Introducing LetsGrow

A psychrometric software

https://gpe.letsgrow.com/psychro

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Psychrometrics

Simulation models

Radiation monitor

Absolute Humidity AH (g/kg) or (g/m3)

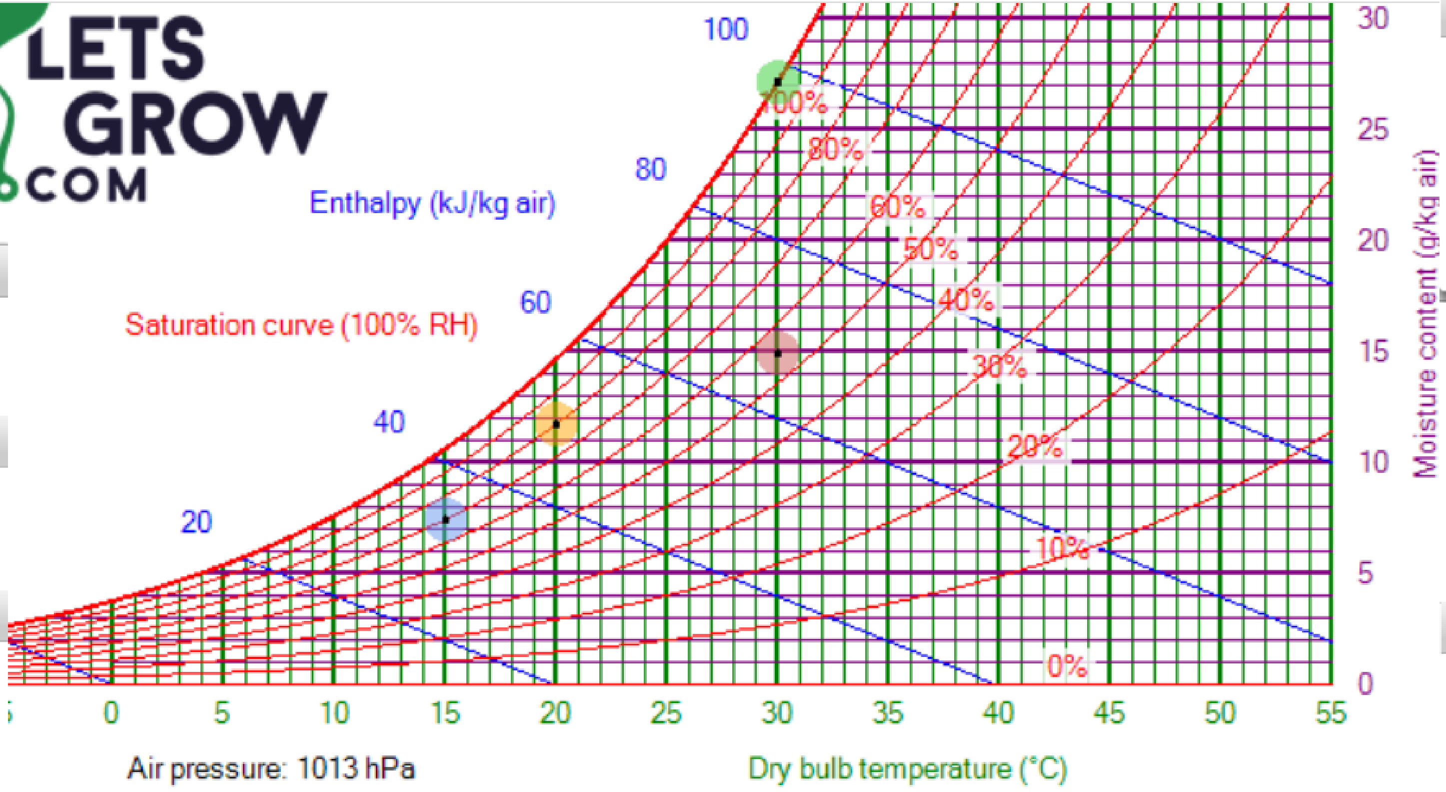
The Absolute Humidity AH is the number of grams of watervapour that is actual present per kilo of air or per m3 of air.

Humidity Deficit HD (g/kg) or (g/m3)

Humidity Deficit is the amount of water vapour in grams that is needed to achieve full saturation of 1 kilo of air or 1 m3 of air at the current temperature.

Enthalpy (kJ/kg) or (kJ/m3)

The Enthalpy in kJ/kg is the energy content of 1 kilo of air in kiloJoule: the energy that is needed to heat up 1 kilo of air to the current temperature (sensible heat) plus the energy that is needed to evaporate the present watercontent (latent heat). The enthalpy in kJ/m3 is the energy content of 1 cubic meter of air in kiloJoule.



VPD Vapour Pressure Deficit (kPa)

Vapour Pressure Deficit is the difference between the maximum possible vapour pressure VPsat at the current temperature and the actual vapour pressure VP in kilo Pascal (kPa).
Note that VPD can also mean: Vapour Pressure Difference between the Plant and the Inside air. This Vapor Pressure Difference is shown in the column "Difference" between the VP value "Inside" and VP value "Plant".

Dewpoint temperature (°C)

The Dewpoint temperature of the air is that temperature at which the actual moisture content equals the maximum possible moisture content. If air is beeing cooled down below dewpoint condensation will occur.

sychro diagram | More info

Air pressure 1013 hF

	Outside	Difference	Above screen	Difference	Inside	Difference	Plant
Temp	15 °C	5.00	20 °C	10.00	30 °C	--	30 °C
RH	70 %	10.00	80 %	-25.00	55 %	--	100 %
Absolute Humidity AH	7.44 g/kg	-3.95	11.73 g/kg	3.20	14.93 g/kg	--	27.15 g/kg
Humidity Deficit HD	3.19 g/kg	-2.32	2.93 g/kg	9.28	12.22 g/kg	--	0.00 g/kg
Enthalpy	33.63 kJ/kg	-22.91	49.33 kJ/kg	17.95	67.29 kJ/kg	--	97.67 kJ/kg
VPD	0.51 kPa	-0.37	0.47 kPa	1.44	1.91 kPa	--	0.00 kPa
VP	1.19 kPa	-0.63	1.87 kPa	0.46	2.33 kPa	--	4.25 kPa
VPsat	1.71 kPa	-1.00	2.34 kPa	1.91	4.25 kPa	--	4.25 kPa
Dewpoint	9.6 °C	-10.7	16.4 °C	3.5	20.0 °C	--	30.0 °C

Air pressure 1013 hPa

1 ATM = sea level, altitude = 0 m

Inside		Difference	Plant	
Temp	30 °C	--	Temp	30 °C
RH	55 %	--	RH	100 %
Absolute Humidity AH	14.93 g/kg	12.22	Absolute Humidity AH	27.15 g/kg
Absolute Humidity AH	17.19 g/m³	13.84	Absolute Humidity AH	31.02 g/m³
Humidity Deficit HD	12.22 g/kg	-12.22	Humidity Deficit HD	0.00 g/kg
Humidity Deficit HD	14.[illegible]	[illegible]	[illegible] Deficit HD	0.00 g/m³
Enthalpy	67.[illegible]	[illegible]	[illegible]	97.67 kJ/kg
Enthalpy	77.[illegible]	[illegible]	[illegible]	111.61 kJ/m³
VPD = VPsat - VP	1.91 kPa	-1.91	VPD	0.00 kPa
VP	2.33 kPa	1.91	VP	4.25 kPa
VPsat	4.25 kPa	0.00	VPsat	4.25 kPa
Dewpoint	20.0 °C	10.0	Dewpoint	30.0 °C

RH inside stomata is 100%

This is AH_{dif}

This is AHD or HD

This is VP_{dif}

$AH_{dif} > 0$ to ensure water vapor inside stomata can be escaped to outside

Micro-climate

Inside		Difference	Plant	
Temp	30 °C	-1.00	Temp	29 °C
RH	80 %	10.00	RH	90 %
Absolute Humidity AH	21.72 g/kg	1.29	Absolute Humidity AH	23.01 g/kg
Absolute Humidity AH	24.90 g/m³	1.55	Absolute Humidity AH	26.44 g/m³
Humidity Deficit HD	5.43 g/kg	-2.87	Humidity Deficit HD	2.56 g/kg
Humidity Deficit HD	6.22 g/		HD	2.94 g/m³
Enthalpy	84.16 kJ/			86.38 kJ/kg
Enthalpy	96.49 kJ/m³	2.79	Enthalpy	99.28 kJ/m³
VPD = VPsat - VP	0.85 kPa	-0.45	VPD	0.40 kPa
VP	3.40 kPa	0.21	VP	3.61 kPa
VPsat	4.25 kPa	-0.24	VPsat	4.01 kPa
Dewpoint	26.2 °C	1.0	Dewpoint	27.2 °C

This is AH_{dif}

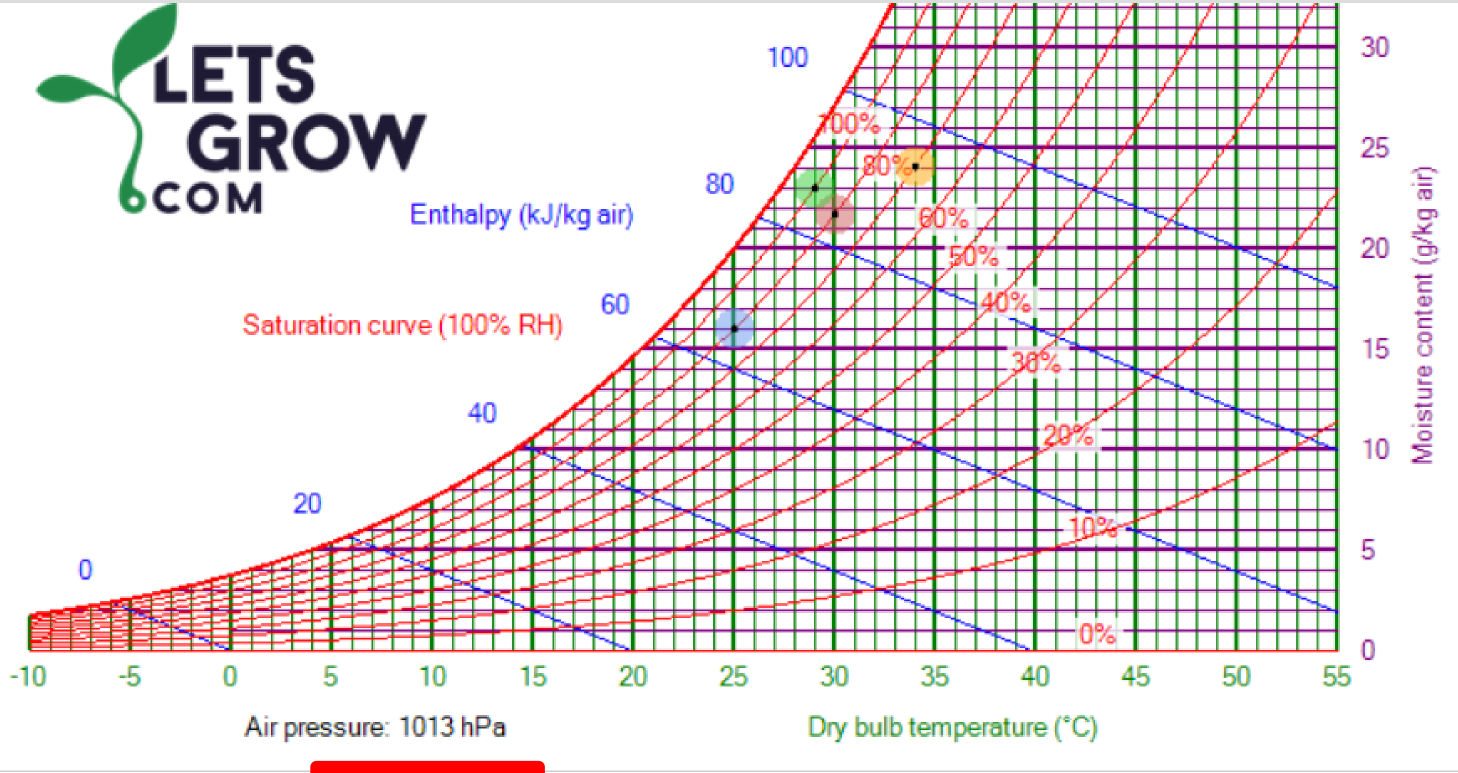
This is VP_{dif}

AH_{dif}>0 to ensure water vapor move away from crop canopy

AHD is not equal to AH_{dif}, AHD is the AH@Tsat – AH@Tdb

VPD is not equal to VP_{dif}, VPD is the VP@Tsat – VP@Tdb

Detail version



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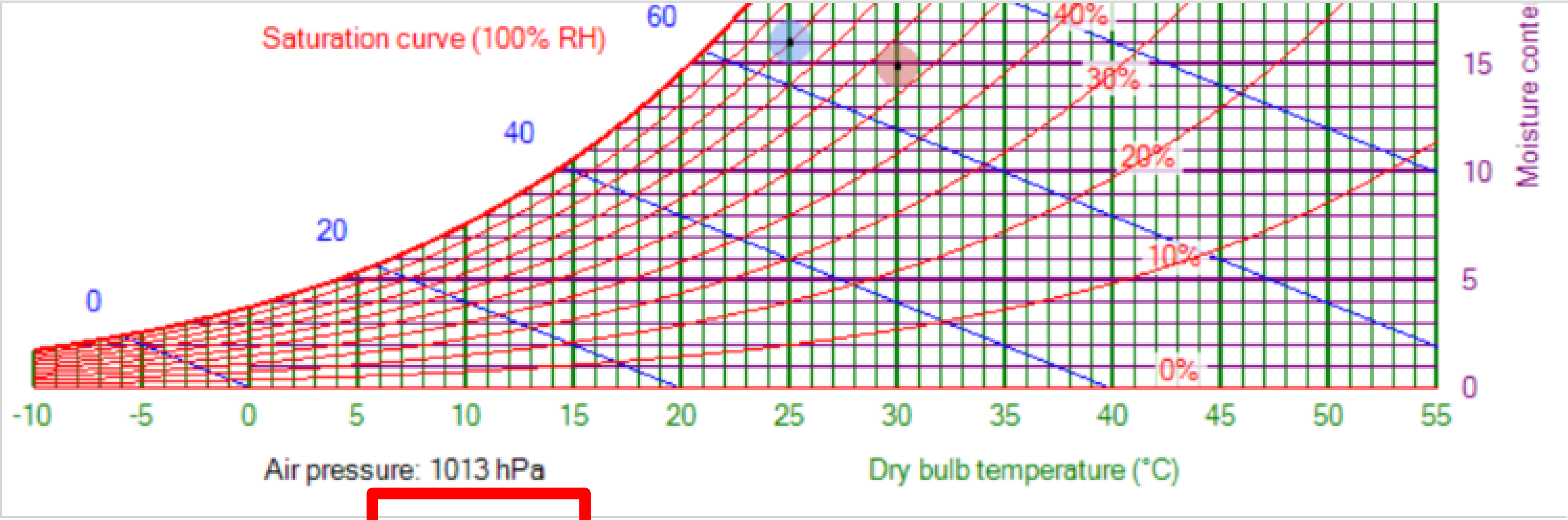
Air pressure 1013 hPa

	Outside	Difference	Above screen	Difference	Inside	Difference	Plant
Temp	25 °C	9.00	34 °C	-4.00	30 °C	-1.00	29 °C
RH	80 %	-10.00	70 %	10.00	80 %	10.00	90 %
Absolute Humidity AH	16.03 g/kg	8.06	24.10 g/kg	-2.38	21.72 g/kg	1.29	23.01 g/kg
Absolute Humidity AH	18.75 g/m³	8.47	27.23 g/m³	-2.33	24.90 g/m³	1.55	26.44 g/m³
Humidity Deficit HD	4.01 g/kg	6.32	10.33 g/kg	-4.90	5.43 g/kg	-2.87	2.56 g/kg
Humidity Deficit HD	4.69 g/m³	6.98	11.67 g/m³	-5.44	6.22 g/m³	-3.29	2.94 g/m³
Enthalpy	65.04 kJ/kg	29.02	94.05 kJ/kg	-9.89	84.16 kJ/kg	2.21	86.38 kJ/kg
Enthalpy	76.07 kJ/m³	30.20	106.27 kJ/m³	-9.78	96.49 kJ/m³	2.79	99.28 kJ/m³
VPD	0.63 kPa	0.96	1.60 kPa	-0.75	0.85 kPa	-0.45	0.40 kPa
VP	2.53 kPa	1.19	3.73 kPa	-0.33	3.40 kPa	0.21	3.61 kPa
VPsat	3.17 kPa	2.15	5.32 kPa	-1.08	4.25 kPa	-0.24	4.01 kPa
Dewpoint	21.3 °C	6.4	27.8 °C	-1.6	26.2 °C	1.0	27.2 °C

Simplify version



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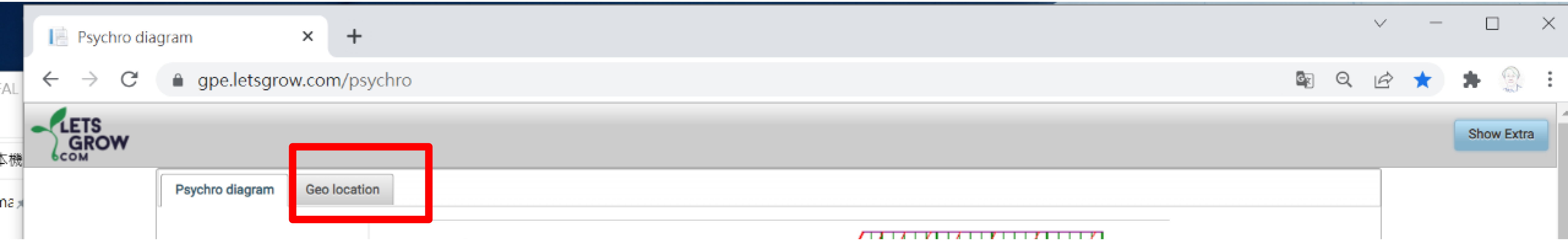
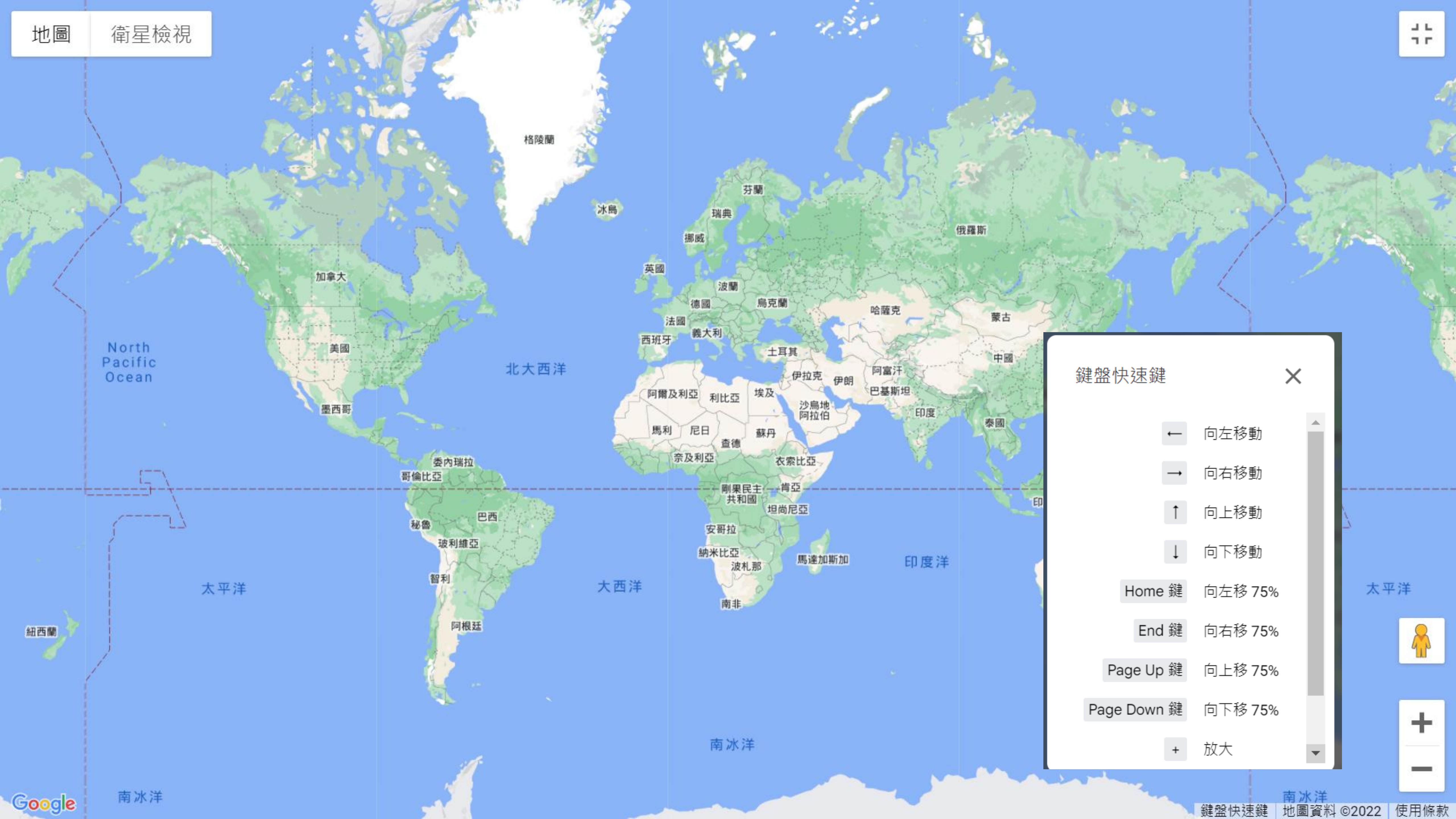
Air pressure 1013 hPa

	Outside	Difference	Above screen	Difference	Inside	Difference	Plant
Temp	25 °C	9.00	34 °C	-4.00	30 °C	0.00	30 °C
RH	80 %	-10.00	70 %	-15.00	55 %	45.00	100 %
Absolute Humidity AH	16.03 g/kg	8.06	24.10 g/kg	-9.16	14.93 g/kg	12.22	27.15 g/kg
Humidity Deficit HD	4.01 g/kg	6.32	10.33 g/kg	1.89	12.22 g/kg	-12.22	0.00 g/kg
Enthalpy	65.04 kJ/kg	29.02	94.05 kJ/kg	-26.77	67.29 kJ/kg	30.38	97.67 kJ/kg
VPD	0.63 kPa	0.96	1.60 kPa	0.31	1.91 kPa	-1.91	0.00 kPa
VP	2.53 kPa	1.19	3.73 kPa	-1.39	2.33 kPa	1.91	4.25 kPa
VPsat	3.17 kPa	2.15	5.32 kPa	-1.08	4.25 kPa	0.00	4.25 kPa
Dewpoint	21.3 °C	6.4	27.8 °C	-7.8	20.0 °C	10.0	30.0 °C

Geo location



Bring in the outdoor T and RH info from worldwide weather station into the psychrometric software



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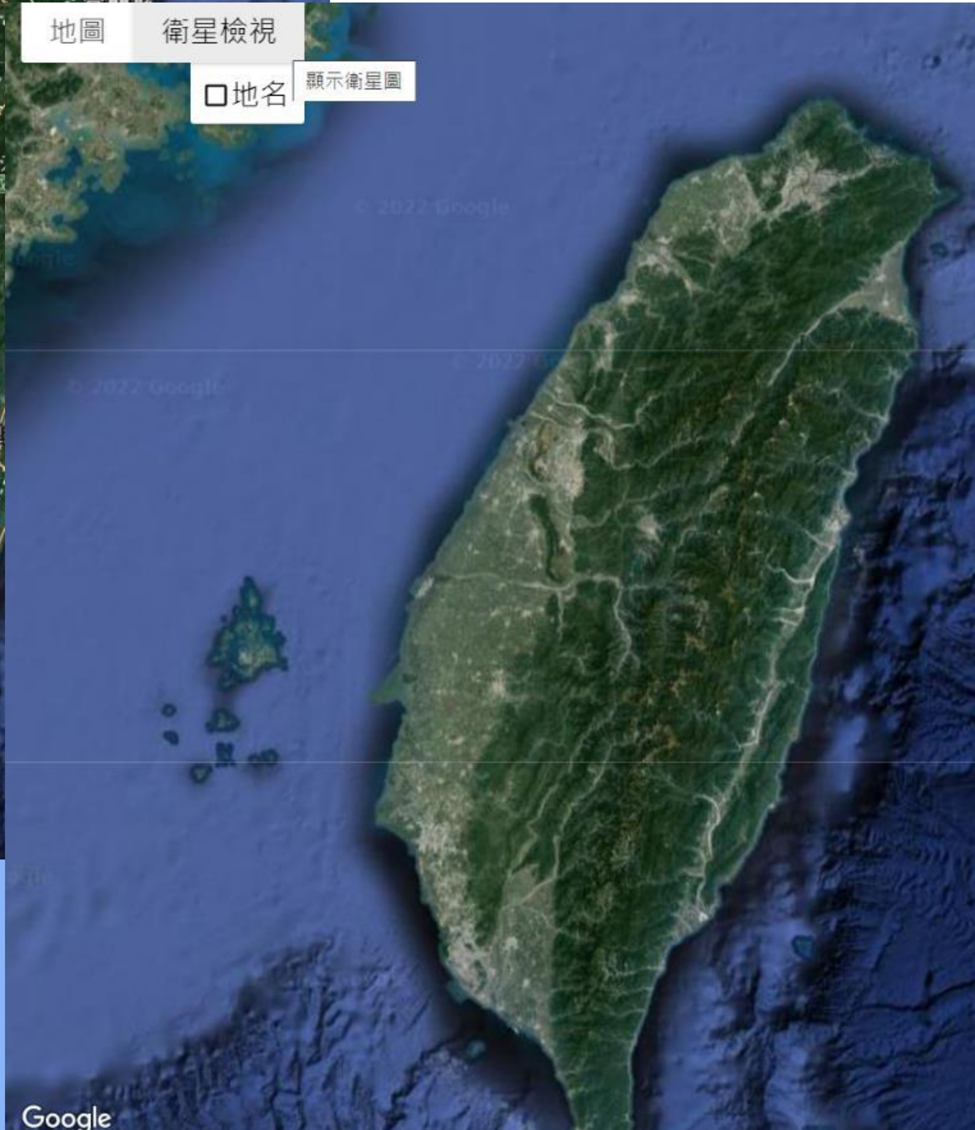
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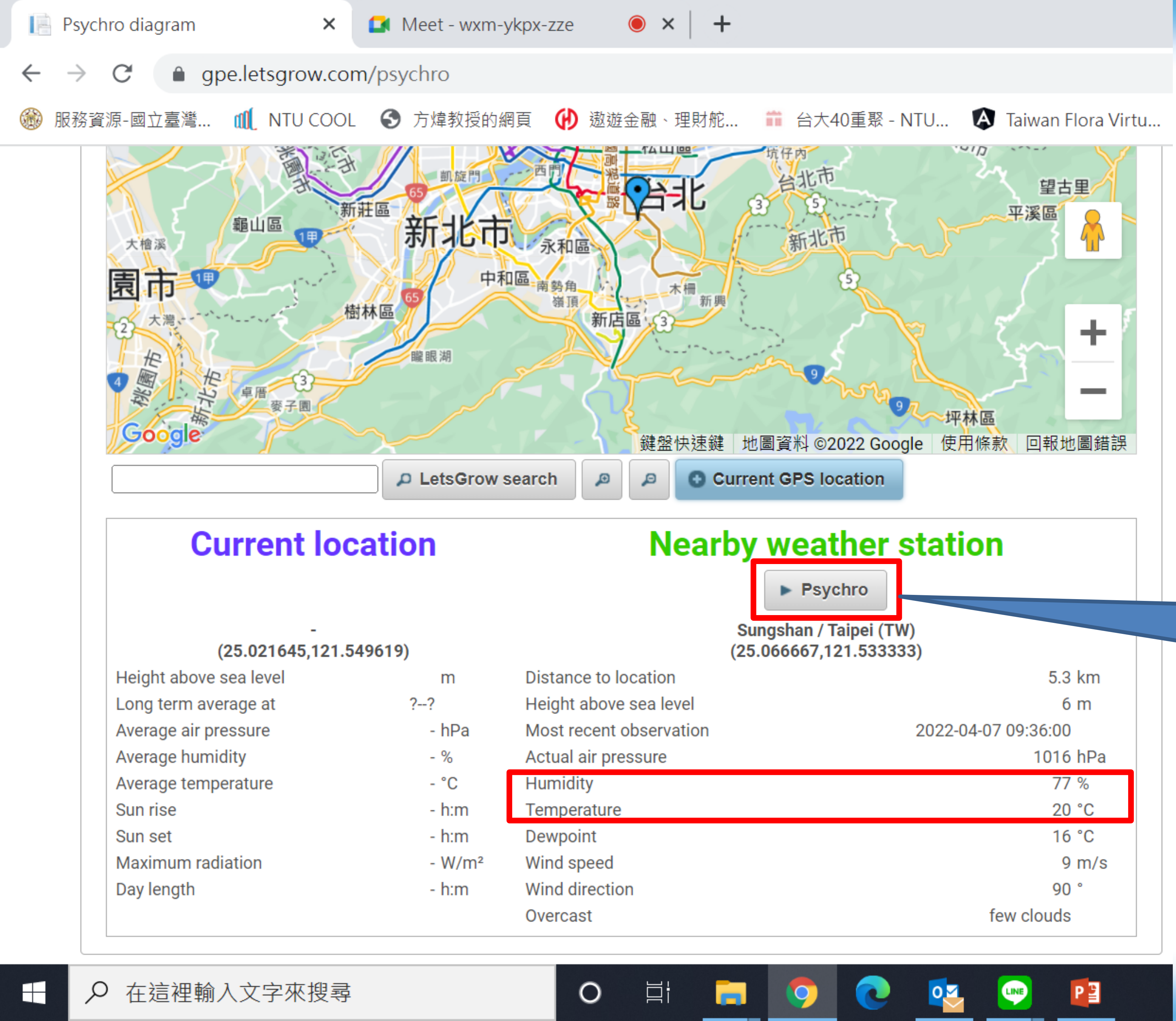

Click on this icon can bring the weather condition to the Psychro software

Meet - wxm-ykpx-zze | Psychro diagram

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LetsGrow search | Current GPS location

Current location

-

(51.915473,4.339428)

Height above sea level		m
Long term average at	?--?	
Average air pressure	-	hPa
Average humidity	-	%
Average temperature	-	°C
Sun rise	-	h:m
Sun set	-	h:m
Maximum radiation	-	W/m²
Day length	-	h:m

Nearby weather station

▶ Psychro

Rotterdam Airport Zestienhoven (NL)
(51.950000,4.450000)

Distance to location	8.5 km
Height above sea level	-5 m
Most recent observation	2022-04-07 09:55:00
Actual air pressure	982 hPa
Humidity	66 %
Temperature	10 °C
Dewpoint	4 °C
Wind speed	24 m/s
Wind direction	250 °
Overcast	scattered clouds

Meet - wxm-ykpx-zze | Psychro diagram

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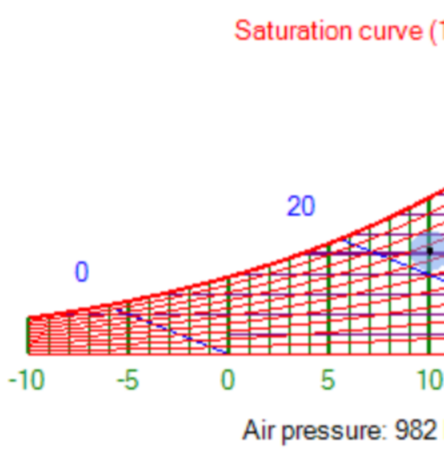
服務資源-國立臺灣... NTU COOL 方煒教授的網頁 遨遊金融、理



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	Outside		Difference	Above se
Temp	10	°C	9.00	Temp
RH	66	%	12.00	RH
Absolute Humidity AH	5.19 g/kg		5.89	Absolute Humidity AH
Humidity Deficit HD	2.67 g/kg		0.45	Humidity Deficit HD
Enthalpy	23.00 kJ/kg		23.71	Enthalpy
VPD	0.42 kPa		0.07	VPD
VP	0.81 kPa		0.90	VP
VPsat	1.23 kPa		0.97	VPsat
Dewpoint	3.9 °C		11.1	Dewpoint

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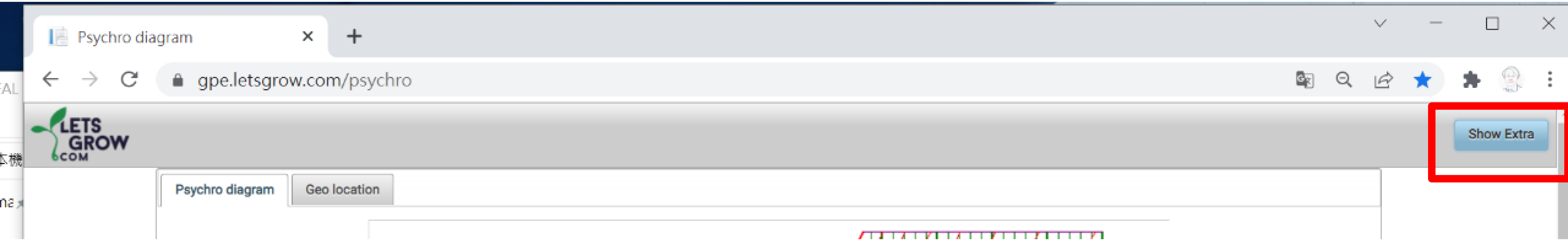
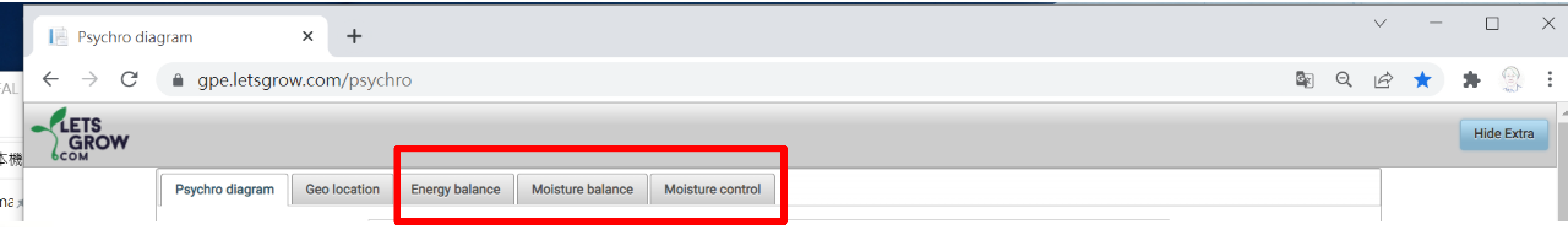
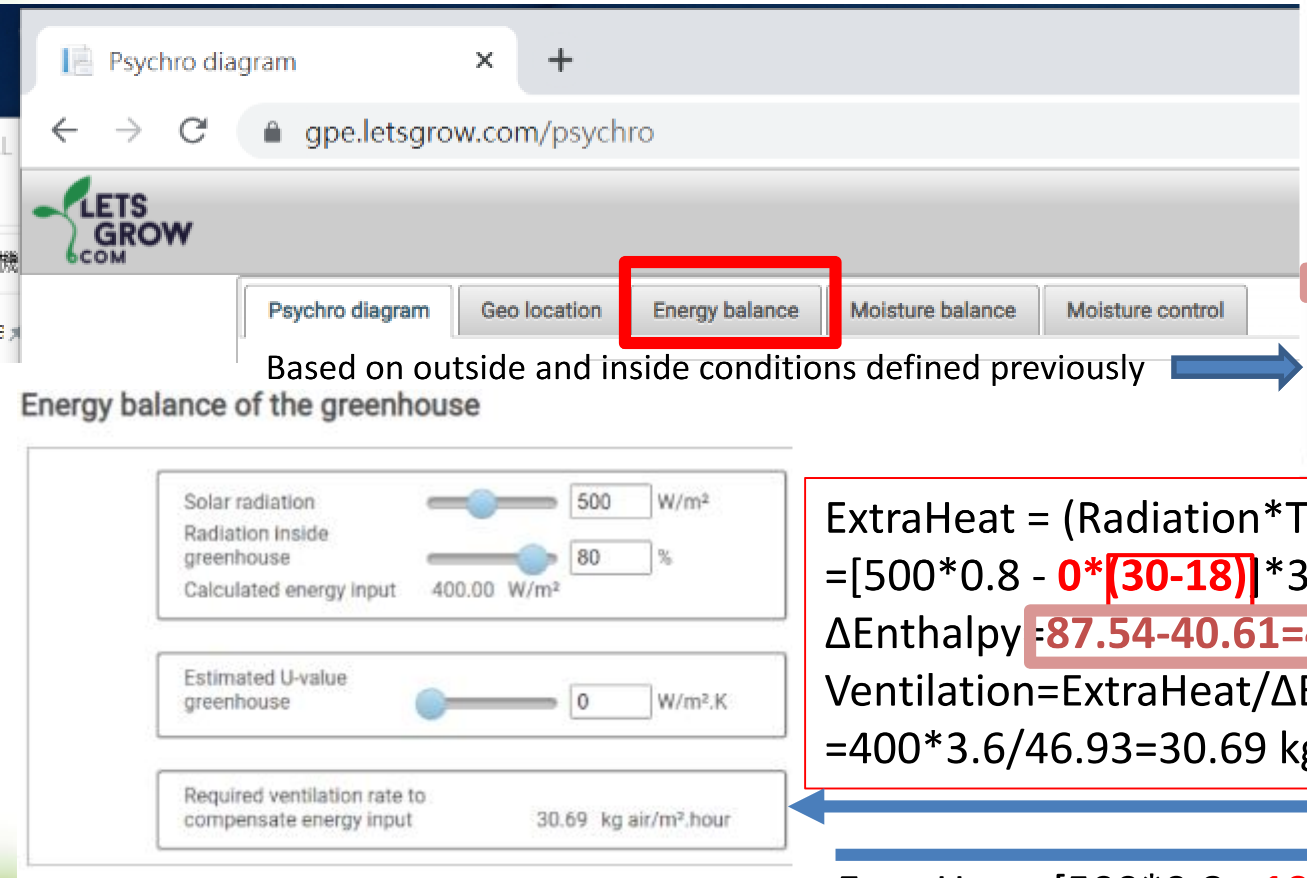
Three Extra Analysis

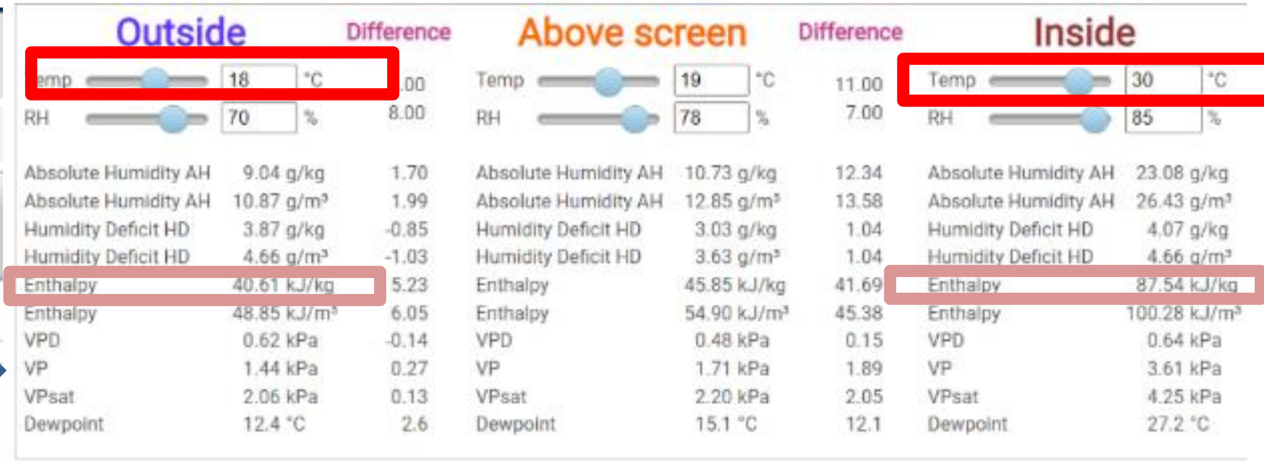




Energy Balance



Based on outside and inside conditions defined previously



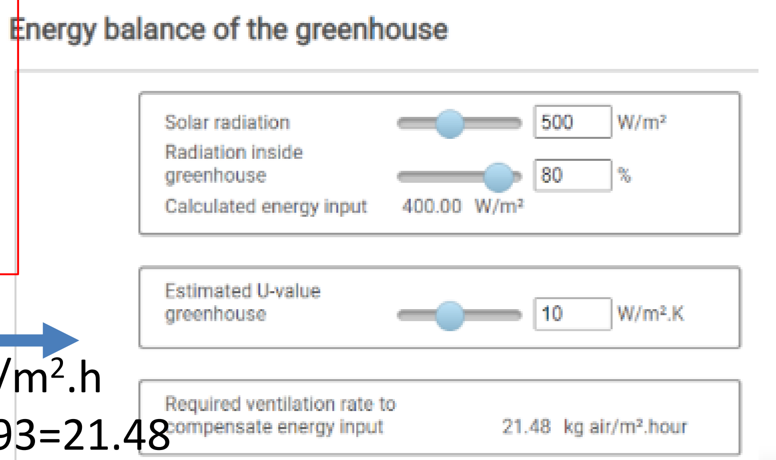
ExtraHeat = (Radiation*Transmittance) – (U*dT)

=[500*0.8 - **0*(30-18)**]*3600/1000 kJ/m².h

ΔEnthalpy =**87.54-40.61=46.93** kJ/kg

Ventilation=ExtraHeat/ΔEnthalpy

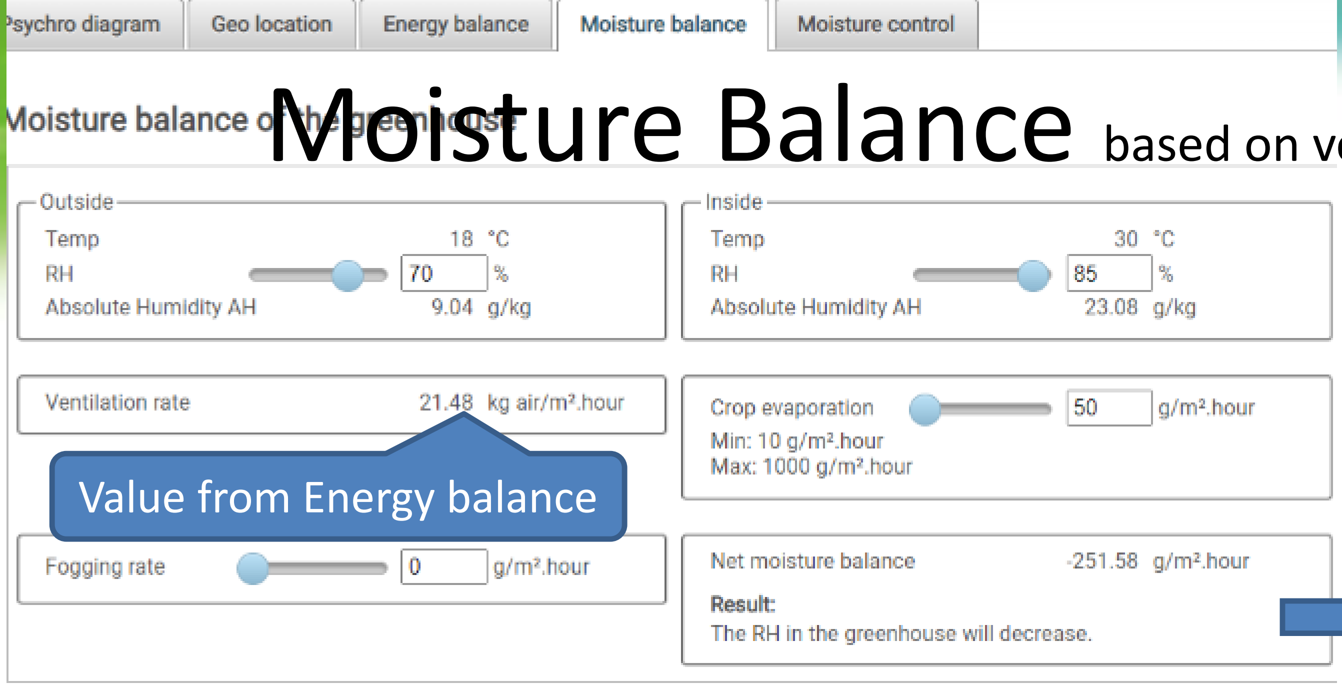
=400*3.6/46.93=30.69 kg/m².h



ExtraHeat=[500*0.8 - **10*(30-18)**]*3600/1000 kJ/m².h

Ventilation=ExtraHeat/ΔEnthalpy=(400-**120**)/46.93=21.48

Moisture Balance based on ventilation rate derived from energy balance



AH_{dif} = 23.08 - 9.04 = 14.04 g/kg air

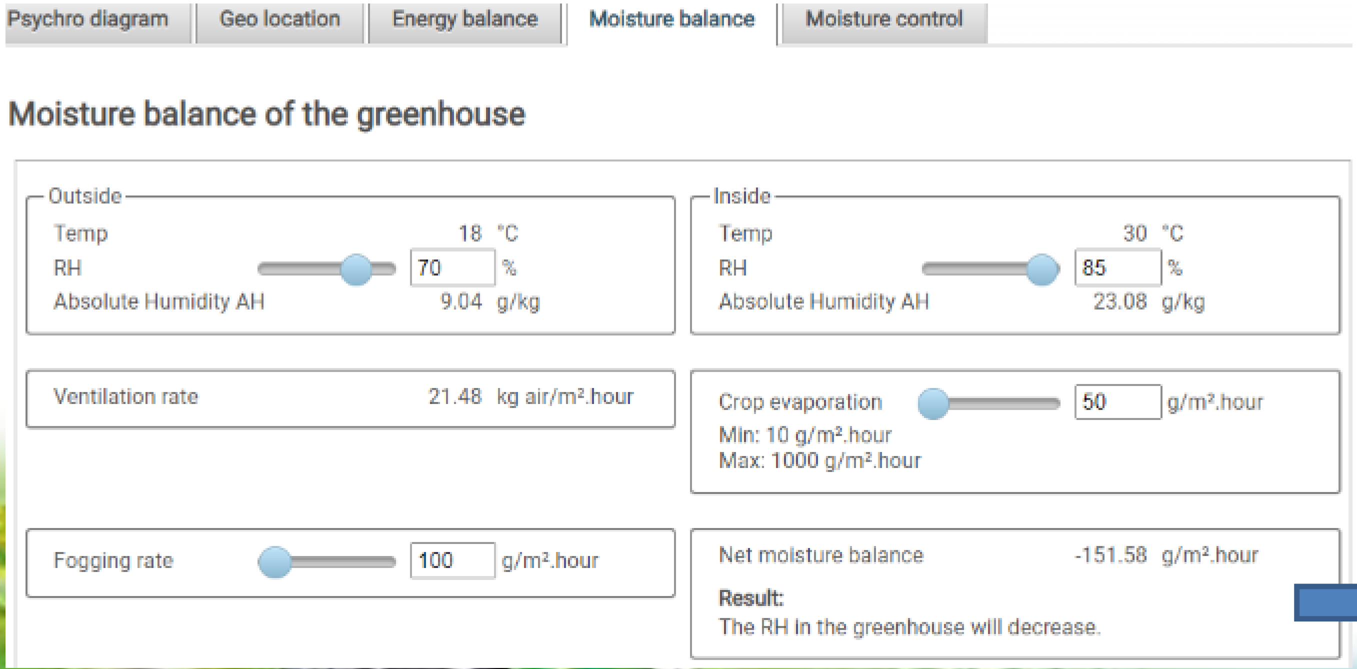
Moisture removed @given ventilation rate

= 21.48 * 14.04 = 301.58 g/m^2.h

Net moisture balance =

Moisture removed – Crop evaporation – fogging rate

= 301.58 – 50 - 0 = 251.58 g/ m^2.h



Net moisture balance =

Moisture removed – Crop evaporation – fogging rate

= 301.58 – 50 - 100 = 151.58 g/ m^2.h

Moisture Control

Moisture control by injection of outdoor air

$dT = T_{inside} - T_{outside}$

Outside

Temp 18 °C
RH 70 %
Absolute Humidity AH 9.04 g/kg
10.87 g/m³

Inside

Temp 30 °C
RH 85 %
Absolute Humidity AH 23.08 g/kg
26.43 g/m³

Fan outside air

Greenhouse area 100 m²
Capacity 10 m3/m².hour
Total flow 1000.00 m3/hour
Electrical power
Pressure difference duct 1000 Pascal (dP)
Efficiency 100 %
Fan power 277.78 W

Moisture exhaust

Moisture exhaust 160.8 g/m².hour

Air conditions in the crop

Temp 30 °C
RH 90 %
Absolute Humidity AH 24.43 g/kg

Moisture transport through crop

Crop height 1 m
Diffusion 0.332 g/m².hour
Air movement 0.28 cm/sec
Total moisture transport 279.99 g/m².hour

Heat exchanger

Power 38.21 W/m²
Electrical consumption 13.76 MJ/hour

Moisture exhaust= Fan capacity x AH_{dif} (g/m³) ✗
= 10 m³/m².h * (26.43 – 10.87) g/m³ = 155.6 g/m².h

Moisture exhaust= Fan capacity x AH_{dif} (g/kg) x $density_{insideAir}$
= 10 m³/m².h x (23.08 – 9.04) g/kg x (26.43/23.08) kg/m³ = 160.778 g/m².h

Inside

Temp 30 °C
RH 85 %
Absolute Humidity AH 23.08 g/kg
Absolute Humidity AH 26.43 g/m³

Air density
= (26.43/23.08) = 1.1451473

Fan power = dP x (total flow/3600) / Efficiency
= 1000 x (1000/3600) /1 = 277.78 W

Heat Exchanger (HX) Power = f(dT, fan capacity)
If dT or fan capacity = 0, HXPower=0

HXPower=Cp*dT*(capacity/3.60)*$density_{in}$
= 1.001 * 12 * 10 /3.6* (26.43/23.08)
= 38.2 W/m²

Elec. Consumption = HXPower *GHarea
= 38.21*100 = 3821 W
= 3821*3600/10^6 MJ/h
= 3.821*3.6 = 13.7556 MJ/h

Moisture control by injection of outdoor air

Outside

Temp 18 °C
RH 70 %
Absolute Humidity AH 9.04 g/kg

Inside

Temp 30 °C
RH 85 %
Absolute Humidity AH 23.08 g/kg

Fan outside air

Greenhouse area 100 m²
Capacity 10 m3/m².hour
Total flow 1000.00 m3/hour
Electrical power
Pressure difference duct 100 Pascal (dP)
Efficiency 40 %
Fan power 69.44 W

Moisture exhaust

Moisture exhaust 160.8 g/m².hour

Air conditions in the crop

Temp 30 °C
RH 90 %
Absolute Humidity AH 24.43 g/kg

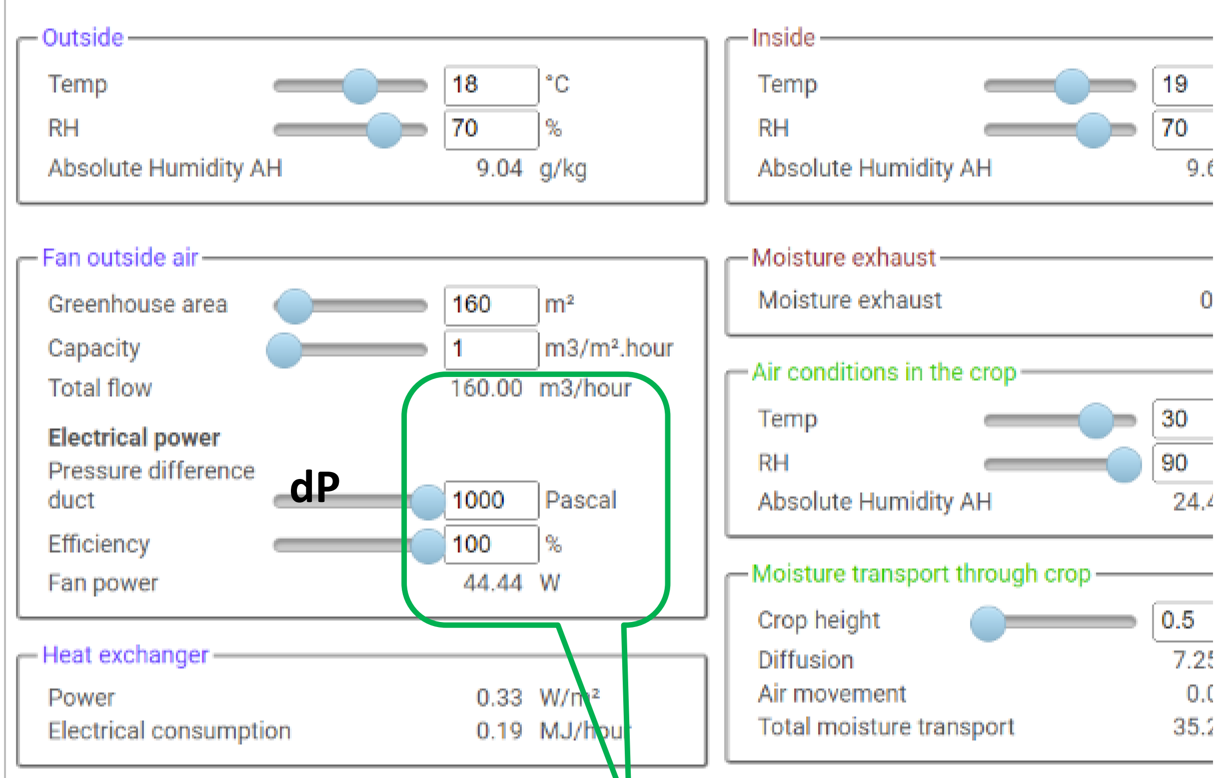
Moisture transport through crop

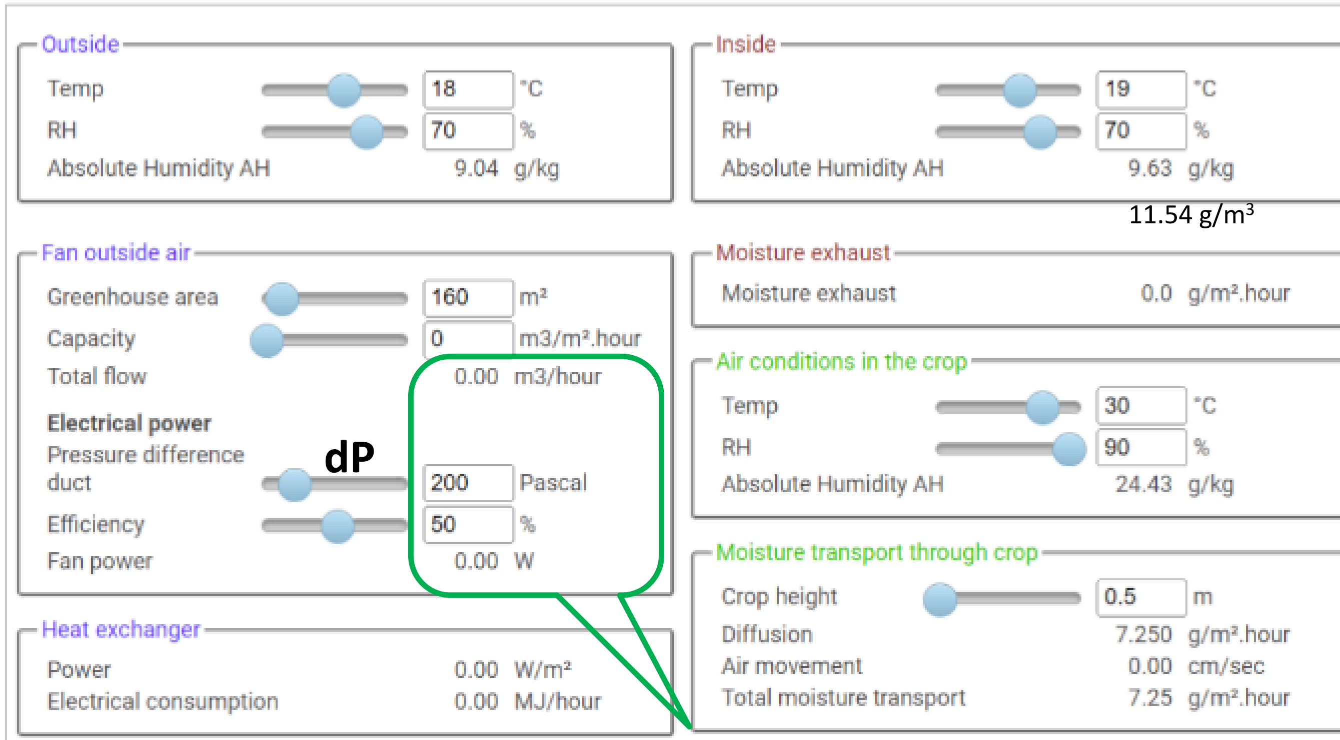
Crop height 1 m
Diffusion 0.332 g/m².hour
Air movement 0.28 cm/sec
Total moisture transport 279.99 g/m².hour

Heat exchanger

Power 38.21 W/m²
Electrical consumption 13.76 MJ/hour

Fan power = = 100 x (1000/3600) /0.4 = 69.444 W





Fan power = dP x (Total flow/3600)/ Efficiency

= 1000 x (160/3600) /1 = 44.44 W

HXPower = Cp * dT * capacity/3.6 * density

= 1.001 * 1 * 1/3.6 * (11.54/9.63) = 0.333 W/m²

Elec.Consumption = HXPower *Gharea * 3.6/1000

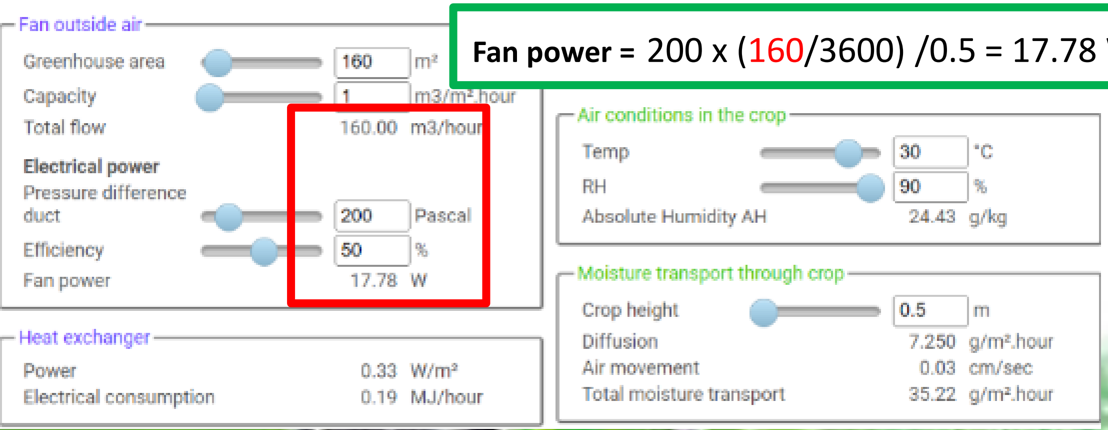
= 0.3184*160 = 50.944 W= 50.944*3600/10⁶

= 0.18336 MJ/h

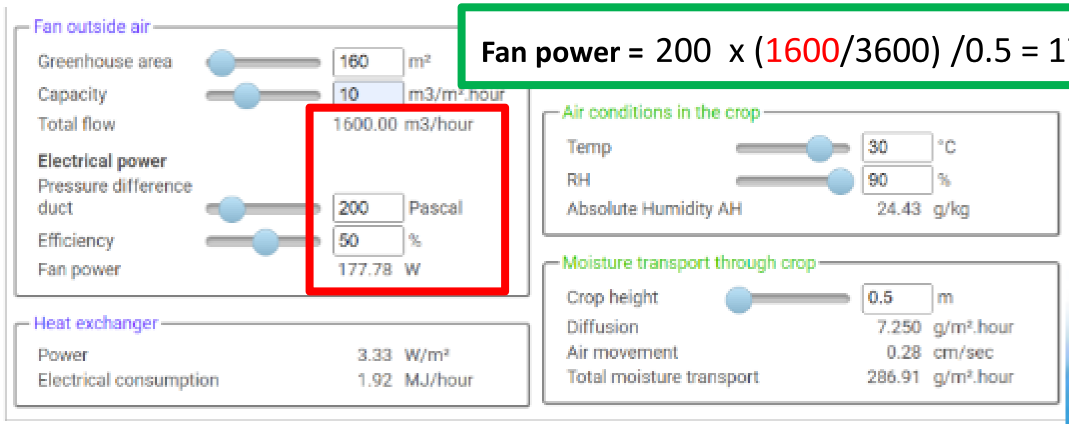
Total flow = Capacity * GH area

Fan power = dP x (Total flow/3600)/ Efficiency

= 1000 x (0/3600) /1 = 0 W

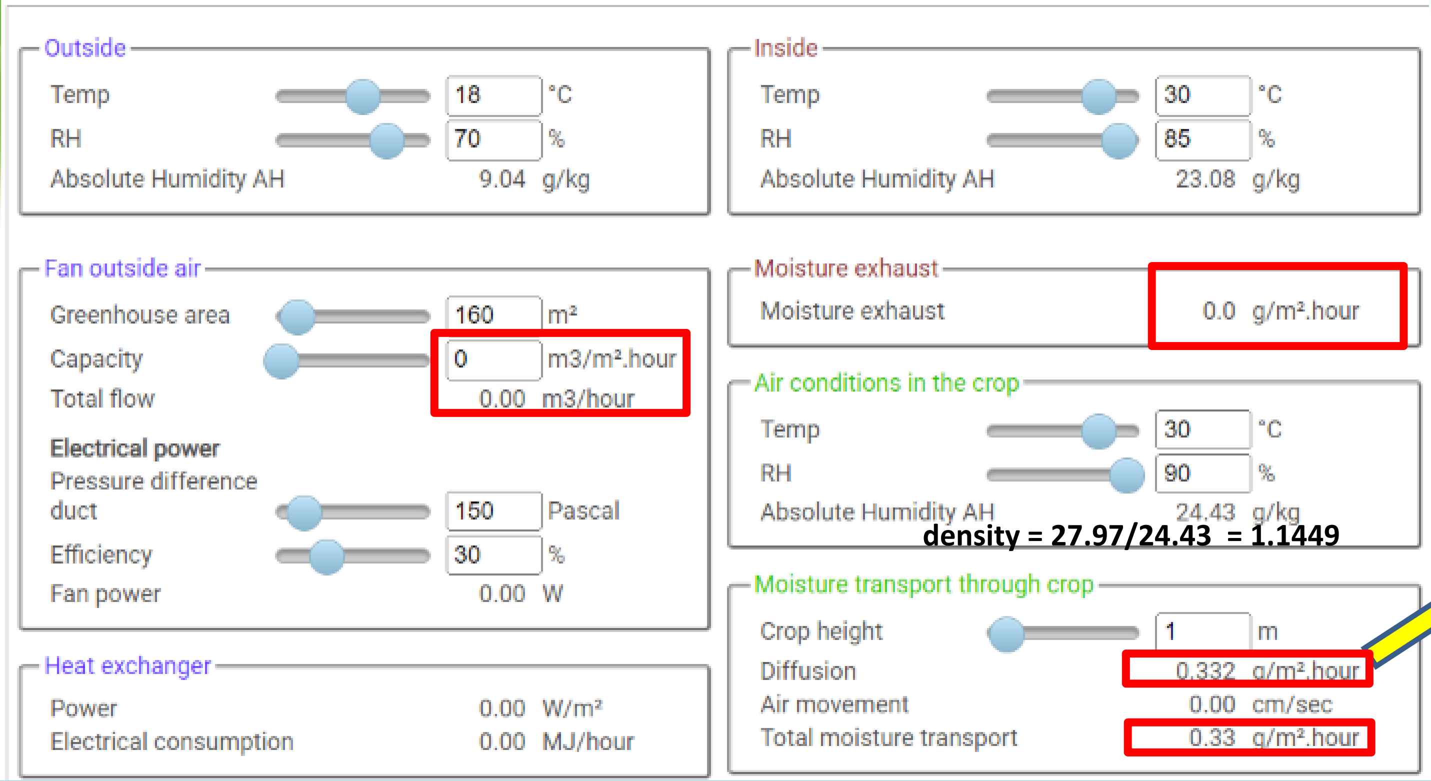


Fan power = 200 x (160/3600) /0.5 = 17.78 W



Fan power = 200 x (1600/3600) /0.5 = 177.78 W

Moisture control by injection of outdoor air



When fan capacity = 0 m^3/m^2.h,
There is no air exchange between in & outdoor,
thus, Moisture exhaust = 0

However, there still exist AH difference between indoor and micro-climate around crop

AH_{dif} = 24.43 – 23.08 = 1.35 g/kg

When Crop height =1 m, Air volume around crop per unit area (1 m^2) = 1 m^3

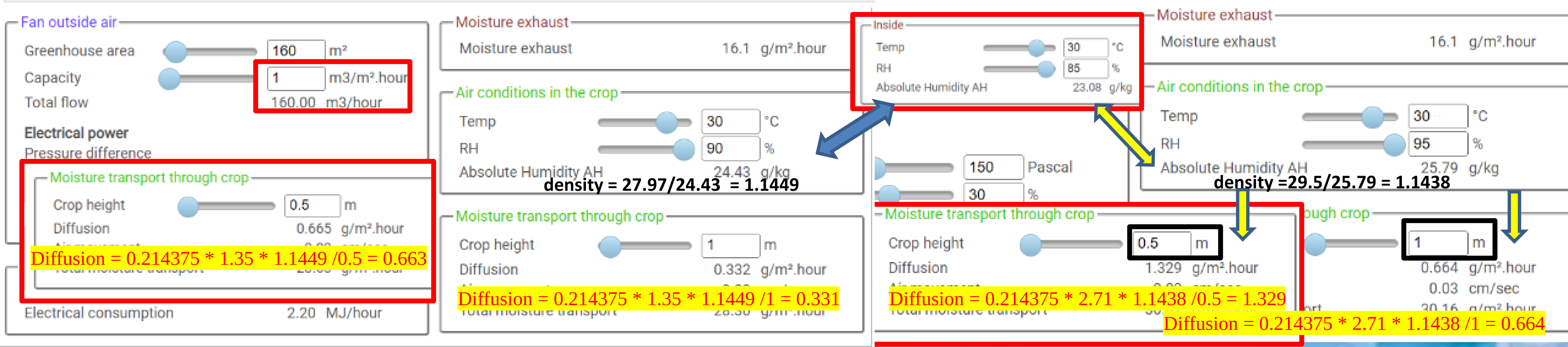
An empirical equation to derive Diffusion:

Diffusion = 0.214375 * AH_{dif} * density /crop height

= 0.214375* 1.35 * 1.1449 /1 = 0.331 g/m^2.h

Fan capacity = 0, air movement through crop = 0 cm/s

Total moisture transport (TMT) = Diffuse



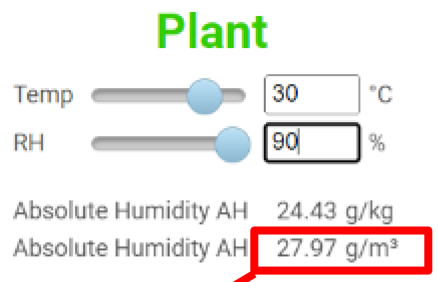
Air movement = f(fan capacity)

Total moisture transport (TmT)

$= \text{moistureTransport}_{fan} + \text{moistureTransport}_{diffuse}$

$=$ Fan capacity * AH + Diffusion

in $m^3/m^2.h$ * g/m^3 + $g/m^2.h$



$1\ m^3/m^2.h = 100\ cm/3600\ s$ = air movement 0.0277 cm/s

$TmT = 1 * 27.9658 + 0.332 = 28.2978 \approx 28.30\ g/m^2.h$

$10\ m^3/m^2.h = 10 * 100/3600 = 1/3.6 = 0.2777$ cm/s

$TmT = 10 * 27.9658 + 0.332 = 279.99\ g/m^2.h$

$30\ m^3/m^2.h = 30 * 100/3600 = 0.8333$ cm/s

$TmT = 30 * 27.9658 + 0.332 = 839.306 \approx 839.31\ g/m^2.h$

Psychrometrics

Simulation models

Radiation monitor

Introducing LetsGrow

Greenhouse Simulation

https://gpe.letsgrow.com/

Wei FANG
NTU_BME and Global ATGS
National Taiwan University
2022/03/16

Greenhouse simulation models

gpe.letsgrow.com

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Psychro diagram | Explanation

Introduction | Moisture discharge | Moisture transport | Energy consumption | Energy screens | Ventilation rate

Growing by Plant Empowerment

Growing by Plant Empowerment focuses on achieving an optimal growth climate with low energy costs by using partly existing and partly new techniques based on the energy and moisture balances of the greenhouse, using plant knowledge and physical principles. This website demonstrates some of these physical principles in the form of simplified simulation / calculation models. By playing with these models, you get a better picture of the processes that play a role around the energy and moisture balance in the greenhouse, a first step in applying the principles of Plant Empowerment in practice.

These simulation / calculation models are developed by LetsGrow.com.

Moisture discharge

Injection of outdoor air by fans is a controlled way of ventilation and thus discharge of moisture. This model shows how much moisture can be exhausted depending on outside conditions and fan capacity.

Moisture transport

To prevent moisture accumulation in the crop, water vapour must be moved upwards from the plants to the roof of the greenhouse. This calculation model shows that diffusion of water vapor in still air causes only very little moisture transport and that this is strongly promoted by air movement.

Energy consumption

The energy consumption of a greenhouse depends on the outside conditions and the insulation factor (u-value) of the greenhouse.

Energy screens

Effective use of energy screens is an important means of reducing energy demand. This calculation model focuses on the energy aspect. However, the use of single or multiple screens also provides a better and more uniform greenhouse climate due to less heat emission and cold fall.

Ventilation rate

Ventilation affects the energy balance, the moisture balances and the CO2 emissions of the greenhouse. This calculation model demonstrates the influence of greenhouse temperature and RH on the required ventilation

在這裡輸入文字來搜尋 20°C 英 上午 11:23 2022/3/24

Greenhouse simulation models × | Psychro diagram ×

gpe.letsgrow.com/psychro

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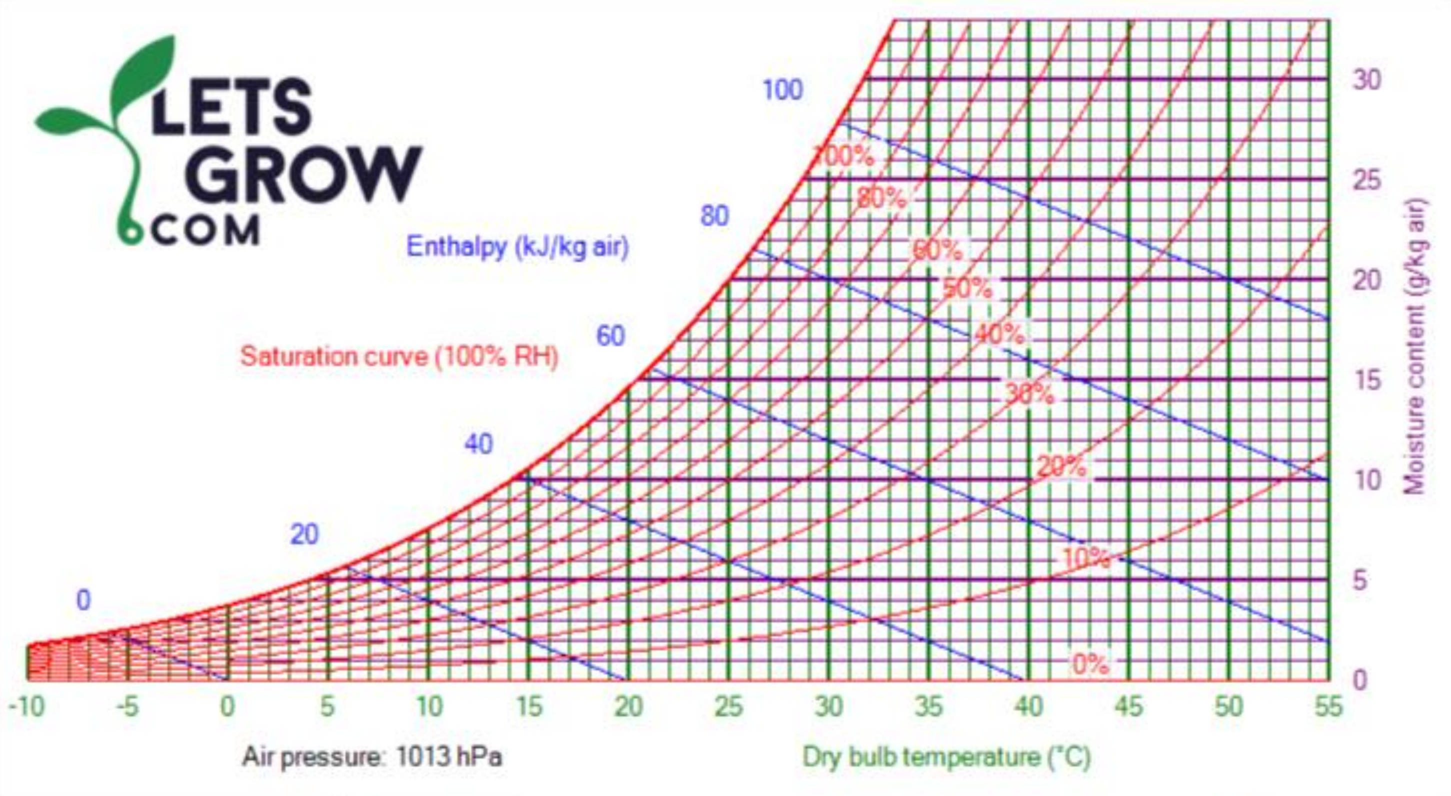
Show Extra

Psychro diagram | Geo location



Hide Psychro diagram | More info

Air pressure 1013 hPa

Outside | Difference | Above screen | Difference | Inside | Difference | Plant

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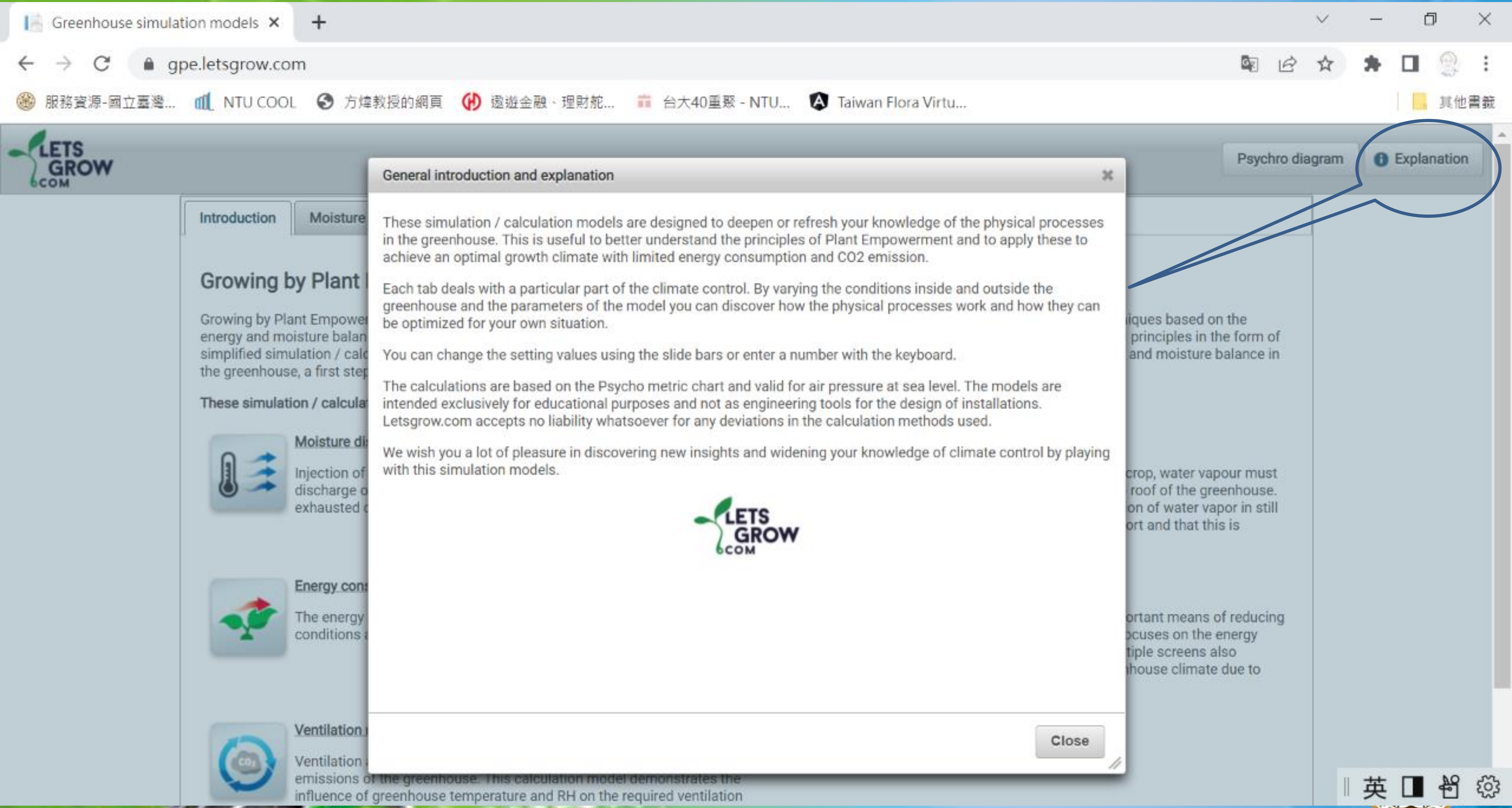
Greenhouse simulation models
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LETS GROW .COM
Psychro diagram
Explanation
Introduction
Moisture
Growing by Plant
General introduction and explanation
These simulation / calculation models are designed to deepen or refresh your knowledge of the physical processes in the greenhouse. This is useful to better understand the principles of Plant Empowerment and to apply these to achieve an optimal growth climate with limited energy consumption and CO2 emission.
Each tab deals with a particular part of the climate control. By varying the conditions inside and outside the greenhouse and the parameters of the model you can discover how the physical processes work and how they can be optimized for your own situation.
You can change the setting values using the slide bars or enter a number with the keyboard.
The calculations are based on the Psycho metric chart and valid for air pressure at sea level. The models are intended exclusively for educational purposes and not as engineering tools for the design of installations. Letsgrow.com accepts no liability whatsoever for any deviations in the calculation methods used.
We wish you a lot of pleasure in discovering new insights and widening your knowledge of climate control by playing with this simulation models.
Close
英

Moisture discharge

Injection of outdoor air by fans is a controlled way of ventilation and thus discharge of moisture. This model shows how much moisture can be exhausted depending on outside conditions and fan capacity.

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Introduction | Moisture discharge | Moisture transport | Energy consumption | Energy screens | Ventilation r

Moisture control by injection of outdoor air.

Outside

Temp	18	°C
RH	70	%
Absolute Humidity AH	9.04	g/kg

Inside

Temp	20	°C
RH	85	%
Absolute Humidity AH	12.47	g/kg

Injection fan

Flow	5	m3/m².hour

Moisture exhaust

Moisture exhaust	20.4	g/m².hour

Outside

Temp	18	°C
RH	70	%
Absolute Humidity AH	9.04 g/kg	
Absolute Humidity AH	10.87 g/m³	
Humidity Deficit HD	3.87 g/kg	
Humidity Deficit HD	4.66 g/m³	
Enthalpy	40.61 kJ/kg	
Enthalpy	48.85 kJ/m³	
VPD	0.62 kPa	
VP	1.44 kPa	
VPsat	2.06 kPa	
Dewpoint	12.4 °C	

Inside

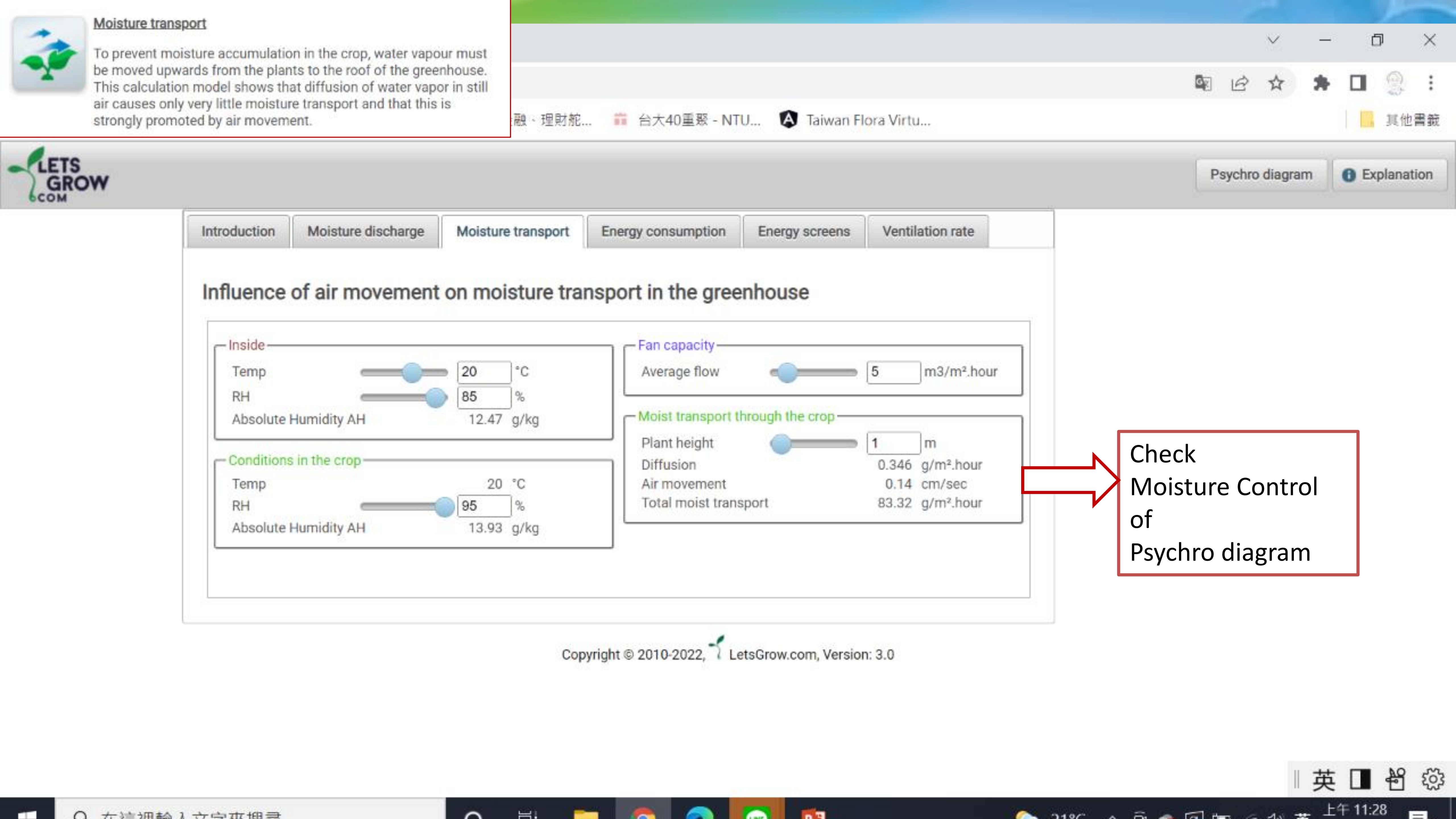
Temp	20	°C
RH	85	%
Absolute Humidity AH	12.47 g/kg	
Absolute Humidity AH	14.86 g/m³	
Humidity Deficit HD	2.20 g/kg	
Humidity Deficit HD	2.62 g/m³	
Enthalpy	51.16 kJ/kg	
Enthalpy	60.99 kJ/m³	
VPD	0.35 kPa	
VP	1.99 kPa	
VPsat	2.34 kPa	
Dewpoint	17.4 °C	

AH_{dif}=12.47-9.04=3.43 g/kg

= 3.43 * (10.87/9.04)= 4.12 g/m^3

Moisture exhaust= Flow * AH_{dif}

= 5 * 4.12 = 20.6 g/m^2.h



Check
Moisture Control
of
Psychro diagram

Energy consumption

The energy consumption of a greenhouse depends on the outside conditions and the insulation factor (u-value) of the greenhouse.

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Psychro diagram | Explanation

Introduction | Moisture discharge | Moisture transport | Energy consumption | Energy screens | Ventilation rate

The Influence of outdoor temperature and crop evaporation on the energy demand of the greenhouse (no radiation).

Outside	Temp	18 °C
Inside	Temp	20 °C
Greenhouse	Estimated U-value	7 W/m².K
Crop	Crop evaporation	50 g/m².hour

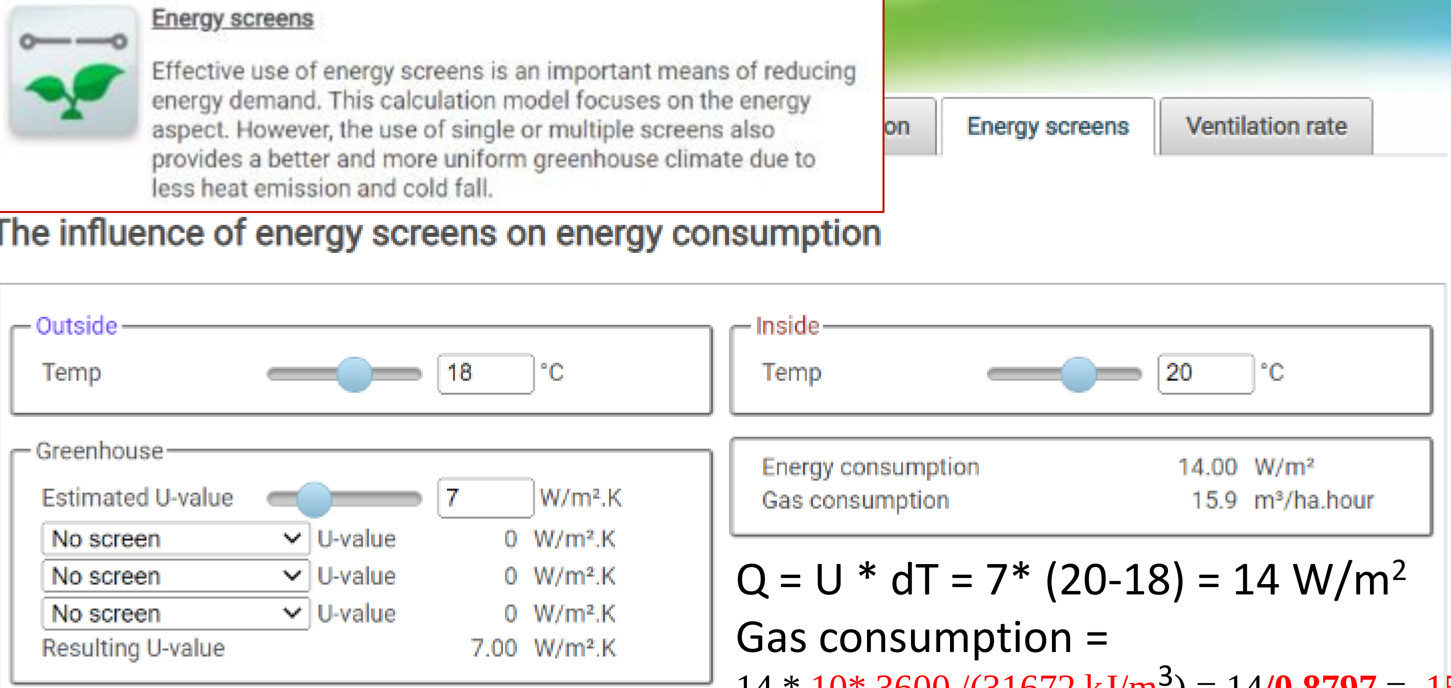
Energy consumption	48.74	W/m²
Gas consumption	55.4	m³/ha.hour

Temp	20 °C	0.00	Temp	20 °C
RH	0 %	100.00	RH	100 %
Absolute Humidity AH	0.00 g/kg	14.67	Absolute Humidity AH	14.67 g/kg
Absolute Humidity AH	0.00 g/m³	17.46	Absolute Humidity AH	17.46 g/m³
Humidity Deficit HD	14.67 g/kg	-14.67	Humidity Deficit HD	0.00 g/kg
Humidity Deficit HD	17.62 g/m³	-17.62	Humidity Deficit HD	0.00 g/m³
Enthalpy	20.10 kJ/kg	36.54	Enthalpy	56.64 kJ/kg
Enthalpy	24.14 kJ/m³	43.29	Enthalpy	67.44 kJ/m³

Heat of vaporization = dEnthalpy / dAH
= 36.54 / 14.67 = 2.49 kJ/g

Energy consumption = $U*dT + H_{fg}$ * crop evaporation
= 7*2+2.49 kJ/g * 50 g/m².h /3.6
= 14 + 34.58 = 48.58 W/m²

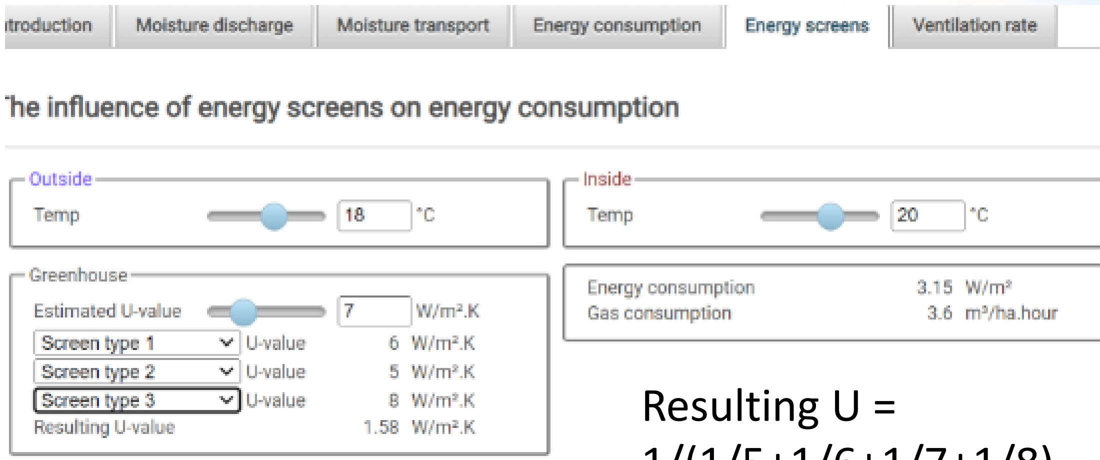
Gas consumption (Nature gas) =
= 48.74 * 10^{4-3} * 3600 / (37377 heat value熱值 * 0.84 efficiency)
= 48.74 * 36000 /(31672 kJ/m³) = 48.74/0.8797= 55.4 m³/ha.h



$Q = U * dT = 7* (20-18) = 14\ W/m^2$

Gas consumption =

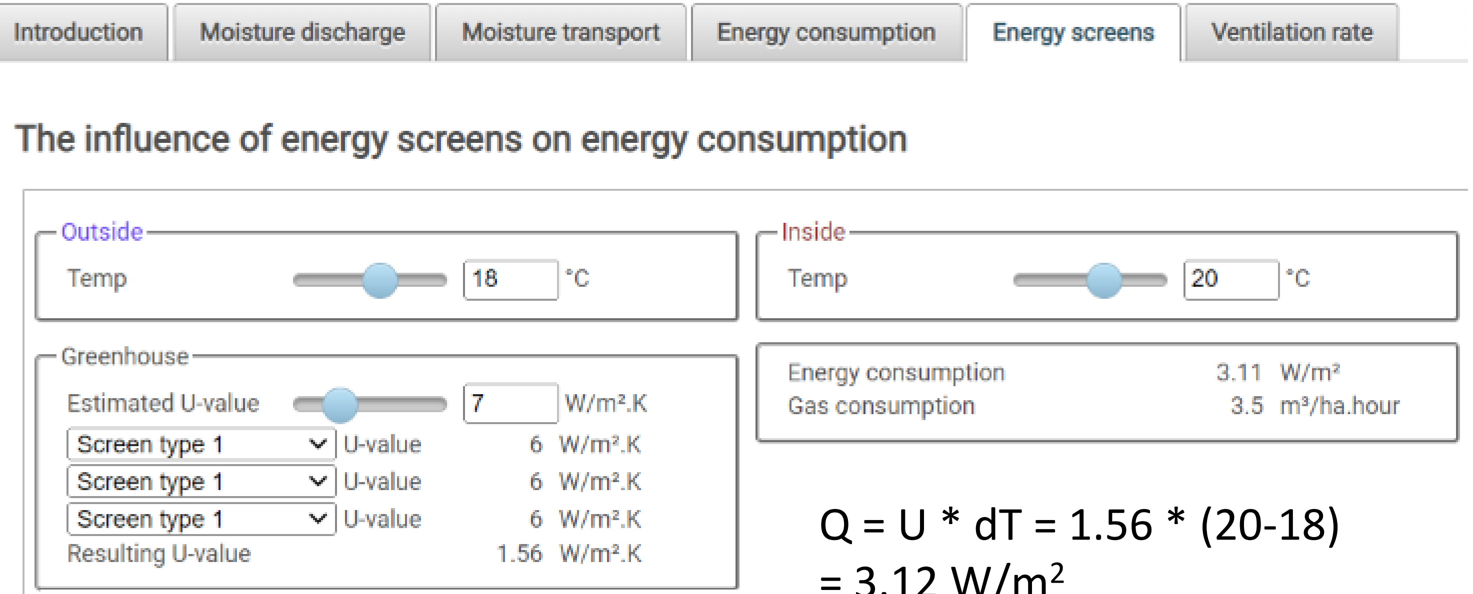
$14 * 10* 3600 /(31672\ kJ/m^3) = 14/\mathbf{0.8797} = 15.9\ m^3/ha.h$



Resulting U = 1/(1/5+1/6+1/7+1/8) =1.576

$Q = U * dT = 1.576 * (20-18) = 3.15\ W/m^2$

Gas consumption = 3.15 **/ 0.8797** = 3.58



$Q = U * dT = 1.56 * (20-18) = 3.12\ W/m^2$

Resulting U = 1/(1/7+1/6+1/6+1/6)=42/27=1.56

Gas consumption =

$3.11 / \mathbf{0.8797} = 3.53\ m^3/ha.h$

Introduction | Moisture discharge | Moisture transport | Energy consumption | Energy screens | Ventilation rate

The influence of greenhouse temperature and RH on ventilation rate and CO_2 loss

Outside

Temp	18	°C
RH	70	%
CO_2	400	ppm
Absolute Humidity AH	9.04	g/kg
Enthalpy	40.61	kJ/kg

Inside

Temp	20	°C
RH	85	%
CO_2	600	ppm
Absolute Humidity AH	12.47	g/kg
Enthalpy	51.16	kJ/kg

Solar radiation

Outdoor	700	W/m²
Radiation inside the greenhouse 70%	490.00	W/m²

Required ventilation rate for energy exhaust	166.17	kg air/m².hour
Calculated CO_2-loss	506.0	kg/ha.hour

Moisture exhaust

Moisture exhaust	569.93	g/m².hour

Qin = (700 * 0.7 * 3.6) in $kJ/m^2.h$
dEnthalpy = (51.16 – 40.61) in kJ/kg
Vent. rate = Qin / dEnthalpy
= (490 * 3.6) / (51.16-40.61) = 167.2 $kg/m^2.h$ ~ 166.17

dCO2 = 600-400=200 ppm = 200 * 1.522 mg/kg
CO2 loss = Vent.rate * dCO2/(10^{6-4})
= 166.17 * (200*1.522)/100=505.8 kg/ha.h

Moisture exhaust = Vent.rate * dAH
= 166.17 * (12.47-9.04) = 569.96

Ventilation rate

Ventilation affects the energy balance, the moisture balances and the CO2 emissions of the greenhouse. This calculation model demonstrates the influence of greenhouse temperature and RH on the required ventilation rate and shows how a better choice of target values for temperature and humidity can substantially improve CO2 efficiency.

The influence of greenhouse temperature and RH on ventilation rate and CO_2 loss

Outside

Temp	18	°C
RH	70	%
CO_2	400	ppm
Absolute Humidity AH	9.04	g/kg
Enthalpy	40.61	kJ/kg

Inside

Temp	20	°C
RH	85	%
CO_2	500	ppm
Absolute Humidity AH	12.47	g/kg
Enthalpy	51.16	kJ/kg

Solar radiation

Outdoor	600	W/m²
Radiation inside the greenhouse 70%	420.00	W/m²

Required ventilation rate for energy exhaust	142.27	kg air/m².hour
Calculated CO_2-loss	216.6	kg/ha.hour

Moisture exhaust

Moisture exhaust	487.98	g/m².hour

Qin = (600 * 0.7 * 3.6) in $kJ/m^2.h$
dEnthalpy = (51.16 – 40.61) in kJ/kg
Vent. Rate = Qin / dEnthalpy
= (420 * 3.6) / (51.16-40.61) = 143.31 $kg/m^2.h$ ~ 142.27

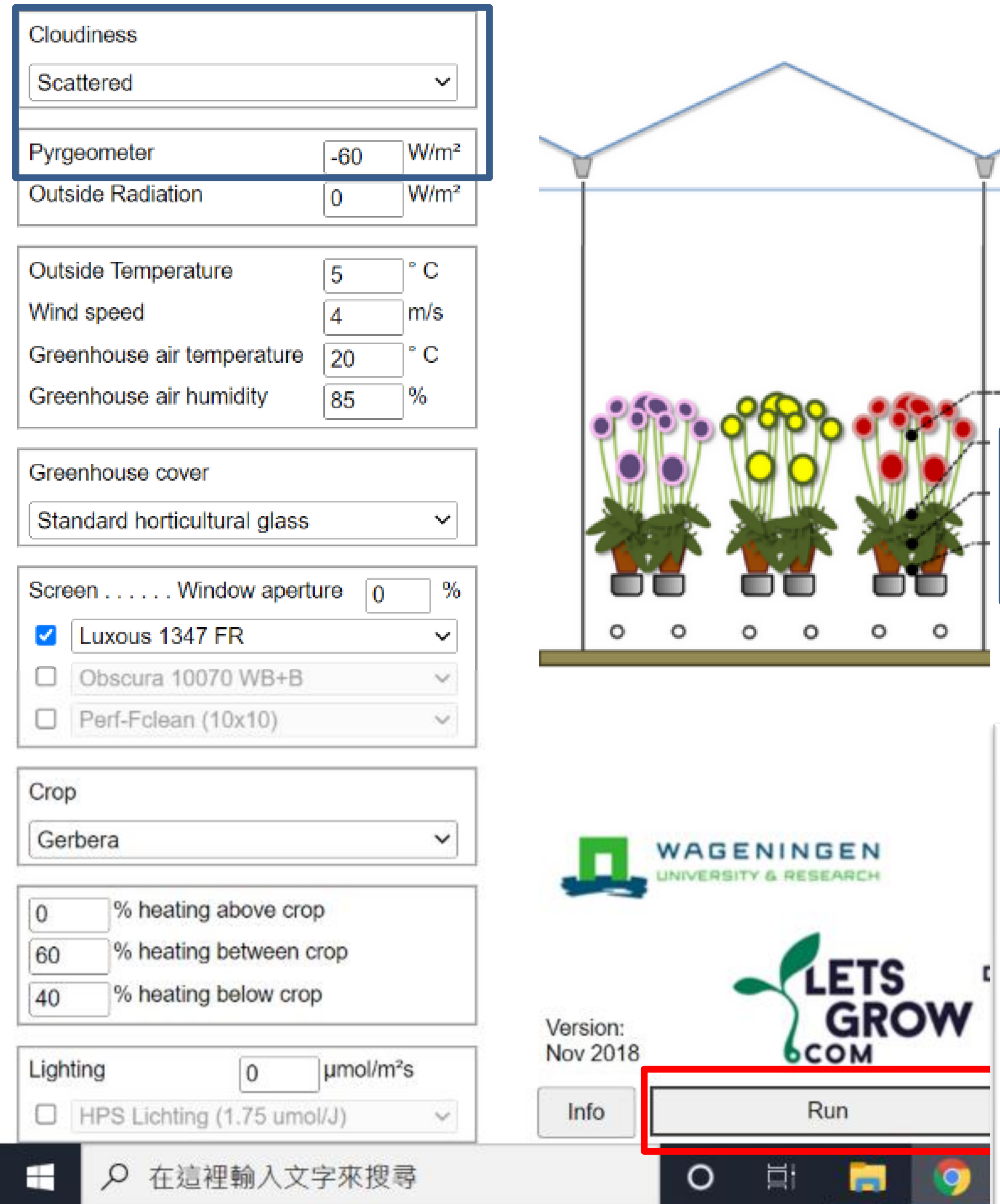
dCO2 = 500-400=100 ppm = 100 * 1.522 mg/kg
CO2 loss = Vent.rate * dCO2/100
= 142.27 * (100*1.522)/100=216.53 kg/ha.h

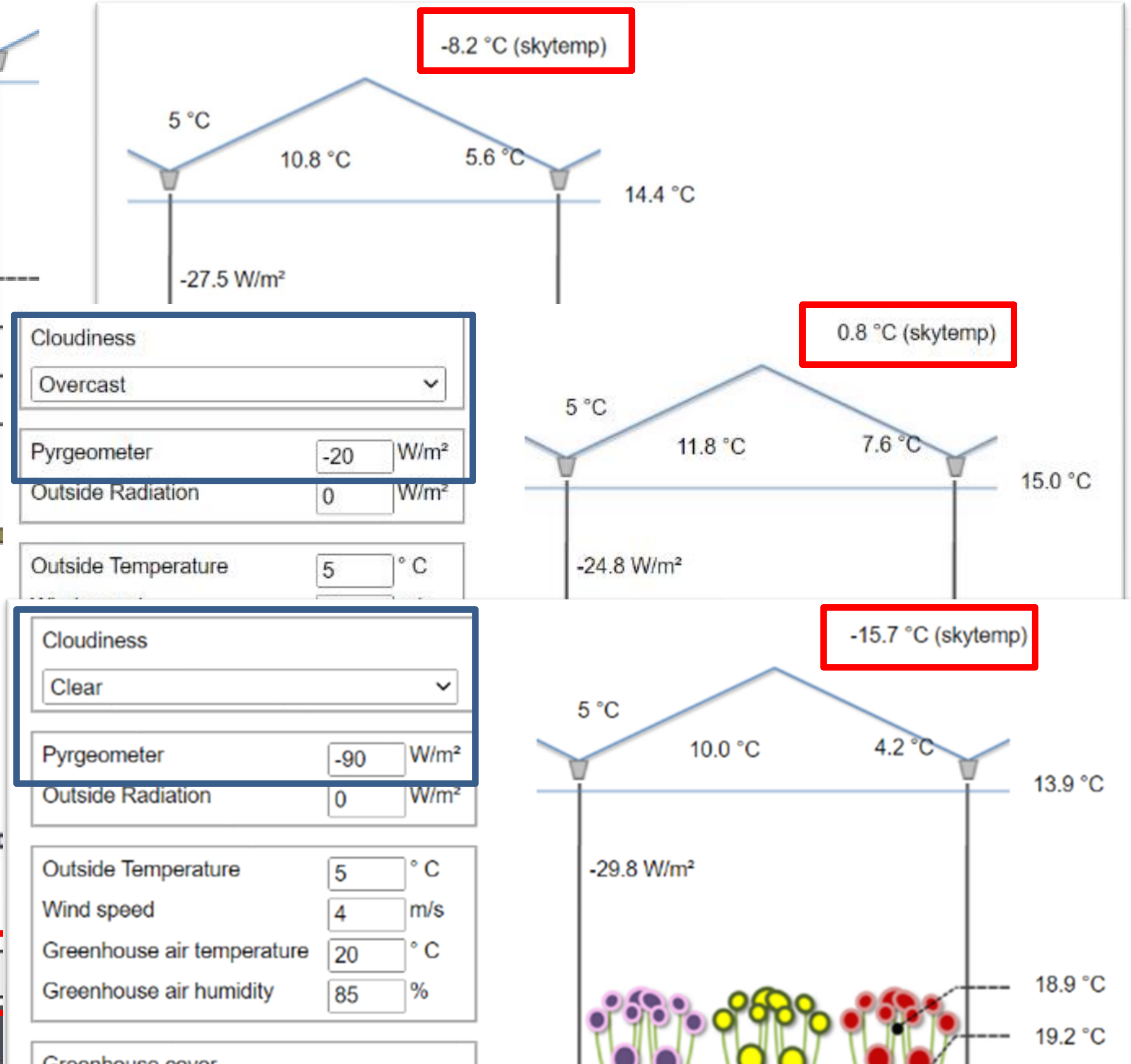
Moisture exhaust = Vent.rate * dAH
= 142.27 * (12.47-9.04) = 488.00

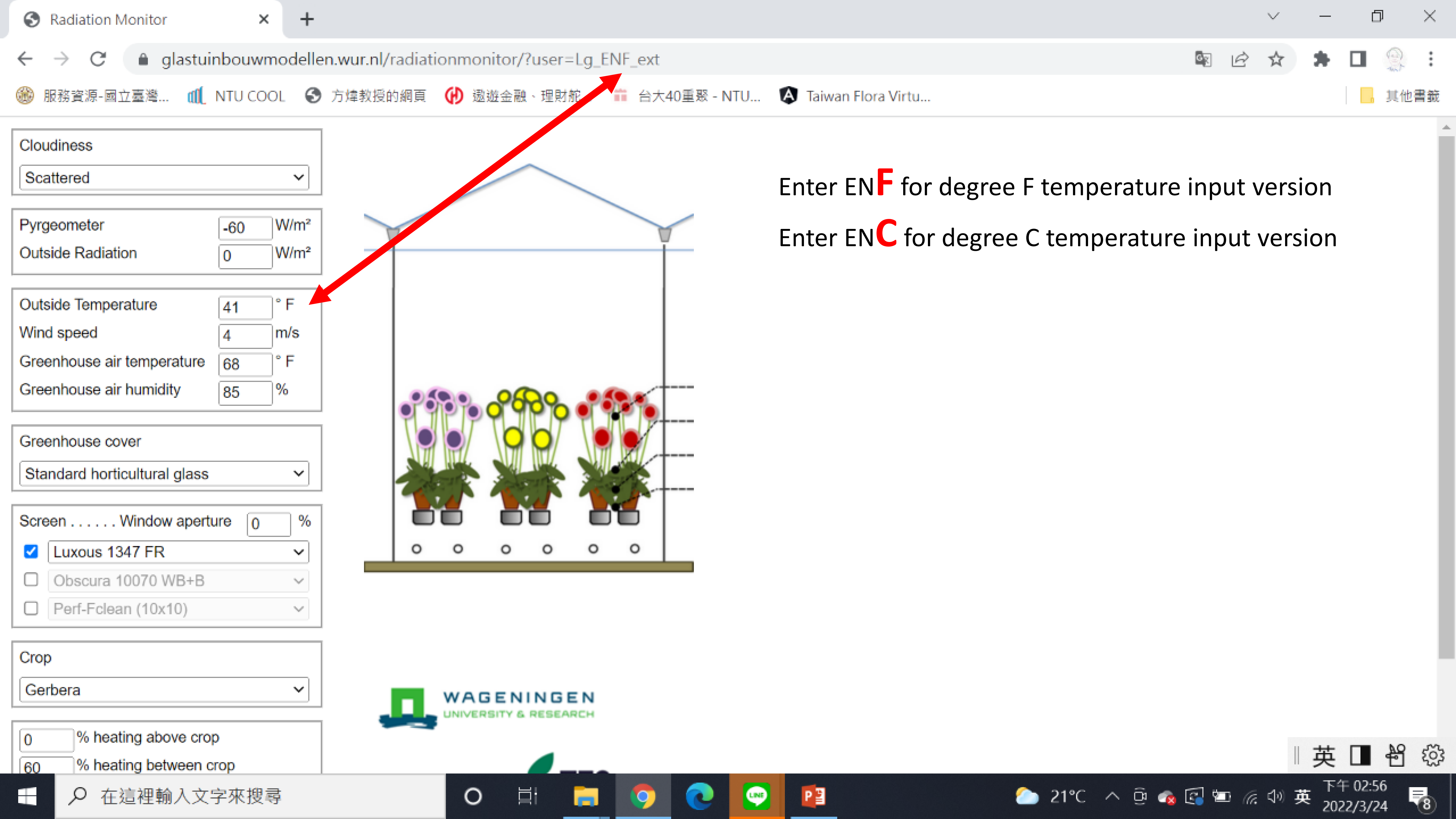
- Psychrometrics
- Simulation models
- Radiation monitor

More models from WUR

https://www.glastuinbouwmodellen.wur.nl/radiationmonitor/?user=Lg_ENC_ext






Radiation Monitor
glastuinbouwmodellen.wur.nl/radiationmonitor/?user=Lg_ENF_ext
Cloudiness
Scattered
Pyrgeometer -60 W/m²
Outside Radiation 0 W/m²
Outside Temperature 41 ° F
Wind speed 4 m/s
Greenhouse air temperature 68 ° F
Greenhouse air humidity 85 %
Greenhouse cover
Standard horticultural glass
Screen . . . . . . Window aperture 0 %
Luxous 1347 FR
Obscura 10070 WB+B
Perf-Fclean (10x10)
Crop
Gerbera
0 % heating above crop
60 % heating between crop
WAGENINGEN
UNIVERSITY & RESEARCH
Enter ENF for degree F temperature input version
Enter ENC for degree C temperature input version

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Disclaimer

The radiation monitor is a simulation tool that has been developed with care and dedication by Wageningen UR Greenhouse horticulture.

The radiation monitor however stays to be only a model which never exactly reflects the real world situation. Moreover, the model computes a stationary situation, whereas in reality a greenhouse is governed by dynamical processes and can have large variations in the vertical and horizontal dimension.

Wageningen UR Greenhouse Horticulture therefore does not accept liability for financial losses that are attributed to desicions that were based on output shown by the model.

LETS GROW COM DATA DRIVEN GROWING

Version: Nov 2018

Info | Run | Help

WAGENINGEN UNIVERSITY & RESEARCH

Help document on the Radiation Monitor

https://www.glastuinbouwmodellen.wur.nl/radiationmonitor/Content/HlpEN.pdf

Home

The radiation monitor is an internet application that shows the effect of covering materials, screens, heating and illumination on the temperature distribution in the crop region of a greenhouse crop.

It is meant to help with the strategical and operational discussions in greenhouse climate control.

This document gives an explanation on the user interface and presents the Theoretical background.

88 pages in total

The software was developed by Wageningen UR Greenhouse horticulture

Cloudiness

Scattered

Overcast
Scattered
Clear

Outside Radiation 0 W/m²

User Interface

The left pane of the interface gives the inputs used for the computations whereas the right pane shows the results of a computation.

Input pane

Cloudiness

Scattered

Radiative energy loss of a greenhouse is strongly influenced by the cloudiness of the sky.
Some greenhouses are equipped with a pyrgeometer, a device that tells this radiative heat loss so growers used to such a device might fill in the Pyrgeometer reading to characterize the sky conditions. People that do not know the typical values of the radiation loss to the sky will prefer to use the descriptive parametrisation of the sky conditions ('Clear', 'Scattered' or 'Overcast'). Note that when changing the description the Pyrgeometer value will change to corresponding typical figures.

Pyrgeometer -60 W/m²
Outside Radiation 0 W/m²

This is the solar radiation

Outside Temperature 5 °C
Wind speed 4 m/s
Greenhouse air temperature 20 °C
Greenhouse air humidity 85 %

The temperature can be expressed in Centigrade or in Fahrenheit. To change to Fahrenheit you have to change the last C in the address in your browser to an F (or vice versa)

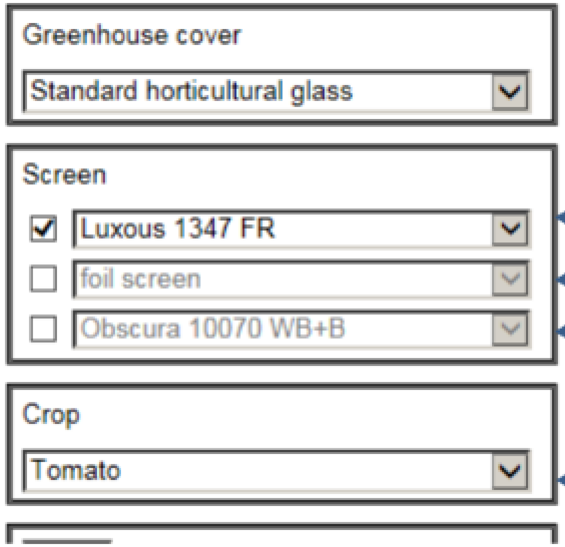
http://www.glastuinbouwmodellen.wur.nl/radiationmonitor/?user=xxxxx_ENC

Here you can define to which temperature the greenhouse is heated. In cold conditions the model will compute the heating needed to reach this temperature. In warm conditions or conditions with a lot of solar radiation, the model will determine a ventilation rate that establishes this temperature (if possible)

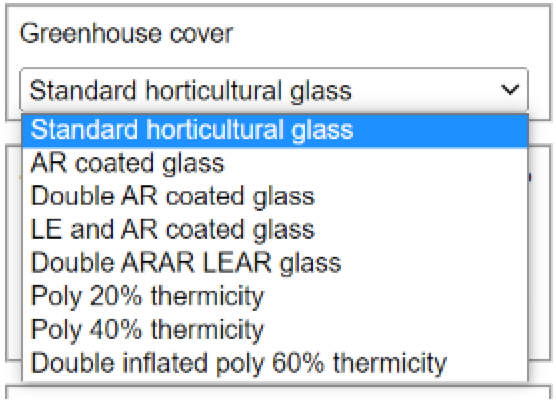
Greenhouse cover

Here you can define the humidity in the greenhouse. The model does not take the humidity balance into account (but does account for transpiration, see explanation of the crop selection box). The value filled in here is used to compute the dew point temperature of the greenhouse air and in the crop transpiration computation.

Input pane (continued)

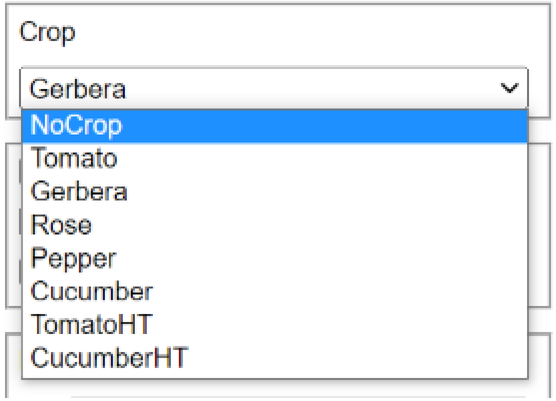


Here you can select an appropriate greenhouse cover. The list contains a number of typical greenhouse coverings, ranging from glass to poly coverings and can be single or double. For each of the coverings the model uses typical properties for its transmissivity for solar radiation, convective exchange and its transmissivity for thermal radiation.

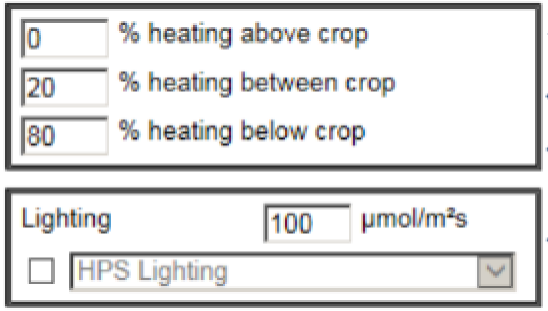


Here one can select to use none up till three screens. For each screen used, the type of screen can be selected from a list. The properties of each screen in the list were determined in the Wageningen UR Greenhouse horticulture Lightlab. The properties of the screens are described here.

The radiation monitor has a number of crops for which the optical properties and typical architecture was determined by the Wageningen UR researchers. For all crops the full grown crop is considered. Also, for each crop the typical transpiration is taken into account, being a constant base transpiration and a light dependent component. The crop parameters that are used are listed here.

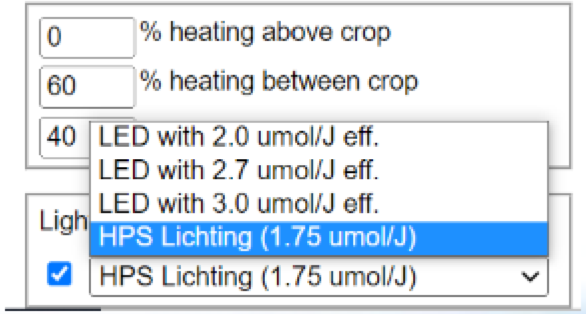


Input pane (continued)

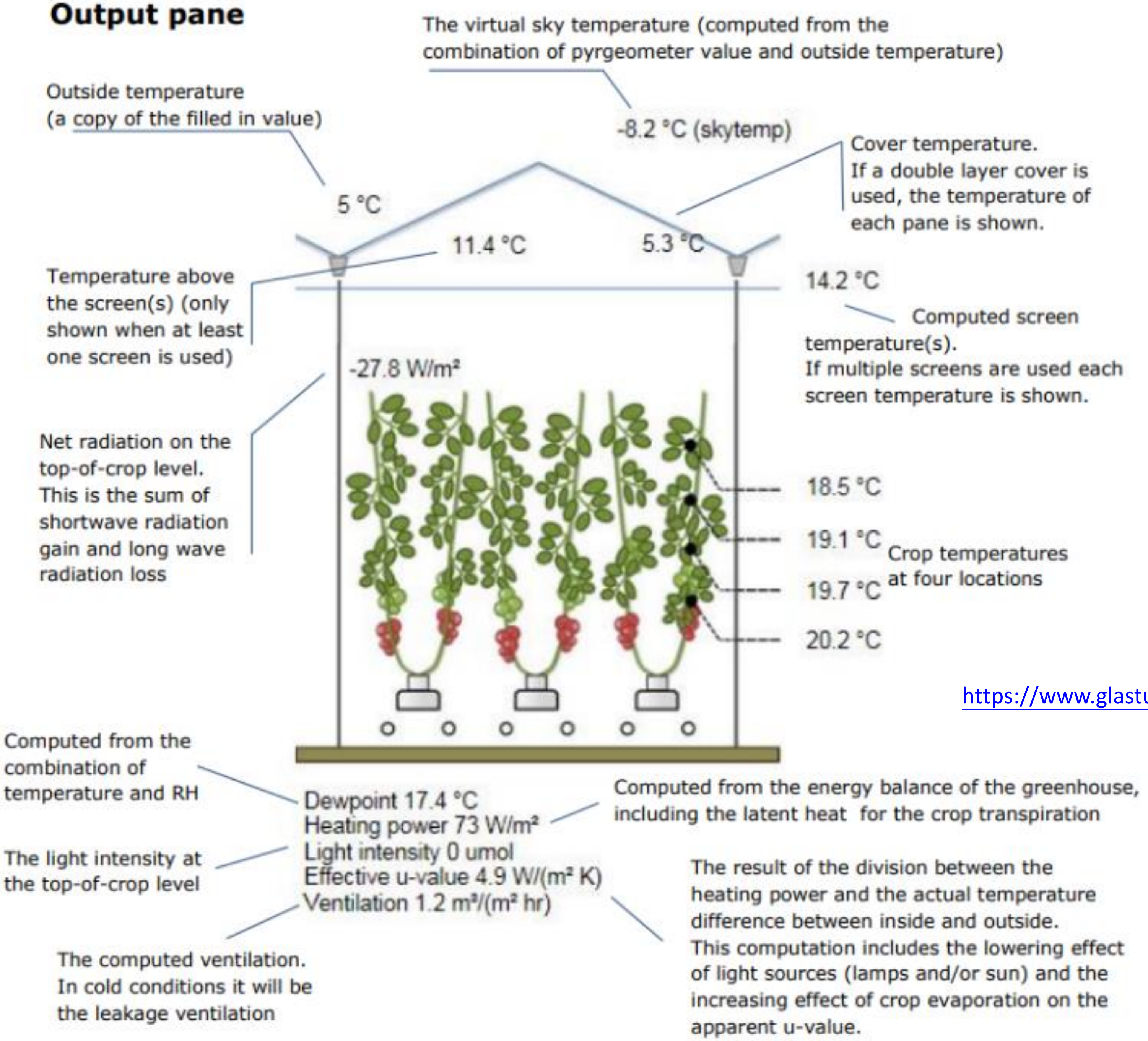


Heating systems in greenhouses can be located below the crop, in between the crop or as an overhead heating system. Here you can determine what percentage of the heating power is released where in the greenhouse. Of course the sum of the percentages should be 100. Normally only one or two systems will be used. When changing from one crop to another, the default heat distribution over the different systems may be changed.

When using artificial illumination the type of illumination can be selected (HPS or LED) and the intensity can be defined (in μmol/(m² s) PAR radiation. The parameters used for the different light-sources are described here



Output pane



88 pages in total

https://www.glastuinbouwmodellen.wur.nl/radiationmonitor/Content/HlpEN.pdf

Theoretical Background

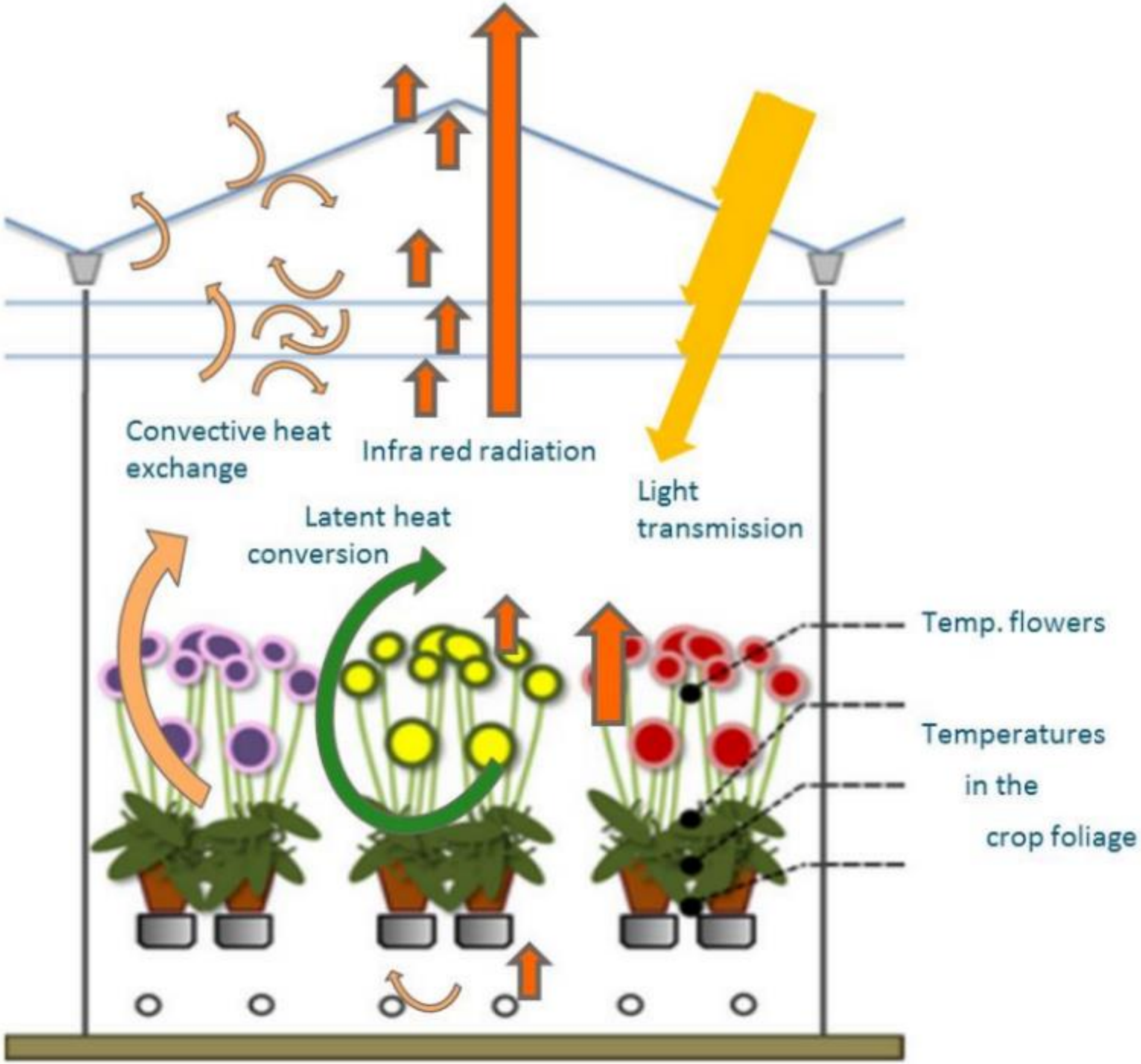
started at page 5

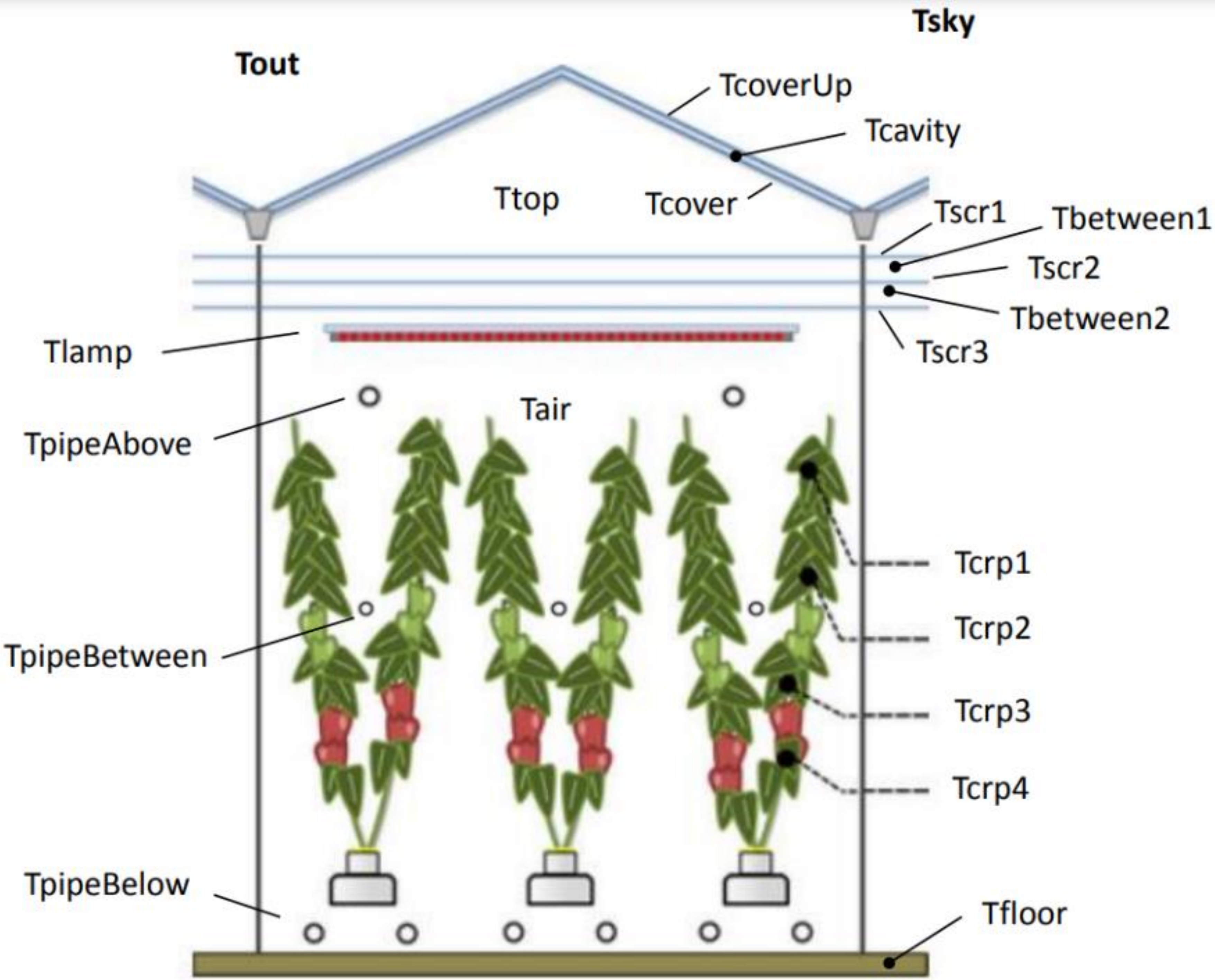
The climate conditions in a greenhouse are the result of the interaction of the outside climate with the enclosure and the canopy inside the enclosure. During daytime, solar energy is trapped in the greenhouse. Shortwave solar radiation passes the transparent cover, but the heat, generated by absorption in the crop and construction elements, is prohibited to escape from the enclosure.

During night time, in modern greenhouses it is the heating system that assures a favourable inside air temperature, although the energy stored in the soil might as well provide some energy supply. For unheated greenhouses, this night time energy supply from the soil, or sometimes also additional elements with a large thermal mass, is the only and therefore the primary energy source. However, this dynamic behaviour of greenhouses is not taken into account in the Radiation monitor. It uses a **steady state approach**, which means that the temperatures computed are the temperatures that would be achieved when the environmental conditions would remain constant for an infinite long time.
Of course this will not be the case in reality, but since the thermal mass of all components in a greenhouse, except for the soil is small, the steady state approach is a sound way to compute the effect of screens and covering material on the **temperature profile in the crop**, which is the objective of this tool.

The model was designed to do simulations for **low-light** conditions (from darkness up to 150 W/m^2 outdoor light) and for **cold conditions**. This means that the model assumes that crop transpiration is not limited by drought or temperature stress and that, the ventilation capacity of the vents is always enough to achieve the temperature that the user provides as an input.

In a steady state solution, where all temperatures are at an equilibrium value, the sum of the energy fluxes from and to all the greenhouse elements is zero. When looking at the picture below, this means that for instance the cover temperature is at such a value that the energy gained by the absorption of light in the glass (typically 4% of the solar radiation) plus the


Convective heat exchange
Infra red radiation
Light transmission
Latent heat conversion
Temp. flowers
Temperatures
in the
crop foliage


Tsky
Tout
TcoverUp
Tcavity
Ttop
Tcover
Tscr1
Tbetween1
Tscr2
Tbetween2
Tscr3
Tlamp
Tair
TpipeAbove
Tcrp1
Tcrp2
TpipeBetween
Tcrp3
Tcrp4
TpipeBelow
Tfloor

Crop transpiration

When leaves of a crop evaporate water, energy is converted from sensible heat to latent heat. At higher intensities of solar radiation or artificial illumination, this energy originates almost all from the absorption of the shortwave radiation, but at night, this energy is derived from the environment. This requires that the leaf temperature is below the ambient temperature. At a certain point, an equilibrium temperature will be found where the energy needed for transpiration equals the energy supply from the warm environment to the colder leaf.

The transpiration rate is driven by the difference between the vapour content of the air volumes inside the leaves and the vapour content of the surrounding greenhouse air. The vapour content in the leaf equals the saturated vapour content at the leaf temperature and the greenhouse air vapour content follows from the user defined temperature and relative humidity.

As a formula, the transpiration can be described as:

$$\text{transpiration} = A_{leaf} \times 2 \times (X_{leaf} - X_{air}) / \text{resistance} \qquad \text{[gram/s per leaf layer]}$$

'A_{leaf}' denotes the total surface of leaves associated to a leaf layer in the model. The surface is multiplied by 2 because a leaf has two sides. The fact that the upper side of leaves has less stomata than the bottom side is incorporated by the value fitted as the stomatal resistance.

X_{leaf} is the moisture content of the air volumes inside the leaf and X_{air} is the moisture content of the greenhouse air, both in gram/m³.

The saturated moisture content of air at a certain temperature can easily be computed by the formula below.

$$X^* = 1255 * 10^{\wedge}(7.9 * \text{Temp}/(237 + \text{Temp})) / (273 + \text{Temp}) \qquad [\text{gram/m}^3]$$

The moisture content of the air inside the leaf follows by filling in the leaf temperature in the formula. When using this formula after replacing 'Temp' with the greenhouse air temperature and multiplication by the relative humidity, the absolute moisture content of the greenhouse air is obtained.

The resistance for moisture transport from leaf to air is the sum of the boundary layer resistance and the stomatal resistance.

$$\text{Resistance} = \text{boundary layer resistance} + \text{stomatal resistance} \quad [\text{s m}^{-1}]$$

called **free convection** and the second is called **forced convection**. The present model distinguishes only one forced convective flux and that is the air exchange between the outside air and the inside air below the roof, which can be the top-compartment (Ttop) or the main greenhouse air compartment (Tair), depending on whether or not a screen is deployed.
So with at least one screen deployed, the energy exchange by forced convection between the outside air and the top compartment follows:

$$\text{HTopOut} = \text{fVent}/3600 * 1200 * (\text{Ttop} - \text{Tout}) \quad [\text{W/m}^2]$$
$$\text{HTopAir} = 0;$$

When all screens are stowed the temperature of the top-compartment is left out of the computations and the ventilation acts on the greenhouse air temperature.

$$\text{HTopOut} = 0;$$
$$\text{HTopAir} = \text{fVent}/3600 * 1200 * (\text{Tair} - \text{Tout}) \quad [\text{W/m}^2]$$

In both equations, fvent is the air exchange rate between the greenhouse and the outside air in m^3/hr and 1200 is the volumetric specific heat of air in J/(m^3 K).
Because every greenhouse has some leakage, fVent has a minimum value. This value is linearly dependent on the wind speed and is 0.3 $m^3/(m^2$ hr) per m/s of wind speed, with a minimum of 1.2 $m^3/(m^2$ hr). This means that only when the wind speed exceeds 4 m/s (a small breeze), the leakage of the greenhouse is supposed to grow with this 0.3 $m^3/(m^2$ hr) per m/s of wind speed increment.

In the above mentioned forced convection, the actual heat exchange is a linear relation between the temperature difference between the state variables. For free convection, the relation between the actual heat exchange and the temperature difference is in general not constant, but a function of the temperature difference itself. The general formula for heat exchange between a horizontal warm surface and a colder air volume above it reads:

$$\text{HWarmCold} = 1.7 * (\text{Twarm} - \text{Tcold})\hat{}1.33 \quad [\text{W/m}^2]$$

This formula holds for large surfaces, like screens and covers, where the convective heat exchange around the cover is enlarged by the 1.2, due to the larger surface of the tilted pane

For warm heating pipes the relation shows a very similar non-linearity. For round pipes, the sensible heat loss is described by

$$\text{HPipeAir} = \text{Dpipe} * \text{Lpipe} * 6.25 * (\text{Tpipe} - \text{Tair})\hat{}1.32 \quad [\text{W/m}^2]$$

$$\text{HPipeAir} = \text{Dpipe} * \text{Lpipe} * 6.25 * (\text{Tpipe} - \text{Tair})\hat{}1.32 \quad [\text{W/m}^2]$$

where Dpipe is the diameter of the pipe and Lpipe is the number of meters of pipe per m^2 greenhouse surface. For common greenhouses, the bottom heating system consists of pipes with a 51 mm diameter and there are commonly 10 of these pipes in an 8 meter trellis, meaning an average length of 1.25 m of pipes in the pipe rail circuit per m^2 greenhouse.

For the sensible heat release from the luminaires of artificial illumination, if applied in the computation, the same type of relation is used, and the term that takes account for the

surface (Dpipe * Lpipe) is set to a value dependent on the electrical lamp power. For a 100 W/m^2 HPS luminaire this surface is 0.02 m^2 per m^2 greenhouse and from that the model uses a linear relation between electric power and surface of luminaires.
Of course in reality, the efficiency and type of lamps will also determine the surface per W of installed lighting power. However, since this will only give some change in the equilibrium temperature at which the lamps release their heat and not in the total amount of heat released (because that is defined by the lamp characteristics such a fixed power-to-surface relation gives only a very small inaccuracy.

For small distributed surfaces, like the leaves of a crop, the free convective heat exchange coefficient is hardly affected by the temperature difference. This follows from the work of Stanghellini (1987). According to her work, the convective heat exchange from canopy leaves is more determined by local air velocities than by temperature differences. When the local air velocity around the leaves of for instance a tomato crop is supposed to be 0.1 m/s, the heat exchange from a leaf to the air is described by

$$HecLeafAir = 10 * LAI * (1+ (TLeaf-Tair)/140) \qquad [W/(m^2\ K)]$$

This dependency of the heat exchange is that small (1/140 times the temperature difference) that it is simply neglected.
In this formula LAI denotes the leaf surface in a specific crop layer per m^2 greenhouse surface.

Finally there is one more convectieve heat exchange that is not computed by the standard formulas for free convective heat exchange, which is the heat loss from the cover. This is strongly influenced by the wind speed. According to the work of Bot[1] this convective exchange is described by:

$$HecCovOut = 3.1 + 1.31 * Windsp \quad \text{for wind speeds} < 4\ m/s \qquad [W/(m^2\ K)]$$

and

$$HecCovOut = 2.72 * Windsp0.8 \quad \text{for wind speeds} > 4\ m/s \qquad [W/(m^2\ K)]$$

With the three types of convective heat fluxes, sensible heat exchange processes from surface to air in the present model can be computed, after having used the appropriate parameters.

through leakage and vents.
So, for example, when using a single screen, the heat exchange from air to top through the screen can be computed by

$$HAirTop = 2.3e3 * (Tair - Ttop) * permeability * 1200 * (Tair - Ttop) \qquad [W/m^2]$$

It is easy to see that this results in a quadratic relation between temperature difference and heat exchange through the screen. However, since the permeability is in general a small number for tight screens, the resulting energy flux is quite small as well.

Long wave radiative exchange

Besides the external fluxes and the free and forced convective heat fluxes, the model calculates radiative heat exchange in the wavelength region between 5 and 50 μm.

This long-wave radiative heat is exchanged between opaque surfaces in the greenhouse and between the greenhouse cover and the sky. In the current model, the number of opaque surfaces is maximal 15, namely the 14 real surfaces that can be distinguished plus the sky, which acts as a virtual surface. Since all surfaces in principle can radiate to each other, there are maximal 105 radiative heat fluxes to be determined (14+13+ … 2+1). However, in practical situations, the number of radiative fluxes will be a lot smaller. Double coverings are not widespread used, just like using all three screen layers. Moreover, surfaces at a certain point in the stack can be non-transparent for longwave radiation, which means that lower layer cannot 'see' all layers above them.

The general description of radiative heat transfer reads:

$$R_{S1S2} = \frac{\varepsilon_{S1}\,\varepsilon_{S2}\,F_{S1S2}\,A_{S1}}{1-\rho_{S1}\rho_{S2}\,F_{S1S2}F_{S2S1}}\,\sigma\,(T_{S1}^4 - T_{S2}^4)\ [W]$$

This equation, computing the energy exchanged from surface S1 to surface S2, is governed by the optical material properties of both surfaces and the geometrical configuration. The

$$F_{S2S1} = F_{S1S2}\, A_{S1} / A_{S2} \qquad [-]$$

With this formula it can also be seen that R_{S2S1} is equal to R_{S1S2}, except for the sign, which will be opposite.

Going from the top of the greenhouse model downwards through the layers of the greenhouse, the radiative heat exchange between the cover and the sky is the first to be defined.

The sky by definition as a black body with a temperature Tsky, an emission coeeficient 1 and a reflection coefficient 0.

Therefore the radiative heat exchange between the cover and the sky is simply

$$R_{CovSky} = \varepsilon_{cov,up}\, F_{CovSky}\, A_{cov}\, \sigma\, (T_{cov}^{4} - T_{sky}^{4}) \qquad [W]$$

The surface of the cover of a greenhouse is larger than the floor surface of the cover, but due to the repetitive tilted surfaces, the cover partly sees itself. This makes that the product FCovSky Acov equals 1 and the radiative exchange from the upper cover per m² of greenhouse surface is simply

$$R_{CovSky} = \varepsilon_{cov,up}\, \sigma\, (T_{cov}^{4} - T_{sky}^{4}) \qquad [W/m^2]$$

The term $\varepsilon_{cov,up}\, \sigma$ will be called the radiative exchange coefficient (REC) and refers to the typical multiplication factor in a the computation of a radiative exchange.

Where the upper cover layer has only one upward flux, the second cover layer (if the greenhouse has a double cover) may have two upward fluxes. This depends on the transparency of the upper cover for infrared radiation. If the upper cover blocks all infrared radiation, the full hemisphere of the lower cover is occupied by the upper cover. Then the viewfactor of the lower cover to the sky becomes zero. However, in case the upper cover transmits, say, 40% of the infrared radiation, 60% of the hemisphere of the lower cover is occupied by the upper cover and 40% of the hemisphere is virtually occupied by the sky.

22 / 88 | 67%

Crop parameters

The user can choose for a simulation with different crops. The crops differ with respect to their transpiration rate and with respect to the division of leaf surface into the 4 crop layers described by the model. In all cases, the crop transpiration is computed from relations that describe the behaviour of the stomatal resistance for moisture transport and that compute the driving force for the moisture transport. This driving force is the difference in moisture content in the leaf cavities and the moisture content of the greenhouse air.

The stomatal behaviour is modelled by a simple formula that yet gives a very close match between observed and computed transpiration rates in tomato, especially during the low-light conditions for which the Radiation monitor was designed.

Unfortunately, Wageningen UR does not have ready to use detailed data on the transpiration rate of other crops so, for the other crops, simple multiplication factors compared to tomato are used. These multiplication factors are listed below.

Crop	Transpiration as a factor compared to tomato
Tomaat	1
Komkommer	0.85
Paprika	0.75
Roos	0.95
Gerbera	0.9

The different crops do not only have different transpiration factors compared to tomato, but also all have their typical Leaf area index. The table below shows which leaf surfaces in each layer per m2 greenhouse area are being used

Crop	LAI per layer
Tomato	0.75 - 0.75 -0.75 -0.75
TomatoHT	0.15 - 0.95 -0.95 -0.95
Cucumber	0.75 - 0.75 -0.75 -0.75
CucumberHT	0.15 - 0.95 -0.95 -0.95
Sweet pepper	1 - 1 - 1 – 1
Rose	0.1 – 0.9 – 0.9 – 0.9
Gerbera	0.1 – 0.8 – 0.8 – 0.8

For the two flower crops, the top layer has only a small surface. This top layer represents the flowers and flower buds. These parts of the crop transpire much less than leaves so for the top layer of these crops, the resistance to transpiration is increased by a factor 2.5 compared to the transpiration resistance of leaves.

The crop-descriptions TomatoHT and CucumberHT refer to Tomato and Cucumber crops with a different distribution of the leaf surface over the 4 layers. In the 'HT'-cases the top layer describes the temperature of the top 0.15 m² of the crop which is considered to be the head of the crop.

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