions

Most importantly for outdoor operation is performance over the varying conditions, like temperature, solar radiation, wind, water, dust, and vibrations. Etulipa uses Military Standard 810G [ref 14] as a reference for testing the predicted performance of its displays outdoors.

Most critical for outdoor operation of the electro-wetting display is performance at low temperature, high temperature and under extended solar radiation. MilStd 810G advises that almost all inhabitant area's of the world are covered when the outdoor temperature range is considered from all area's of the defined category C1 (Basic Cold) with a minimum of -31 ^{o}C to all area's of the defined category A1 (Hot Dry) with a maximum of +49 ^{o}C. However displays can become hotter due to induced heating from solar radiation - the MilStd 810G takes into account a possible additional 22 ^{o}C at high temperatures - and from heating from operating electronics. Reflective displays consume very little energy. Etulipa limits additional induced heating of the display to solar radiation only by optimizing the design of the driving electronics and the display cabinet.

Design for reliability requires making use of electrolytes and oils that do not freeze or boil in this temperature range. Etulipa has tested switching of its displays in above defined temperature range and have proven that electro-wetting display devices demonstrate excellent contrast, and fast switching at temperatures from below -20 ^{o}C to above +70 ^{o}C! This is an enormous step forward in comparison with reflective displays that make use of liquid crystal display (LCD) technologies or make use of diffusion in liquids, like electro-phoretics. Thereby electrowetting enables the possibility for world-wide introduction of outdoor reflective displays.

In addition, the displays have to be designed to withstand the solar radiation, being maximally 1120 Watt/m2, during its field life time without performance degradation.

Accelerated Life Time (ALT) testing allows understanding of the predicted failure rates of the product in the field. By understanding the failure rate of products as function of its life time the so-called bath tub curve can be deduced [ref 15]. The graph in Fig 12 shows three regions in such a bath tub curve:

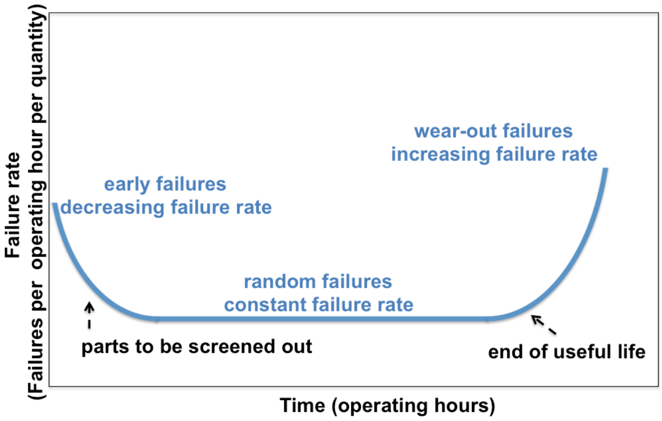

Fig 12. Typical behavior of failure rate as function of life time for a population of products.

1) zone of decreasing failure rates. The group of failures in this period is known as early failures. Adequate screening prevents products prone to such failures to be installed in the field.
2) zone of constant failure rate, also known as a period of random failures. In this zone failure rate is defined by its mean time between failure (MTBF). This parameter is defined as 1/(failure rate). Reliability testing gives adequate prediction of such failure rate, and thus prediction for the expected maintenance costs in the field.
3) zone of increasing failure rate, known as aging, in which failures by wear-out happen. The mean time to failure (MTTF) is the point where 50% of the population has failed its required specification. Obviously the display is removed from operation long before this period point in time. The reliability testing leads to prediction of the expected life time in the field.

Applications

The above described market has many market segments. Etulipa has identified as first target market the electronic changeable copy boards (eCCB's). Changeable copy boards are standardly used in the USA by retailers, and communities as churches and schools to advertise, or share information. A still from an etulipa movie [ref 15] showing such an eCCB is shown in Fig 13.

Fig 13: Still [ref 16] of a movie with an electronic version of a Changeable Copy Board (eCCB)

Etulipa has identified several other promising market segments like digital traffic signs, message centers, full color billboards and wallscaping for esthetic and dynamic camouflage purposes.

Summary

An owner of a DOOH display has two key financial parameters that determine its usefulness: revenues and costs.
Etulipa demonstrates that electro-wetting displays give an excellent proposition for out of home advertisement. Increase of revenues is realized by digitally creating attractive messages fitting the occasion and audience. Permits to surrect a reflective digital display can easily be obtained because of absence of light pollution. The electro-wetting display technology guarantees excellent contrast and saturated colors which implies high quality advertisement at any time of the day. The extremely low energy consumption guarantees low operational costs. In addition, etulipa's focus on quality and reliability leads to low maintenance costs and a long life time of the product. Etulipa has chosen to focus upon on-premise electronic changeable copy boards as first product to the market. The first product introduction of the etulipa Carbon enables business owners in residential area's, to easily get permits for placing such a digital display, and operate it with extremely low energy consumption. In fact, it can be run off-grid using a battery or solar-energy based power supply.

References

1. *"Advertising's Century of Flat-Line Growth"*, E. Chemi, Bloomberg Businessweek Data DB5 Research, 2014.
2. 2015 Reference Document, JCDecaux.
3. 2014 Reference Document, JCDecaux.
4. *"Digital Billboards, Diversions Drivers Can't Escape"*, The New York Times, M. Richtel, March 1, 2010
5. *"Town's ban on electronic billboards ruled unconstitutional*", D. Hutchinson, NJ.com 2016.
6. http://www.usgbc.org/leed
7. *"Review Paper: A critical review of the present and future prospects for electronic paper"* J. Heikenfeld, P.Drzaic, J. Yeo, and T. Koch, J. Soc. Inf. Display, **19**(2), 129-156 (2011).
8. *"The fundamentals of Color: Hue, Saturation, And Lightness",* vanseo design, S. Bradley May 20, 013.
9. https://en.wikipedia.org/wiki/Munsell_color_system
10. SNAP2009, Specifications for Newsprint Advertising Production August 2009.
11. *"Low Power Reflective Display with Print-Like Color via Novel Electronic Inks*", Z-L Zhou, J-S Yeo, Q Liu, M Parent, J Yang, B Benson, G Combs, J Mabeck, S Lam, Y Jeon, D Henze, T Koch, HP Laboratories, Tech report HPL-2011-67.
12. Etulipa youtube channel: https://www.youtube.com/watch?v=D1mHKvGiPE4
13.*"The Electrowetting display",* Glenn Zorpette, IEEE Spectrum https://www.youtube.com/watch?v=Bf1GjCaYzYg
14. Mil. Std. 810G, Department of Defense Test Method Standard, Environmental Engineering Considerations and Laboratory Tests, 31 October 2008.
15. *"The Bathtub Curve and Product Failure Behavior"* D.J. Wilkons, Reliasoft.
16. Etulipa website: https://www.etulipa.com/first-application.html