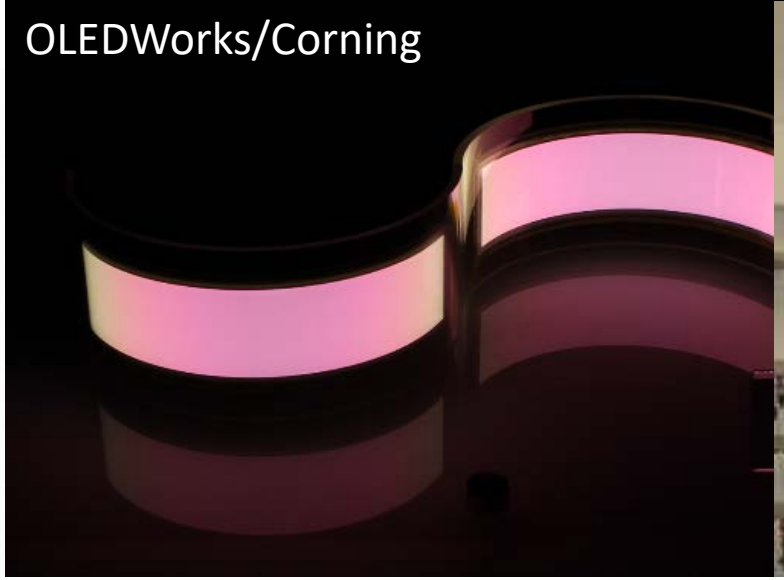
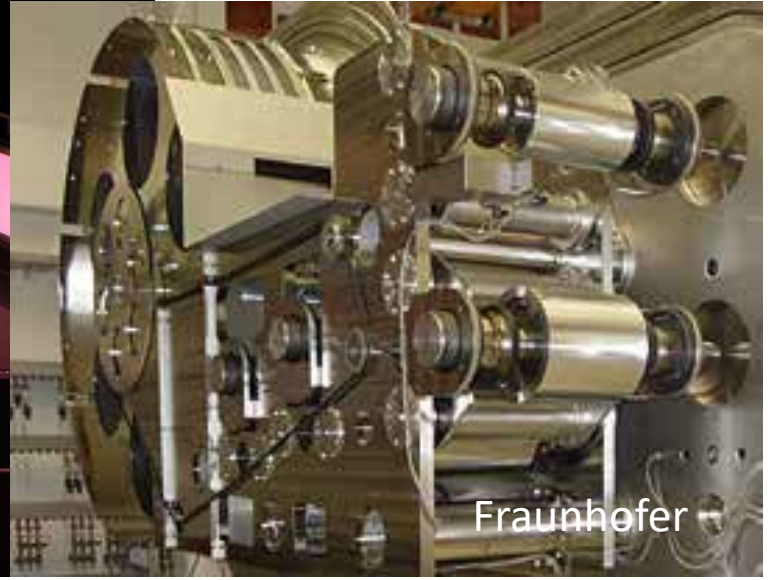




Progress and Manufacturing Challenges in OLED Lighting

Michael Boroson CTO

OLEDWorks LLC

Outline

- Progress
  - Our Vision
  - Performance (Today and Future)
  - Pricing and Volume (Today and Future)
- Manufacturing Challenges
  - Cost vs. Volume
  - Grow Demand
  - Lower Cost
- Summary

Our Vision

- Jump ahead 10 years, and we believe that we will find only Solid State Lighting being installed; shared between LED and OLED

- The lighting applications where OLED will be the favored will be:
  1. Applications that are close to the user
     - Low glare, low temperature, broad spectrum – e.g. office above
  2. Applications using the unique form factor of OLEDs:
     - Thin and light weight – for example transportation
     - With special design elements – for example curved lights – our buying decisions are strongly affected by design

Performance: OLED Panels Today

From 2016 DOE SSL R&D Plan

Today's panel performance:

- >20klm/m^2
- Efficacy of >60 lm/W
- LT70 >50k hours
- CRI > 90
- R9 > 50

These panels deliver the performance needed for many current applications

Limited Availability

New!

Table 6.1 Components of OLED Panel Efficacy

Source	LG	LG	OLEDWorks	OLEDWorks
Product	LL055RS1-62P1[1]	LL055RS1-92P1[1]	Brite 1[2]	Brite 2
Illuminance (lm/m^2)	7,700	7,700	20,700	20,700
LER (lm/W)	328	328	336	302
Electrical Efficiency (%)	80	80	73	70
Internal Quantum Efficiency (%)	65	65	62	62
Extraction Efficiency	35%	52%	31%	47%
Panel Efficiency (%)	18	27	14	21
Panel Efficacy (lm/W)	60	90	46	62
CCT (K)	2700	2700	2900	2956
CRI (R_a)	>87	>87	80	93
CRI (R_9)				76
Lifetime (L_{70}) (hrs)	40,000	40,000	>50,000	>50,000

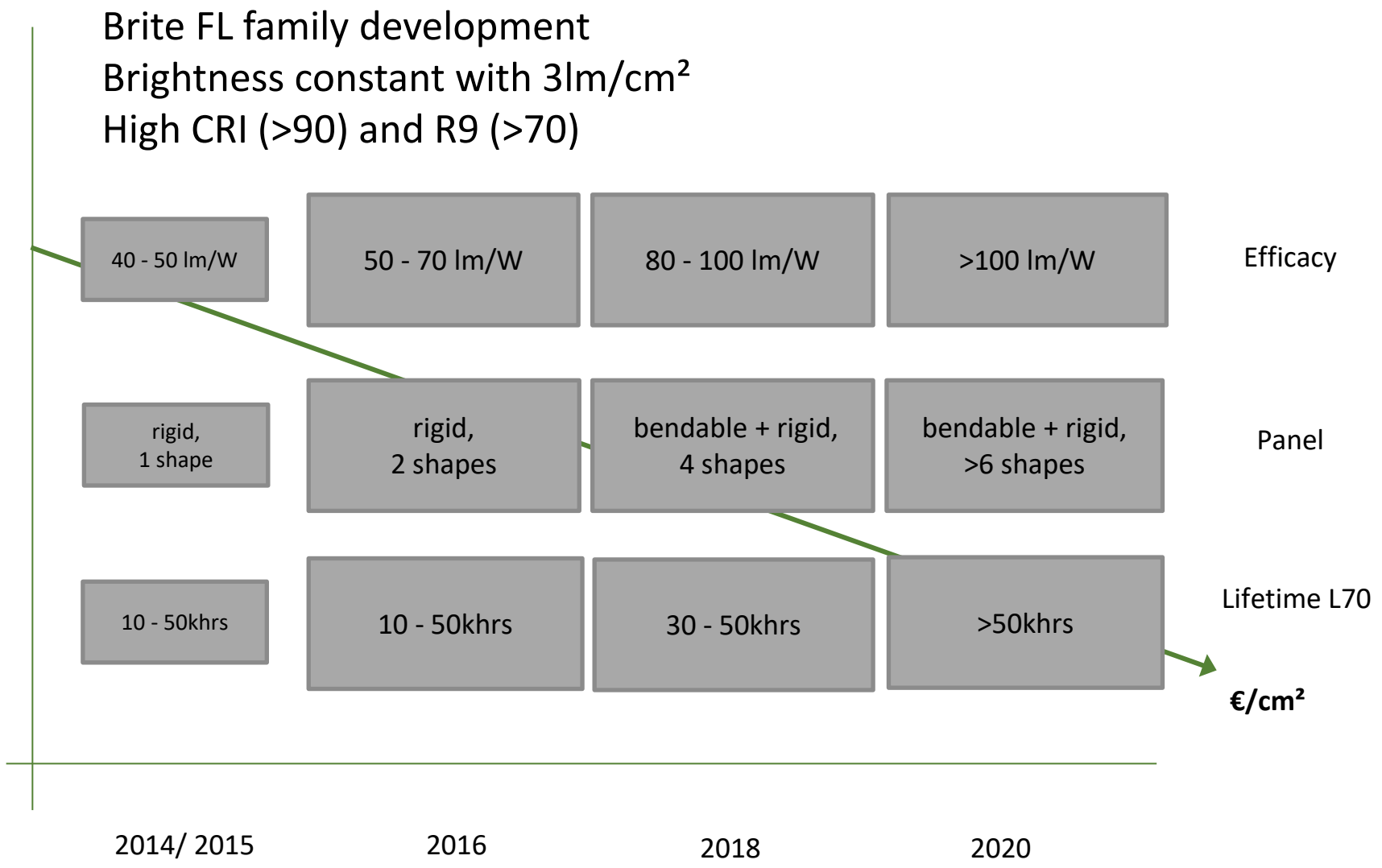
Note: All data provided in communications with represented company.

1. A hybrid triple stack with fluorescent blue emitters and phosphorescent red and green; 2700K
2. A hybrid 6-stage stack with fluorescent blue emitters and phosphorescent red and green; 2700K A double stack with all phosphorescent emitters **[111]**

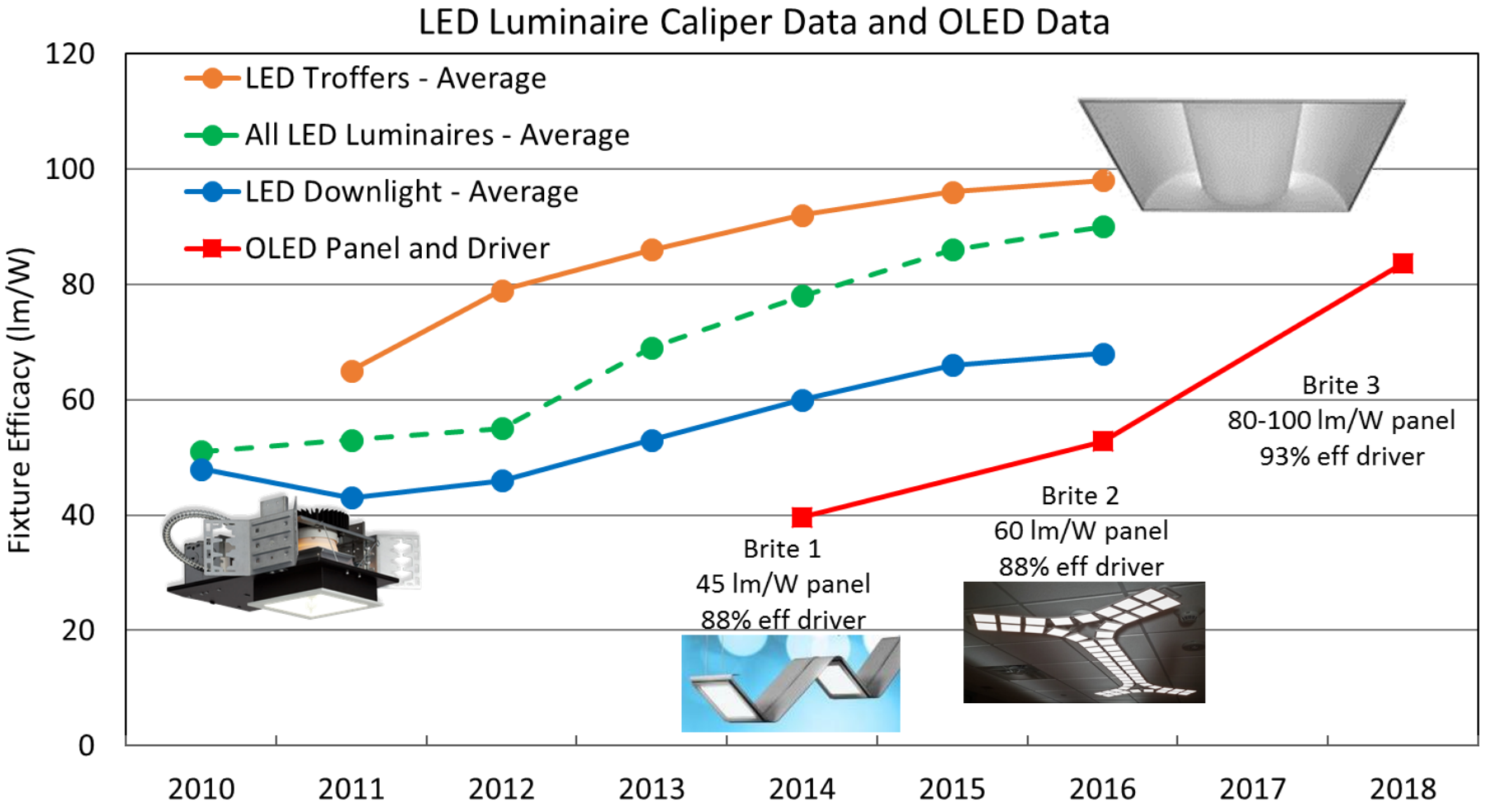
DOE SSL R&D Plan, June 2016, pg 102
Illuminances corrected for total panel area
Efficacy and Lifetime (L70) is quoted for 3000 cd/m2

Performance: Panel Roadmap

OLEDWorks Brite 3 with 80-100 lm/W – for release in early 2018



Performance: Luminaire Efficacy Progress



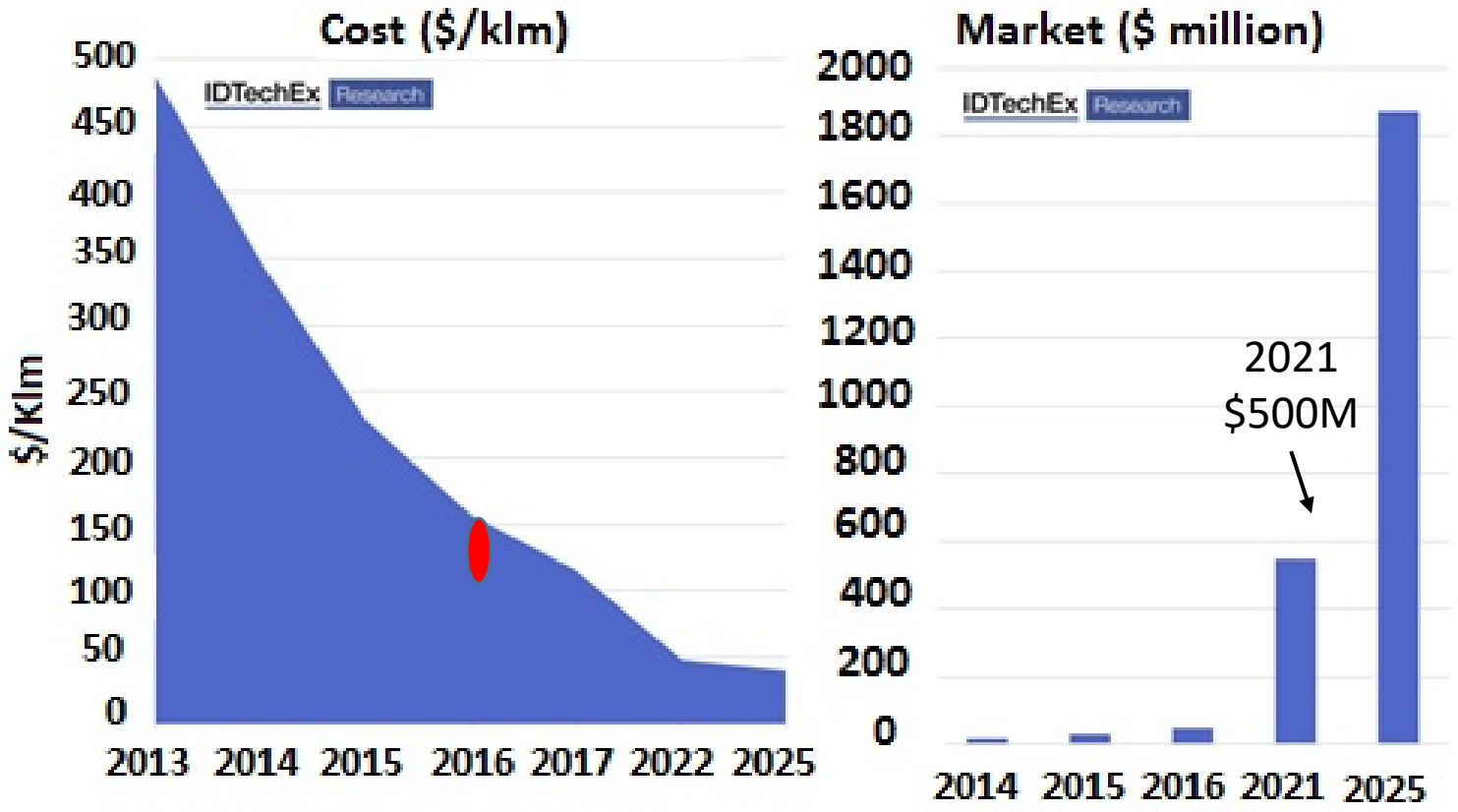
LED data from the DOE EERE CALiPER Snapshot report in April 2016.

These LED data represent the averages in the Lighting Facts Database and contain data on fixtures available in the market.

The OLED line shows OLEDWorks sequence of product offerings.

OLED-LED fixture efficacy gap is shrinking

Performance: Panel Prices and Volumes

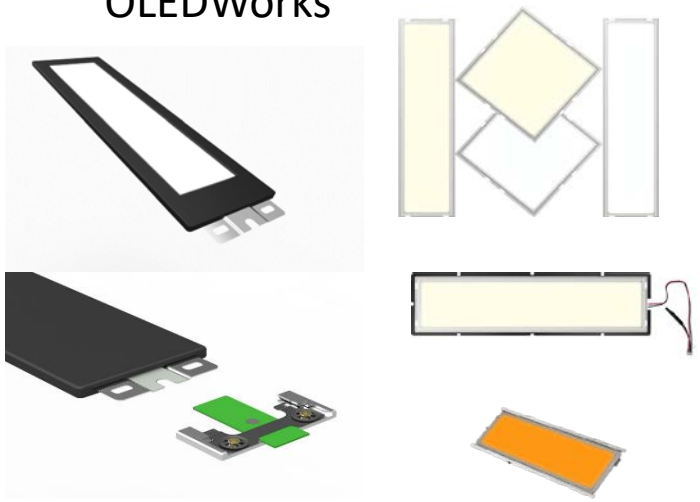


OLED panel prices and market - IDTechEx predictions in 2013, unchanged in 2016

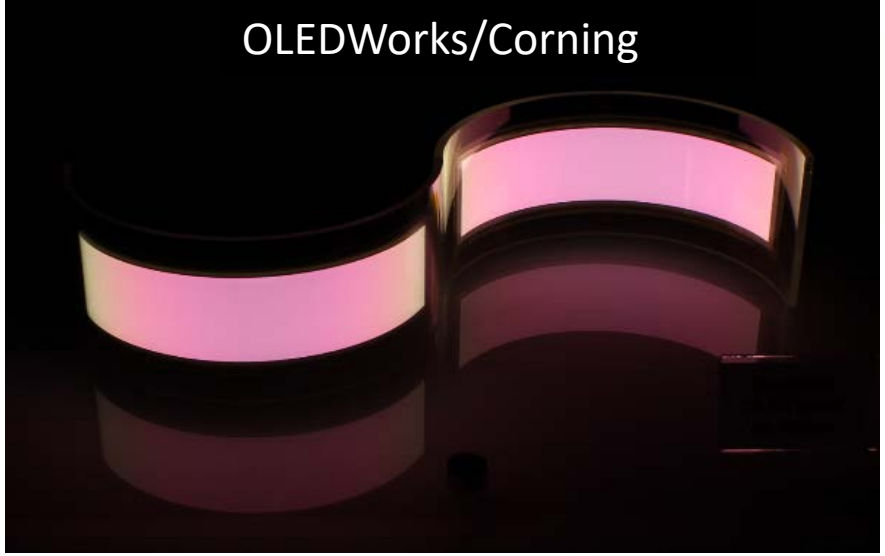
Panel prices – the industry is ahead of the curve as shown by red ellipse.

From "OLED Lighting Opportunities 2016-2026: Forecasts, Technologies, Players", April 2016
http://www.idtechex.com/research/reports/oled-lighting-opportunities-2016-2026-forecasts-technologies-players-000472.asp

OLEDWorks

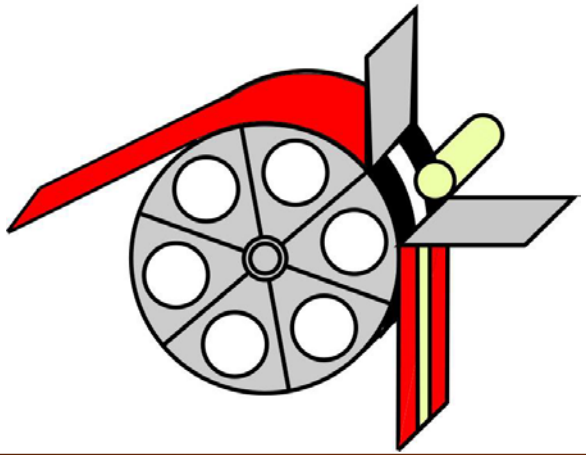


OLEDWorks/Corning

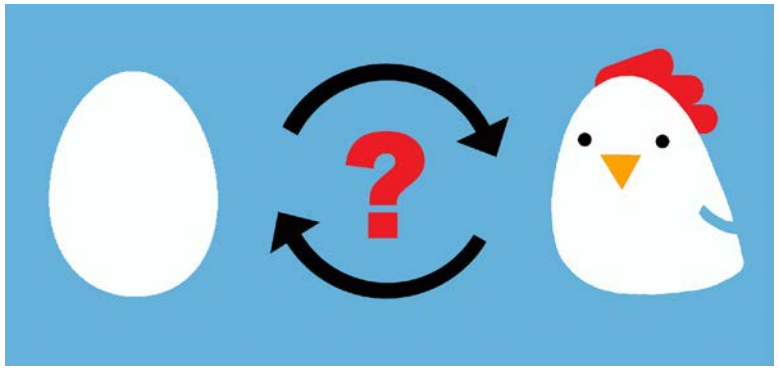


Konica Minolta

Manufacturing Challenges



Cost vs. Volume: Problem

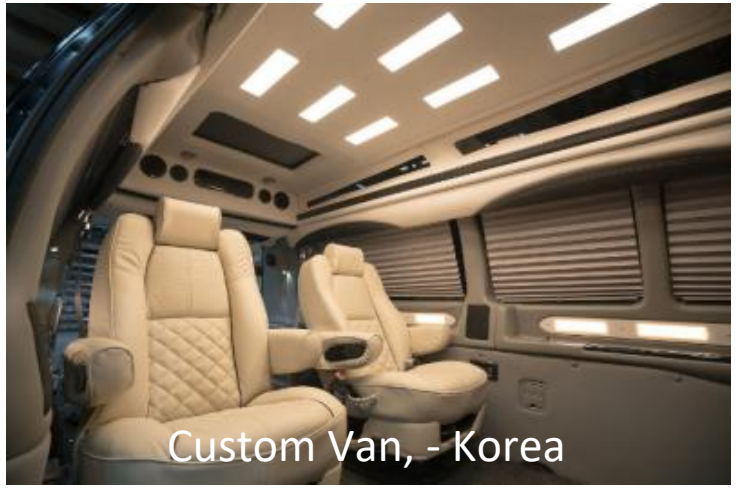


- We need to build a high capacity machine to be cost-attractive for general lighting for high volume
- However, we need to build sales volume to enable investment in a high capacity machine in US
  - For example – the initial capacity of LG G5 machine is about 10M panels/year post yield
    - (1.0mx1.2m, 15k sheets/mo, 80% yield, 60 panels/m2)
  - This is more than 100x current demand

➢We need to grow demand

Grow Demand:
Customers who want something special

- Restaurants, hotels, retail stores, offices, …
  - Look special or offer a special experience.
- Partner to design and build OLED fixtures to meet their needs.
- Build awareness and generate interest in short term.
- Other luminaire makers will follow when the leaders establish the path and vision.


Custom Van, - Korea


Sheraton Grand Walkerhill, Korea

Grow Demand: DKB Offices – DOE Gateway

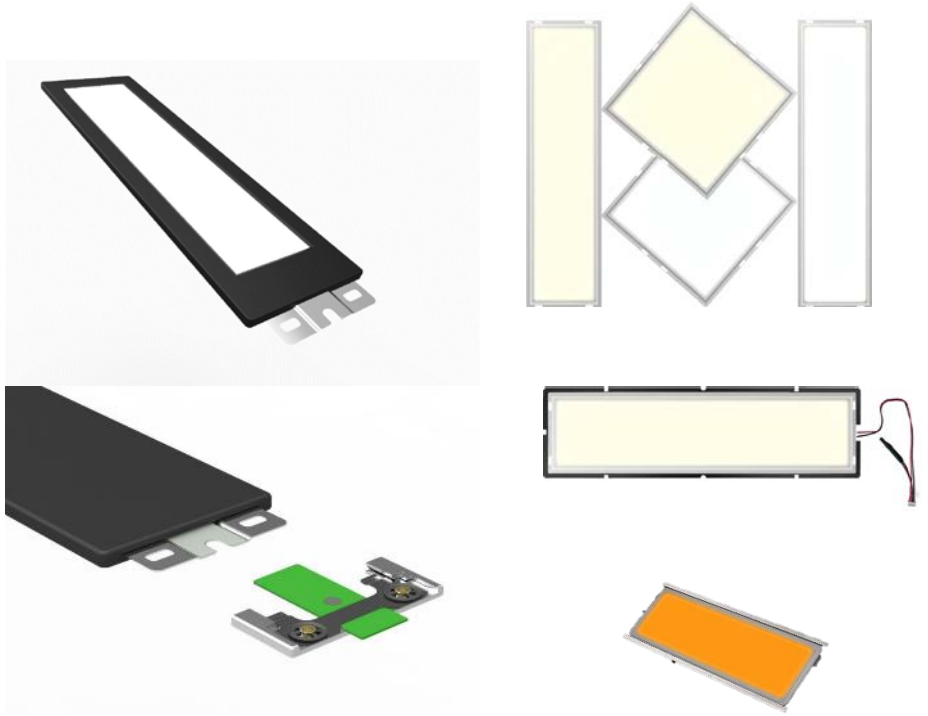
Grow Demand: Panel Variety and Integration Level

Panels: Size, Shape, Color Temperature & Color

Integration Level: Panels, Drivers, Connectors, Light Engines

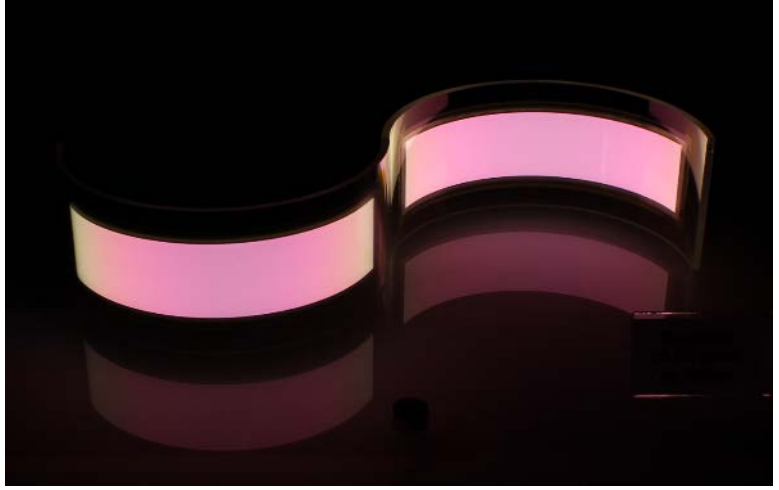
LG Display

OLEDWorks



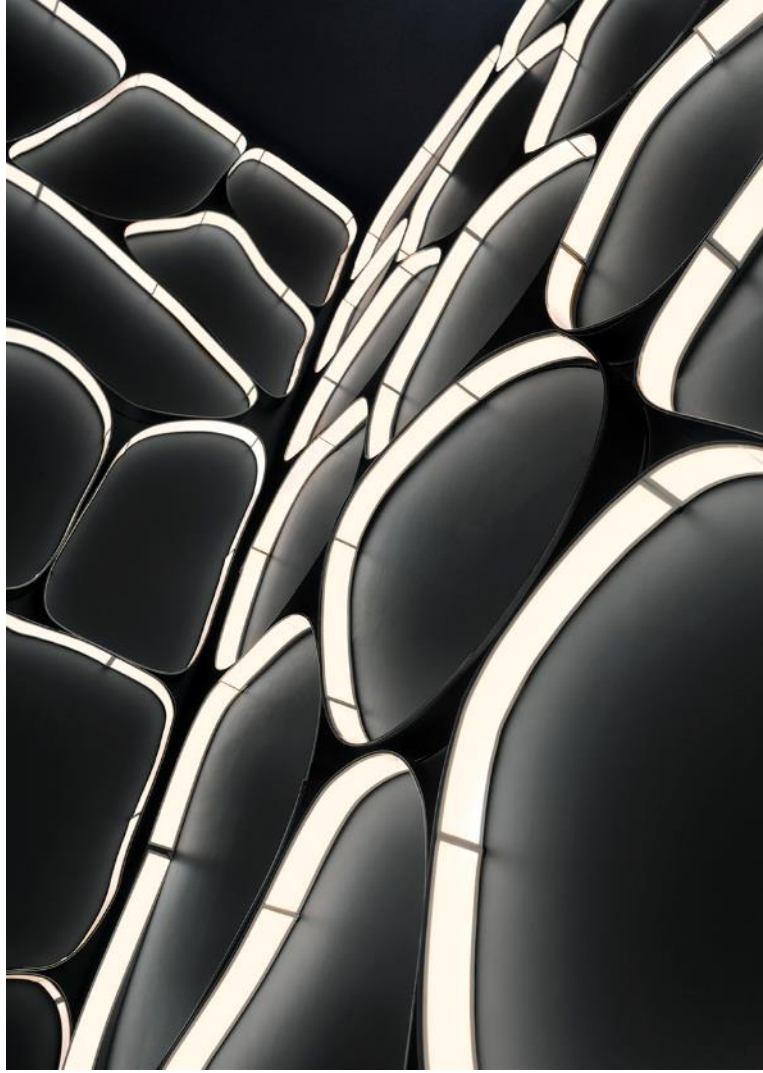
Grow Demand: Bendable, Flexible, Thinner, and Lighter Weight

Glass and Plastic



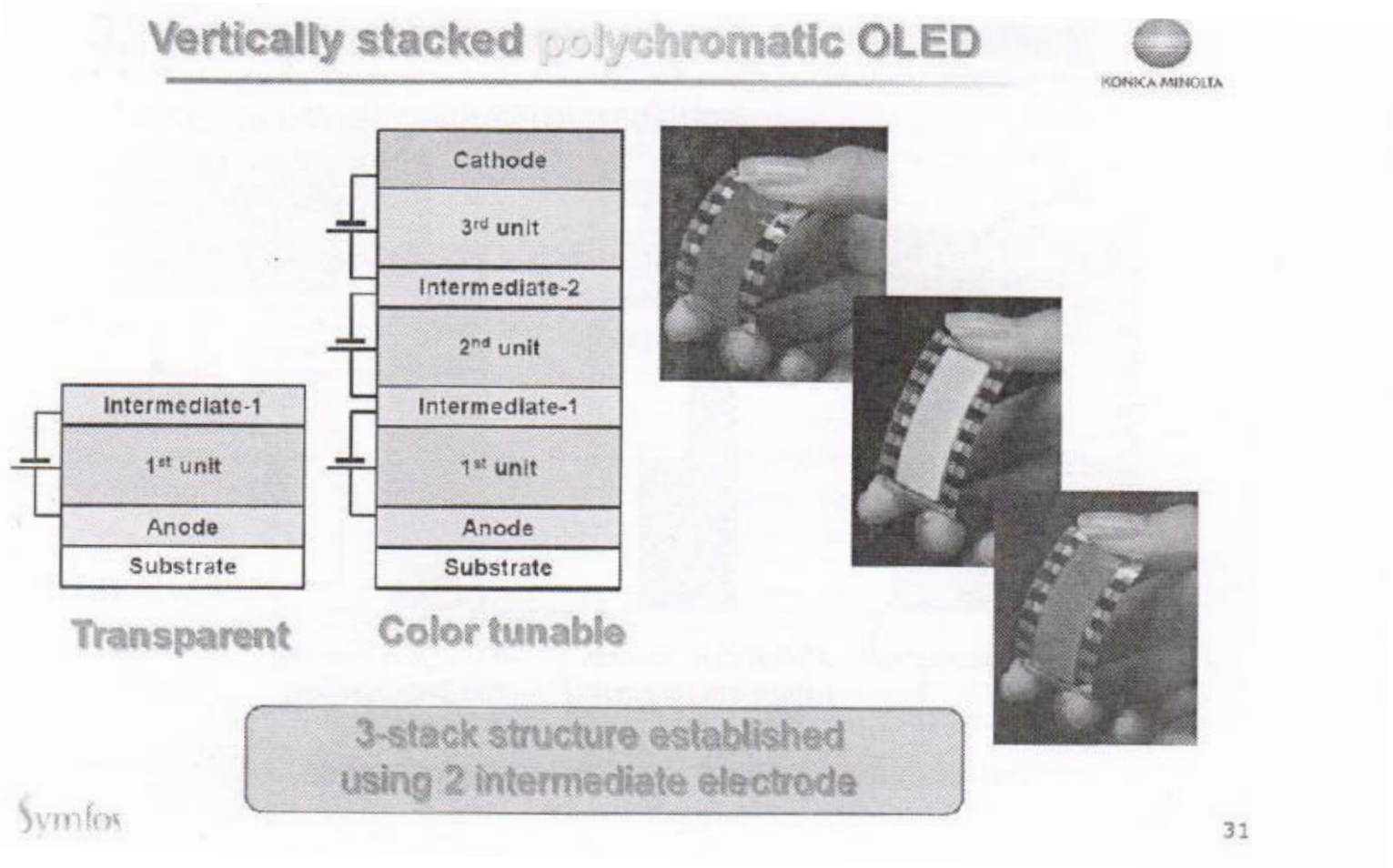
OLEDWorks

LG Display



Blackbody

Grow Demand: Color Changing & CCT Changing



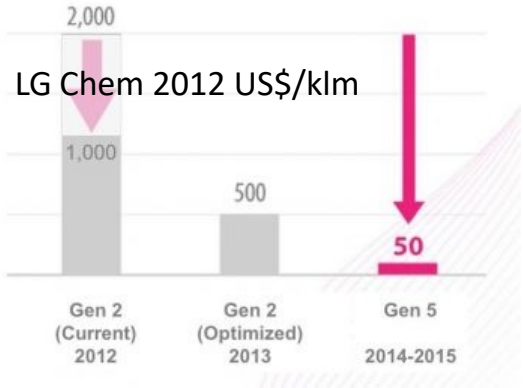
M. Nagato, Konica Minolta 6th Annual China International OLEDs Summit, 2017

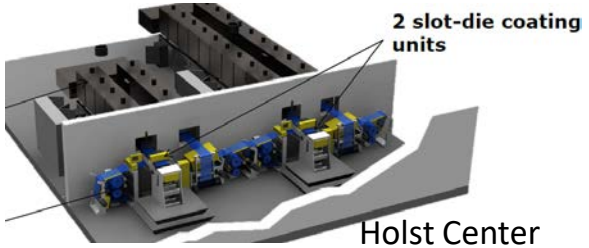
Lower Cost: 2 Steps

- The next step in cost-down will be G5 sheet-cut machines (LG is building this machine now)
  - On-line in Asia in 2017, North America in 201x?
- The step after this will be R2R processing for further cost down
  - Corning estimated R2R processing will reduce the cost of OLED lighting by 30%
  - This make more sense then going to G8 – diverging from the display model.

Lower Cost: Current Programs in Asia and Europe

- LGD announces G5 production line ($185M)
  - Previously predicted to give 10x cost down.
- Pi-Scale Project in Europe for R2R with 14 partners (~$16M gov't funding)
- ITRI in Taiwan working on OLED lighting with R2R
- GJM of Korea develops R2R OLED equipment
- Konica Minolta – starting their G5 R2R machine (capacity of 1 million panels/month)





Holst Center


GJM of Korea – R2R OLED equipment

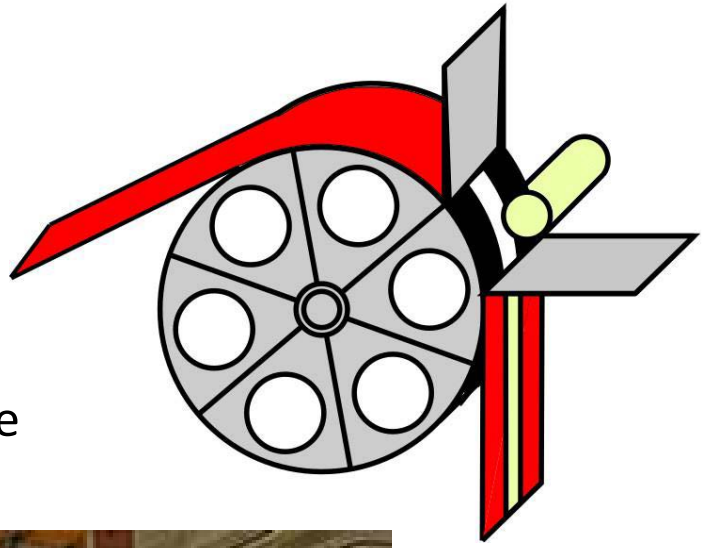
Lower Cost: Match Production to Product Demand

High capacity machine (sheet to sheet or R2R) needs to:

1. Make wide variety of color temperatures and colors (fast chemical change, rate stabilization and calibration)
2. Make wide variety of shapes and sizes (fast product change – substrates, masks)
3. Make flexible/bendable panels (handling and transport for R2R, roll up product without particles and damage, minimize contacting that generates particles, masking)
4. Make color changing panels (masking, transparent intermediate electrodes with good conductivity)

Now is the time to start working on developing and commercializing the technologies that will be required to lower cost and grow demand!

Lower Cost: Example Technology Need

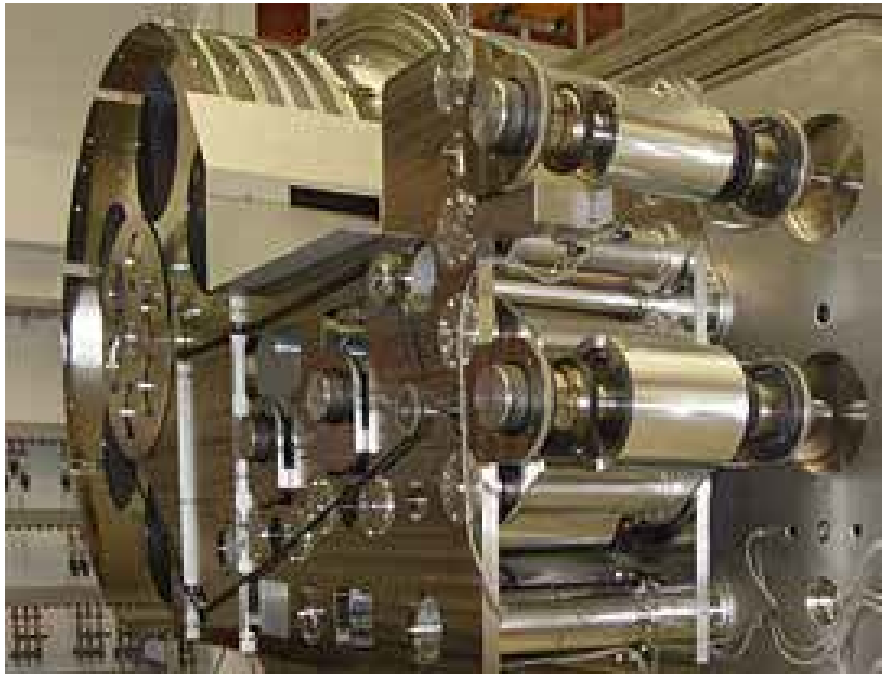


FHR
Von Ardenne

R2R Masking:

- Stationary masks held in very close proximity to the substrate - Fraunhofer
  - Difficult to adjust from one size to another
  - Does not mask deposition in the transverse areas.

Need a better masking method for R2R



Summary

- Solid State Lighting is the future and OLED will be a significant part
- OLED performance is good and improving rapidly
- Performance gap with LED is shrinking
- Price is dropping and volume is growing
- Grow demand with panel and integration level variety, flexible and bendable panels and color changing panels
- Lower cost with high capacity machines
- Keep pace with Asia and Europe by funding projects that enable lower cost production methods that match product demand