THERMODYNAMICS OF GREENHOUSE SYSTEMS: A NEW APPROACH LEADING TO NEW PROPOSALS FOR SUSTAINABLE PRODUCTION

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ABSTRACT

Greenhouse production systems produce in the Netherlands and Flanders economical important quantities of vegetables, fruit and ornamentals. Control of the crop environment has led to a high primary energy use (1500MJ/m²/year). This high primary energy use affects the economical and environmental sustainability. Research projects in the Netherlands and Flanders are launched to achieve sustainable greenhouse systems with high crop yields and low primary energy use.

Until now, these projects didn't result in the desired primary energy savings. On the contrary, the civil building industry succeeds by the passive house technology in a magnitude's reduction for primary energy use.

The primary energy saving research in greenhouse systems was mainly based on analysis of energy balances. However, the thermodynamic theory indicates that an analysis based on the concept of exergy (free energy) and energy is preferred. Such analysis could reveal possibilities for primary energy savings.

The different processes and in/outputs of the greenhouse system are outlined. The appropriate equations for exergy calculations are developed. First, analyses are performed on the processes of transpiration and ventilation. Further, a total system assessment is performed.

The exergy analysis indicates that primary energy saving in greenhouse systems could be the same as in the building industry, but adapted technologies need to be developed.

The Institute for Agricultural and Fisheries Research (ILVO) will use this exergy analysis as a basis for the development of an exergy efficient greenhouse prototype (EXEkas).

INTRODUCTION

In Flanders and the Netherlands greenhouse production systems produce economically important quantities of vegetables, fruit and ornamentals [1]. The traditional greenhouse production system consists essentially of a cover with high light transmittance and climate regulating devices like heating, opening roof vents, CO_2 fertilization units, screens and eventually artificial lighting. Despite poorly suitable weather conditions (ex: in Flanders the average temperature in January is 3°C), greenhouses aim to offer an optimal indoor climate for year-round production of warm climate crops like tomato, paprika and tropical ornamentals allowing a high crop yield.

The indoor climate control has led to a high primary energy use (1500MJ/m²/year in the Netherlands, [2]). This results in greenhouse crops that use 30-40 times more primary energy than the energy of the produced crop. This very high use of primary energy affects the economical and environmental sustainability of the traditional greenhouse systems.

The major challenge lies in the development of sustainable greenhouse systems which still allow high crop yields, but with a primary energy use that is an order of magnitude less than that of traditional systems. Governmental research and development projects in the Netherlands and Flanders are launched to achieve such goals.

There was a lot of optimism based on the hypothesis that the excess of solar radiation that enters the greenhouse in summertime, could be captured using closed greenhouse environments and reused in winter time or when needed. Based on this assumption, research and development projects were started in the Netherlands (under the name “Greenhouse as Energy Source”) and in Flanders.

Until now these projects result in around 50% primary energy savings: About half of these savings are due to better insulation and dehumidification of the greenhouse. The other half is accomplished by heat pumps combined with aquifer storage [3]. For most crops, heat pumps combined with aquifer storage are not economically feasible, even with 40% governmental support. Only better insulation and dehumidification show a real prospective [4]. This in contrast to the civil building industry, where ‘passive’ building reaches energy saving rates of 90% for heating [5] and is economically attractive (market expansion).

So the question can be posed if the current primary energy saving research for greenhouses, is based on an integral vision of the (in)efficiencies. The theory of thermodynamics indicates that first law (enthalpy/energy) analysis and mass analysis (conservation of mass) are especially useful for climate, energy or mass modelling. Exergy or availability analysis on the other hand, reveals possibilities for more efficient primary energy use [6-8].

[9] list primary energy saving methods based on a simplified mass-enthalpy model. Based on heat and mass considerations, [10] indicates the possibilities of new technologies like greenhouse insulation, climate conditioning and energy management. [11] describe the state of the art in primary energy savings and sustainable energy supply. It consists of greenhouse insulation and underground storing of heat excess. These insights are based on enthalpy analyses. [12] describe innovative technologies for an efficient use of primary energy existing essentially in new covering materials, screens, operational control and minimal energy loss through ventilation. Again this is all based on enthalpy considerations. [13] describes the development of different concepts for a zero-fossil-energy greenhouse through expert evaluation and model assessment. They concluded that a combination of geothermal heat and a heat pump/aquifer can cover heat demand in a semi-closed greenhouse concept. All considerations are based on enthalpy/mass flows. The incorporated use of a heat pump is also based on enthalpy calculations. [2] presents the following primary energy saving technologies for greenhouses: maximum use of solar radiation, reduction of energy use in the greenhouse and new design (semi-closed greenhouses, electricity producing greenhouses). Also these findings are based on enthalpy calculations.

Dehumidification in greenhouses is responsible for roughly 10-25% of the overall primary energy demand [14]. Also here, the research about dehumidification with primary energy saving purposes is based on enthalpy or mass balances ([14-18]).

CO_2-management in the greenhouse is another corner stone in the primary energy saving research. In general, optimal production levels in greenhouses are achieved with CO_2 levels of 1000ppm. Primary energy saving for heating or dehumidification results in less CO_2 available for CO_2 fertilization and compromises its economical feasibility. The CO_2 fertilization research for greenhouses is based on a mass approach ([19-21]).

This literature review shows that the current primary energy savings research for greenhouses is founded on first law (enthalpy/energy) analysis or mass analysis (conservation of mass). Up to now, exergy or availability analysis is only rudimentary performed. Only [22] writes about the exergy of greenhouse systems. He focuses on how to obtain more exergy efficient heat or CO_2. Further [23] writes about using low exergy (26°C) heat from a power station’s cooling tower for heating the greenhouse.

All these cited researches didn’t analyse the exergy of the processes and in/outputs in the greenhouse. As a consequence, they could not propose adapted solutions that result from these considerations.

To bridge this gap, this paper gives a thermodynamic analysis of greenhouses processes and in/outputs. Therefore specific exergy equations are derived. As a result of the thermodynamic analysis, some primary energy saving solutions are proposed.

NOMENCLATURE

$cp/m_{H2O,l}$	J/kg/K	Heat capacity of liquid water by mass unit
$cp/m_{H2O,a}$	J/kg/K	Heat capacity of vapour by mass unit
DPE	K	Dew point excess for transpiration, is difference between leaf temperature and condensing temperature of inside air
EX	J	Exergy
H	J	Enthalpy
l23/m	J/kg	Enthalpy of transformation of water by mass
M	[kg]	Mass
m(H2O)	[kg]	Mass of water
M_{H2O}	[kg/mol]	Molar weight of water
n(H2O)	[mol]	Number of moles of water
p_i	[Pa]	Partial pressure of species i in the concerned gas
$p_{i,e}$	[Pa]	Partial pressure of species i in the environment
Q	[J]	Heat
R	[J/mol/K]	Ideal gas constant
T_c	[K]	Condensing temperature of the inside air
T_e	[K]	Temperature of the environment
U	[J]	Energy
W	[J]	Work
y_i	[-]	Mole fraction of species i in the concerned air
$y_{i,e}$	[-]	Mole fraction of species i in the environment

Subscripts

a	Inside air
b	Boiler
coi	Inside cover
coo	Outside cover
e	Environment
g	Ground
h	Heating pipes
l	Leafs, canopy
o	Outside buffer that reacts with the greenhouse

ENERGY AND EXERGY BALANCES OF A GREENHOUSE SYSTEM

For analysis, an energy and exergy balance is calculated for an open system (Figure 1) with well defined boundaries and different in- and outputs.

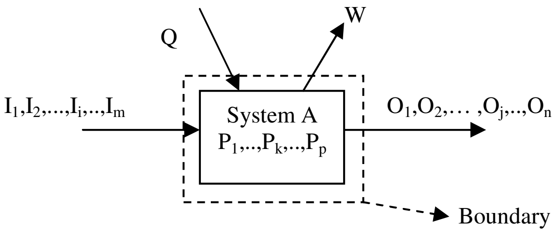

Figure 1 Schematic presentation of an open system with m different inputs (I_i),n different outputs (O_j) and p different processes inside the system (P_k). Q is the heat delivered to the system and W the work delivered by the system.

Neglecting potential and kinetic differences, the energy balance gives for system A[8]:

$$\Delta U_A = Q - W + \sum_{i=1}^{m} H_{I,i} - \sum_{j=1}^{n} H_{O,j} \qquad (1)$$

With $H_{I,i}$ the enthalpy of the inputs i, $H_{O,j}$ the enthalpy of outputs j.

Exergy analysis for the system A differs from the energy/enthalpy analysis since exergy is destructed by the processes in the system or:

$$\Delta EX_A = EX_Q - W + \sum_{i=1}^{m} EX_{I,i} - \sum_{j=1}^{n} EX_{O,j} + \sum_{k=1}^{p} \Delta EX_{P,k} \qquad (2)$$

With EX_Q the exergy of the heat input Q, $EX_{I,i}$ the exergy of the inputs i, $EX_{O,j}$ the exergy of outputs j and $\Delta EX_{p,k}$ the exergy balances for processes p_k inside the system A (negative values).

The definition of the processes p_k and their boundaries must be made clear. Often a process can be analysed in more detail through assuming it as a system and subdividing it by using equation 2.

The boundaries of the greenhouse processes p_k (like long wave radiation between different objects, evaporation, convection, amongst others) are often crossing each other. This makes the graphical presentation of process boundaries disorderly. In our case, however, the graphical presentation is not necessary because the boundaries are inherent to the definition of the processes (like long wave radiation, amongst others) as indicated by the theory of heat and mass transfer.

When the system A is a steady state and no work (W) and heat (Q) is delivered over its boundaries, equation 2 becomes:

$$\sum_{j=1}^{n} EX_{Ii} - \sum_{i=1}^{m} EX_{Oj} = -\sum_{k=1}^{p} \Delta EX_{Pk} \qquad (3)$$

Different processes lead to the dissipation of the exergy in a system. In greenhouses, the energy of solar radiation and primary energy input with high exergy contents degrades by different physical and biological processes into heat on ambient temperature and air with ambient concentrations with no exergy content.

A THERMODYNAMIC ANALYSIS OF A GREENHOUSE SYSTEM

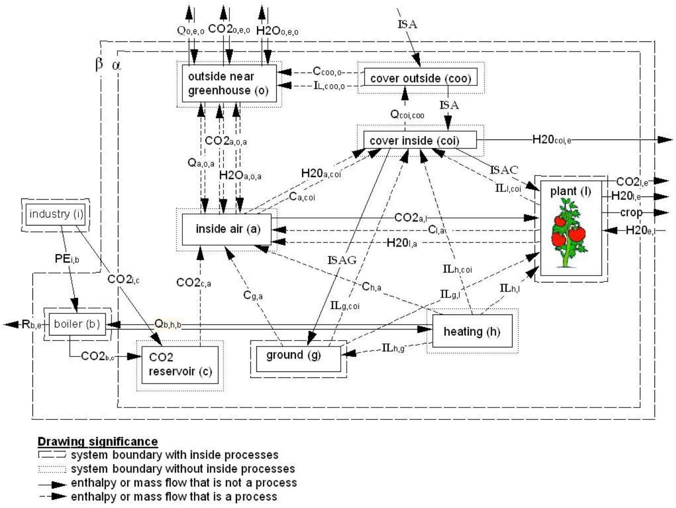

Figure 2 Thermodynamic scheme of a typical greenhouse system with different processes and flows. Flows that are a process: Q = enthalpy flow by heat, IL=enthalpy flow by long wave radiation between different objects, C= enthalpy flow by convection, CO2 =mass flow of CO_2.
Flows that are not a process: ISA =shortwave irradiance which is absorbed in the greenhouse, ISAC=shortwave irradiance which is absorbed by the canopy, ISAG= shortwave irradiance which is absorbed by the ground, PE=primary energy. Lower-case subscripts indicate the source and destiny. A more complete description is given in the text.

Figure 2 presents the thermodynamics of a typical greenhouse system. It consists of the enthalpy/mass flows and exergy destruction processes. This presentation differs with earlier presentations used for enthalpy-mass modelling (ex: [24]) due to the supplementary presentation of the exergy destruction processes.

The α-layer is the greenhouse where plant production takes places. The β-layer includes the processes that produce the α-layer inputs.

In the figure different types of lines are used for the arrows and entity boundaries. A dashed arrow line indicates a flow of enthalpy or mass *in process,* which means with exergy destruction. For example, the process of long wave radiation creates enthalpy flows between different objects, whereby the heat will degrade to a temperature level closer to the ambient temperature. A full arrow line means that this energy flow is *not in process*, which means without exergy destruction. For example, the flow of incoming sun radiation (ISA) goes through the greenhouse air and does not lose exergy as long as it is not absorbed. A dotted boundary line around an entity indicates that there are no inside processes active and that the system is a steady state. This means that the exergy input of the different flows equals the exergy output. In contrast, a dashed boundary line indicates that there are inside processes active with exergy destruction.

The used abbreviations of figure 2 meet to the following conventions:

The physical entities are abbreviated by small letters.

The flows are indicated by capitals and indicate the transport type. They are provided with small letters to indicate the source entity and the destiny entity.

The different processes inside the greenhouse (α-layer) presented in figure 2 consist of:

- long wave radiation (IL)
- convection (C)
- absorption of short wave radiation by the ground and heat diffusion in the ground (g)
- absorption of short wave radiation by the canopy with photosynthesis (l)
- transpiration ($H2O_{l,a}$)
- condensation ($H2O_{a,coi}$)
- mixing of air with different concentrations of CO_2(ex: $CO2_{a,o,a}$), water vapour (ex: $H2O_{a,o,a}$) or heat (ex: $Q_{a,o,a}$)
- heat conduction through the greenhouse cover ($Q_{coi,coo}$).

The process in the β-layer is the combustion of fuel (primary energy) in the boiler (b) for heating of water.

The boundary of the α-layer surrounds also the buffer outside the greenhouse (o) that reacts with the greenhouse system by ventilation ($Q_{a,o,a}$, $CO2_{a,o,a}$,$H2O_{a,o,a}$) or convection ($C_{coo,o}$) or long wave radiation ($IL_{coo,o}$). This outside buffer (o) is interacting with the environment (e) by flows without theoretical exergy destruction ($Q_{o,e,o}$,$H2O_{o,e,o}$,$CO2_{o,e,o}$).

Exergy equations

The different processes and in/outputs of the greenhouse (Figure 2) have exergy values.

The exergy equations related to sensible heat, combustion and solar radiation are given in Table 1.

Table 1 Exergy (J) equations for some in/outputs and processes of the greenhouse system. ΔEX is the exergy balance of a process, temperatures in Kelvin.

In/output description	Equation
Heat (Q) delivered at temperature T ([8])	$EX = Q(1 - {}^{T_e}/_{T})$ (4)
A mass flow (M, kg) that comes in at temperature T_1 and goes out at T_2 with cp/m (J/kg/K) the specific heat ([8])	$EX = M\ cp/m\ (T_1 - T_2)\left(1 - \frac{T_e}{LMT}\right)$ (5) $LMT = (T_1 - T_2)/ln\,(\frac{T_1}{T_2})$
Solar irradiance (Irradiated Energy=IS, [7])	*EX=0.9327 IS* (6)
Natural gas (NCV=Net Caloric Value, [25])	*EX=1.035 NCV* (7)
Average agricultural crops (GCV=Gross Caloric Value, [25])	*EX=1.031 GCV* (8)
Process description	
Heat flow from T_1 to T_2	$\Delta EX = -Q\ T_e(\frac{1}{T_2} - \frac{1}{T_1})$ (9)
Solar radiation (IS) absorbed on a surface of temperature T	$\Delta EX = -0.9327.IS + IS(1 - {}^{T_e}/_{T})$ (10)
Solar radiation (IS) absorbed on a leaf at temperature T + photosynthesis (crop)	$\Delta EX = -0.9327.IS + IS\left(1 - {}^{T_e}/_{T}\right) + crop\ 1.031$ (11)

The exergy value of air on atmospheric pressure with different partial pressures ([8]) is:

$$\boldsymbol{EX = n\,R\,T_e \sum_{i=1}^{m} y_i ln\left(\frac{y_i}{y_{i,e}}\right) = R\,T_e \sum_{i=1}^{m} n_i ln\left(\frac{p_i}{p_{i,e}}\right)} \quad (12)$$

With y_i the mole fraction of species i in the air, $y_{i,e}$ the mole fraction of species i in the environment, p_i the partial pressure of species i in the air, $p_{i,e}$ the partial pressure of species i in the environment, m the number of species in the air, R the ideal gas constant (8.314J/mol/K).

The ventilation of the greenhouse results for CO_2 and H_2O in a limited concentration difference. Therefore, the exergy difference per mol exchanged species is calculated by the first derivate to the concerned species (CO_2, H_2O here x) of equation 12

$$\frac{d(EX)}{d(n_x)} = R\,T_e \frac{d(\sum_{i=1}^{m} n_i ln\left(\frac{y_i}{p_{i,e}}\right)\ )}{d(n_x)}$$

Splitting the equation between the species x and other species

$$\frac{d(EX)}{d(n_x)} = R\,T_e\left[ln\left(\frac{y_x}{y_x^e}\right) + n_x\frac{d(ln\left(\frac{y_x}{y_{x,e}}\right))}{d(n_x)} + \frac{\sum_{i=1(-x)}^{n} n_i\ d(ln\left(\frac{y_i}{y_{i,e}}\right))}{d(n_x)}\right]$$

-x stands for without species x.

Further

$$\frac{d(y_{i(-x)})}{d(n_x)} = \frac{d(\frac{n_{i(-x)}}{n})}{d(n_x)} = -\frac{n_{i(-x)}}{n^2}$$

$$\frac{d(y_x)}{d(n_x)} = \frac{d(\frac{n_x}{n})}{d(n_x)} = \frac{1}{n} - \frac{n_x}{n^2}$$

What results in

$$\frac{d(EX)}{d(n_x)} = R\,T_e\left[ln\left(\frac{y_x}{y_{x,e}}\right) + \frac{n_x}{y_x}(\frac{1}{n} - \frac{n_x}{n^2}) - (\sum_{i=1\,(-x)}^{n}\frac{n_i^2}{y_i n^2}\ )\right]$$

$$\boldsymbol{\frac{d(EX)}{d(n_x)} = R\,T_e\left[ln\left(\frac{y_x}{y_{x,e}}\right)\right] = R\,T_e\left[ln\left(\frac{p_x}{p_{x,e}}\right)\right]} \quad (13)$$

The exergy destruction for the mixing between two buffer systems (1 and 2) with different partial pressure for species x gives a limited difference for x in both systems. Applying this last equation gives for the exergy difference per mol exchanged species x:

$$\frac{d(EX)}{d(n_{x,1})} = R\,T_e\left[ln\left(\frac{y_{x,1}}{y_{x,2}}\right)\right] = R\,T_e\left[ln\left(\frac{p_{x,1}}{p_{x,2}}\right)\right] \quad (14)$$

Note that the heat and pressure exergy equations are different in composition. The heat equation consists of 2 terms (ex: equation 5) and the pressure equation (ex: equation 12) of only a logarithmic term.

This is not to be expected since

- the similarity for the ideal gas entropy equation for pressure and temperature [26]
  $S_2 - S_1 = n\,.\,cp/n\,.ln\left(\frac{T_2}{T_1}\right) - nRln\left(\frac{p_2}{p_1}\right)$
  With cp/n the heat capacity per mol (J/mol/K), n the number of moles
- the exergy balance is the negative of the total entropy creation multiplied by the temperature of the environment (when no work performed) [8]
  $\Delta EX = -(W + T_e \Delta S_{tot})$
  With ΔS_{tot} the entropy difference of the total system: this includes the defined system and the involved environment.

However, the total entropy creation differs fundamentally between the release of heat into the environment and the release of n mol gas with different partial pressures and at atmospheric pressure. The release of heat into the environment leads to an entropy change for the environment in addition to an entropy change for the material that lost heat. On the contrary, the release of n mol gas does not lead to an entropy change for the environment. It led only to an entropy change for the n mol gas. This explains why the exergy equations related to heat (ex: equation 5) exist of 2 terms and related to pressure (ex: equation 12) of only 1.

Further, for the same reason, the exergy balance of mixing n mol gas in a buffer is

$$\boldsymbol{\Delta EX = -n\,R\,T_e \sum_{i=1}^{m} y_i ln\left(\frac{y_i}{y_{i,b}}\right) = -R\,T_e \sum_{i=1}^{m} n_i ln\left(\frac{p_i}{p_{i,b}}\right)} \quad (15)$$

Table 2 indicates which equations calculate the exergy balances of processes or exergy values of in/outputs for the greenhouse system (figure 2).

Table 2 Applied equations for exergy calculations of different in/outputs and processes of the greenhouse system (for abbreviations see figure 2).

INPUTS α	Equation number
$Q_{b,h,b}$	5
$CO2_{b,c}$	12
$CO2_{i,c}$	12
ISA	6
OUTPUTS α	
$Q_{o,e,o}$	Ex=0
$CO2_{o,e,o}$	Ex=0
$H2O_{o,e,o}$	Ex=0
PROCESSES inside α	
$CO2_{c,a}$	15
$CO2_{a,o,a}$,$H2O_{a,o,a}$	13
IL,C,Q	9
$H2O_{l,a}$, $H2O_{a,coi}$	14
L	11, 12 (for CO2 uptake)
G	10, integration over different ground layers of equation 9
INPUTS β	
$PE_{e,b}$	7
PROCESSES β	
B	3

Through the inequilibrium between in/outside conditions, different processes inside the α-layer tend to create unadapted inside climate conditions. They are called “sources”. They are compensated by processes for (re)creating adapted climate inside thereby using primary energy.

Those “source” processes are essentially:

- loss of heat by the cover ($C_{a,coi}$,$H2O_{a,coi}$,$Q_{coi,coo}$,$Q_{coo,o}$)
- transpiration ($H2O_{l,a}$)
- ventilation ($Q_{a,o,a}$,$H2O_{a,o,a}$,$CO2_{a,o,a}$)

Especially there, it must be clear what the exergy balances of the processes are to assess possible primary saving technologies. The exergy destructions of heat related processes are easily estimated from the exergy equations of Table 1. It is related to the temperature differences. But the question is to estimate also the mass-related processes (transpiration, ventilation with different CO_2 and H_2O concentrations) see sections “Transpiration” and “Exergy and enthalpy balance of greenhouse ventilation”. From this whole thermodynamic insight can be assessed primary energy saving technologies (section ”From exergy analysis to new proposals ”).

Transpiration

The process of transpiration is presented in figure 3. The system boundaries include the surrounding air where the produced vapour is mixed with greenhouse air. Convection of leaf heat ($C_{l,a}$ in figure 2) is not included.

The transpiration process receives heat (Q) at leaf temperature (T_l) and some water (H_2O) at temperature T_l. In the first step of the process, the water is transformed from the liquid to the vapour phase. The vapour has a pressure of $p_{H2O,l}$ and a temperature T_l. This is a reversible process [26]. In the second step of the process, the vapour is mixed with the surrounding air. As a result, the vapour degrades to a state at pressure $p_{H2O,a}$ and temperature T_a (conditions of the surrounding air). At these conditions, the vapour leaves the system.

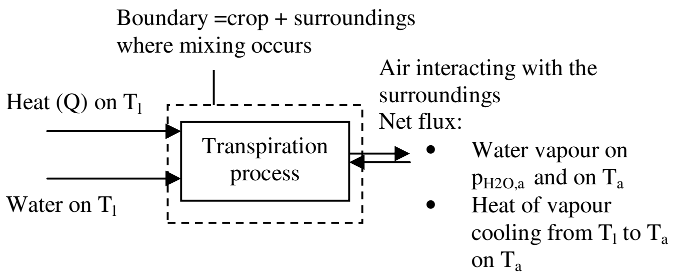

Figure 3 Schematic presentation of transpiration with inputs, outputs and boundary. Convection of heat from the leaf is not included.

The energy balance (equation 1) for the transpiration system gives (reference= temperature T_a):

$$Q + m(H2O)\,.\,cp/m_{H20,l}.\,(T_l - T_a) = m(H2O)\,.\,l23/m_{Ta} + m(H2O)\,.\,cp/m_{H20,g}\,.\,(T_l - T_a)$$

With $l23/m_{Ta}$ the vapour enthalpy by mass at temperature T_a (J/kg), $cp/m_{H2O,l}$ the heat capacity of liquid water by mass (J/kg/K), $cp/m_{H2O,g}$ the heat capacity of water vapour by mass unit (J/kg/K), m(H2O) the mass of water (kg).

Then:

$$Q = m(H2O).\,l23/m_{Ta} + m(H2O)\,.\,(cp/m_{H20,g} - cp/m_{H20,l})(T_l - T_a)$$

From the evaporation enthalpy on different temperatures:

$$Q = m(H2O)\,.\,l23/m_{Tl}$$

Here $l23/m_{Ta} \approx l23/m_{Tl}$,so:

$$Q \approx m(H2O).\,l23/m \qquad (16)$$

With l23/m an average enthalpy of evaporation by mass (J/kg)

The exergy balance (equation 3) is constructed with equations 4,5 for the heat related terms and equation 13 for the mass related term. This gives:

$$\Delta EX = m(H2O)\,.\,cp/m_{H20,g}.\,(T_l - T_a)\left(1 - \frac{T_e}{T_a}\right) + m(H2O)\,.\,cp/m_{H20,g}\,.\,(T_a - T_e)\,.\left(1 - \frac{T_e}{LM(T_a,T_e)}\right) + n(H2O).\,R\,.\,T_e\,.\,ln\left(\frac{p_{H2O,a}}{p_{H2O,e}}\right) - m(H2O)\,.\,l23/m_{Tl}\,.\left(1 - \frac{T_e}{T_l}\right) - m(H2O)\,.\,cp/m_{H20,l}\,.\,(T_l - T_e)\,.\left(1 - \frac{T_e}{LM(T_l,T_e)}\right) \qquad (17)$$

With n(H2O) the number of moles of water.

The thermodynamic interrelation between saturated vapour pressure and different temperatures (T_0 and T_1) is given by:

$$Rln\left(\frac{p_1}{p_0}\right) = l23/m_{T1}\,.\,M_{H2O}\,.\left(\frac{1}{T_0} - \frac{1}{T_1}\right) - \left(cp/m_{H20,g} - cp/m_{H20,l}\right).\,M_{H2O}\,.\,(T_1 - T_0)\,.\left(\frac{1}{T_0} - \frac{1}{LM(T_0,T_1)}\right) \qquad (18)$$

With M_{H2O} the molar weight of water (kg/mol).

Integrating equation (18) in equation (17) gives:

$$\Delta EX = n(H2O).\,R\,.\,T_e\,.\ln\left(\frac{p_{H2O,a}}{p_{H2O,l}}\right) + m(H2O).\,cp/m_{H20,g}\,.\,((T_l - T_a)\,.\left(\frac{T_e}{LM(T_a,T_l)} - \frac{T_e}{T_a}\right)) \qquad (19)$$

This equation indicates that transpiration consists of two irreversible processes. The first term reflects the diffusion of the vapour from leaf pressure to the ambient air pressure and the second term represents the diffusion of the heat of the produced vapour to the ambient air temperature.

Integrating again equation 18, last equation can also be written as:

$$\Delta EX = m(H2O)\,.\,T_e\,.\,l23/m_{Tl}\,.\left(\frac{1}{T_l} - \frac{1}{T_c}\right) + m(H2O)\,.\,T_e\,.\left(cp/m_{H20,g} - cp/m_{H20,l}\right).\,(T_l - T_c)\,.\left(\frac{1}{T_c} - \frac{1}{LM(T_l,T_c)}\right) + m(H2O)\,.\,T_e\ .\,cp/m_{H20,g}\,.\,(T_l - T_a)\,.\left(\frac{1}{LM(T_a,T_e)} - \frac{1}{T_a}\right) \qquad (20)$$

With T_c is the greenhouse air condensation temperature (dew point).

As stated for the enthalpy balance, different terms in equation 19 and 20 are negligible. This results in:

$$\Delta EX \approx n(H2O).\,R\,.\,T_e\,.\ln\left(\frac{p_{H2O,a}}{p_{H2O,l}}\right) \approx m(H2O).\,T_e\,.\,l23/m\,.\left(\frac{1}{T_l} - \frac{1}{T_c}\right) \qquad (21)$$

This means that the exergy balance of transpiration can be approached as a pressure change of the water vapour ($p_{H2O,l}$ to $p_{H2O,a}$) or as an enthalpy flow change between the leaf temperature and the condensation temperature of the air (=DPE, dew point excess, see [14]).

In many greenhouse crops transpiration results in dehumidification when the relative humidity exceeds about 85%. Assuming leaf temperature equals air temperature, this results in an air DPE of about 2.5°. Under circumstances of dehumidification, the transpiration process results for the same sensible heat reduction in a much lower exergy destruction than the heat loss process of the greenhouse during the heating period (temperature difference in/outside is an average of 12.5 °C, applying equation 9). So plants are exergy efficient systems for transpiration. This has to do with their structure which provides in a large surface to allow working under low concentration gradients. A plant is indeed an efficient heat-mass exchanger.

Exergy and enthalpy balance of greenhouse ventilation

Greenhouses need to be ventilated for evacuating vapour excess due to plant transpiration and for evacuating sensible heat excess due to solar radiation. Secondly air leaks away through gaps in the construction (in/ex filtration).

From enthalpy or mass perspective, the α-layer looses by ventilation sensible heat, water vapour and CO_2. From exergy perspective, the ventilation results in mixing of air with different sensible heat, vapour and CO_2 contents. This is presented in figure 2 respectively by $Q_{a,o,a}$, $H2O_{a,o,a}$ and $CO2_{a,o,a}$.

Table 3 illustrates these values on a typical moment of primary energy use (high humidity inside, low temperature outside) in the greenhouse. The exergy balances are calculated from equation (9) for different temperatures and from equation (13) for different vapour and CO_2 contents.

Table 3 Exergy (ΔEx) and enthalpy (ΔH) balance for the greenhouse system (α-layer) per mol air ventilation. Inside air at 19°C, 85%RH, 1000ppm CO_2. Outside environment at 5°C, 385ppm CO_2.

	ΔEx (J/mol)	ΔH (J/mol)
Sensible heat	-19.7	-411
H_20 vapour	-17.1	-434
CO_2	-1.4	0
TOT	-38.2	-845

The exergy balance values of ventilation are low compared to the enthalpy balance values. This results from the low temperature and concentration differences with the outside environment.

The contribution in the exergy destruction of ventilation by vapour and sensible heat is comparable. This is expectable from combination of the equation 14 with equation 21. They indicate that inside air vapour has approximately the same quality as sensible heat on T_c (condensing temperature inside air). Effectively, the vapour in the inside air is produced through the transpiration process that degrades the sensible heat from leaf temperature to T_c (section "Transpiration"). So dehumidification through ventilation is not exergy efficient: the vapour in the air has a small lower exergy value as the sensible heat (for the same enthalpy value) and is lost together with the sensible heat.

Flat plate air-air heat exchangers for dehumidification of greenhouse air, that are recently tested in new greenhouses projects [27], partially recuperate the exergy of the sensible heat of the air but vent out the exergy of the vapour of the air. This is in contrast to its application in civil buildings where the air has less vapour and the heat exchangers partially recuperate the most important fraction of the exergy of the air.

Therefore for primary energy saving purpose, a greenhouse system needs adapted technologies that also recuperate the exergy of the vapour in the air. This could be achieved with a "vapour heat pump" that transforms the exergy of the vapour in sensible heat with a low primary energy input.

Furthermore, the CO_2 contribution to the exergy balance of ventilation is very low. This indicates that from exergy perspective, adapted concentration techniques could be developed to enrich greenhouse air to the desired level of 1000ppm from CO_2 form the outside air. Such a technique could be called a "CO_2 pump". From the exergy balance, this is probably achievable with low primary energy inputs.

From exergy analysis to new proposals for sustainable production

The highest primary energy savings are achievable by reducing the "source" processes because then "compensating" processes are no longer necessary. Reduction in "source" is possible for the processes of

- heat conduction. This can be realized through more insulation. However light transmission is extremely important for crop growth: 1% less light is 1% less production. Therefore mobile screens inside the greenhouse must be used depending on light conditions: high insulating opaque screens during night time (U<0.5W/m²/K) and modular screens with high light transmittance during day time.
- ventilation. This could be realized through ventilation reduction. The reduction of ventilation is for the moments when the greenhouse is "heat demanding".

Reduction in the "source" process is not possible for transpiration ($H2O_{l,a}$): Plants need to transpire for nutrients translocation and CO_2-uptake. However this process has low exergy destruction (see section "Transpiration"). Therefore can the process on the moments of necessary active dehumidification probably be inversed by a technology that transforms the vapour in heat (vapour-heat pump) with low primary energy input.

For CO_2 is the reduction in the "source" process of ventilation a possibility but it results in a heat excess in summer time. The excess of heat can be compensated for example by heat pumps combined with aquifer systems. There was a strong conviction that through such closing and cooling down the greenhouse high CO_2 levels (1000ppm) could be maintained in the greenhouse with resulting optimal production and primary energy savings ([28-30]). However, such systems induce high exergy losses compared to the only low exergy destruction of the CO_2 loss (see section "Exergy and enthalpy balance of greenhouse ventilation"). Therefore, the $CO2_{a,o,a}$ process has not to be reduced by ventilation reduction but, it must be compensated by a technology ("CO_2 pump") that enrich the inside CO_2 level from outside air CO_2. From the low exergy value of the needed CO_2, this will only need a low primary energy input.

CONCLUSIONS

The analysis of the transpiration process showed that its exergy destruction can be seen as a mass flow of vapour that goes from the vapour pressure on leaf level to the vapour pressure of the inside greenhouse air. This can also be seen as the heat of transformation that flows from leaf temperature to the condensing temperature of the inside air. This last interpretation indicates that, due to this low temperature difference during the dehumidification period (≈2.5°C), the exergy destruction by transpiration is much lower than the exergy destruction by heat loss.

The analysis of ventilation showed that its exergy balance is made up equally by its heat and its vapour content. From energy savings perspective, vapour must not be seen as something to get rid of, but as an exergy source for making greenhouse air dryer.

The CO_2 contribution to the exergy balance of ventilation is minimal.

The proposals from the thermodynamic analysis of the greenhouse system for the highest primary energy savings are:

- The reduction of the exergy destruction of heat conduction and ventilation on the moments of heating.

- A vapour heat pump that transforms the inside vapour in sensible heat for active dehumidification.
- A CO_2 pump that enrich inside CO_2 level from outside air CO_2.

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