Optimizing Greenhouse HVAC and the Growing Environment for Maximum Yield with Minimal Energy Waste

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Jim Leidel
DTE Gas, Major Accounts
Outline

• The Potential for Greenhouses
• What do plants need to grow and thrive?
• Elements of indoor, controlled growing environment
  – Envelope, Heating, Ventilation, Cooling, Dehumidif.
• Lighting: Extra attention is given artificial lighting options
• Case Studies
### Total Area in Major Greenhouse Production Countries in the World

<table>
<thead>
<tr>
<th>Country</th>
<th>Greenhouse area (ha)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 China</td>
<td>2,760,000 (2010)</td>
<td>Yang, 2011</td>
</tr>
<tr>
<td>3 Spain</td>
<td>52,170</td>
<td>EuroStat, 2005</td>
</tr>
<tr>
<td>4 Japan</td>
<td>49,049</td>
<td>MAFF, 2011</td>
</tr>
<tr>
<td>5 Turkey</td>
<td>33,515</td>
<td>TurkStat, 2007</td>
</tr>
<tr>
<td>6 Italy</td>
<td>26,500</td>
<td>EuroStat, 2007</td>
</tr>
<tr>
<td>7 Mexico</td>
<td>11,759</td>
<td>SAGARPA, 2010</td>
</tr>
<tr>
<td>8 Morocco</td>
<td>11,161</td>
<td>Choukr-Allah, 2004</td>
</tr>
<tr>
<td>9 Netherlands</td>
<td>10,370</td>
<td>EuroStat, 2007</td>
</tr>
<tr>
<td>10 France</td>
<td>9,620</td>
<td>EuroStat, 2005</td>
</tr>
<tr>
<td>11 United States</td>
<td>8,425</td>
<td>US Census of Hort. Spec., 2010</td>
</tr>
</tbody>
</table>

(The data presented excludes low tunnel and shade structures covered areas)
The Netherlands is a small agricultural powerhouse. It is the second largest exporter of food by dollar value after the U.S.A. using only a very small area of, by use of greenhouses.

**Legend**
- Green bar = yield per area
- Red circle = total production
- Grey square = land area

Source: “A Tiny Nation that Feeds the World”, National Geographic, Sept 2017
The Netherlands
Elements for Healthy Plant Growth

- Temperature
- Humidity
- Wind
- Solar Energy
- Carbon Dioxide
- Water and Minerals
- Nutrients
Photosynthesis – chemical reaction

\[6\text{CO}_2 + 6\text{H}_2\text{O} + \text{ solar energy} \rightarrow 6\text{O}_2 + \text{ glucose}\]

Glucose = C\text{\_}_6 H\text{\_}12O\text{\_}6
Nearly all life on the planet is supported by this reaction.
Controlled Environment Agriculture

• Provide Light Energy
  – Solar or Artificial

• Macro Nutrients
  – CO$_2$ and H$_2$O

• Micro Nutrients: N, P, K, other Minerals
  – Soil or Hydroponics

• Suitable Environment
  – Temperature, Humidity, Wind
Elements of a Greenhouse

• Building envelope
  – Weatherization / air infiltration,
  – heat insulation,
  – light transmittance
• Lighting
• Heating
• Ventilation
• Cooling
• Humidity control
• Delivery of nutrients
  – CO2, water, fertilizer (N,P,K and minerals)
• Supply of electricity: utility, renewables, CHP
Structure Envelope

- **Reduce Air Leaks**
  - Weatherstrip doors, vents and fan openings
  - Service louvers frequently to close tightly
  - Repair broken glass or holes in the plastic
  - Seal and weatherize foundation

- **Double Coverings**
  - Cover "inside" sidewalls and end walls inside with poly or bubble wrap
  - Install double wall polycarbonate panels to get insulation effect and reduce recovering labor.
  - Use poly with an infrared inhibitor on the inner layer for 15% savings
  - Use single or double layer of plastic over older glasshouses to reduce infiltration and heat loss

- **Energy Conserving Curtain**
  - Install a thermal curtain for 20%-50% savings. An energy curtain can significantly reduce nighttime heat loss from a greenhouse. Payback within 1 to 2 years.

- **Foundation and Sidewall Insulation**
  - 1-2" extruded polystyrene board to 18-24" below ground to reduce heat loss. This can increase the soil temperature near the sidewall as much as 10 degrees during the winter.
  - 1-2" board insulation on kneewall or sidewall up to bench height.

- **Site Location**
  - Locate greenhouses in sheltered, reduced wind areas (but not shaded)
  - Windbreaks on the north and NW exposures with rows of conifer trees or plastic snow fencing.

- **Space Utilization**
  - Optimize space utilization: movable benches, multi-level racks for low light crops, try addition of hanging baskets, and roll-out bench system can double growing space, where top level plants are moved outside during the day.
## Properties of Glazing Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Life expectancy (years)</th>
<th>Light transmission (photosynthetically active radiation, %)</th>
<th>Heat transfer coefficient (U-value, Btu per hour per sq. ft. per °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>30+</td>
<td>90</td>
<td>1.1</td>
</tr>
<tr>
<td>Polyethylene (single layer)</td>
<td>3-4</td>
<td>88</td>
<td>1.1</td>
</tr>
<tr>
<td>Polyethylene (double layer)</td>
<td>3-4</td>
<td>77</td>
<td>0.7</td>
</tr>
<tr>
<td>Polycarbonate (twin wall)</td>
<td>10</td>
<td>75</td>
<td>0.6</td>
</tr>
<tr>
<td>Acrylic (twin wall)</td>
<td>20</td>
<td>74</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Modified from Greenhouse Glazings, A.J. Both, Rutgers University, 2008.*

Glazing Classifications

- Plastic Thin Films
  - 2-8 **mills** .002 - .008” inch
  - Polyethylene, EVA, PVC films, and polyester

- Flexible Plastics
  - FRP, polycarbonate, acrylics, plastic fused to glass

- Rigid Glass
  - float glass, tempered class, rolled glass
Automated Night Thermal Curtains

Photo: John Bartok, Jr., University of Connecticut
An inexpensive method of increasing greenhouse energy efficiency is sealing cracks in glazing and insulating heating pipes.
North-facing greenhouse walls that receive a minimal amount of light can be insulated to reduce heat loss.
Heating Options

• Consider Thermal Storage
• Direct fired unit heaters (CO2 + heat)
• Indirect fired unit heaters
  – High efficiency condensing unit heaters (90%+)
• Natural gas boiler
  – Radiant piping heat
  – Radiant floor heat
• Combined Heat and Power (CHP)
• Ground source heat pumps
• Renewable options
  – Solar thermal
  – Biomass (wood chips)
Condensing Unit Heaters
An under-bench forced air heating system with polyethylene air duct to evenly distribute heat.
An under-bench radiant heat can be finitue or bare pipe
Dutch Style
Geothermal heat storage systems, in which groundwater is used to store solar energy, have come into their own in Holland over the past few years. The dimensions seen at right are from a system installed at a “semi-closed” research bay at Hydro Huisman B.V., a Dutch greenhouse company.

HOT
4:1 ratio to greenhouse space

200 ft

COLD
4:1 ratio to greenhouse space

700 ft
Ventilation Options

- None: sealed environment
- Automated roof vents
- Sidewall electric fans
- Need to control interactions with CO2 supplementation systems
Natural ventilation from proper venting
Cooling Options

• Natural ventilation only
• Side wall evaporative cooling
• Ground source heat pumps
• Conventional refrigeration cooling
• Shading
  – Shade curtains
  – Exterior spay on white-wash
Humidity Control

- Ventilation with outdoor air
- Active refrigeration based dehumidification
- Desiccant dehumidification with thermal reactivation (new concept for grow-rooms)
Delivery of Nutrients

• Fertilized Soil
• Hydroponics
CO2 Supplementation

- Yields can increase ~33% if CO₂ doubles
- Supplementation sources
  - Liquid CO₂ (*relatively inexpensive*)
  - Combustion of natural gas or propane
    - Direct fire burners
    - Boiler exhaust
    - CHP exhaust

![Diagram of CO2 Supplementation]

**Conventional**
- BOILER:
  - Natural gas
  - HW
  - CO₂
  - H₂O

**Cogeneration**
- CHP:
  - Natural gas
  - Electricity
  - HW
  - CO₂
  - H₂O
CO2 vs Photosynthesis

RELATIVE PHOTOSYNTHETIC RATE

CO2 CONCENTRATION, ppm

Ambient (April 2018)
Natural Gas Combustion

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]
Direct Fired CO2 Burners
Carbon Dioxide Fertilization

• Ambient CO2 ~410 ppm (April 2018)
• During daylight hours CO2 may be rapidly depleted during crop production
• Depletion may be exacerbated during winter production when there is less ventilation
CO$_2$ Greenhouse Levels

• 1,000 ppm or more have shown to increase tomato yields economically
• However, you must adjust based on plant maturity and environmental conditions
  • Bright, sunny weather 1000 ppm
  • Cloudy weather 750 ppm
  • Young plants 700 ppm
  • During moderate ventilation 350-400 ppm
  • Less needed as temperature and ventilation rates increase
Supply of Electricity

• Utility company
• Renewables
  – Solar PV
  – Wind turbines
• Combined Heat and Power
  – Special case for greenhouse application
  – It is a heating source (boiler)
  – It is a distributed generation source
  – It is the best “Energy Efficiency” technology
  – It is also a source of CO2 and H2O
Combined Heat and Power

• Use **Condensing** waste heat recovery
• Gas treatment is required
  – Oxidizing catalyst
  – SCR urea based NOx scrubber
  – Test for NOx and ethylene
• Inherently CHP is:
  – a heating source: HW boiler
  – a source of electric power
  – the best “Energy Efficiency” technology
  – a source of CO2 and H2O
Lighting

• Natural light
• Artificial light sources
  – HPS
  – MH
  – LED
Full Spectrum of Solar Radiation

[Graph showing the full spectrum of solar radiation with peaks at specific wavelengths and labels for 
H$_2$O, O$_3$, CO$_2$, and Chl a fluorescence, along with the absorption and fluorescence of pigments like Chl a, Chl b, carotenoids, phycoerythrin, phycocyanin, and the irradiance at different atmospheric levels.]
Full Spectrum of Solar Radiation
Photosynthetically Active Radiation
400nm to 700nm
Photosynthesis Activity

The graph shows the absorption spectrum of chlorophyll a and b, as well as carotenoids, across different wavelengths (nm).
First and foremost, maximize the use of free, natural solar energy!!

To estimate the DLI inside your greenhouse for a particular month:

1. Use a light sensor to determine light intensity outdoors at noon on a clear day.
2. Go into your greenhouse and take light intensity measurements at plant level.
3. Use these values to determine the percentage of light outdoors that reaches your crops. For example, if you measure 6,300 footcandles outside the greenhouse and an average value of 4,100 footcandles inside, your light transmission value is about 65%.
4. Multiply the DLI value indicated in the maps above by the transmission value to obtain the average DLI inside your greenhouse. For example, if your transmission value is 65% and the DLI for your location is 20 mol m$^{-2}$ d$^{-1}$, then your average DLI that month is 13 mol m$^{-2}$ d$^{-1}$.
At solar noon

2000 μmol m\(^{-2}\) s\(^{-1}\) 1000 W m\(^{-2}\)

photovoltaic panels: 15% efficient

150 W m\(^{-2}\)

The best LEDs can produce 1.74 μmol/J

70% transmission

1400 μmol m\(^{-2}\) s\(^{-1}\)
transmitted to the plant canopy

260 μmol m\(^{-2}\) s\(^{-1}\)
delivered to the plant canopy

Less than 20%

Source: Vertical Farming, Bruce Bugbee, Dept. of Plants Soils and Climate, Utah State University (Sept 2015)
Light Measurement Terminology

**Full Solar Spectrum**
Radiation Power, $P$ [units: watt / m$^2$]
300 to 3000 nm Solar Radiation
380 to 780 nm Human Vision

**Illumination or luminous intensity for the human eye**
Luminous power (in 360°) [unit: lumen] [or candlepower]
Illuminance or illumination intensity = Lux [unit: lumen / m$^2$]
 or Footcandle [unit: lumen / ft$^2$]

**Light for plant growth**
400 to 700 nm Photosynthetically Active Radiation (PAR)
Quanta = number of photons [unit: mole]
Mole = the quantity of $6.02 \times 10^{23}$ of anything
Photosynthetic photon flux (PPF) [unit: $\mu$mole / s
Photosynthetic photon flux density (PPFD) [unit: $\mu$mole / (s m$^2$)]
Energy in Light

\[ E = \frac{hc}{\lambda} \]

\( E = \) photon’s energy [Joules]
\( h = \) Planck constant [6.626×10\(^{-34}\) J sec]
\( c = \) speed of light [3.0×10\(^8\) meters / sec]
\( \lambda = \) photon’s wavelength
Energy in Light

\[ E = \frac{hc}{\lambda} \quad \text{and} \quad \frac{c}{\lambda} = f \]

Planck–Einstein EQ

\[ E = hf \]

\( E \) = photon’s energy [Joules]
\( h \) = Planck constant \([6.626 \times 10^{-34} \text{ J sec}]\)
\( c \) = speed of light \([3.0 \times 10^8 \text{ meters / sec}]\)
\( \lambda \) = photon’s wavelength
\( f \) = frequency [hertz]
Measurements of Light

Luminous Flux (lumens)

Luminous Intensity (candela)

Illuminance (lux = lumens/m²)

Luminance (candela/m²)
Cloudy day, 4-27-2018, Detroit, MI downtown 2:45pm
70 Watt HPS (82 watts on meter)

Y axis: Absolute spectral irradiance (μW /cm2 / nm)
X axis: Wavelength (nm)
70 Watt MH (98 W on meter)
250 W halogen incandescent (251 W on meter)
(qty 4) 3500K CFL’s at 42 watt total
(qty 4) 3000K LED's at 34.5 watt total
(qty 4) 5000K LED’s at 60 watts total
Typical LED spectral power distributions normalized for constant luminous intensity.

(qty 4) grow light LED at 20 watts
# Light Source PAR Efficacy

<table>
<thead>
<tr>
<th>Lighting Type</th>
<th>Watt</th>
<th>PAR $\mu$W / cm$^2$</th>
<th>PAR $\mu$W/W$_{elect}$/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 70 W HPS</td>
<td>82</td>
<td>838</td>
<td>10.2</td>
</tr>
<tr>
<td>(1) 70 W MH</td>
<td>98</td>
<td>1,578</td>
<td>16.1</td>
</tr>
<tr>
<td>(1) 250 W halogen</td>
<td>251</td>
<td>3,182</td>
<td>12.7</td>
</tr>
<tr>
<td>(4) 3500K CFL</td>
<td>40</td>
<td>343</td>
<td>8.6</td>
</tr>
<tr>
<td>(4) 5000 K 15 W LED</td>
<td>60</td>
<td>4,430</td>
<td>73.8</td>
</tr>
<tr>
<td>(4) 3000k 9W LED</td>
<td>34.5</td>
<td>1,938</td>
<td>56.2</td>
</tr>
<tr>
<td>(4) grow LED</td>
<td>20</td>
<td>552</td>
<td>27.6</td>
</tr>
</tbody>
</table>
Two Case Studies

- Howling Tomatoes – California
- Great Northern – Kingsville, Ontario
Houweing Tomatoes

- 125 acre greenhouse
- Camarilo, California (north of Los Angeles)
- Three reciprocating natural gas engines
  - Over 40% electrical efficiency
  - Over 90% overall efficiency
- 13 MW total with excess power exported to grid
  - condensing waste heat exchanger
- Natural Gas CHP: four products utilized
  - electricity
  - heating
  - CO2 exhaust (treated for use)
  - Condensed H2O (treated for use)
Houweling Tomatoes - California

**CO₂ Fertilization Process**

37,000 tons of CO₂ are diverted yearly by purifying engines exhaust into fertilizer.

**Heat**

Over 15.9 MW of thermal power is captured from the heat produced in the engines during the power generation.

**Condensed Water**

Condensed water from the exhaust gas system helps conserve 9,500 gallons of water per day.

**Power**

The gas engine provides 13.2 MW of electrical power. It is equivalent to over 5,000 homes' electrical demand.

**Greenhouse**

Heat, power, condensed water, and fertilization are provided by this process.

**Reciprocating Engines**

Three Jenbacher ultra-low emission natural gas fueled reciprocating engines provide the electricity needed for greenhouse operations while lowering carbon dioxide emissions and saving water resources. The system generates more electricity than the greenhouse can use, allowing it to sell the excess back to the power grid.

Image: Southern California Gas
• Kingsville, ONT, Canada
• 50 acres of hydroponics tomatoes
• 5 acres under HPS lighting
• 12 MW electric CHP system
  – Sells electricity to Ontario Power Authority
• Uses mainly heat and CO2 on-site
Scrubbing of flue gases results in the capturing of CO2. Exhaust gases go through a catalytic converter to remove ethylene and then urea is injected to convert these NOx gases into non-harmful particles. The good CO2 is directed to the greenhouse for plant fertilization.
Conclusions

• Maximize use of solar lighting,
• Fully indoor grow environments have different load profiles and energy use requirements,
• LED lighting is maturing and will be the most efficient option for artificial light,
• Conventional efficiency measures in weatherization and HVAC apply,
• The balancing of heating, dehumidification, CO2 supplementation is complex but can be optimized.
Questions?

Thank You!

DTE Energy

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