LEDs in Horticulture

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ISA-BRICS Solid State Lighting Collaboration Working Group
Hangzhou, China
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ISA International SSL Alliance

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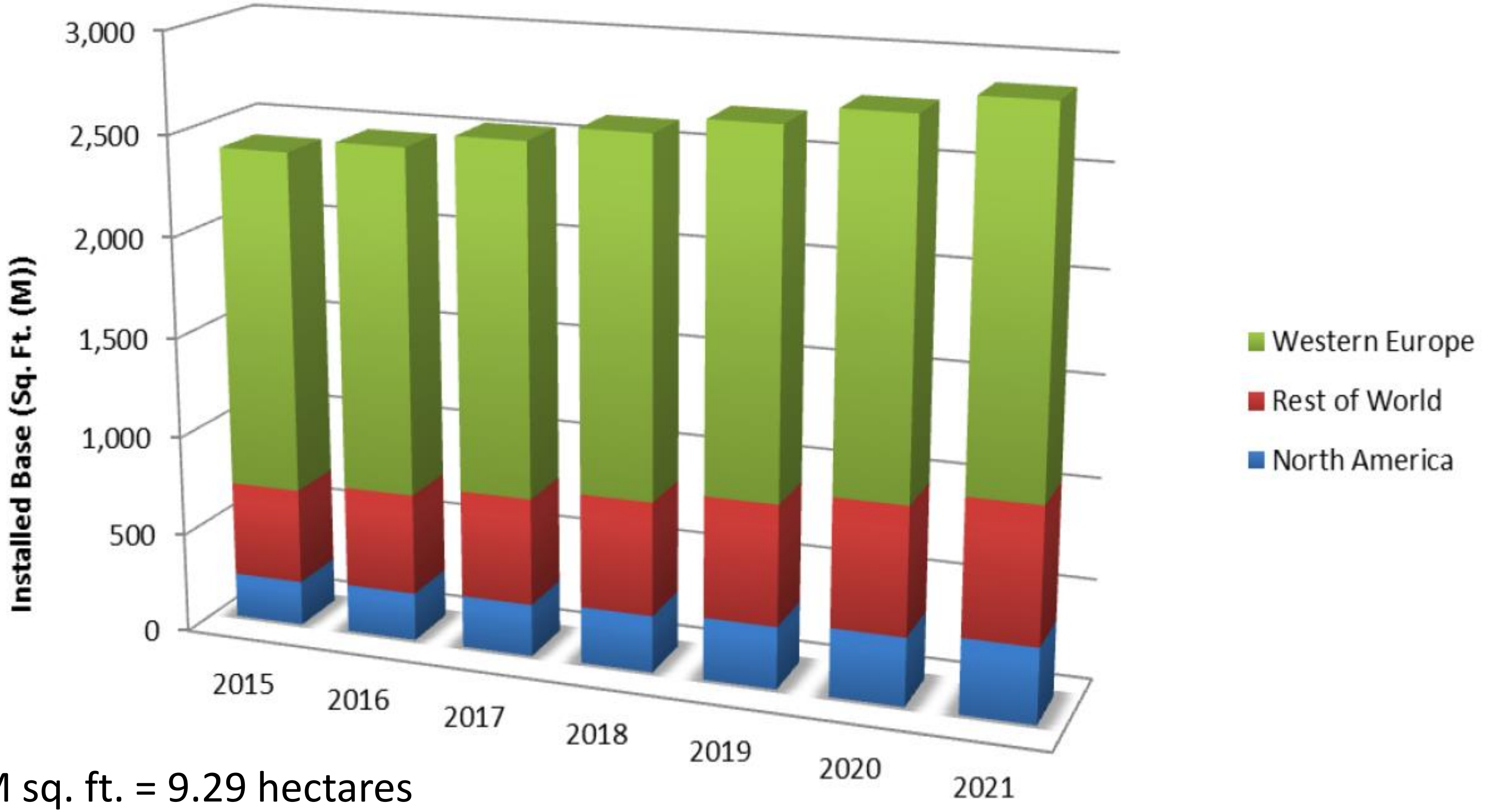
Outline of Presentation

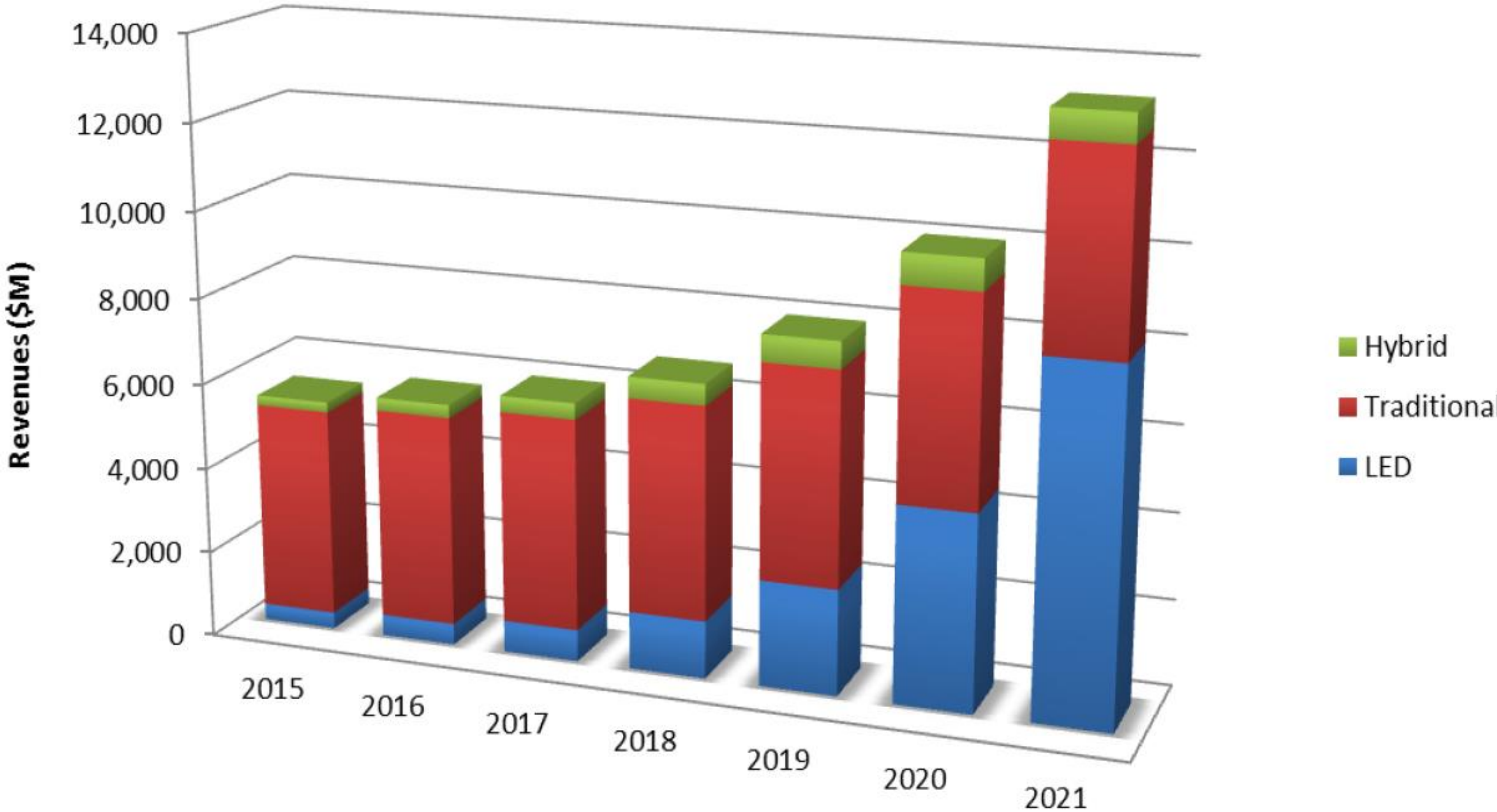
- Potential Market
  - Supplemental light in greenhouses
  - Factory farming in cities
- Economic Analyses
  - Value of light
  - LED vs HPS
- Spectral Tuning
- System Studies
- Conclusions

Square Feet of Illuminated Greenhouses (Installed Base) By Region

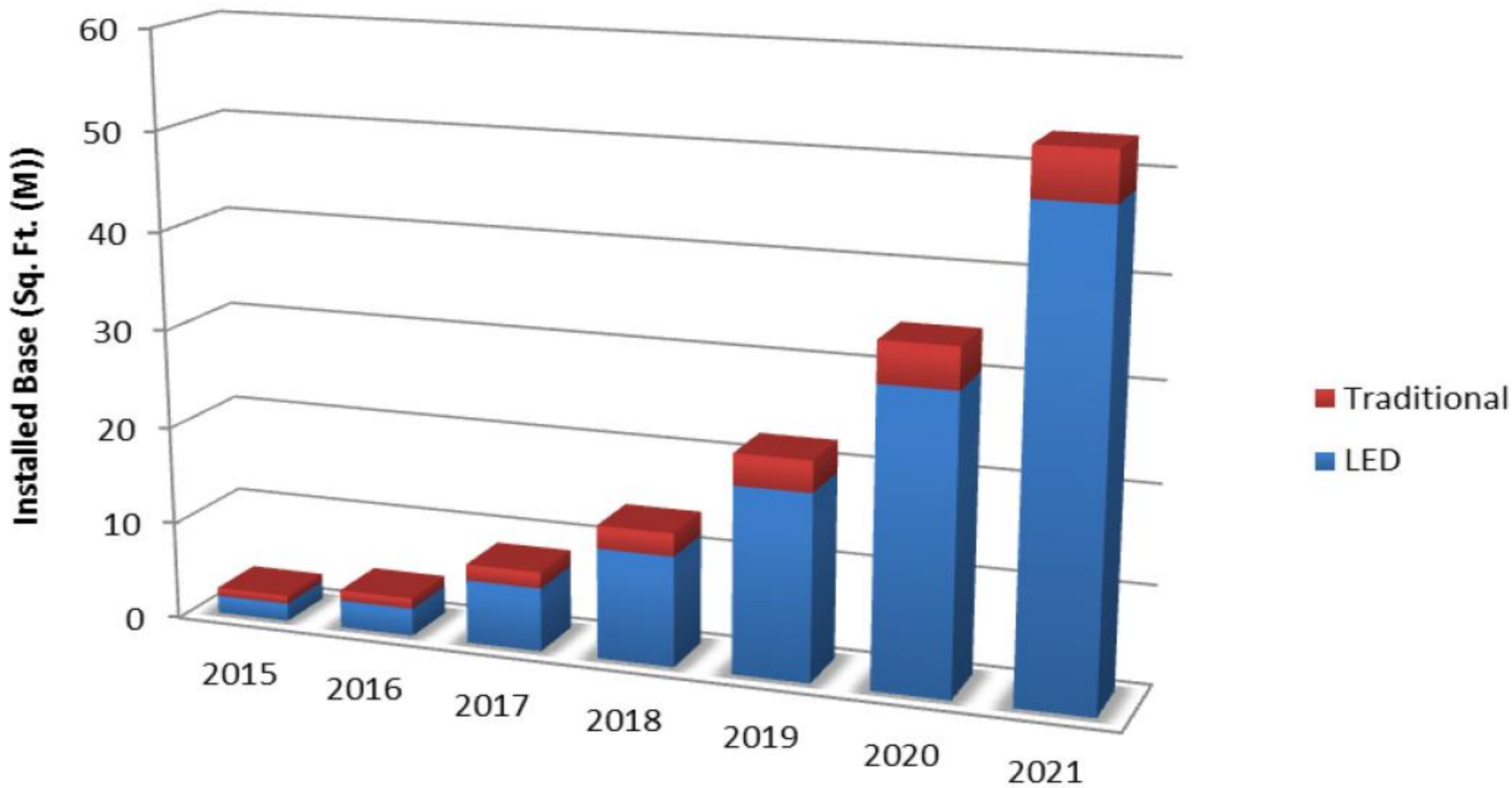


1M sq. ft. = 9.29 hectares

Global Greenhouse Supplemental Lighting Market

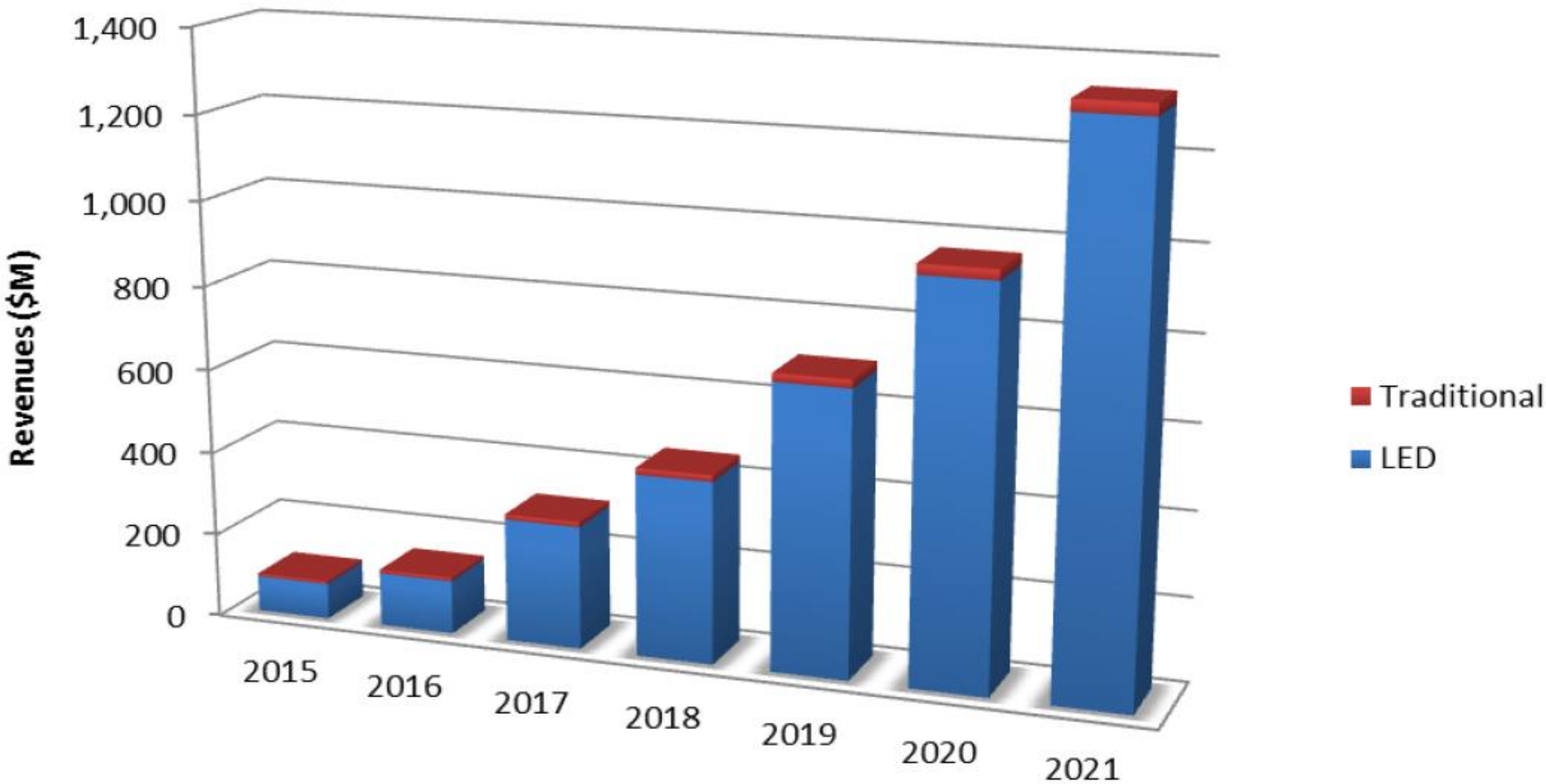


Global Vertical Farm Square Ft. of Growing Area



1M sq. ft. = 9.29 hectares

Vertical Farms Lighting Revenue



Check of Potential Market Size

- Area of illuminated greenhouses in North America = 25M m^2
- Average light required for growing vegetables = 400 µmoles/m^2/s
- Lamp efficiency = 2 µmoles/J
- Lamp power required = 200 W/m^2
- Total lamp power required in North America is 5000 MW
- With an average life of 5 years, annual sales should provide 1000MW
- Assuming a lamp cost of $1/W, the annual market is $1B
- The global market size might then be $5B

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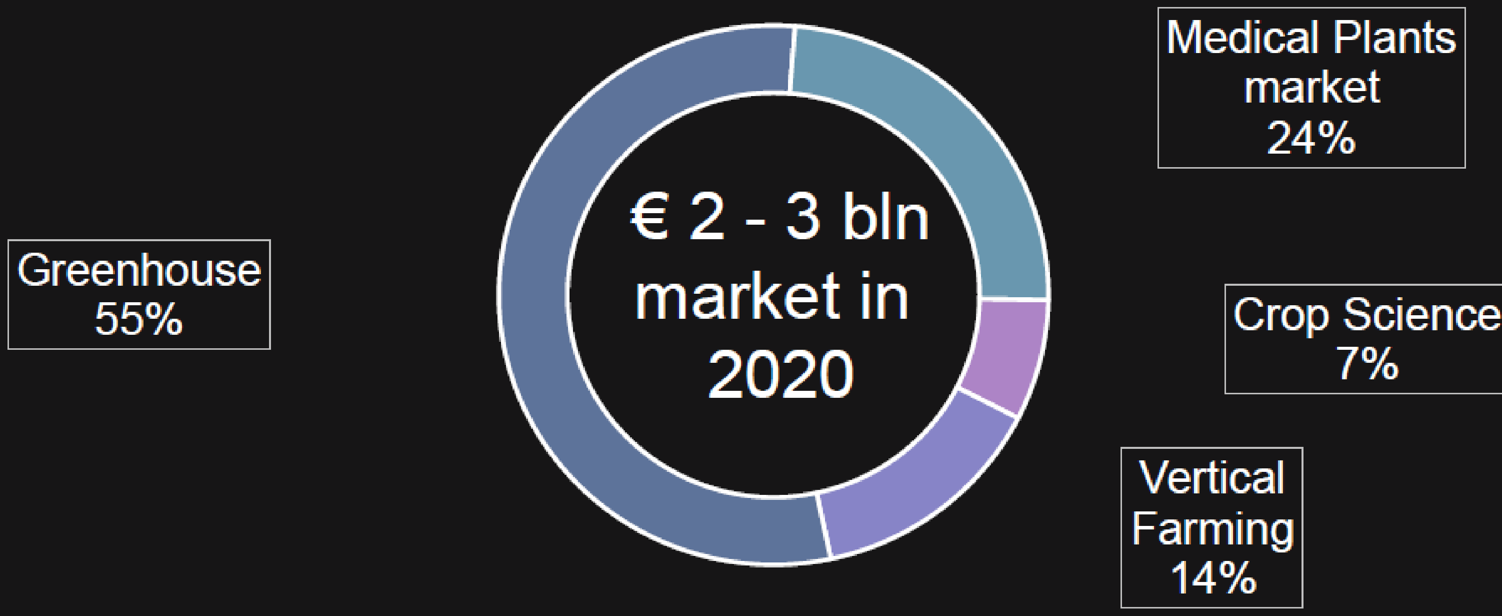
Global Market Estimate from Europe



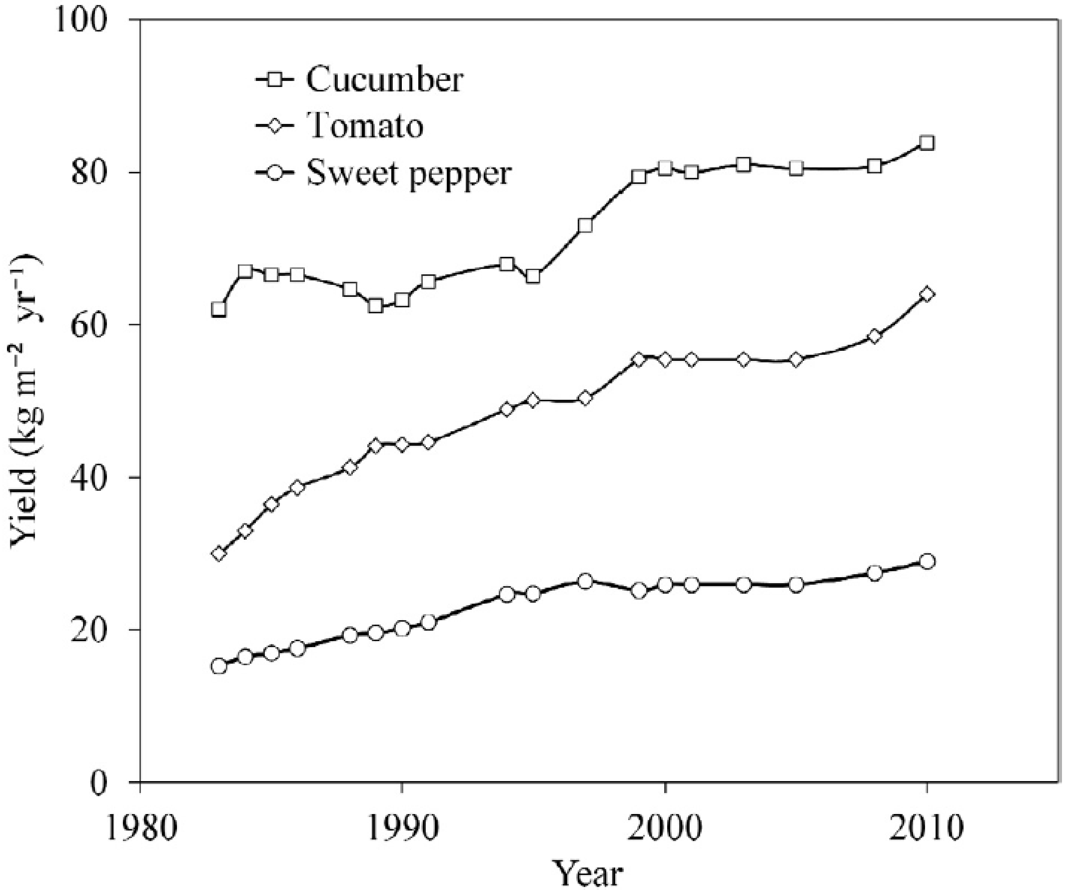
Customer segment by illumination type

	Supplementary	Sole source
Greenhouse	X	-
Vertical Farming	-	X
Crop Science	X	X
Medical Plants	(x)	X

Source: MarketsandMarkets (with a haricut) + Valoya estimates

Greenhouse Productivity in the Netherlands

Source: A De Gelder at al, Wageningen University
Neil Mattson, Cornell University



Yields in Production (kg/m^2)

Lettuce	**110**
Cucumber	**80**
Tomato	**60**
Pepper	**30**

Greenhouse Production in Canada in 2016

Source: Statistics Canada: CANSIM Table 001-0006

Crop	Area	Production		Sales	
	Hectares	M kg	kg/m²	US $M	$/m²
Tomato	598	276	46	420	70
Pepper	519	136	26	324	62
Cucumber	396	178	45	258	65
Lettuce	17.5	12.2	70	21.7	124
Total	1530	602	39	1024	67

Indoor Farming in US

In the US there is relatively little indoor farming now,
but interest is growing rapidly
See Agrilyst report:
http://stateofindoorfarming.agrilyst.com/stateofindoorfarming-report-2016.pdf

Area: 2.4M m^2

Revenues: ~ $1B

~ 5X Growth
over next 5 years

Types of Facilities

Aeroponic Greenhouse
translucent, climate controllable structure where plant roots are suspended in the air and misted with a nutrient solution

Aquaponic Greenhouse
translucent, climate controllable structure where plants are grown in water that has been used to cultivate aquatic organisms (typically, fish)

Container Farm
standardized, self-contained growing unit that employs vertical farming systems and artificial lighting.

Hydroponic Greenhouse
translucent, climate controllable structure where plants are grown in water as opposed to soil

Indoor Vertical Farm
fully enclosed and opaque room with a vertical hydroponic, aeroponic, and/or aquaponic system. Artificial lights are used.

Soil-based Greenhouse
translucent, climate controllable structure where plants are grown in soil

In Home Systems
small standardized growing unit for use by consumers in home settings.

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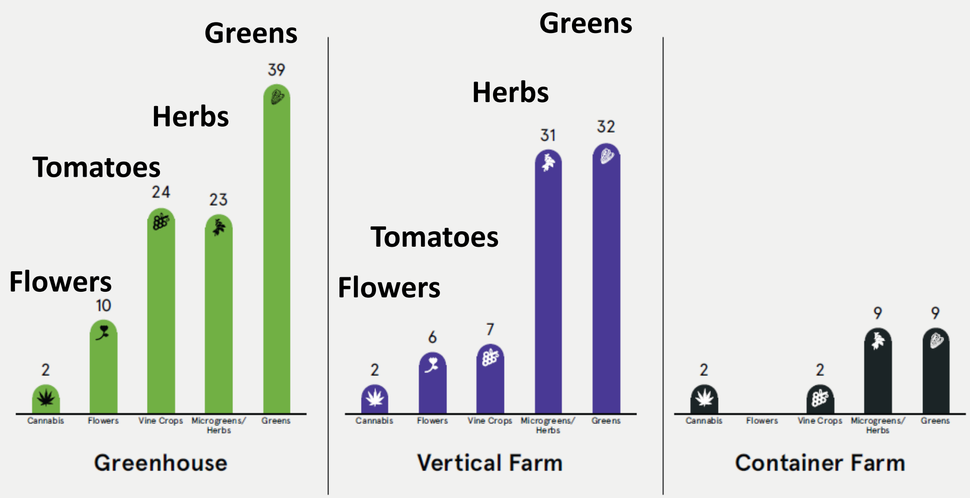
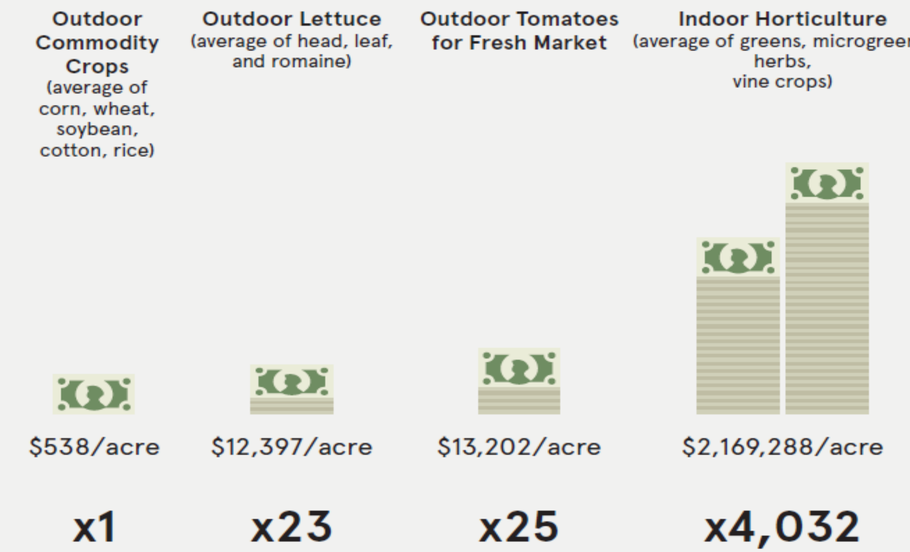
Data from Agrilyst Report

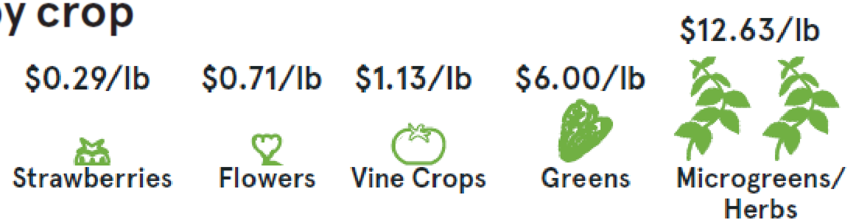
Crops grown by facility



Farm productivity

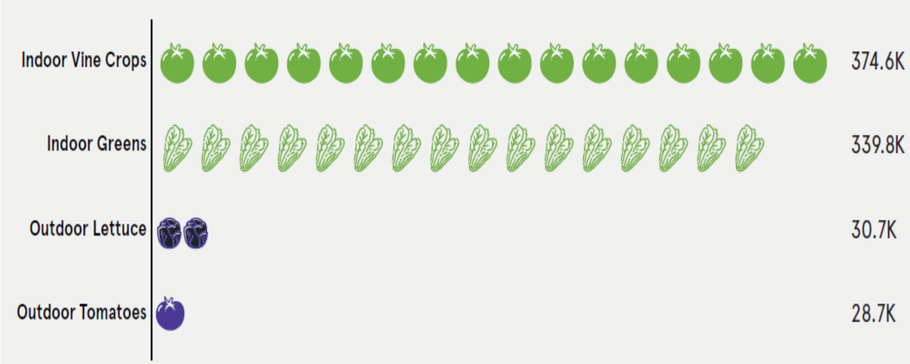


Annual reported revenue by crop



Annual production capacity of indoor crops vs. outdoor crops

Avg. lb/acre/year



Many sales are direct to end customer

agrilyst

1 kg = 2.2 lb
1 hectare = 2.47 acre

Greenhouse Production in US in 2015

Data from US Department of Agriculture

https://www.agcensus.usda.gov/

Crop	Area	Annual Sales	
	Hectares	$M	$/m2
Tomato	396	401	101
Herbs	129	71	55
Cucumber	102	78	76
Lettuce	40	56	140
Others	201	191	95
Total	868	797	92

The Situation in China is Very Different

- Much larger area of protected agriculture
  - Growing from 0.8M hectares in 2015 to 1.5M hectares in 2020
- Plastic sheets more common than glass
- Heating is more important
- Lamps may be less expensive
- Is there reliable data on market size?

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Economics of Horticultural Lighting

- Light measure: 1 µmol implies 6 x 10^{17} photons
- Lamp output is often expressed in 1 µmol/s (second)
- Lamp efficacy is usually expressed in µmol/J (Joule)
- For a perfect lamp, 1 Joule could produce
  - 5.5 µmol of deep red light (~660nm)
  - 4.6 µmol of green light (~550nm)
  - 3.8 µmol of royal blue light (~450nm)

Turning photons into food
potentially achievable yield for tomatoes

Input: one mole of photons

1. Absorption of photosynthetic photons by leaves:	0.90	.80
2. Quantum yield: moles of carbon fixed per mole of photons absorbed:	0.07	.06
3. Conversion efficiency in respiration:	0.65	.60
4. Harvest Index:	<u>0.85</u>	<u>.60</u>
mol C/mol photons	= 0.035	0.017

Lettuce biomass (minimal protein) can be a low carbon fraction (42%)
12/0.42 = 28.6 grams biomass per mole of carbon

28.6 x 0.035 = 1 $gram_{dry}$ / mole 0.5 g_{dry}/mol

Bruce Bugbee, Utah State University

Theoretical economics

(conversion at 4.4 µmol/J))

Potential efficiency

Cost of electricity

$$\frac{\$\,0.10}{1\ \text{kWh}} * \frac{1\ \text{kwh}*}{16\ \text{mol}} = \frac{\$\,0.006}{1\ \text{mole}} * \frac{1\ \text{mole}}{0.5\ g_{dry}} = \frac{\$\,12}{kg_{dry}}$$

Value of products

Wheat

$$\frac{\$\,9}{1\ \text{bushel}} = \frac{\$\,0.32}{kg_{dry}}$$

Tomatoes

$$\frac{\$\,4.54}{1\ \text{lb.}} = \frac{\$\,10}{\text{kg fresh (90\% water)}} = \frac{\$\,100}{kg_{dry}}$$

Lettuce

$$\frac{\$\,4.54}{1\ \text{lb.}} = \frac{\$\,10}{\text{kg fresh (95\% water)}} = \frac{\$\,200}{kg_{dry}}$$

* Nelson JA, Bugbee B (2014) Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLoS ONE 9(6): e99010.

Best Traditional Technology: HPS

ePapillon by Philips

2100 µmol/s from 1060W
>95% fixture efficiency
3 year warranty on fixture
1 year warranty on bulb
Cost: ~$520 complete
~ $60 replacement bulb
Efficiency: 2.0 µmol/J
3-year cost: $0.30/µmol/s

Gavita Pro 1000 E-Series

2100 µmol/s from ~1050W
>95% fixture efficiency
3 year warranty on fixture
1 year warranty on bulb
Cost: ~$450 complete
~ $95 replacement bulb
Efficiency: 2.0 µmol/J
3-year cost: $0.30/µmol/s

LED Fixtures – GE ARIZE Life

Technical Specifications

Growth Spectrums:

- **Reproductive:** Higher red content to promote flowering and fruit generation.
- **Vegetative:** Higher blue content to promote healthy and thick leafy plants.
- **Balanced:** Balanced red to blue ratio for overall growth.

8 ft tube replacement

85 µmol/s from 30W at 2.8 µmol/J

L80 of 36,000 hours

5 year warranty

5 year price $360* or $4.26/µmol/s

**Price in small volumes*

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LED Fixtures – Philips Production Module

Blue (B)	positive effects on compactness and hardening
White (W)	working light / full spectrum
Deep red (DR)	most efficient for photosynthesis, vegetative reproduction and stimulating shoot development
Far red (FR)	positive effect on generative properties, flower formation and rooting

Specifications	Value	
	DR/B/FR	DR/W/FR
Photosynthetic efficacy	2.2 μmol/J	2.0 μmol/J
Power consumption	37 W	41 W
Dimensions (LxWxH)	151.3 x 40.5 x 40.2 cm / 59.57 x 1.594 x 1.583 inch	
Weight (driver included)	1.7 kg / 3.7 lbs	
Initial Photon Flux	83 μmol/s	
Power input	120-277 V AC, 50-60 Hz	
Power factor	> 0.95	
Lifetime	25.000 hrs, L90B50 (90% flux maintenance) (T_a 25 °C / 77 °F)	
Ingress protection rating	IP66, UL suitable for wet locations	
Cooling	Passively air-cooled	
Approval marks	UL, CE, RoHS, ISO	
Accessories	Comprehensive range of accessories available for easy and quick installation	
Warranty	3 years	

3-year price $176 or $2.12/μmol/s

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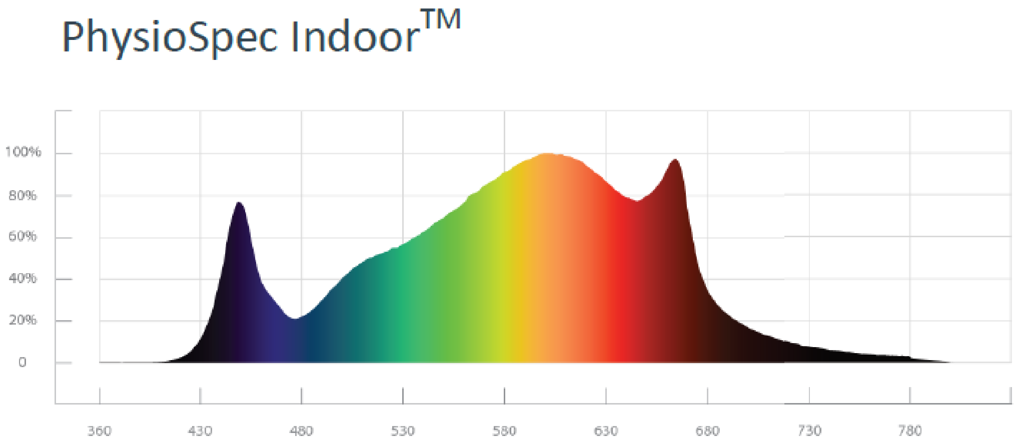
LED Fixtures – SPYDRx Plus Full Spectrum



1410 µmol/s from 660W at 2.1 µmol/J

L70 100,000 hours

Warranty 3 years

3 year price $1350 at $0.96/ µmol/s

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LED Fixtures – LumiGrow Pro 650 Series E

Blue Light (400-500nm)	20%
Green Light (501-600nm)	5%
Red Light (601-700nm)	75%

1100 µmol/s from 580W at 1.9 µmol/J
5 year warranty
5 year price $1370 or $1.29/µmol/s

Spatial Distribution

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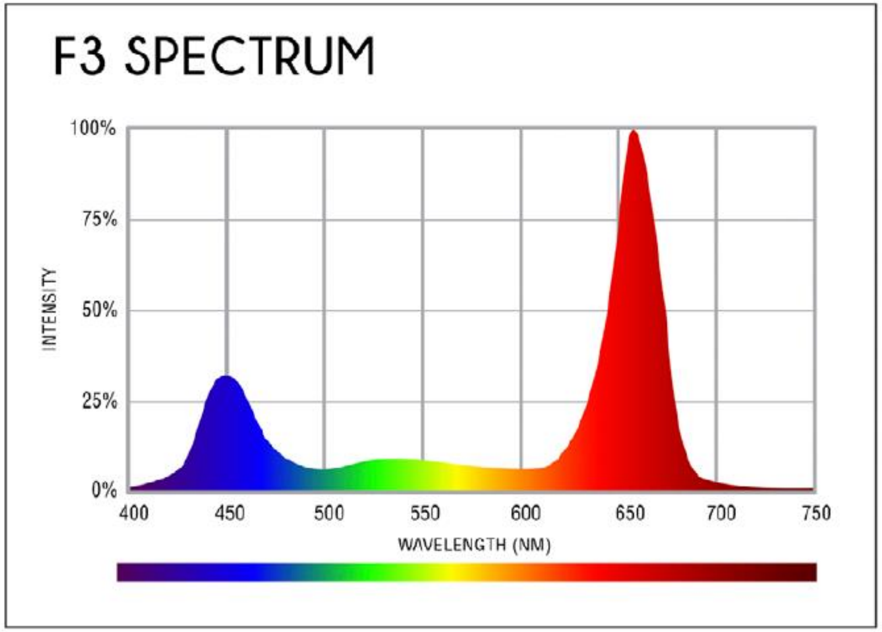
LED Fixtures – Illumitex Power Harvest



F3 WAVELENGTH MIX	
Blue (400 - 499 nm)	22.4 ± 1.3%
Green (500 - 599 nm)	13.4 ± 0.6%
Red (600 - 699 nm)	63.9 ± 0.8%
Far Red (700 - 780 nm)	0.4 ± 0.1%

1000 µmol/s from 565W at 1.8 µmol/J

L70 50,000 hours

5 year warranty

5-year price $1199 or $1.20/ µmol/s

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LED Fixtures – Status

- Several choices of spectrum offered by most vendors
- Efficacy up to 40% higher than best HPS
- Most products have similar efficacy to best HPS
- Most prices are much higher than HPS for same output
- Value seems to depend on
  - Lamps outlasting the warranty
  - Greater productivity achieved through color tuning
  - More uniform distribution of light

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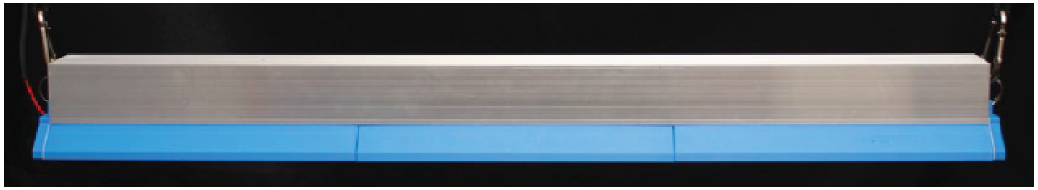
LED Sources– Cree Red & Blue Mix

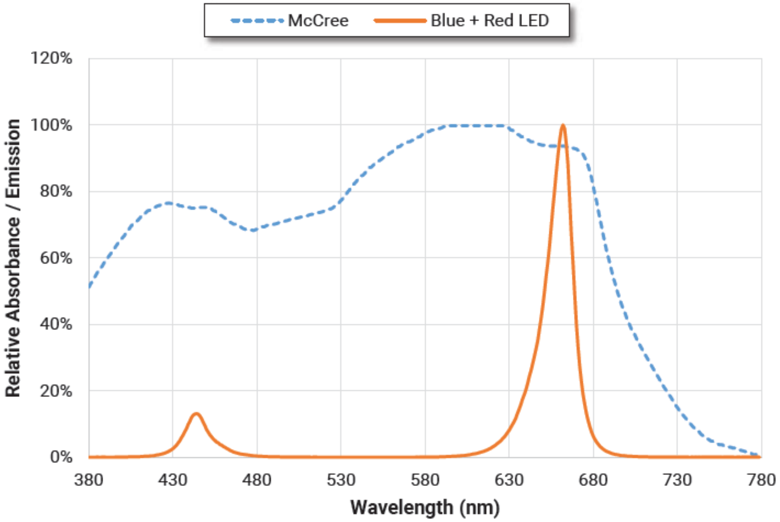
REFERENCE DESIGN: BLUE + RED LINEAR

Small, lightweight linear luminaire optimized for chlorophyll response with uniform spectral output @ 6" distance



System Measurements (Steady-State) - Excludes Driver Losses

Output Mode	Low	Medium	High
Blue LED Current	350 mA	700 mA	1000 mA
Red LED Current	175 mA	350 mA	500 mA
PPF	144 µmol/s	240 µmol/s	311 µmol/s
PPF/W	3.2 µmol/J	2.9 µmol/J	2.6 µmol/J
Power	45 W	82 W	119 W
LED Tsp	45 °C	65 °C	90 °C



Cost of 108 chips –
$124 at $0.40 µmol/s

CREE

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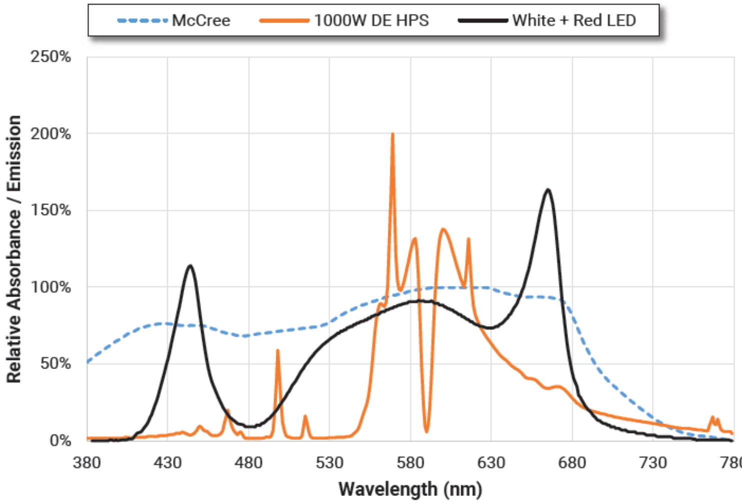
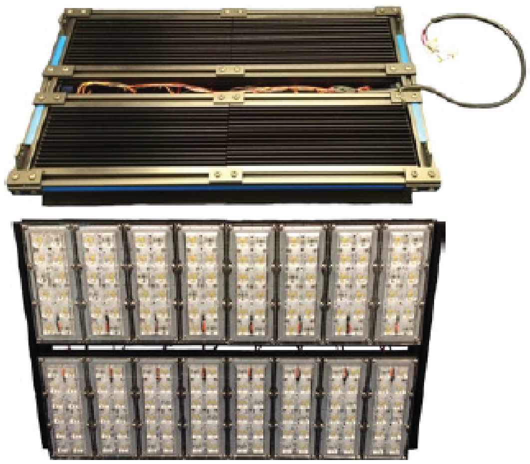
LED Sources– Cree White & Red Mix



REFERENCE DESIGN: WHITE + RED HIGH BAY

Modular design employing 4 engines - designed to match PPFD of 1000-W DE HPS

System Measurements (Steady-State)



PPFD Average	320 μmol·s^{-1}·m^{-2} @ 4.9 ft
PPF/W	1.82 μmol/J
Power	553 W
Dimensions (LWH)	25″ x 15″ x 3″ / 63 cm x 38 cm x 8 cm
Weight	27 lbs / 12.2 kg

Cost of 192 chips - $188 at $0.19 μmol/s

CREE

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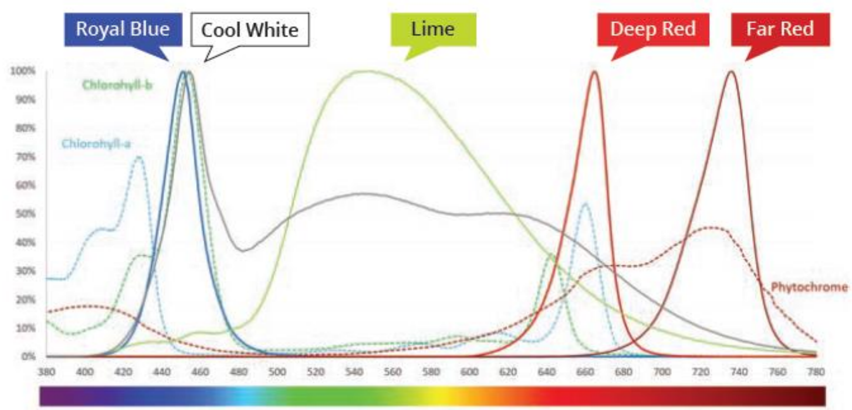
LED Sources– Lumileds SunPlus Series

LUXEON SunPlus Series product performance at test conditions.

PRODUCT	COLOR	PEAK WAVELENGTH (nm)		PPF (µmol/s) [1] in PAR (400 to 700nm) [2]		PPF/W TYPICAL (µmol/J)
		MINIMUM	MAXIMUM	MINIMUM	TYPICAL	
LUXEON SunPlus 20 Line	Far Red	720	750	1.10	1.19 [3]	1.97
	Deep Red	655	670	1.60	1.72	2.56
	Royal Blue	445	455	1.90	2.04	2.11
	Lime	–	–	1.50	1.59	1.66
	Cool White	–	–	1.40	1.51	1.57



Cost of 360 chips - $545

LUMILEDS

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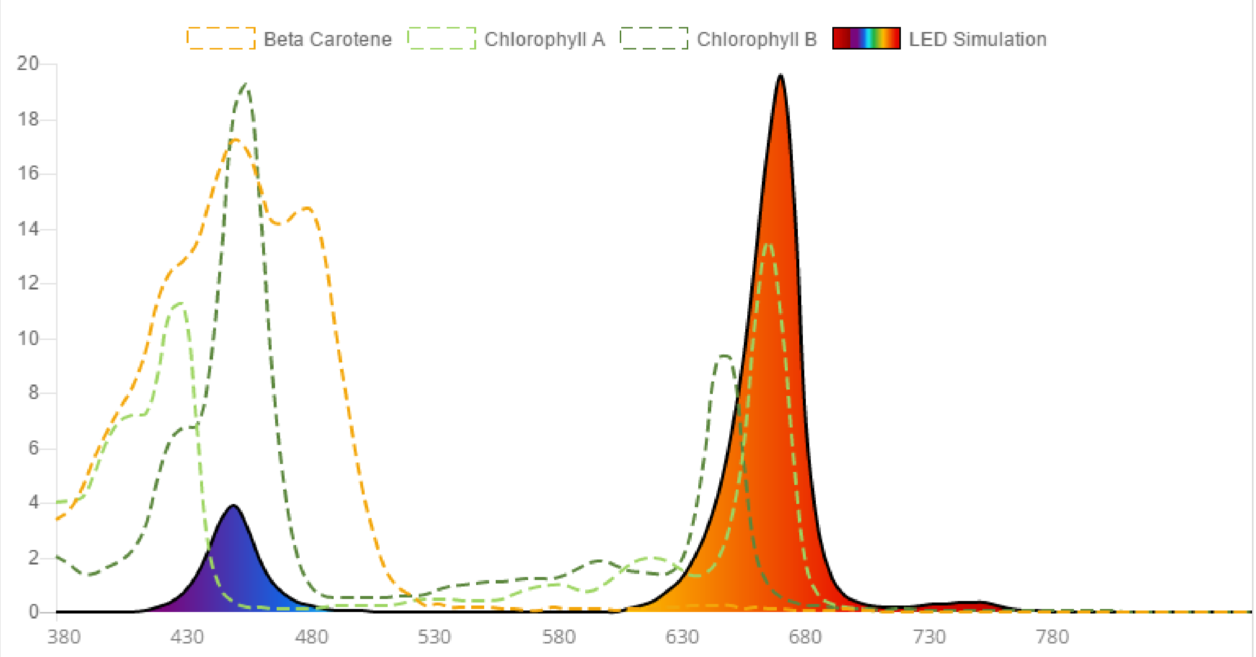
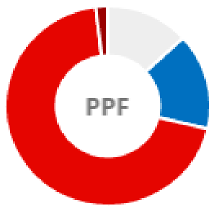
LED Sources – SunPlus On-Line Design Guide

Color	Part Number	# LEDs	Current [mA]	Tj [°C]		Forward Voltage	Photosynthetic Photon Efficacy	Electrical Power
	L1SP-DRD0002000000 (Deep Red)	300	350 [50 - 1200]	85 [-25 - 135]		1.92 V	2.55 µmol/J	201.99 W
	L1SP-RYL0002000000 (Royal Blue)	50	350 [10 - 1200]	85 [0 - 135]		2.73 V	2.08 µmol/J	47.69 W
	L1SP-FRD0002000000 (Far Red)	10	350 [100 - 1200]	85 [-25 - 135]		1.73 V	0.18 µmol/J	6.05 W





µmol/J	WPE
2.41 micromol/J	**48.0** %

Elec. Power	R-B Ratio
255.73 W	**4.46**

TOTAL	380nm - 850nm	630.61 µmol/s
Blue	420nm - 480nm	95.96 µmol/s
Red	620nm - 670nm	427.64 µmol/s
FarRed	710nm - 750nm	11.53 µmol/s

LED Sources – SunPlus Design Guide Results

Using fewer chips at high current reduces purchase cost,
but increases cost of electricity
and reduces lifetime

Current	Tj	Power	Light	B/R	Efficiency		Cost
mA	^{0}C	W	µmol/s	ratio	µmol/J	WPE	$/µmol/s
350	85	256	631	4.5%	2.41	48%	0.86
700	85	559	1218	4.8%	2.13	42%	0.44
1050	85	902	1753	5.0%	1.9	38%	0.31
1050	25	1000	2006	5.5%	1.96	39%	0.27
1050	135	859	1338	4.0%	1.52	30%	0.40

LUMILEDS

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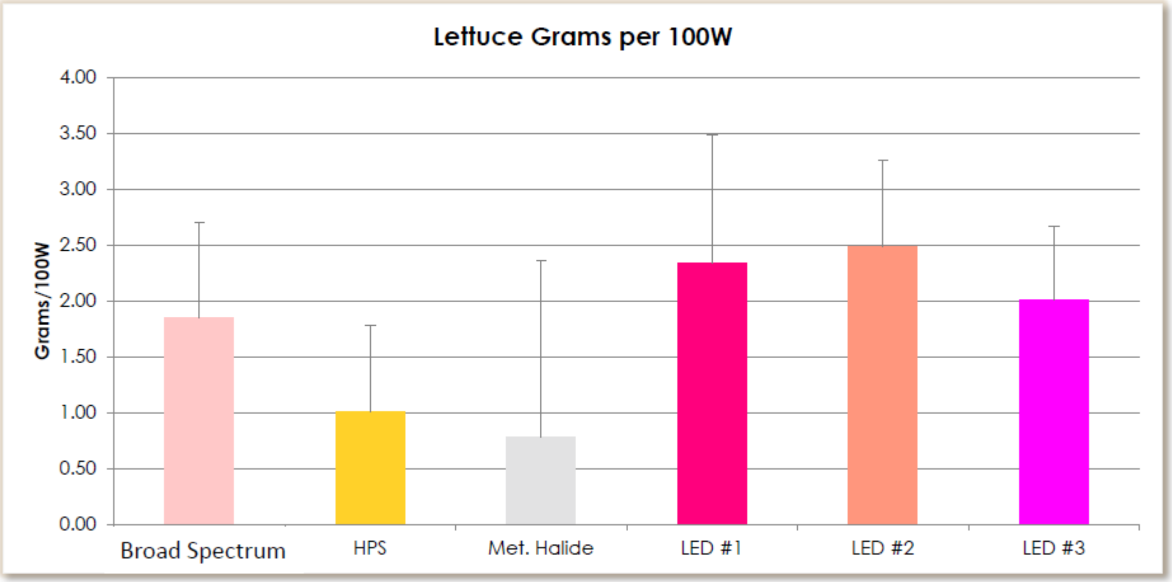
Effect of Color Tuning on Plant Size

- LED 1 (1/3 Blue, 2/3 Red),
- Led 2 (30% Blue, 25% White, 45% Red),
- LED 3 (60% Blue, 40% Red),
- Broad Spectrum (Blue 18%, Green 24%, Red 51%, Far Red 7%)

West Virginia University Testing - Results



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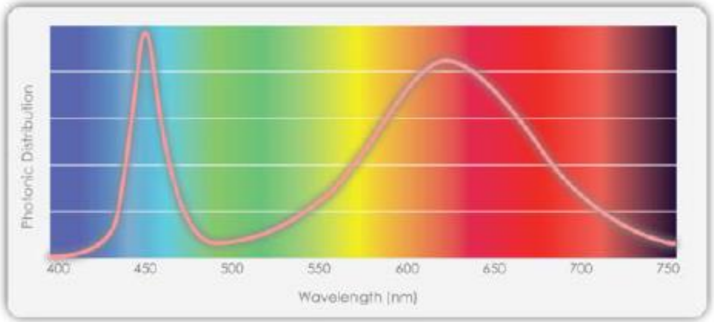
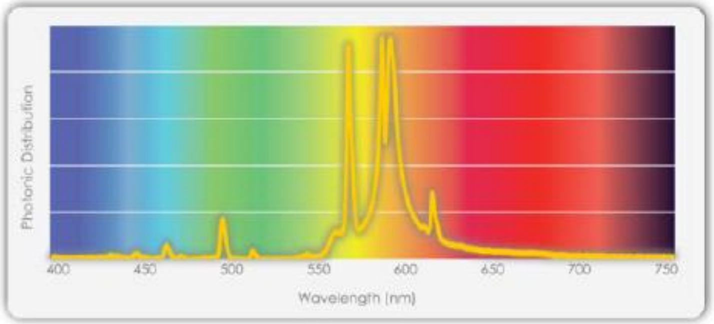
Effect of Color Tuning on Plant Size

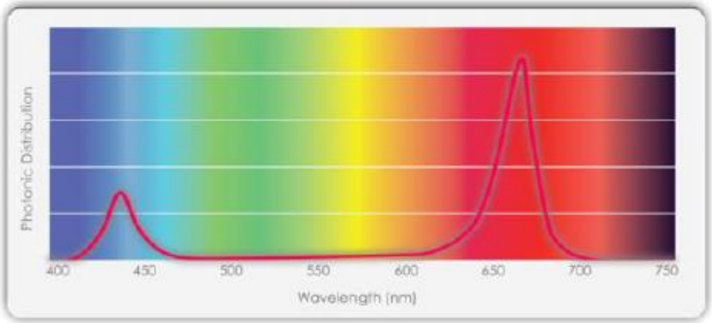
West Virginia University Testing - Spectra



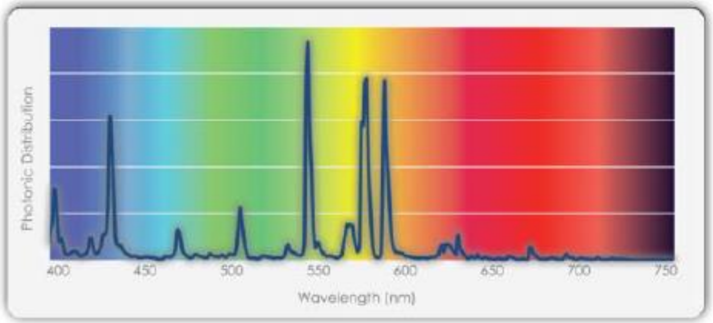
Broad Grow Spectrum



High Pressure Sodium Spectrum



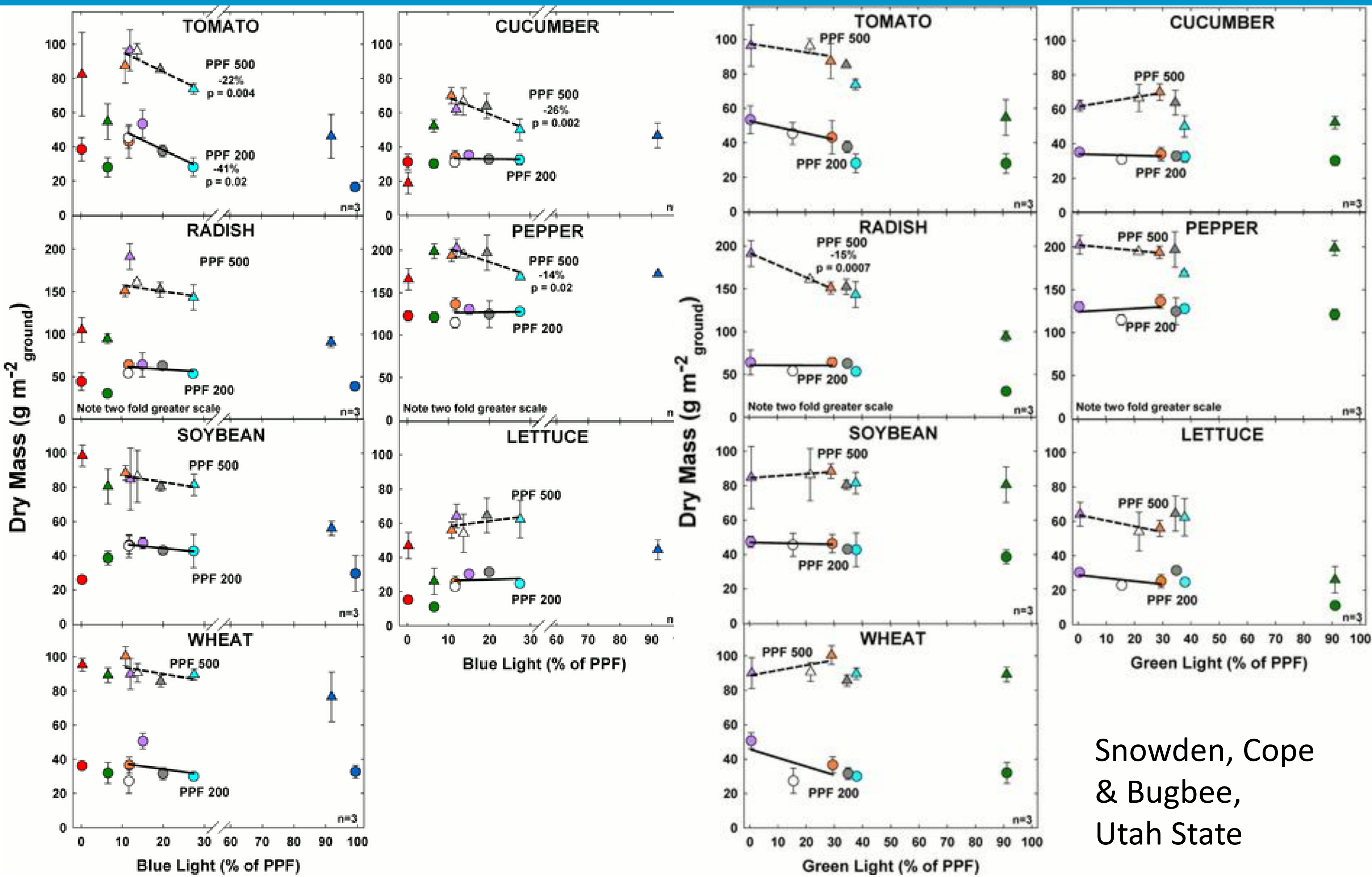
Typical LEDs (multiple versions)



Metal Halide Spectrum

Preliminary Tests– *"All plants we have tested (petunia, basil, and tomato) looked healthier under Broad Spectrum lighting and used far less energy than the competing light sources"*

Effect of Color Tuning on Plant Size

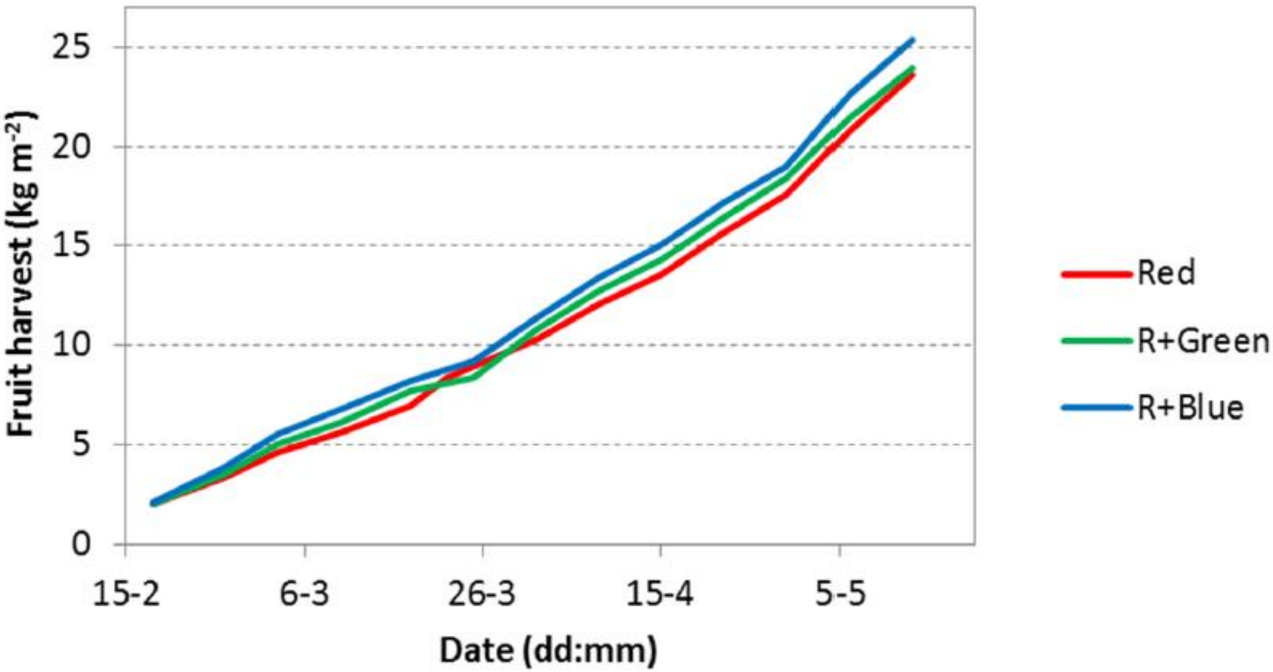


Snowden, Cope & Bugbee, Utah State

Effect of Color Tuning on Plant Size

Dynamic lighting strategies: start the day with 3 h blue or green light, proceed with red light (tomato)

- Effect on plant architecture and light interception
- Production increase (especially blue: 8%)



WAGENINGEN UNIVERSITY & RESEARCH

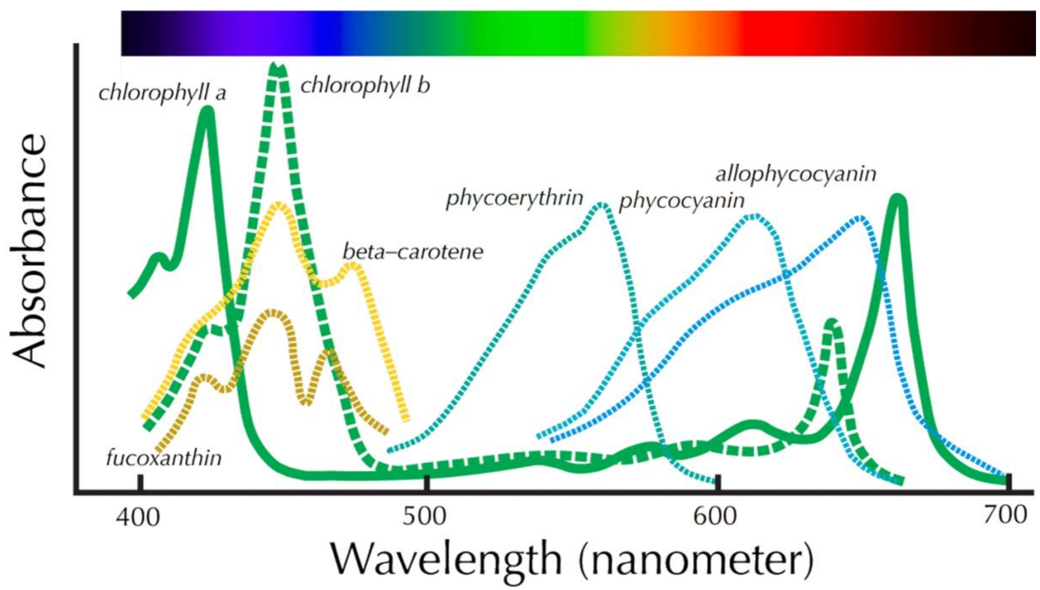
Source: Anja Dieleman

Plant Quality and Nutritional Value

- Chlorophyll content
- Antioxidant
- Carotenoid
- Vitamin C
- Anthocyanin
- Polyphenol
- Lutein
- Nitrates
- Root development
- Stomatal (pore) opening
- Flavor
- Sugar content
- Color
- Disease resistance

West Virginia University

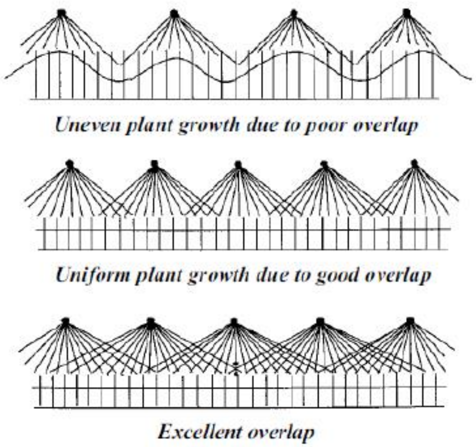
Pigment Absorption



Nadia Sabeh – Dr Greenhouse at Strategies in Light 2017

Lighting Impacts on Facility Design

- Electrical Panel Size and Service
- Structural Support of Equipment
- Lighting Plan
  - spacing, height, number
- Interior reflectors/Interlighting
- **HVAC System**
- **Irrigation System**
- Renewable Energy System
- Generator Size



See also http://urbanagnews.com/magazine/issue-16

Dr. Greenhouse

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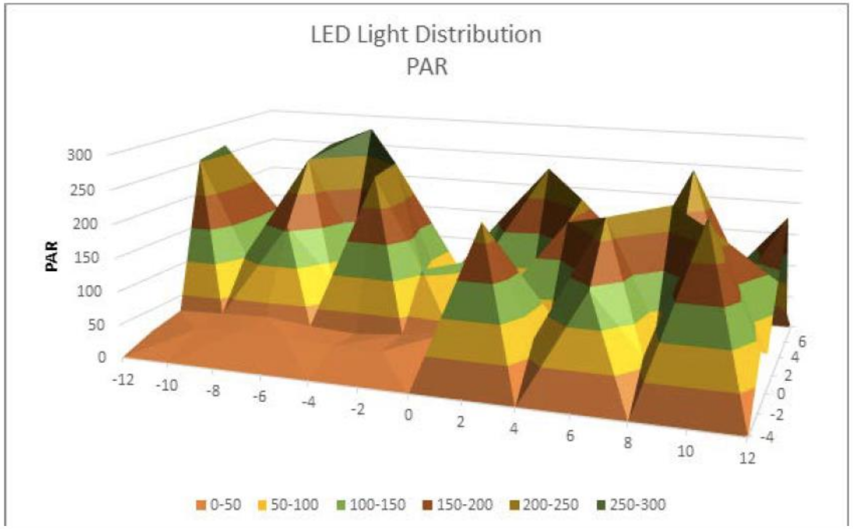
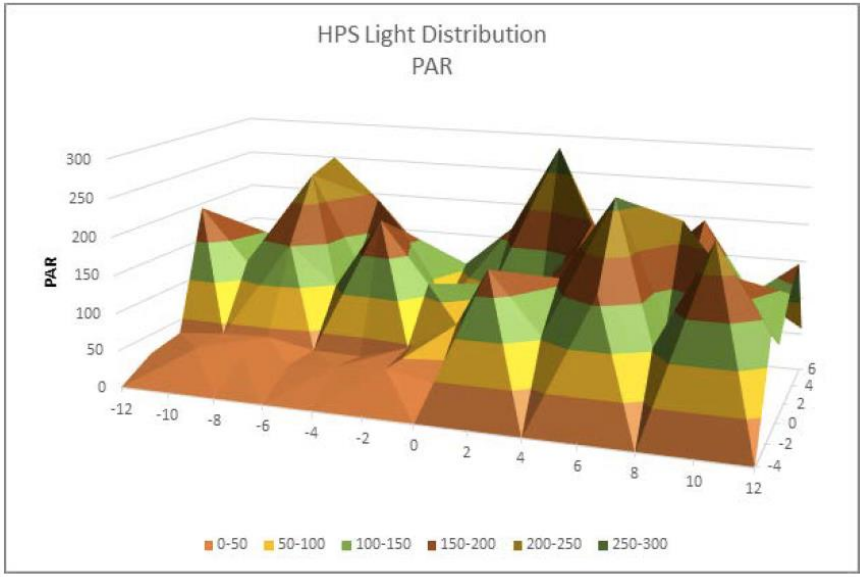
Light Distribution

Conservation Applied Research & Development
Minnesota Department of Commerce

Source: Celina Gomez & Cary Mitchell
(U Purdue)
Lamps from Orbitec





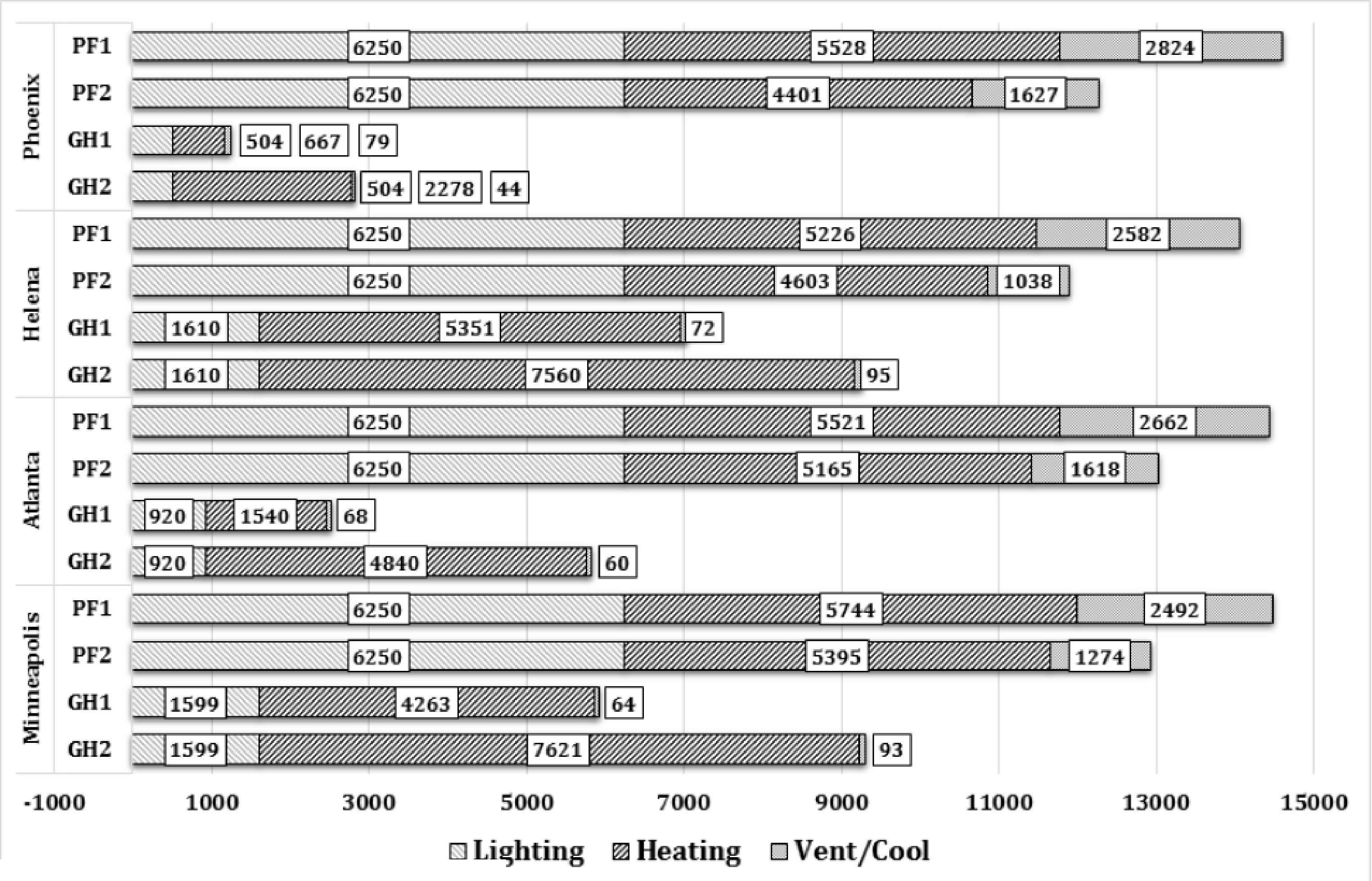
Energy Use in Greenhouses & Plant Factory

K. Harbick and L.D. Albright, Cornell University

Energy in GJ
(278 kWh)

Area of 1712m^2

LED or HPS with efficacy of 1.7 µmol/J



Cornell University
College of Agriculture and Life Sciences

Bardsley Consulting

Focus on Energy

2^{nd} largest production input (after labor)

CARBON FOOTPRINT

Imported to NY

Transport 2,963 miles

0.7 lbs CO_2/lb lettuce

Locally Grown

Central NY light/heat

2.0 lbs CO_2/lb lettuce

Advances in

- Lighting
- Reducing heat loss
- Greenhouse control

0.6 lbs CO_2/lb lettuce

Neil Mattson, Cornell University

Conclusions

- Horticultural applications are very challenging for LEDs
- More research on effects on specific plants is needed
- Plant health and nutritional value are important
- LED efficiency needs to be increased and price reduced
- LED reliability and lifetime are critical
- Effects on total system must be taken into account
- Environmental effects must be further evaluated
- Be skeptical about expectations for market growth

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Questions for BRICS Representatives

- How large is the market for expensive produce in your country?
- How much is artificial lighting used in growing plants?
- How much do your farmers pay for electricity?
- What is the typical efficiency of horticultural lamps?
- What is the typical cost of horticultural lamps?
- Would you be willing to help to analyze your market?
- If so please contact me at

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Back-up Slides

Rationale for Urban Plant Factories

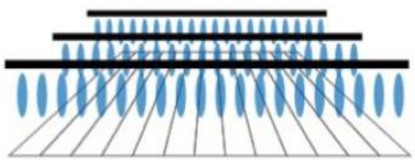
Association for Vertical Farming

Four Global Agriculture Challenges we can Address

#1 Pesticide use

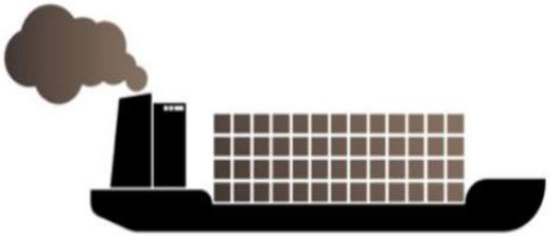
leading to:
Agricultural runoff
Ocean Acidification

#2 Fresh water use



80 % of all freshwater
is used in agriculture

#3 Food transport



leads to:
Significant food waste
Greenhouse gas emisions

#4 Rapid urbanization

Expected 10 billion people globally by 2050
80% urban population by 2050
Increasing demand for food in cities

Explore our infographic to learn more about vertical farming and the problems it can solve: vertical-farming.net/info/

Promises of Urban Plant Factories

Association for Vertical Farming

Vertical Farming Benefits II

- Less food waste
- Less land use
- Less food miles
- Faster to consumer (fresher)
- Guaranteed food safety
- No heavy metals/pesticides
- Up to 98% less water
- 2-3x faster growth rates
- High vitamin and mineral content
- Uniform and exceptional flavor
- Uniform yield