

SIMULATION FOR FOOD

EVALUATING URBAN GREENHOUSES

Case study: UW greenhouse

Shafiul Islam
Mehlika Inanici

University of Washington, Department of Architecture

Overview

What are we
simulating?

01

Tool:
Kybele

02

What are we
Calculating?

03

Kybele
Workflow

04

Case
Study

05

Questions

06

PLANT PHOTOBIOLOGY

Like humans, plants also evolved under the natural cycle of light and dark, but they respond to light differently from human beings.

The main photobiological responses of plants



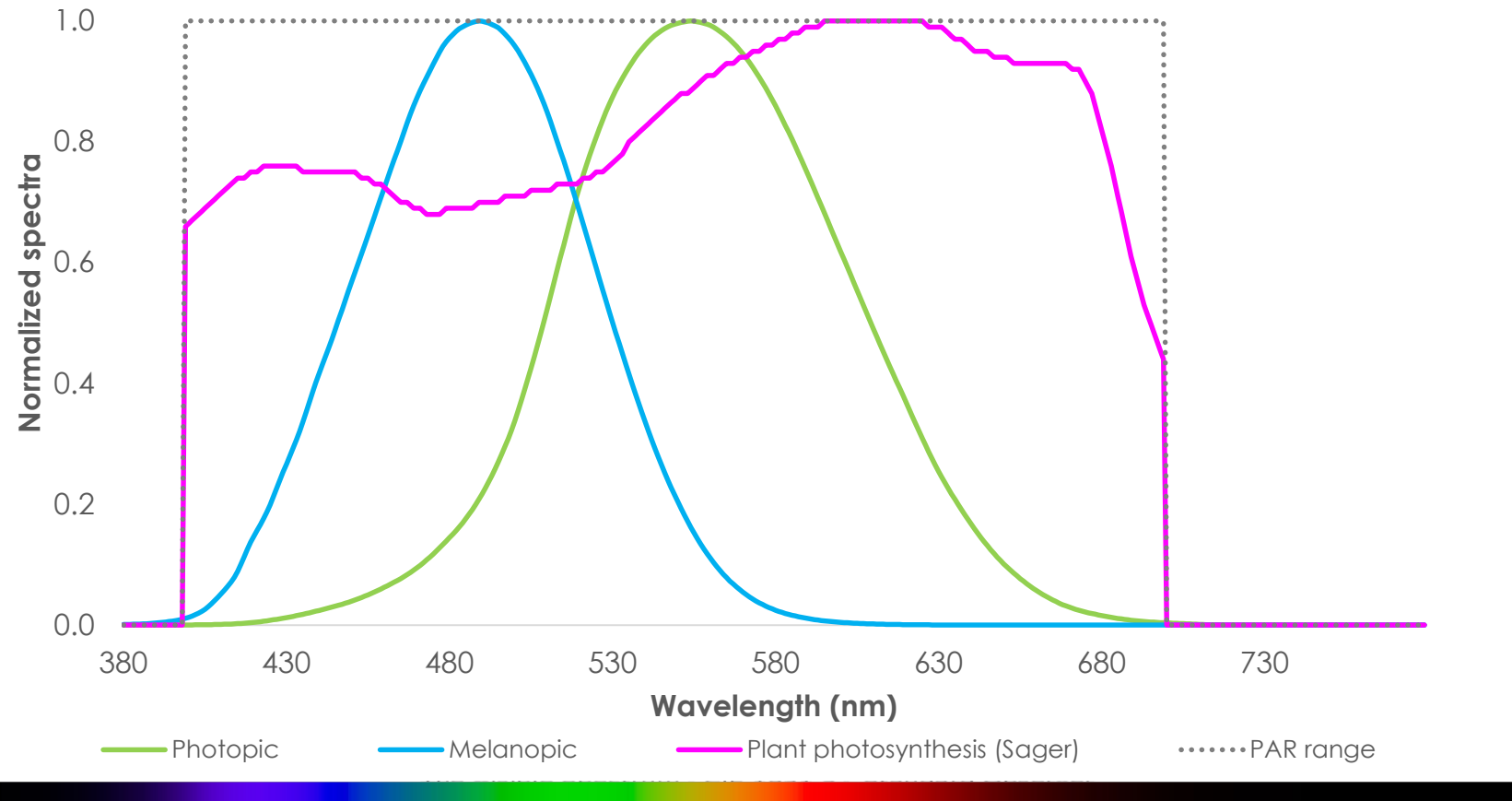
Photosynthesis



Photo-morphosis



Photoperiod



Human and plant photobiological responses

- Photopic response curve (CIE $V(\lambda)$);*
- Melanopic response curve (CIE 2018);*
- Photosynthetic Active Radiation (PAR) curve (McCree, 1972 and Sager, 1988)*
- PAR range as recommended by ANSI/ASABE (American National Standards Institute / American Society of Agricultural and Biological Engineers)*

Plants' Lighting Metrics

1

PPFD

Photosynthetic Photon Flux Density: the number of photons between 400 and 700 nm reaching one square meter each second, expressed in $\mu\text{mol}/\text{m}^2/\text{s}$.

2

DLI

Daily Light Integral: the accumulated PPFD over 24 hours, expressed in $\text{mol}/\text{m}^2/\text{day}$.

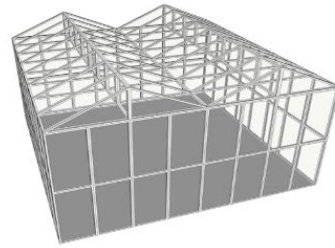
3

Energy use

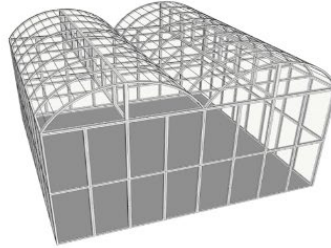
Energy use with supplemental electric lighting, if needed, KWh/yr.

What are we Simulating?

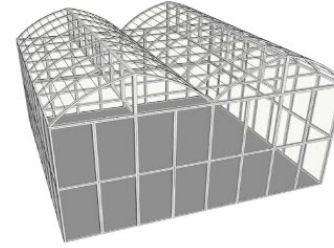
URBAN GREENHOUSES



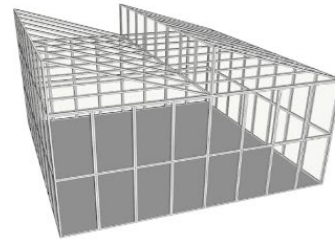
Venlo



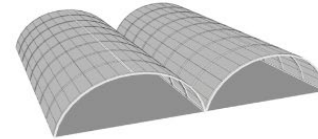
Arch



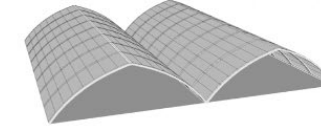
Gothic



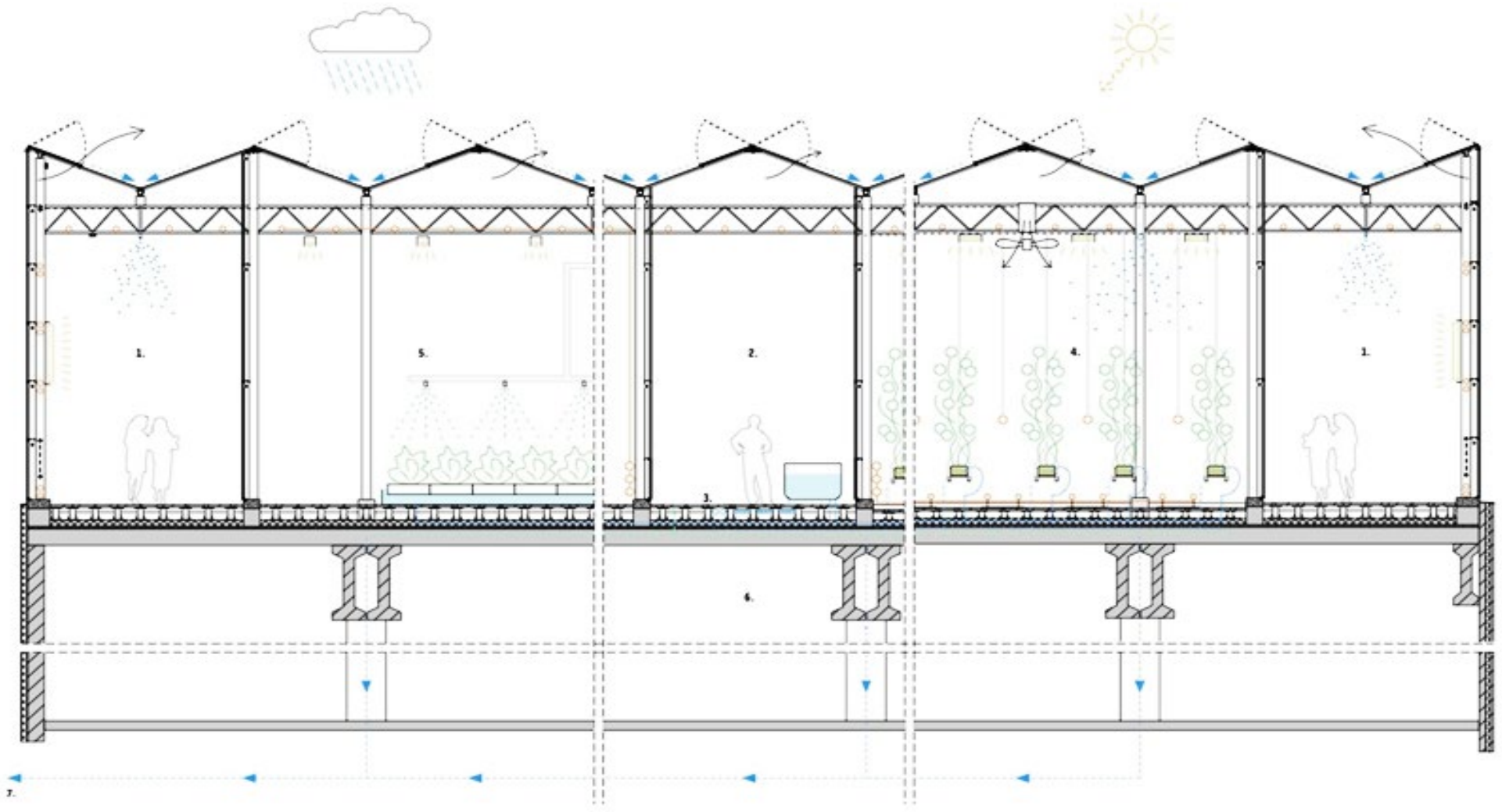
Sawtooth



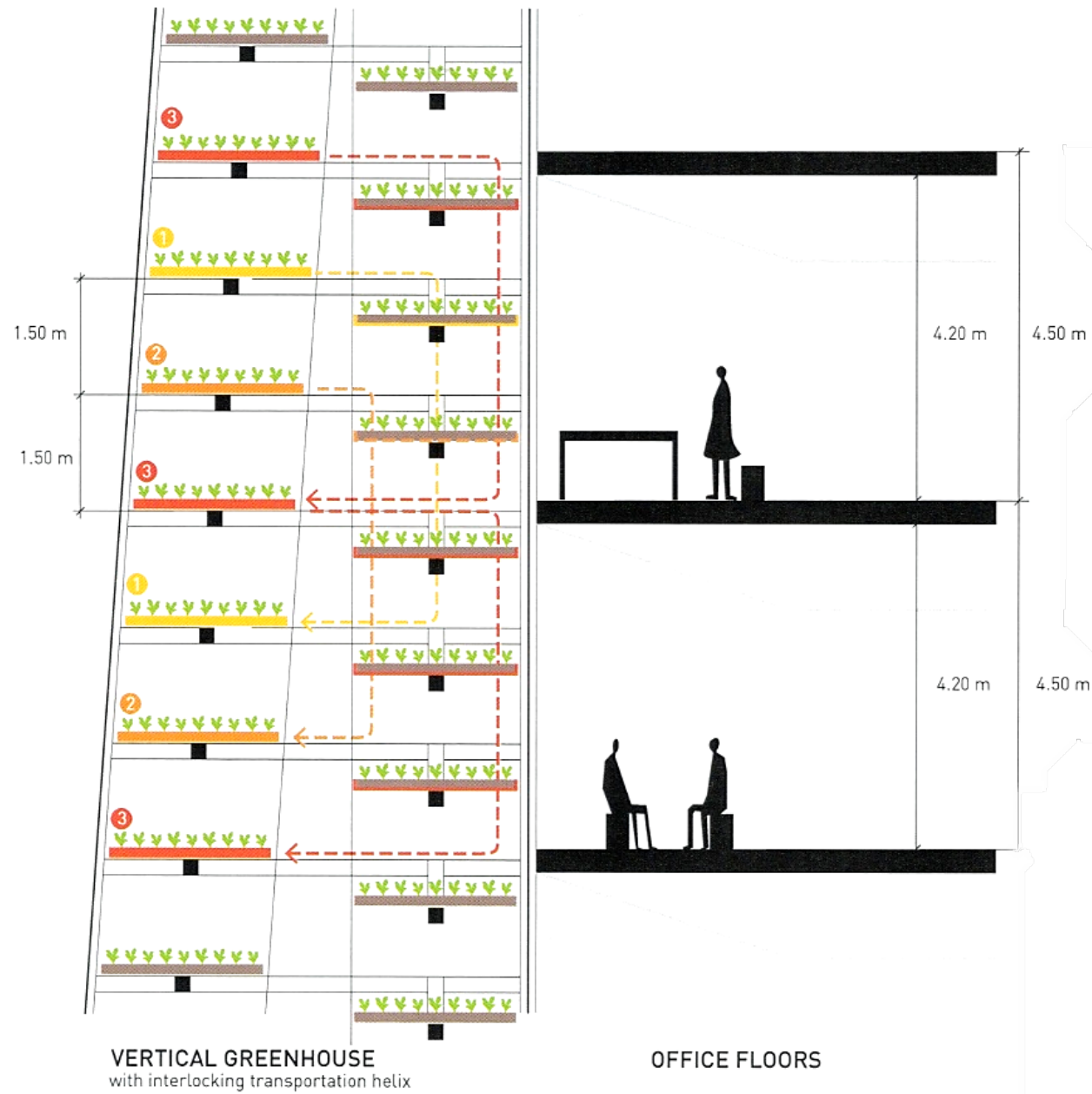
Arch Tunnel



Gothic Tunnel



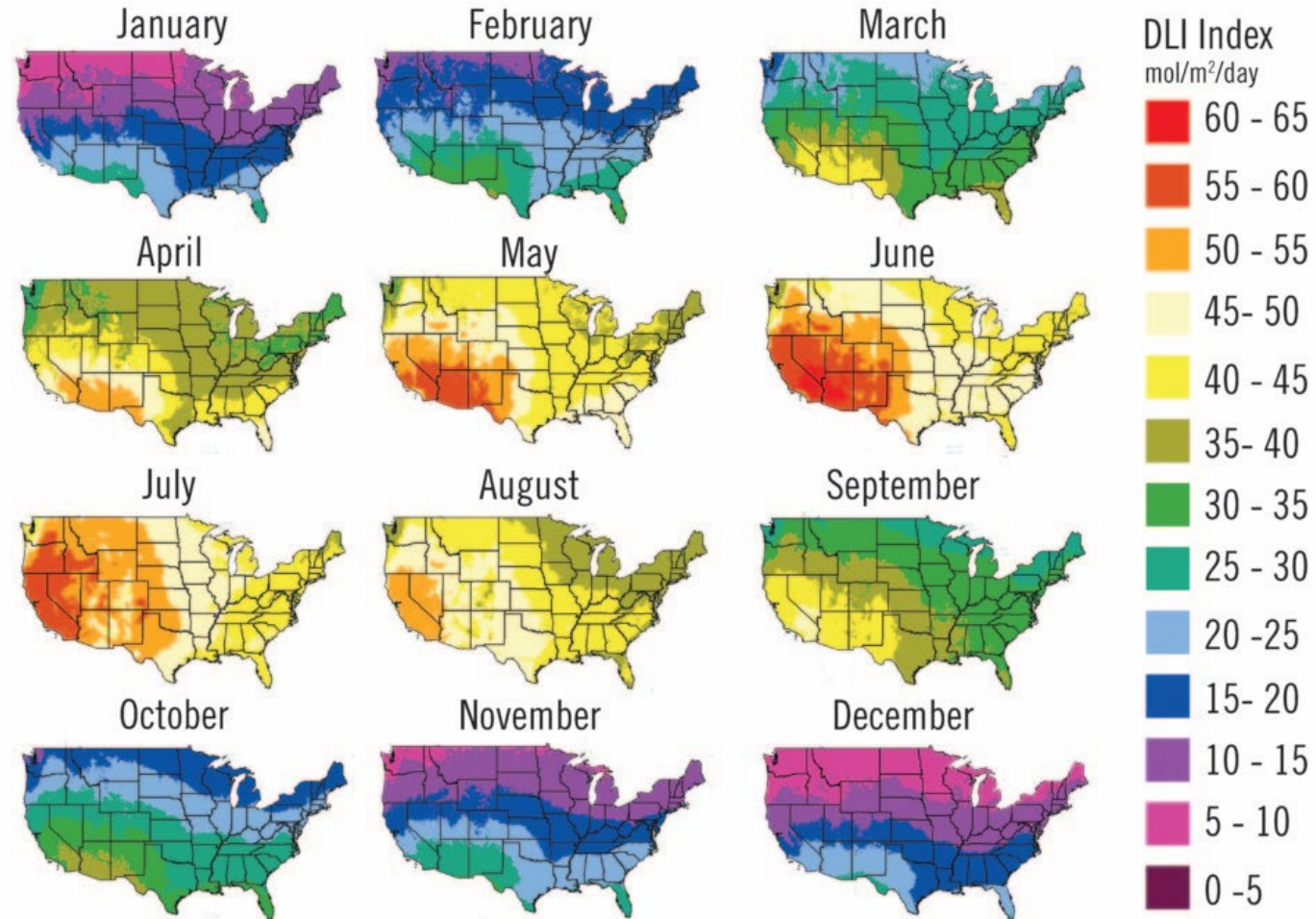
Rooftop greenhouse, detailed section, Agrotopia Research Center for Urban Food Production (van Bergen Kolpa architects + META architectuurbureau)



U.S. Daily Light Integral Maps

by James Faust and Joanne Logan

Daily Light Integral (DLI) represents the total photosynthetically active radiation accumulated over one day. Since plants are accumulators of solar radiation, this measurement is extremely useful for describing solar radiation as it affects plant growth. DLI has become a familiar measurement for plant scientists and commercial growers.





KYBELE

Kybele (Cybele) is an Anatolian goddess whose worship spread to Greece and Rome

Symbolizes the abundance and fertility of the earth, with connections to agriculture.



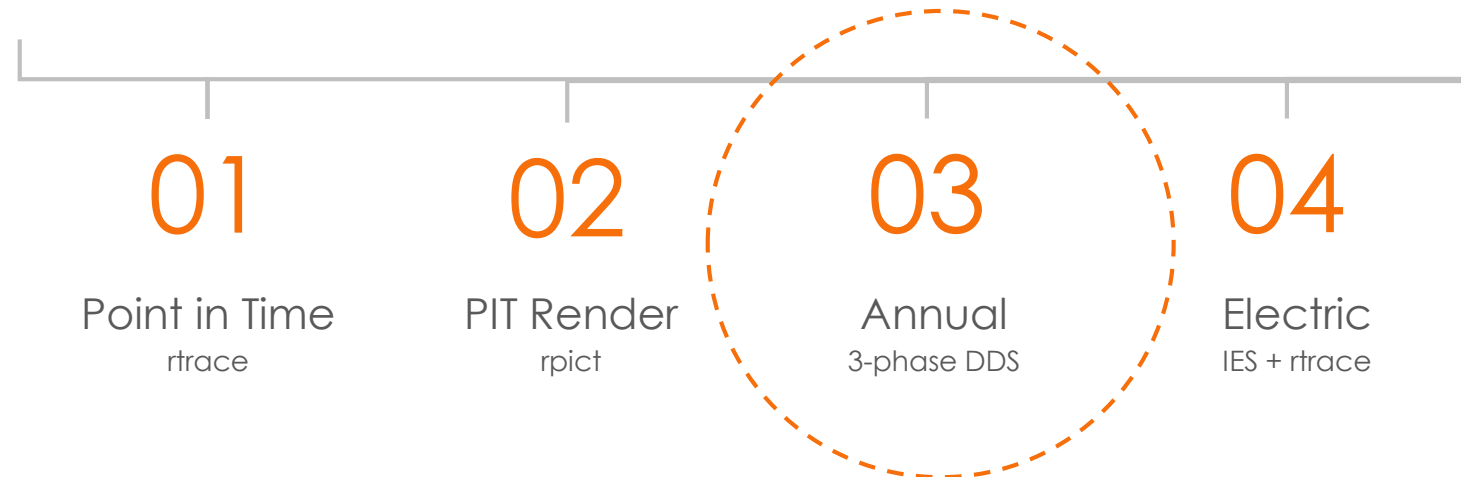
Simulation Workflows

Workflow flow for the four simulation types

Rhino 8 · CPython 3.9 · Radiance

Three Channel

Hyperspectral



Simulation Workflows

INPUTS

01
STEP

MODEL PREP

02
STEP

SIMULATE

03
STEP

RESULTS

04
STEP

CONVERT

05
STEP

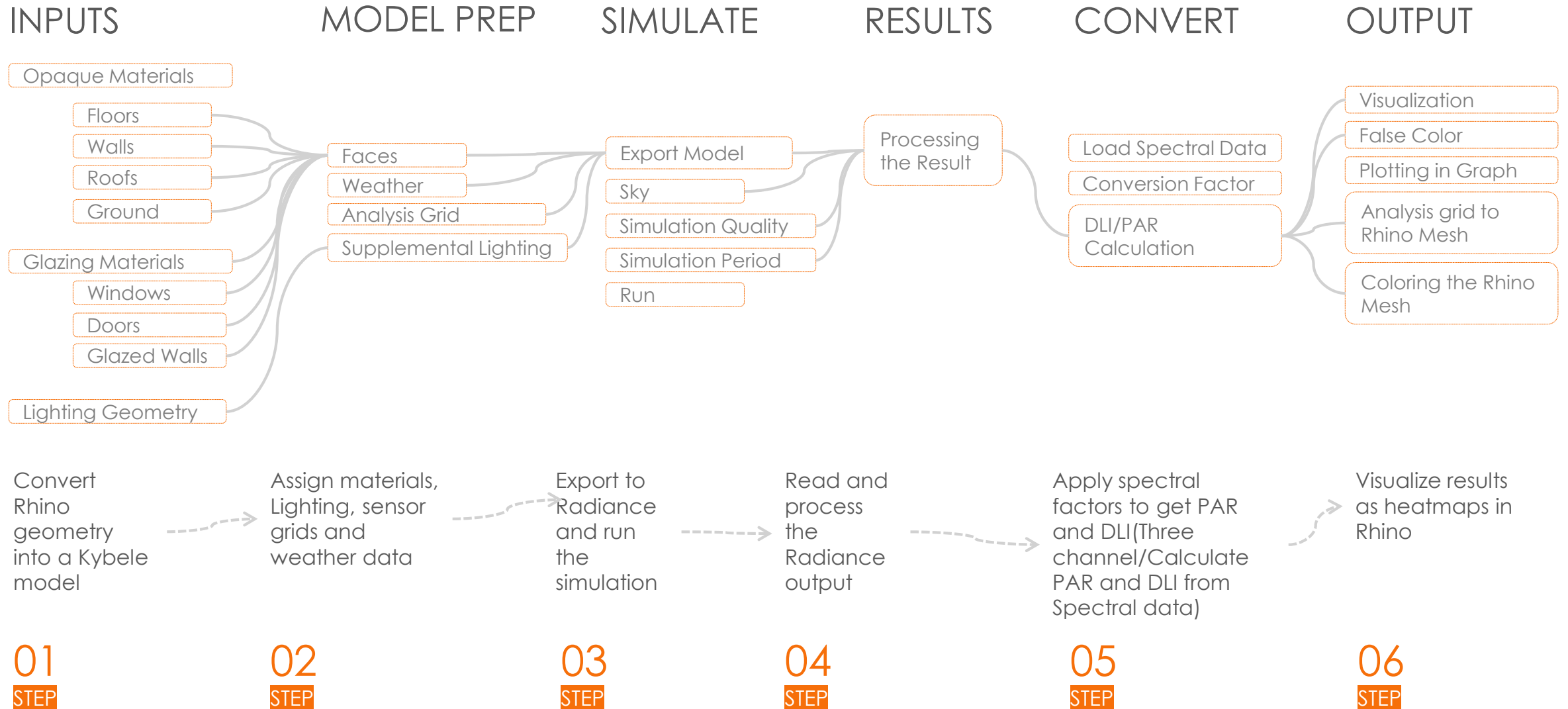
OUTPUT

06
STEP

Simulation Workflows



Simulation Workflows





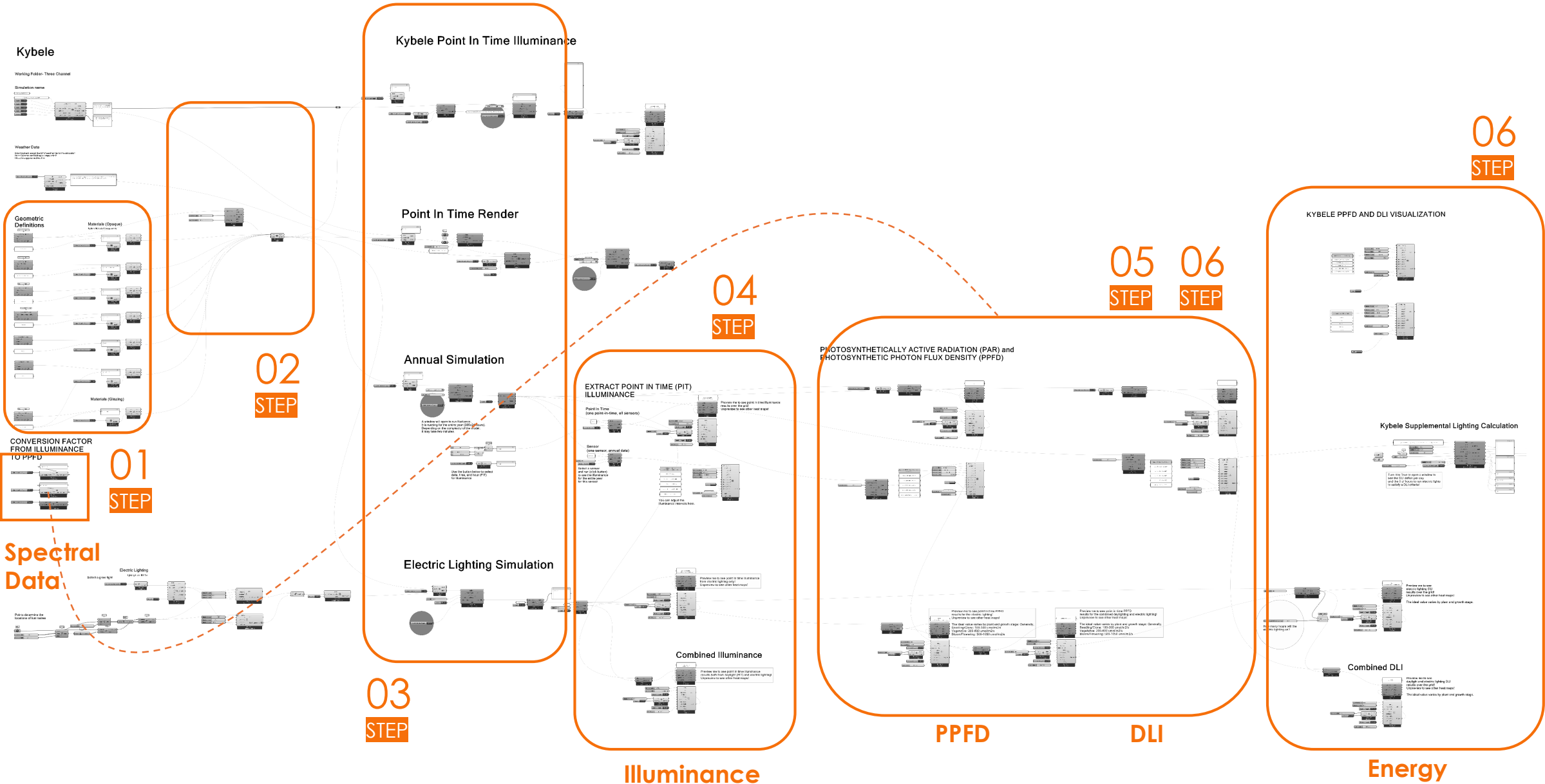
KYBELE

Works with 3D modeling tool Rhinoceros, and its native visual programming environment Grasshopper

Uses the industry gold standard simulation engines: Radiance for solar radiations, Energy+ for thermal simulations

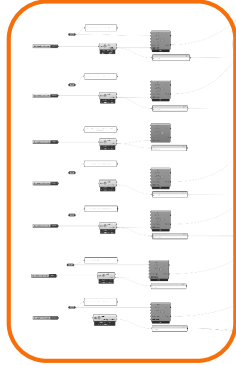
Components written in Python

Three-Channel Radiance



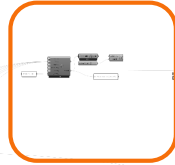
Hyperspectral Radiance

01
STEP



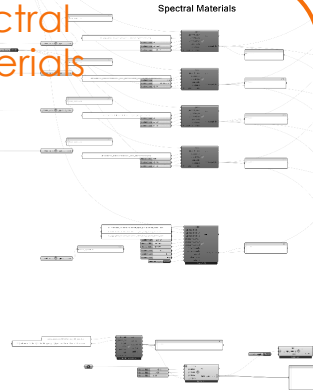
Spectral
Atmospheric
data

02
STEP



Spectral Point In Time

Spectral
Materials

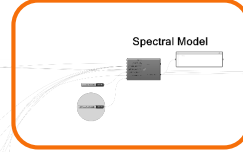


Spectral PIT Render

Spectral Annual

03
STEP

04
STEP

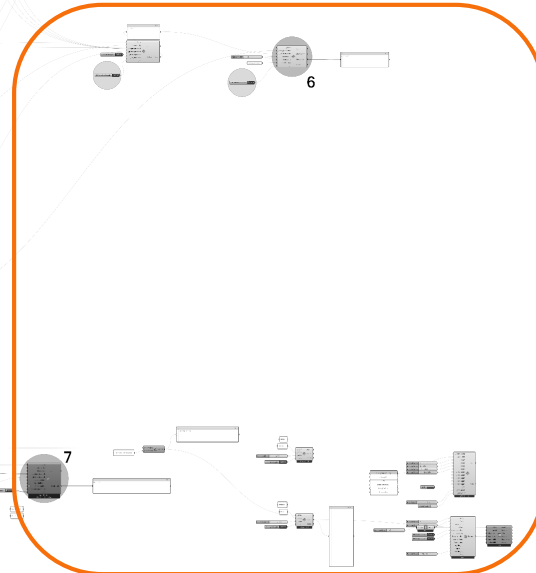


Spectral Model

Validation

05
STEP

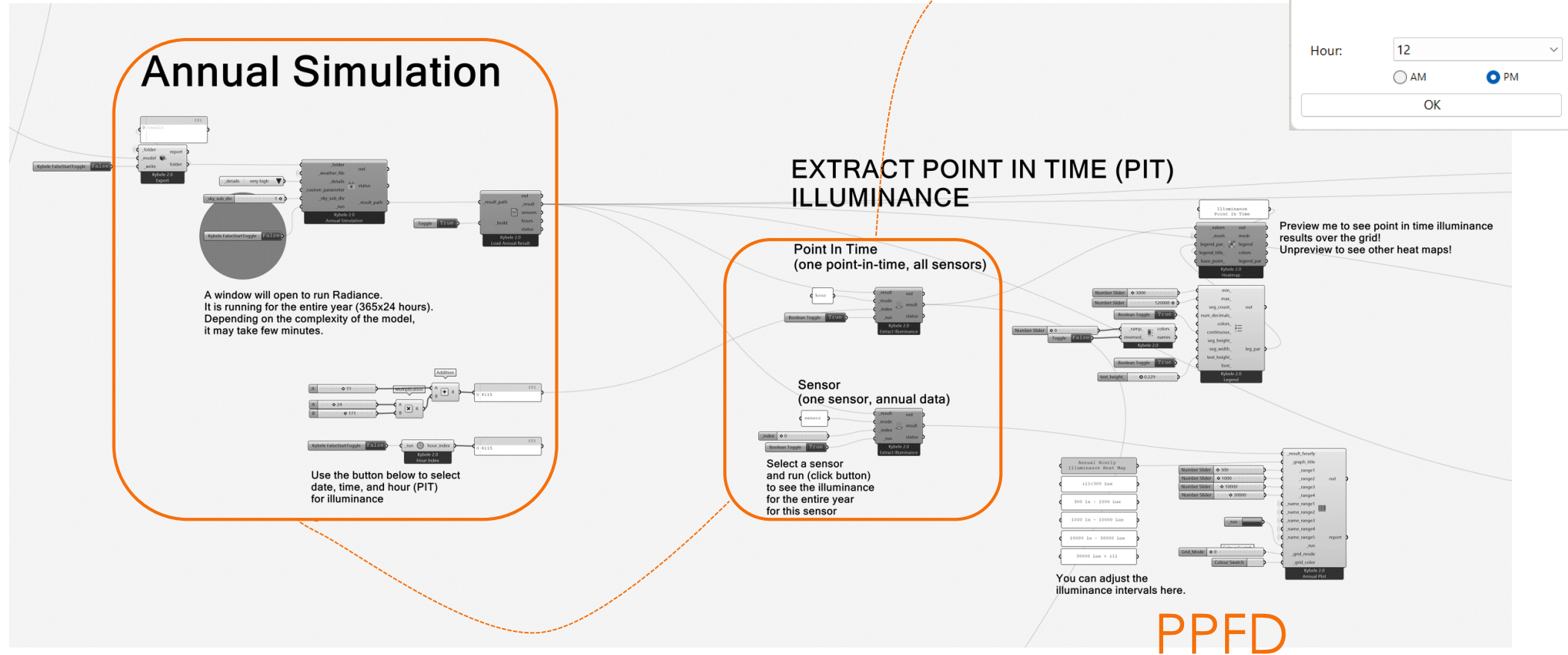
06
STEP



Irradiance

PPFD

Daily Data from Annual Simulation



Simulation Workflows

Greenhouse and surrounding geometry, material properties...



Aluminum

metal | RGB(0.900, 0.880, 0.880) | VLR: 0.9%

Material	R	G	B	Specularity	Roughness	VLR
Aluminum	0.900	0.880	0.880	0.80	0.02	0.9
Antique Copper	0.136	0.102	0.083	0.30	0.20	0.1
Birch Wood	0.494	0.313	0.181	0.00	0.00	0.4
Brass	0.726	0.563	0.223	0.85	0.00	0.6
Brushed Aluminum	0.790	0.790	0.790	0.50	0.10	0.8
Chrome	0.808	0.821	0.789	0.82	0.05	0.8
Conc Dirt	0.600	0.600	0.600	0.03	0.15	0.6
Concrete Grey	0.478	0.490	0.459	0.00	0.00	0.5
Dull Brass	0.700	0.200	0.080	0.40	0.10	0.3
Galvanized	0.975	0.975	0.975	0.80	0.15	1.0
Ground	0.200	0.200	0.200	0.03	0.15	0.2

Select

Reload



Glazing 55

glass | transmissivity 0.500 | -VLT 50.0%

Glazing	R	G	B	VLT
Glazing 55	0.500	0.500	0.500	50.0
Glazing 60	0.550	0.550	0.550	55.0
Glazing 65	0.600	0.600	0.600	60.0
Glazing 76	0.700	0.700	0.700	70.0
Glazing 82	0.750	0.750	0.750	75.0
Glazing 92	0.850	0.850	0.850	85.0
Glazing Clear Single	0.960	0.960	0.960	96.0
Glazing Double Clear	0.870	0.870	0.870	87.0
Glazing Double Low E	0.710	0.710	0.710	71.0
Glazing Triple	0.620	0.620	0.620	62.0
Greenhouse Poly Double	0.800	0.800	0.800	80.0

Select

Reload

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Simulation Workflows

Greenhouse and surrounding geometry, material properties, weather data, ...

Kybele Weather Stations - showing 1500, 68141 more (type to narrow)

All

Location	Country	State	WMO	Lat	Lon	Period	Local
Dhaka-Shahjalal.Intl.AP	BGD	DH	-	23.8430	90.3980	BGD_DH_Dhaka-Shahj...	yes
Seattle-Tacoma.Intl.AP	USA	WA	-	47.4500	-122.3000	USA_WA_Seattle-Taco...	yes
Seattle	USA	WA	-	47.6050	-122.3380	USA_WA_Seattle.9940...	yes
A.Coruna GA ESP	ESP	GA	080010	43.3658	-8.4214	TMYx.2004-2018	no
A.Coruna GA ESP	ESP	GA	080010	43.3658	-8.4214	TMYx.2007-2021	no
A.Coruna GA ESP	ESP	GA	080010	43.3658	-8.4214	TMYx.2009-2023	no
A.Coruna GA ESP	ESP	GA	080010	43.3658	-8.4214	TMYx.2011-2025	no
A.Coruna GA ESP	ESP	GA	080010	43.3658	-8.4214	TMYx	no
A.Coruna.AP GA ESP	ESP	GA	080020	43.3069	-8.3719	TMYx.2004-2018	no
A.Coruna.AP GA ESP	ESP	GA	080020	43.3069	-8.3719	TMYx.2007-2021	no
A.Coruna.AP GA ESP	ESP	GA	080020	43.3069	-8.3719	TMYx.2009-2023	no
A.Coruna.AP GA ESP	ESP	GA	080020	43.3069	-8.3719	TMYx.2011-2025	no
A.Coruna.AP GA ESP	ESP	GA	080020	43.3069	-8.3719	TMYx	no
A.Lu.Chih.Lao.Ka NM CHN	CHN	NM	535230	39.8830	108.0000	TMYx	no
Aachen NW DEU	DEU	NW	105010	50.7830	6.0950	TMYx.2011-2025	no
Aachen NW DEU	DEU	NW	105010	50.7830	6.0950	TMYx	no
Aadorf.Tanikon TG CHE	CHE	TG	066790	47.4800	8.9050	TMYx.2004-2018	no
Aadorf.Tanikon TG CHE	CHE	TG	066790	47.4800	8.9050	TMYx.2007-2021	no
Aadorf.Tanikon TG CHE	CHE	TG	066790	47.4800	8.9050	TMYx.2009-2023	no
Aadorf.Tanikon TG CHE	CHE	TG	066790	47.4800	8.9050	TMYx.2011-2025	no
Aadorf.Tanikon TG CHE	CHE	TG	066790	47.4800	8.9050	TMYx	no

Update world catalog...

Browse local EPW...

Download from URL...

Select

Reload

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Simulation Workflows

Greenhouse and surrounding geometry, material properties, weather data, electric light source, simulation type

Kybele IES Selector

GLR-390W12F-VBD All On

Lumens: 12285 | CCT: - | 307 W

Name	Lumens	Size	CCT	CRI	Vert Range	Horiz Range
☐ Silver metal housing with patterned lens	-	584x584x0 mm	-	-	0-180 (361)	0-90 (5)
☒ GLR-390W12F-VBD All On	12285	0x0x0 mm	-	-	0-180 (37)	0-360 (17)
☐ GLR-390W12F-VBD Bloom	5670	0x0x0 mm	-	-	0-180 (37)	0-360 (17)
☐ GLR-390W12F-VBD Veg	6735	0x0x0 mm	-	-	0-180 (37)	0-360 (17)

Select

Reload

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Simulation Workflows

Select Conversion Factor

Choose a source for the illuminance to PAR conversion factor

CIE-D55 = 0.017833

CIE-D65 = 0.018043

CIE-D75 = 0.018345

CIE-HPS-1 = 0.011640

CIE-HPS-5 = 0.016180

CIE-LED-BH1 = 0.013633

CIE-LED-V2 = 0.017691

Custom Spectra (CSV)
Load a CSV or enter the conversion factor.
Tip: if the CSV contains the pre calculated factor, open it to view and then paste the value here.

Open CSV...

Factor: 0.018043 Use this factor

CIE-D65: 0.018043

Set Factor and Close

Spectral Data

Load Spectral Data

Conversion Factor Calculation
0.000000000 Update Conversion Factor

Calculated: (No file loaded)
Sum of Calculated PAR: 0.000000
Sum of Calculated Lx: 0.000000

Save as CSV File

Set conversion factor and close

Wavelength (nm)	Equal PAR	PAR Spectral	OPN1	Spectral Power	Calculated PAR	Calculated Lx
380	0	0	3.9E-05	0	0	0
381	0	0	4.28264E-05	0	0	0
382	0	0	4.69146E-05	0	0	0
383	0	0	5.15896E-05	0	0	0
384	0	0	5.71764E-05	0	0	0
385	0	0	6.4E-05	0	0	0
386	0	0	7.23442E-05	0	0	0
387	0	0	8.22122E-05	0	0	0
388	0	0	9.35082E-05	0	0	0
389	0	0	0.0001061361	0	0	0

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How are we calculating PPFD?

PPDF DLI Values

3-channel annual lighting simulations: user-specified light source type or user-specified light spectra
Spectral simulations: calculated directly from spectral radiance

Conversion from Lux to PAR:

$$\text{PPFD} = \text{Lux} * \text{coef}$$

Conversion from Irradiance to PAR

$$\text{PPFD} = \int_{400}^{700} \frac{\lambda * E(\lambda)}{N_A * h * c} d(\lambda)$$

λ : Wavelength of the light.

$E(\lambda)$: Spectral irradiance (energy per wavelength).

Avogadro's constant ($6.022 \times 10^{23} \text{ mol}^{-1}$).

h : Planck's constant ($6.626 \times 10^{-34} \text{ J}\cdot\text{s}$).

c : Speed of light ($2.998 \times 10^8 \text{ m/s}$)

CONVERSION FACTOR FROM ILLUMINANCE TO PPFD

Kybele FalseStartToggle: False

Kybele Spectral Data

0.011655

Select Conversion Factor

Choose a source for the illuminance to PAR conversion factor

CIE-D55	= 0.017833
CIE-D65	= 0.018043
CIE-D75	= 0.018345
CIE-HPS-1	= 0.011640
CIE-HPS-5	= 0.016180
CIE-LED-BH1	= 0.013633
CIE-LED-V2	= 0.017691

Custom Spectra (CSV)

Load a CSV or enter the conversion factor.
Tip: if the CSV contains the pre calculated factor, open it to view and then paste the value here.

Open CSV...

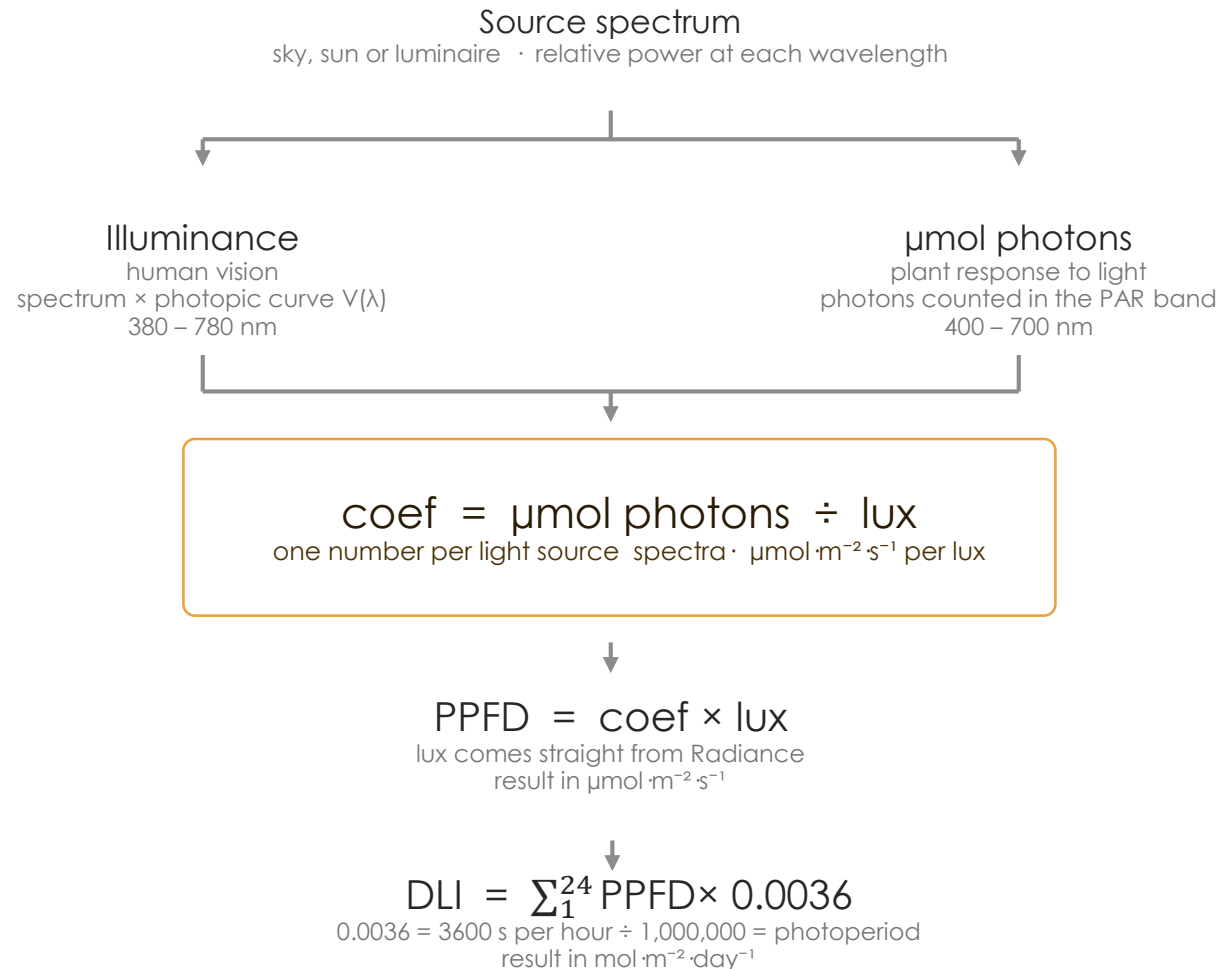
Factor: 0.011655 Use this factor

testCustom.csv: 0.011655

Set Factor and Close

Spectral conversion — lux to PPFD and DLI

Radiance reports radiometric / photometric units. Plants count photons.



Conversion factors

cf in $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ per lux

D55 daylight	0.017833
D65 daylight	0.018043
D75 daylight	0.018345
HPS-1	0.011640
HPS-5	0.016180
LED-BH1	0.013633

D65 is the Kybele default

Typical crop targets

lettuce $\approx 17 \text{ mol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$
tomato $\approx 30 \text{ mol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$

How are we calculating DLI?

Integrating from PPFD over 24 hour period

DLI Values - Generic

Vegetative Growth (Leafy Greens/Herbs): $> 17 \text{ mol/m}^2/\text{d}$

Flowering Crops (Peppers/Tomatoes): $20\text{-}40 \text{ mol/m}^2/\text{d}$

Broccoli: $15\text{-}35 \text{ mol/m}^2/\text{d}$

Tomatoes: $22\text{-}30 \text{ mol/m}^2/\text{d}$

Cucumbers: $20\text{-}30 \text{ mol/m}^2/\text{d}$

Zucchini: $22\text{-}28 \text{ mol/m}^2/\text{d}$

Peppers: $20\text{-}30 \text{ mol/m}^2/\text{d}$

Butter Lettuce: $14\text{-}17 \text{ mol/m}^2/\text{d}$

Cantelope: $25\text{-}30 \text{ mol/m}^2/\text{d}$

Arugula: $15\text{-}20 \text{ mol/m}^2/\text{d}$

Basil: $15\text{-}25 \text{ mol/m}^2/\text{d}$

Bok Choy: $10\text{-}12 \text{ mol/m}^2/\text{d}$

Avocado: $18\text{-}24 \text{ mol/m}^2/\text{d}$

African Violet: $4\text{-}14 \text{ mol/m}^2/\text{d}$

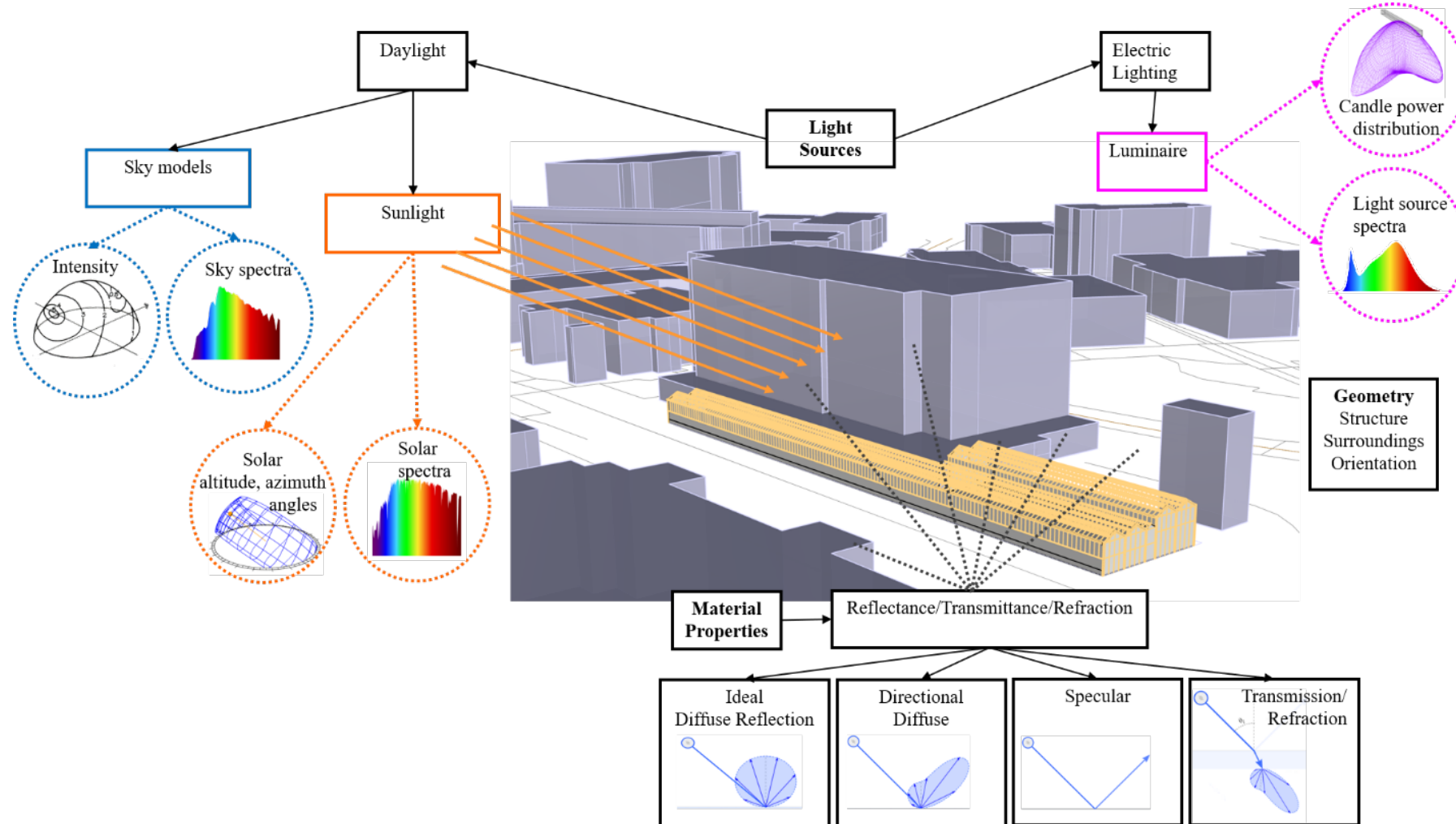
Cyclamen: $6\text{-}8 \text{ mol/m}^2/\text{d}$

Succulents: $3\text{-}6 \text{ mol/m}^2/\text{d}$

Chrysanthemums: $20\text{-}30 \text{ mol/m}^2/\text{d}$

Case Study:

University of Washington Greenhouse



Case Study:

University of Washington Greenhouse: Materials



Floor: Concrete
plastic (Concrete_grey)



Structure: Aluminum
metal (aluminum)



Wood
plastic (larch_wood)



Ground
plastic (ground)



Glazing
glass (glazing_92)

Floor: Concrete

```
void plastic Concrete_grey
0
0
5 0.478431 0.490196 0.458824 0 0
```

Structure: Aluminum

```
void metal aluminum
0
0
5 0.9 0.88 0.88 0.8 0.02
```

Ground

```
void plastic ground
0
0
5 0.20 0.20 0.20 0.03 0.15
```

Glazing

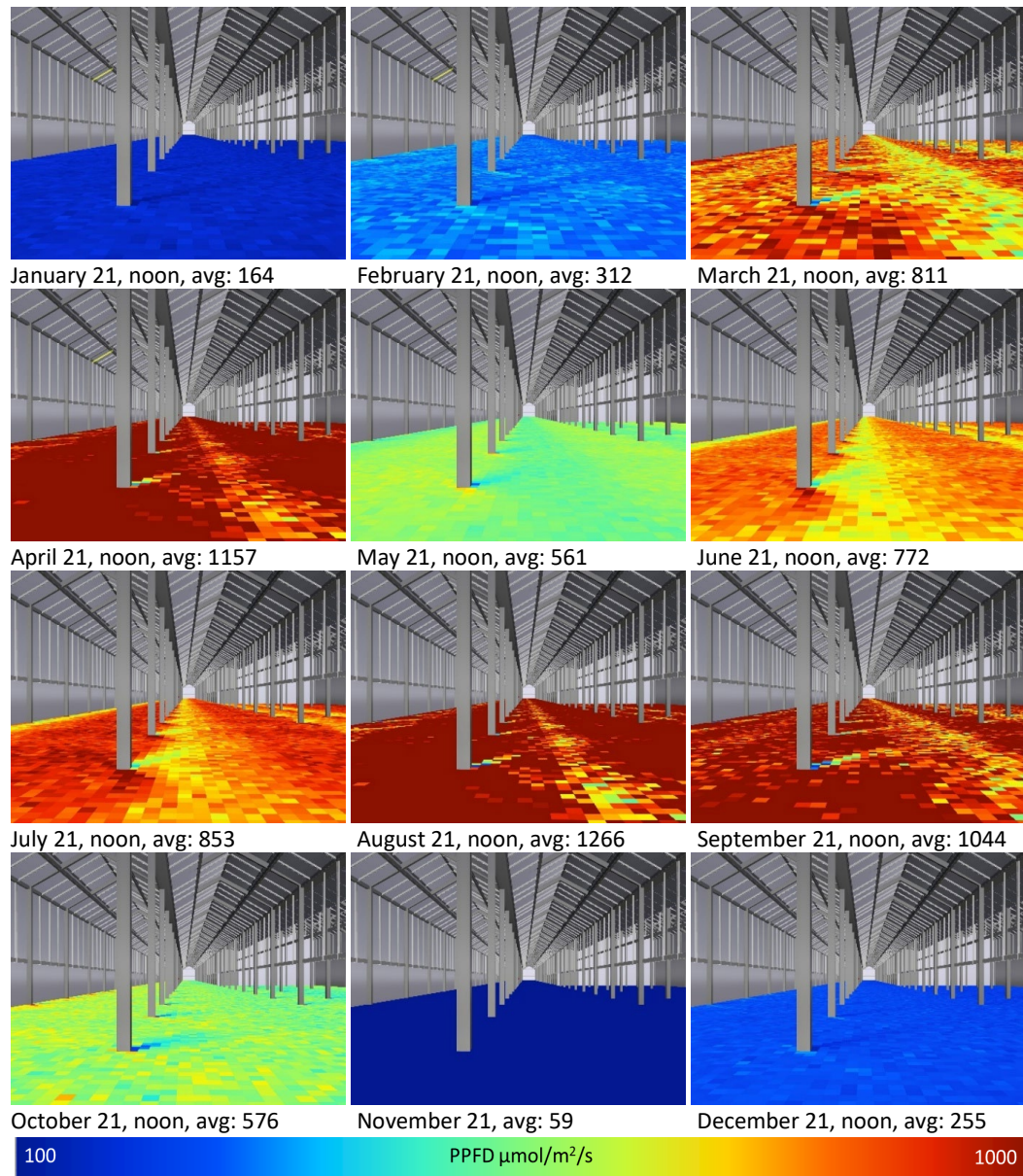
```
void glass glazing_92
0
0
3 0.85 0.85 0.85
```

Wood

```
void plastic larch_wood
0
0
5 0.528 0.294 0.14 0.0 0.0
```

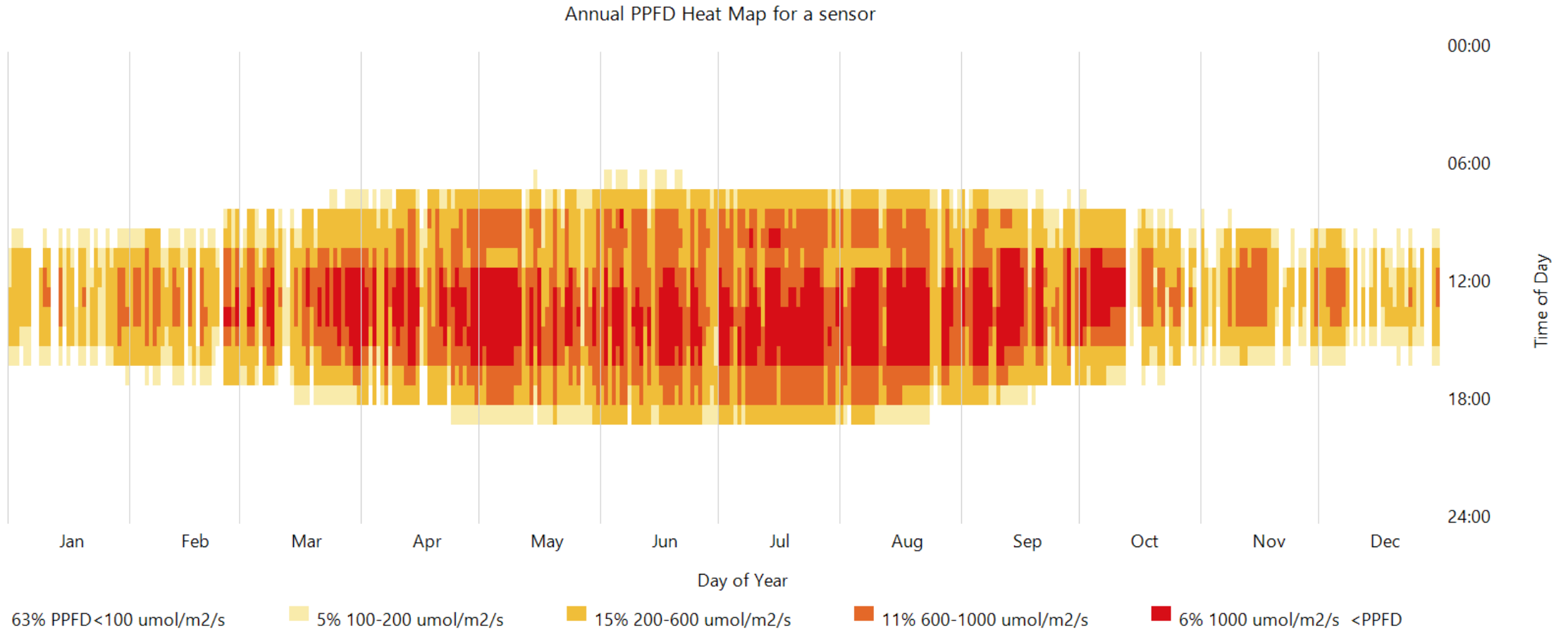
PPFD

One Point in Time Each Month



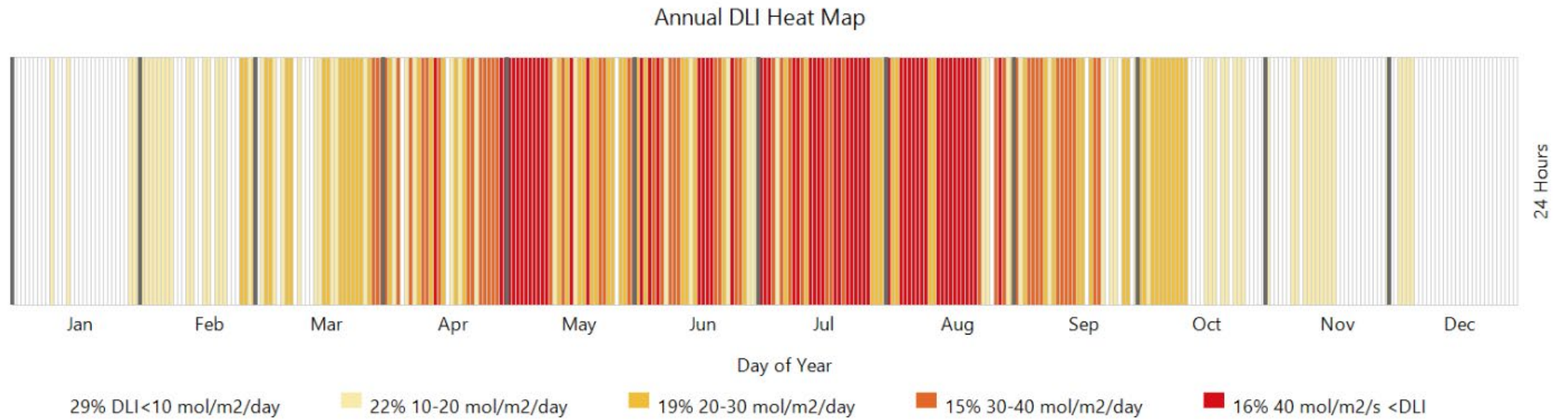
PPFD

At One Sensor Throughout the Year



DLI

At One Sensor Throughout the Year

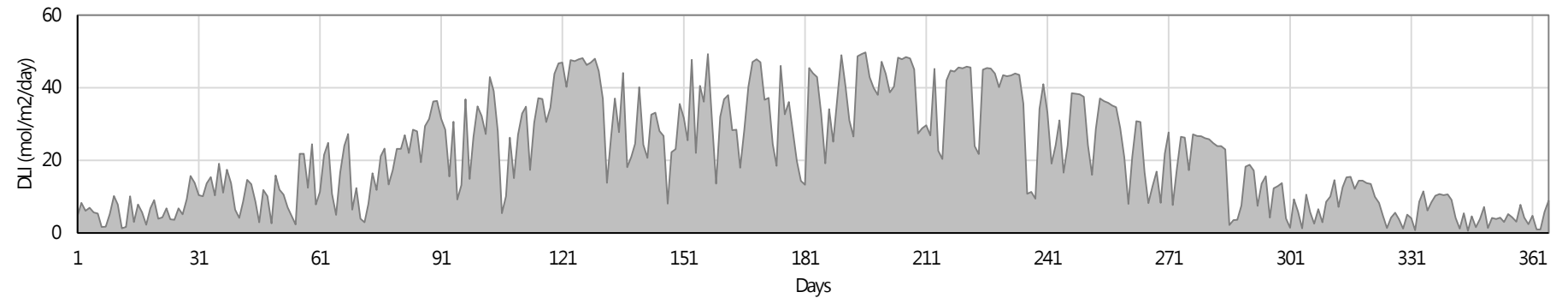


ENERGY

Energy required to meet the target DLI

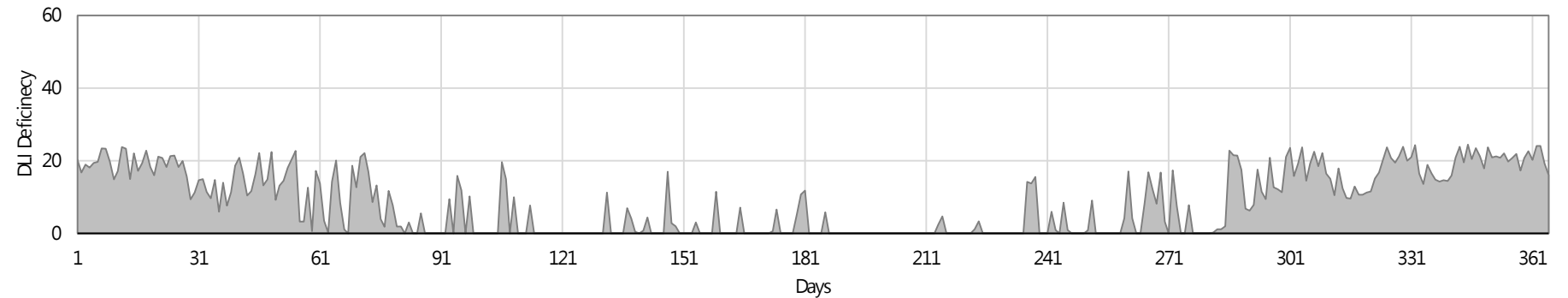
01 DLI Availability

DLI Availability of the modeled Greenhouse



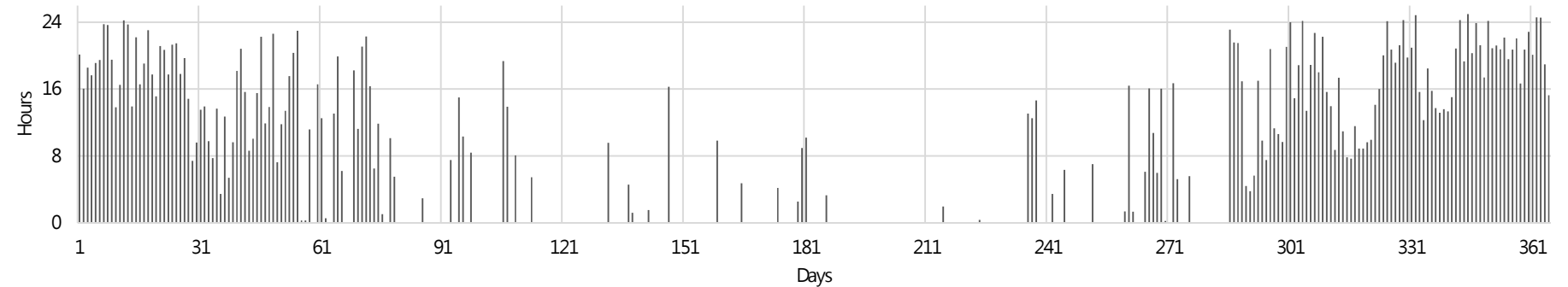
02 DLI Deficiency

DLI deficiency for a crop requiring 22 $\text{mol.m}^2/\text{day}$ year-round



03 Hours Required

Daily supplemental electric lighting that provides an average of 238 $\mu\text{mol/m}^2/\text{s}$



SUPPLEMENTAL LIGHTING OVERVIEW

Energy and sustainability
concern in CEA

LESS THAN

<1%

of U.S. food crops
supplied by CEA

YET

MORE ENERGY

than all open-field agriculture

Meta-analysis scope: 116 studies, 40 countries, 23 crop types. Source: Mills, 2025.

ELECTRIC LIGHTING SHARE

0–95%

of total CEA energy use,
depending on building type,
location, crop, and light-source
efficiency.

Mills, E. (2025). "The emergence of indoor agriculture as a driver of global energy demand." npj Sustainable Agriculture, 3, Article 52. <https://doi.org/10.1038/s44264-025-00091-z>



Available to download from Food4Rhino and Github

Previous release includes:

Three Channel

Next Update: **Hyperspectral**

Continuing Development: **Thermal simulations**

Forthcoming publication: Inanici M and Islam S. "Lighting simulations in greenhouses," Oliver Körner and Gundula Proksch (Eds.), Advances in Controlled Environment Agriculture, Burleigh Dodds Science Publishing.

This work has been funded by the NSF project "Belmont Forum Collaborative Research: Aquaponics optimization in a local climatic, economic, and cultural context", 2024-2027.

We thank Prof. Gundula Proksch for her collaboration.



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EVALUATING URBAN GREENHOUSES

QUESTIONS



Shafiul Islam
Mehlika Inanici
University of Washington, Department of Architecture