Greenhouse Systems with Integrated Water Desalination for Arid Areas Based on solar Energy

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Abstract

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The limited water resources in arid areas have led to the use of low-quality irrigation water in agriculture which may reduce crop yields and damage the environment. This study is focused on a greenhouse concept with integrated water desalination considered for small scale applications at remote locations in areas where only saline water is available.

In this greenhouse the roof light transmission is reduced as solar radiation is absorbed by a layer of flowing water on a glass covered by a top glass. Fresh water is evaporated, condensed on the top glass and collected at the roof eaves.

The main objective of this research work is to analyze the fresh water production as well as the crop growth capacity and water demand for the concept. Included are theoretical and experimental studies with a focus on the total system performance and design. The work also includes perspectives on the potential for more advanced cover materials and system concepts of particular interest for further development into future applications.

For the theoretical analysis simulation models with high accuracy have been developed for the water desalination, the light transmission into the greenhouse, the greenhouse climate and for the crop growth and water demand.

The assessment of this concept compared to conventional, single glass greenhouses includes extensive simulations and field experiments in Tunisia. Considerably less extreme climate conditions were registered in an experimental greenhouse with roof desalination compared to a conventional greenhouse. A system integrated in 50% of the roof area of a widespan greenhouse has the capacity to cover the annual demand for a low canopy crop. A similar capacity for a high canopy crop requires asymmetric roof design and desalination system in the whole roof area. Simulated yield reductions for these cases are 25 and 18 % and seasonal fresh water storage is required. Lower yield reductions could be achieved with application of more light selective glass materials in the roof absorber. Here, interesting future prospects are identified for advanced glass materials with dynamic absorptance control.

Economic analyses including water costs and grower revenues indicate that this greenhouse concept competes well with solar collector based technologies for water desalination.

Keywords: solar desalination, greenhouse irrigation, water balance, light transmission, crop growth, economy.

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“Everything should be made as simple as possible, but not simpler”

Albert Einstein

To my parents and Emna and Ahmed

Contents

Appendix

Papers I-VI

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Chaibi, M.T. 2000. An overview of solar desalination for domestic and agriculture water needs in remote areas. Desalination 127, 119-133.

II. Chaibi, M.T. 2000. Analysis by simulation of a solar still integrated in a greenhouse roof. Desalination 128, 123-138.

III. Chaibi, M.T. 2002. Validation of a simulation model for water desalination in a greenhouse roof through laboratory experiments and conceptual parameter discussions. Desalination 142, 65-78.

IV. Chaibi, M.T. Optical performance and crop growth capacity for solar desalination systems integrated in greenhouse roofs – experiments and theories. (In review, Biosystems Engineering).

V. Chaibi, M.T. and Jilar, T. System design, operation and performance of roof-integrated desalination in greenhouses. (In review, Solar Energy).

VI. Chaibi, M.T. and Jilar,T. Economy prospects for roof integrated water desalination in greenhouses. (Accepted for presentation at the International Solar Energy Society Conference in Gothenburg, Sweden, June 2003)

Papers I, II, and III are reproduced by permission of the journal concerned.

Notations

C_p	specific heat of air, J kg^{-1} K^{-1}
c_α	conversion of assimilated CO_2 to sugar, dimensionless
c_β	yield factor, dimensionless
ea	air vapour pressure, Pa
eas	air vapour pressure at saturation air temperature, Pa
f	mass rate of change, g m^{-2} m^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
I	global solar radiation intensity, W m^{-2}
m	specific fresh water production, kg m^{-2} s^{-1}
L	latent heat of vaporisation of water, J kg^{-1}
LAI	leaf area index, dimensionless
p	partial pressure of water vapour, pa
r	reflection coefficient dimensionless
re	canopy external resistance for vapour flow, s m^{-1}
r_{gr}	specific growth rate, s^{-1}
ri	canopy internal resistance for vapour flow, s m^{-1}
rpa	average reflection coefficient for the parallel component of polarized radiation, dimensionless
rpe	average reflection coefficient for the perpendicular component of polarized radiation, dimensionless
S	thermal storage, W m^{-2}
T	temperature, K
U	thermal conductance loss, W m^{-2} K^{-1}
v	wind velocity, m s^{-1}
w	plant weight, g m^{-2}
W	water quantity per time, kg m^{-2} h^{-1}

Greek letters

α'	fraction of energy absorbed, dimensionless
λ	wavelength, nm
γ	psychrometric constant, 66 Pa K^{-1}
δ	slope of saturation vapour pressure curve, Pa K^{-1}
ρ	density of air, kg m^{-3}
τ	transmission coefficient, dimensionless

Subscripts

a	ambient
ab	absorber
abs	absorption
ab,w	convective loss between absorber and water
ai	inside the greenhouse
c	convective loss
c,ga	convective loss between cover and ambient air

cr	sum of the convective and radiative heat transfer coefficient from the bottom of the module to the greenhouse environment
c,wg	convective loss between water and the cover
ew	evaporative transfer between the water surface and the internal surface of the glass cover
g	glass cover
i	insulation layer or initial
irr	demand of mixed and brackish water for irrigation
IR	infra red radiation
ndw	non structural dry weight
phot	carbon dioxide assimilation
PAR	photosynthetically active radiation
resp	maintenance respiration
r,ga	radiative loss between glass cover and sky
r,wg	radiative loss between water and glass cover
sdw	structural dry weight
t	total transmission for specific wavelength interval
tot	total transmission for solar spectrum
tr	transpiration or transmitted
UV	ultra violet radiation
w	water

Introduction

Background and problem formulation

As the world's population has increased and the general standard of living has been improved, the quantities of freshwater needed and used has increased drastically. In some cases this has severely strained available freshwater sources and has adversely affected development and people's everyday life (Gishler, 1979; Ad Hoc Panel, 1974)

Arid areas constitute about 60% of the earth's land area and are characterised by scare, limited water resources (Miller, 1991), often of poor quality which also are sensitive for salinisation and pollution (Horchani, 1991).

The limited resources of water have enforced the use of low-quality irrigation water in many arid areas. Recycled urban wastewater, agricultural wastewater and saline groundwater are sources of low-quality water supplied to agriculture. In many situations farmers have no alternative but to use low-quality water. In other cases, farmers have the alternatives of choosing between cheap low and more expensive good quality irrigation water and of mixing water from different sources.

Using low-quality irrigation water may reduce crop yields or damage the environment, soils, and aquifers. For instance, salts applied to soils via irrigation are either left in the soil to harm subsequent crop growth or are leached below the root zone to affect groundwater (Tanji & Enos, 1994). Also, there can be long-term damage to soils and aquifers that may not be easily recoverable.

In a general perspective, however, these fields should have a quite high potential for solar energy utilization. Probably, this potential could be best developed by solar desalination concepts and methods specifically suited to supply remote areas in dry regions with fresh water (Seufert, 1978; Lawand et al., 1973).

One of the major considerations in the use of solar desalination processes is the cost. In comparison to the costs of the most water sources developed and treated by more conventional means, it is expensive and often from two to ten times as expensive (Ayoub & Alward, 1996; Delyannis & Belessiotis, 1995).

Most studies published in the last decade have focused on small scale systems for solar desalination with capacities below 25 m^3 day^{-1} and for application in remote areas (Wangnick, 1992). Some of these have proposed solar desalination processes used in combination with water efficient greenhouse concepts based on solar energy (Tinaut et al., 1978; Sodha et al., 1980; Luft & Froechtenight, 1981).

Thus, integrated design of greenhouses combined with solar stills represents an interesting possibility for the development of small scale cultivation in places where only saline water or brackish water is available (Malik et al., 1996). The main arguments behind this combination are the following:

- Water production levels from solar stills are not on levels corresponding to the water requirement for crops grown in open irrigated fields, but may be suitable for fresh water supply to protected cultivation (Kudish & Gale, 1986).

- Water requirements of crops in protected cultivation heve a diurnal and seasonal fluctuation which is similar to the productivity variation of solar stills. Both processes are primarily driven by the varying solar irradiation and therefore well correlated (Tiwari et al., 1992).

- A solar still can be built as a part of the greenhouse envelope. This simplifies the water transport to the irrigation system as extra arrangements for collection and distribution of temporary excesses can be minimized and the water can be supplied directly to the crop cultivation area (Kudish, 1991).

- A solar still integrated in the roof will reduce the solar energy transmission. This might exclude the need for screens and lower the excess of solar energy in the greenhouse which often represents harmful plant stress conditions with reduced growth capacities (Dumont and Cachard, 1984).

However, the use of desalinated water based on solar energy for agricultural purposes has not yet gone beyond the experimental phase (Chaibi, 2000). A more complete analysis of a system combining a solar still with a greenhouse was first presented by Trombe & Foex (1961) and later more extensive experimental and theoretical studies of the concept were presented by Boutiere (1971), Bettaque (1999), Luft & Froechtenight (1981) and by Dumont & de Cachart (1984)

The basic principle of a system concept for roof-integrated water desalination in greenhouses is illustrated in figure 1. The central part of the system is the roof including a thin layer of down flowing, saline water on a sloped glass sheet covered by a top glass sheet. The lower glass is only partly light transparent why a substantial proportion of the solar irradiation is absorbed. The remaining proportion is transmitted into the cultivated crop. Through the heat generation in this glass fresh water is evaporated from the water layer and then condensed on the inner surface of the top glass. This water is adsorbed to the surface in a drip formation which follows the surface down to collection troughs at the roof eaves.

A saline water store is integrated in the pump assisted water loop through the roof. This water volume represents a certain thermal inertia and the stored heat can be used during hours when solar irradiation is not available.

The water from the collection troughs is supplied to a fresh water store which could be used for short or long term storage. A mixing valve connects the saline and fresh water store for the supply of mixed irrigation water to the greenhouse.

The performance analysis of this very integrated concept includes a number of specific and closely interlinked balance problems. First of all, the water production capacity through light absorptance in the roof has an impact on the crop growth capacity and irrigation water demand. Secondly, the greenhouse air temperature and humidity conditions are strongly linked to the roof light transmittance. As further on the greenhouse climate conditions are influenced by the crop cultivation and vice versa, primarily through the water transpiration, the balance problem is multidimensional to a high and very complex degree.

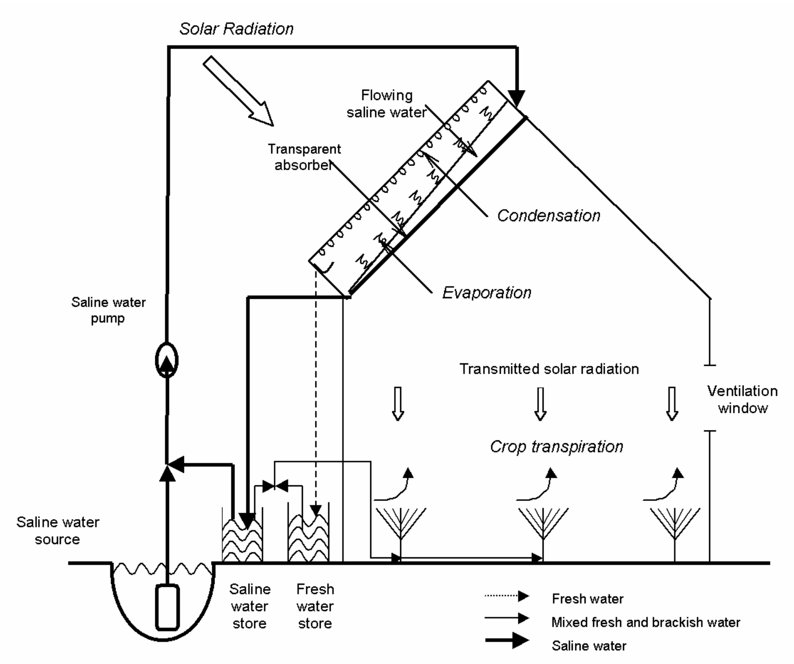

Fig.1. System principle for water desalination integrated in a greenhouse roof.

Concerning the importance of solar irradiation and material optical properties for the total system performance some basic facts should be noted in particular. In order to favour crop growth the transmission of the photosynthetic active radiation (PAR - wavelength interval 380 nm - 710 nm) through the desalination roof should be high. The spectral distribution for the terrestrial beam irradiation corresponding to typical clear sky condition in Tunis is shown in figure 2. Here PAR radiation represents about 42% of the total energy. Addition of scattered diffuse irradiation, which includes a higher proportion of PAR radiation, will give about 50% PAR radiation and 50% infrared radiation (IR) (Ross, 1975). This IR radiation proportion consequently represents the maximum absorptance in a desalination roof without any plant growth reduction.

Typical optical properties for common greenhouse cover glass, a thin water layer and green leafs are presented in figure 3. As illustrated here, if compared to figure 2, the cover glass and water layer has a very high transmittance level for the whole solar spectrum. A feasible and more selective absorber glass should preferably have a similar transmittance level for PAR radiation and a lower transmittance for IR radiation. This would also mean positive impacts on the excess heat prevention for the greenhouse environment as well as the crop water demand. Figure 3 illustrates the very high absorptance selectivity of a single green leaf.

Here, the absorptance level is about 0.85 for the PAR radiation and about 0.15 for IR radiation with typical spectrum distribution for solar radiation. However, for crops with canopies including leaves in several layers the IR absorptance is on the level 0.65.

In addition to the experimental results, some authors have proposed mathematical models for a greenhouse combined with a solar still. These models all include separate control of the solar still and the greenhouse climate. Here the basin of the still is regarded as painted black why it does not allow transmission of the spectral parts of the solar irradiation needed for crop cultivation (Oztoker & Selsuk, 1971; Tiwari & Dhiman, 1985; Sodha et al., 1980). This makes it possible to efficiently control the greenhouse climate and to maximize the water production. However, the greenhouse roof as a window for photosynthetic active radiation with respect to plant growth is not regarded at all. None of the models used incorporate heat and mass transfer aspects for the solar still in combination with these aspects for the greenhouse environment.

In the present research work, the model developed is specifically oriented at solar still solutions with flowing water layer integrated in greenhouse roofs. Also included in the work are analyses of the specific impact on the greenhouse light and thermal conditions from the greenhouse roof.

The transmitted light is considered as the most important climate parameter for crop growth and production with a focus on quantitative yield. Integrated light and climate analysis are used for simulations of crop growth and water demand. However, earlier the light control and greenhouse climate analysis have been separately performed in presentations by Baille et al. (1990), Kozai (1977), Kozai & Kimura (1977), Critten (1983, 1987, 1988) and by many other authors. Furthermore, no model studies are published concerning the impact on the light conditions and the related crop production from structural designs of greenhouse roofs. However, a few results are reported concerning light transmission through greenhouse roofs covered by flowing water (Morris et al., 1958; Cohen et al., 1982; Heinemann & Walker 1987).

For practical application of the integrated concept, it is necessary to have a quantitative model of the water production as well as the crop water demand. These issues have not been given much attention in the literature while several researchers have found encouraging results concerning improvement of the greenhouse climate through the use of a roof covered by light absorbing, flowing water as illustrated by van Bavel et al. (1981), Damagnez (1976), Chiapale et al. (1977), Feuermann et al. (1997), Pollock et al. (1992), Korin et al. (1987), and Strauch (1985).

Literature surveys presented by Al Kasabi et al. (1981), Hassan et al. (1989) and Gala & Zeroni (1984) indicate clear, principal benefits for the integrated concept. However, as drawbacks are mentioned high supposed costs and the lack of appropriate analysis tools for the system performance and economy in specific, practical cases.

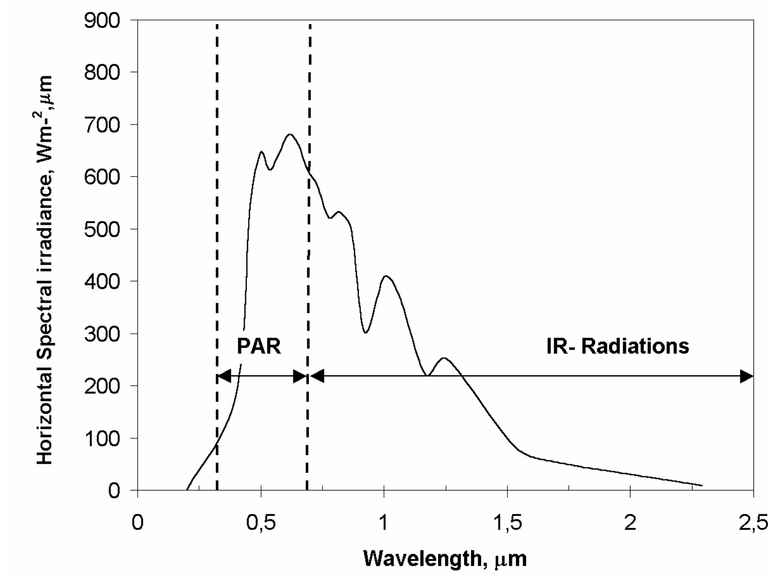

Fig.2. Spectral distribution for the terrrestrial beam irradiation on a horizontal surface for typical clear sky conditions in Tunis.

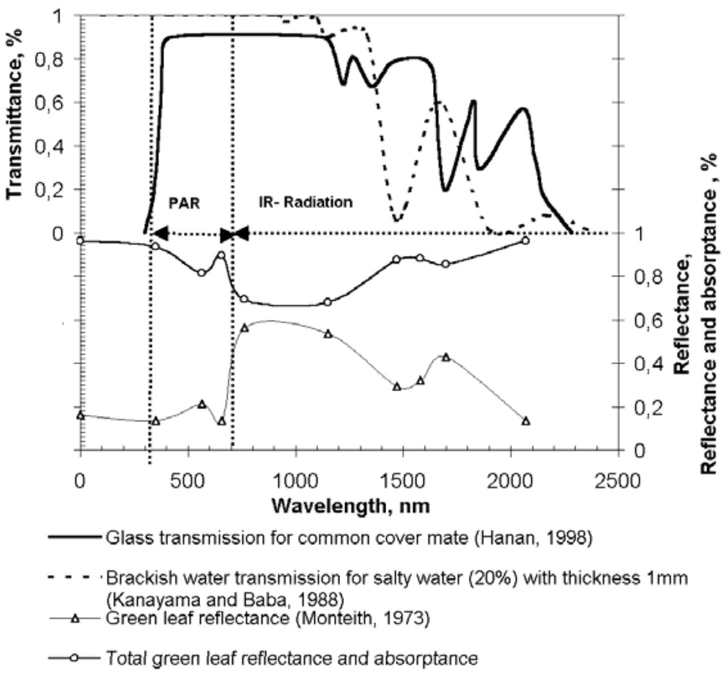

Fig.3. Typical optical properties for common greenhouse cover glass and a thin water layer (upper diagram). Reflectance and absorptance as typical for a single green leaf (lower diagram).

Objectives and hypotheses

The main objective of this research work is to analyze the fresh water production capacity as well as the crop growth capacity for the actual system concept. Included are experimental and theoretical studies with a focus on the total system performance and design for cases with the full capacity to cover the annual water demand for irrigation. Primarily considered applications are remote greenhouse locations in arid areas where the water source is groundwater. The work also includes perspectives on the potential for more advanced cover materials and system concepts of particular interest for further development into future applications.

The aim of the findings is also to form a first basis for the principal operation of this system.

Six hypotheses were formulated behind the present work:

1. A greenhouse with a fully self supported irrigation water supply should be possible to design with the concept.
2. This kind of very integrated concept has not been developed into practical applications earlier because the required performance analysis includes technical and biological problems which are interlinked in a complex way.
3. In arid areas with typical continental climate conditions the intensive daytime irradiation in combination with the bright and cold night-time should be especially favourable for water production with the concept.
4. Roof desalination with transmission reduction similar to shading screens should have a positive impact on the greenhouse climate and the related crop conditions.
5. Cover materials with selective or variable light transmission properties should have a particular interest in these applications.
6. From an economical point of view the concept could be competitive to other solar energy based technologies for greenhouse water desalination.

Structure of the work

The thesis is based on six compiled studies and papers focused on the topics below. In papers V and VI, Professor T. Jilar, the supervisor of the work, has contributed to M.T. Chaibi´s work with the general discussion, perspective aspects and concept identification. The remaining work behind these papers, i.e. measurements, compilation of simulation models and calculations as well as all levels of analysis has been carried through by M.T. Chaibi.

Paper I presents solar desalination systems and working principles for applications in rural arid areas. It also describes some research projects carried out in the field of solar energy desalination in conjunction with greenhouses. Operational, economical and environmental possibilities as well as limitations for solar desalination technologies are reported and discussed.

A systematic approach to improve the efficiency of solar desalination plants, including three main research topics is reviewed. These are related to the basic blocks which are incorporated in a plant, the solar collectors, heat storage arrangements and the process unit.

Paper II describes the simulation method and tool developed and gives calculated results concerning the thermal performance for an integrated solar still. The model developed in this work is concentrated on predictions of the quantitative fresh water production under various climate conditions typical for arid areas and for physical characteristics of different greenhouse cover materials.

Paper III describes laboratory experiments in an indoor solar simulator with a small desalination roof module and presents measurements compared to simulations obtained in order to validate the simulation model developed in Paper II. A further theme is parameters of particular importance when principal system designs and operation methods are considered. Included are the main parameters with impact on the water production capacity. This concerns the light absorptance and temperature of the absorber, the water flow rate and temperature, the inlet water temperature and the water storage volume.

Paper IV presents experimental and theoretical results with a focus on the influence of the material optical properties on the crop growth capacity. The presentation has two main themes. The first is based on the measured spectral composition of the radiation including the photosynthetic active radiation (PAR) transmitted through an experimental roof module (Paper III) equipped with specific absorbers and operated with a water layer in a solar simulator. These measurements are compared to simulations based on spectral models for the optical performance of the roof type. The second theme is a specific as well as a more general analysis concerning the differences in crop growth and yield between greenhouses with conventional roof and with desalination. Here, the emphasis is on the plant biomass production related to light and climate conditions for the crop. Field experiments compared to simulations for a lettuce crop are presented in this assessment. The more general analysis includes theoretical parameter analyses for light transmission and the related crop yield.

Paper V includes analysis of the total system performance with a focus on the balance between water production in the roof and water demand for crop irrigation. Greenhouse cases with conventional and desalination roofs are compared. The first main part is a greenhouse climate analysis based on a detailed simulation model for heat and mass balance of the greenhouse air. Climate conditions of particular importance for the water demand are simulated and compared to field measurements. In the second part simulations and field measurements for water production and demand are compared. The theme of the third part is the system design and typical performance for practical examples. This analysis is also based on results from Paper IV for calculation of crop yield reductions. Furthermore, a short analysis concerning the future prospects for advanced materials and systems is included.

Paper VI is focused on water production costs and commercial grower revenues for climate and market conditions as typical for countries like Tunisia. For production schedules including low value or high value crops these parameters are compared for the roof integrated concept and desalination technologies powered by solar collectors. Included is an analysis of the investment cost margins for high selective glasses in desalination roofs resulting in extra low crop yield reductions. The water and crop yield analysis is based on results from Papers IV and V.

Methodology

Model description

Due to the number and complexity of the heat and mass transfer mechanisms included in the greenhouse system with integrated desalination in the roof, it was felt that modelling the whole greenhouse and crop system was too complex and critical, and that it would be more beneficial to divide the system into separate sub-systems and model these independently (Kindelan 1980). Consequently, models have been developed for the solar desalination roof (Papers II and III), the total light transmission into the greenhouse (Paper IV), the crop growth (Paper IV) and for the greenhouse climate and water balance (Paper V). The interaction and coordination between these parts is managed and organized through the use of an advanced form of the EES (Engineering Equation Solver) computer program (Klein & Alvarado, 1997).

Water desalination

The model for water desalination presented in Paper II is specifically oriented at solar still solutions integrated in roofs with semi-transparent cover materials. The simulation is carried out in an advanced form of the EES (Engineering Equation Solver) computer program (Klein & Alvarado, 1997) for efficient equation system solving and the TRNSYS program (Klein & Beckman, 1994) for solar irradiation calculations.

The structure of the mathematical model describing the heat and mass transfer for the integrated solar still is shown in figure 4. The equations included in the model are similar to those suggested by Oztoker & Selsuk (1971), Sodha et al. (1980), Maalej (1991), and Malik et al. (1996).

The model contains equations for the energy balance of the external greenhouse cover, the flowing water layer in the solar still, the light absorber and the insulation layer under the absorber. The EES-program simultaneously solves these equations resulting in the temperatures of all layers. Also determined is the thermal efficiency of the desalination process defined as the ratio between the water productivity multiplied by the average value for the latent heat of water vaporization and the accumulated solar irradiation during the period of interest. Furthermore, the total light transmittance of the roof and the heat loss through radiation and convection from the bottom of the solar still to the greenhouse environment is calculated.

The fresh water production is predicted from the temperature of the brackish water and the cover glass using mass diffusion relations. The mass flux of water vapour is estimated on the basis of Chilton-Colburn´s analogy between heat and mass transfer (Coulson & Richardson, 1977). The mass flux as a function of the water temperature (T_w) and the cover glass temperature (T_g) is given by Malik et al. (1996):

$$m = 16.273 \; 10^{-3} \; h_c \; (p_w - p_g) / L \qquad (1)$$

Here, h_c is the heat transfer coefficient for convection. The partial pressures of water vapour at saturation, p_w and p_g, are calculated for the water and glass temperatures. The parameter L is the latent heat of vaporisation of water.

This approximate form of Chilton-Colburn´s analogy is commonly used for studies of solar still conditions in practical applications (Maalej, 1991; Malik et al., 1996; Duffie & Beckman, 1991). A central assumption behind this expression is that the partial pressure of water vapour at actual water and glass temperatures is lower than the total pressure for the mixture of air and water vapour of the adjacent humid air at equilibrium. The developed simulation model has been simplified, assuming that errors introduced through these simplifications are smaller than those resulting from the inaccuracy of status variable values in the system boundaries like ambient temperatures and irradiances. It is assumed that the enclosure around the water layer is completely vapour sealed, the water vapour has no radiation absorption and that the temperature of the water layer on the absorber is equal to the average of the water inlet and outlet temperature.

The energy balance for the storage volume has been included in the simulation analysis (Paper III) in order to analyze the combined influence of the storage water volume and the flow rate on the water temperature and water productivity for systems with a closed loop, i.e. incorporating a fully mixed container with connected supply and return pipes. This considers system applications with diurnal heat storage in a water volume, in order to operate the desalination system during daytime as well as night-time.

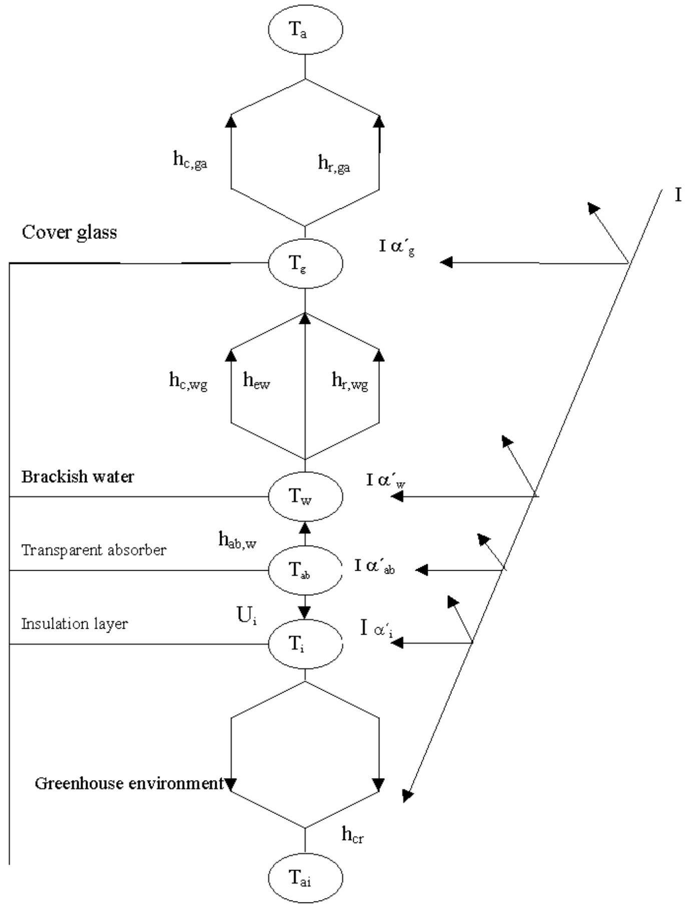

Fig.4. Structure of the mathematical model for heat and mass transfer analysis of the roof desalination process.

Total light transmission

In order to model the light transmission through the three layers of the desalination roof, the top glass, the water layer and the absorber mathematical relationships which describe the detailed optical performance have been derived.

Because of the problems involved in developing general relationships which takes into account all internal reflections, the model analysis has been restricted to only two reflections of each beam. This approximation concerning multiple reflection effects is supposed to have a minor impact on the total transmission. In order to regard the contribution from diffuse radiation in the total optical performance the scattered, diffuse radiation has been regarded as a beam radiation with an equivalent angle of 64° (Kimball, 1973).

The total light transmission through the three layers of the roof, for a specified wavelength, is calculated by the following expression (Jaffrin & Makhlouf, 1990; Nijskens et al., 1985):

$$\tau_t = \tau_{g,w}\,\tau_{ab}\,(1 + r_{g,w}\,r_{ab} + r_{g,w}^{2}\,r_{ab}^{2} + \ldots\ldots. + r_{g,w}^{n}\,r_{ab}^{n}) \qquad (2)$$

Where $\tau_{g,w}$ represents the total transmission coefficient for the combined glass and water layer which is expressed by:

$$\tau_{g,w} = \tau_g\,\tau_w\,[1 + r_g\,r_w + r_g^{\ 2}\,r_w^{\ 2} + \ldots\ldots. + r_g^{\ n}\,r_w^{\ n}] \qquad (3)$$

Here τ_g and τ_w represents the transmittance and r_g and r_w represents the reflectance of the glass and the water layer respectively.

For the top glass layer the transmittance is calculated by:

$$\tau_g = \tau_{r,g}\,.\tau_{abs,g} \qquad (4)$$

Here the transmission $\tau_{r,g}$ through the top cover glass is defined when only multiple reflection losses at the upper and lower glass surface have been considered. The parameter $\tau_{abs,g}$ is the transmitted fraction, when only absorption losses corresponding to light extinction in the material have been considered.

The fraction of incident light reflected from the upper surface of the cover glass (r_g) is determined from the average reflection coefficient for the parallel (rpa_g) and perpendicular (rpe_g) component of the polarized beam using the following equation:

$$r_g = (rpa_g + rpe_g)/2 \qquad (5)$$

The water layer parameters τ_w and r_w are calculated with equivalent equations (4 and 5) regarding the optical characteristics of the saline water.

The resulting reflection coefficient for the combined top glass and water layer is given by:

$$r_{g,w} = [r_g + r_w - 2\,r_g\,r_w]/[1 - r_g\,r_w] \qquad (6)$$

The parameters τ_{ab} and r_{ab} represent the total transmittance and reflectance of the absorber layer. These have been calculated with equations similar to those given for the cover glass (4 and 5).

The total transmittance τ_{tot} of the roof for the solar spectrum is calculated by the equation below where the integrated energy proportion I(λ) dλ for the ultra-violet radiation (UV-300 to 400 nm), the photosynthetic active radiation (PAR-400 to 700 nm) and the near infrared radiation (NIR-700 to 2200 nm) is taken into account:

Here, the parameters τ_t for the separate wavelengths are used.

$$\tau_{tot} = \frac{\int_{\lambda=300}^{\lambda=400} I(\lambda)\tau_t(\lambda_{UV})\,d\lambda + \int_{\lambda=400}^{\lambda=700} I(\lambda)\tau_t(\lambda_{PAR})\,d\lambda + \int_{\lambda=700}^{\lambda=2200} I(\lambda)\tau_t(\lambda_{NIR})\,d\lambda}{\int_{\lambda=300}^{\lambda=2200} I(\lambda)\,d\lambda} \qquad (7)$$

Crop growth

The growth of a crop is a result of the interaction between the crop and its environment. The desalination roof will modify the climate conditions in the greenhouse, and consequently the crop growth will be influenced (Takakura et al., 1971).

The crop growth model used in the present work is the one developed by van Henten (1994). His model is based on central principals of plant physiology and the sub-models for the greenhouse micro-climate and crop growth are structured and integrated in a clear and feasible way.

According to this model, the total plant dry weight is the sum of two components, the non-structural dry weight (w_{nsdw}) and the structural dry weight (w_{sdw}). The first component consists of substances as for instance glucose, sucrose and starch and the second, remaining component of the dry weight represents structural components like cell walls and cytoplasm. This model assumes that, at a given time, the plant size is defined by these two component variables.

The growth rate is a function of climate parameters as the flux of photosynthetic active radiation, the carbon dioxide concentration of the air, and the greenhouse air temperature. Van Henten proposed the following equations for description of the dynamic growth rate of the two components:

$$dw_{nsdw}/dt = c_{\alpha}\, f_{phot} - r_{gr}\, w_{sdw} - f_{resp} - ((1-c_{\beta})/c_{\beta})\, r_{gr}\, w_{sdw} \qquad (8)$$

$$dw_{sdw}/dt = r_{gr}\, w_{sdw} \qquad (9)$$

The four right hand terms in equation (8) represent the gross canopy photosynthesis rate, the rate with which non structural material is used for growth of structural dry weight, the maintenance respiration rate and the synthesis and respiratory loss rate due to the growth. The factor r_{gr} is the specific growth rate, i.e. the growth rate expressed as relative structural dry weight change per time unit. The factors c_{α} and c_{β} represent the conversion of assimilated CO_2 into sugar equivalents, given a value of 0.68, and the yield factor, indicating the respiratory and synthesis losses of non-structural material due to growth, which is estimated to 0.8 for the crop simulated in this work.

For the crop growth simulations presented in this work, the input climate parameters are the transmitted PAR radiation, the greenhouse air temperature and the carbon dioxide concentration of the air. Diurnal variations with hourly values are used for the radiation and temperature while the CO_2 – concentration in the greenhouse air is assumed to be 330 ppm and similar to the ambient air concentration (Enoch, 1977).

The sum of growth rate during the day and night period for one hour steps, gives the predicted diurnal growth rate. The cumulative total plant dry weight per floor area unit is the sum of the diurnal increase in dry weight over the whole growth period from day 1 to day n:

$$w_{plant} = \sum_{day=1}^{day=24} \int_{t=0}^{t=24} (w_{nsdw} + w_{sdw})dt - w_i \qquad (10)$$

Where w_i represents the initial plant weight (g m^{-2}).

Greenhouse climate and water balance

The heat and mass transfer mechanisms occurring in the greenhouse are divided into four main parts (Cooper & Fuller, 1983; Deltour et al, 1985; Garzoli, 1973; Jolliet, 1994). Consequently, models have been developed for the crop canopy, the floor, the greenhouse air and the greenhouse envelope. For this analysis with focus on greenhouse climate and crop water demand the desalination roof is regarded as single glass roof having specific optical and thermal properties.

General assumptions for simplifications are:

- The moisture is freely available on the whole crop canopy surface.
- The air is uniformly mixed in the whole greenhouse volume each time interval considered.
- The greenhouse air mass is negligible.
- The surface temperature of the greenhouse envelope each time step is described by one average temperature which is area weighted.
- There is no heat loss from the floor to the ground.

Equations for the heat balances are described separately for each part (Paper V). For the air, a water mass balance is also established.

The crop transpiration is calculated with the following equation (Stanghellini, 1987) based on the classical relation developed by Penman - Monteith (Monteith,1965):

$$W_{tr} = \frac{\frac{\delta}{\gamma}\left(I_{abs} - S\right) + \frac{2\,LAI\,\rho\,C_p}{\gamma . re}(eas - ea)}{(1 + \frac{\delta}{\gamma} + \frac{ri}{re})\,L} \qquad (11)$$

Here, I_{abs} represents the net short and long wave radiation absorbed by the crop canopy per floor area unit. This parameter is calculated according to expressions given by Stanghellini (1987) where the temperature of the canopy and the surrounding greenhouse surfaces and the optical characteristics of the canopy are regarded.

S represents the thermal energy stored or generated by the plant canopy due to biochemical reactions which can be neglected for climate and transpiration analyses like in this case (Short et al., 1991). LAI is the leaf area index of the crop canopy, ri and re is the internal respectively external canopy resistance for vapour flow. The parameter eas is the saturated vapour pressure and ea the actual vapour pressure of the air. The remaining factors are the physical constants for the vapour pressure relation to temperatures and humid air thermal properties.

Laboratory experiments

The validation of the mathematical model for water desalination, presented in Paper III, has an emphasis on the main parameters with impact on the water production capacity. This concerns the light absorptance and temperature of the absorber, the water flow rate and temperature, the inlet water temperature and the water storage volume. For the model validation purposes, a small roof module was built by a greenhouse equipment company in Sweden.

The module is about 2 m long, i.e. in the flow direction, and 1m wide with a cross section according to figure 5. It is connected to equipment for water supply and collection, water storage and flow control. All the equipment has been designed to be mobile in an easy way. It is built up in three main parts. These are the top cover glass, the water loop with flow control and two plastic tanks equipped with electrical heating and the absorber which consists of a semi-transparent material. The slope of the module has been fixed at 30° as it is assumed that this angle will secure efficient adhesive water drop transport along the lower surface of the top glass.

Three absorber material alternatives have been tested. Solar protection films for window applications have been attached to a rigid material of single glass or double layer acrylic sheet. For the single glass alternatives two absorber film types were included, one with total light absorptance around 40% and one around 56%. This is the nominal absorptance at incidence angle 90^0 and for the whole light spectrum according to data from the film manufacturer. For the film-coated acrylic material the total nominal absorptance is around 33 %. This lower absorptance compared to the glass alternatives was selected because of the lower thermal losses downwards which were assumed to compensate to some extent for the lower optical performance when considering the water production efficiency.

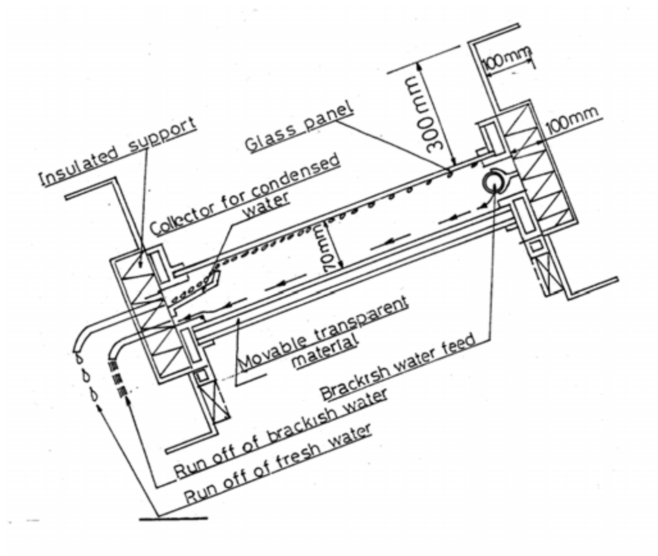

Fig.5. Vertical cross section through the experiment roof module for water desalination.

During a test period of about one week, at the laboratory of the Department of Buildings and Energy at the Technical University of Denmark, a number of evaluations were carried out using artificial solar irradiation from a multiple lamp equipment indoors (figure 6). The irradiation intensity on the top cover glass was constant with a slight distribution over the surface. The distribution is the result of the somewhat non-uniform lamp performance and the distance variation between the lamp arrangement and the front respectively back end of the inclined module.

Irradiation intensities are measured with pyranometers (0.3-3 μm) which have been moved over the surface in a grid network. The average intensity is 570 W m^{-2} while the maximum value is 11.5 % higher and the minimum value is 7.8 % lower. As compared to this average intensity clear day average intensities from one hour after sunrise to one hour before sunset are about 630 W m^{-2} during July and 370 W m^{-2} during December for typical southern Mediterranean conditions. Consequently, the laboratory conditions represent about 90% of the July conditions and 150% of the December conditions.

A number of fans have been used for creating an artificial wind. These fans generate an upward air flow along the top glass surface with a velocity of about $4ms^{-1}$. Thermocouples are used at the surface of the top cover glass, at the bottom surface of the absorber layer and in the water inlet and outlet flow. The sensors on the surfaces are located along the mid line and the two symmetry lines on both sides. The volume of fresh water, i.e. the condensed water flowing down the inner surface of the top cover glass, has been be quantified through precision volume measurement with intervals of one hour. Fresh water production is evaluated for two water flow rates and inlet temperatures in the interval 20°C to 55°C.

The flow rates have been chosen to be one low, around 10 l h^{-1} m^{-2}, and one high, around 100 h^{-1} m^{-2}. The system has been operated over several hours with continuous temperature increase in the system. The total water volume corresponds to 30 l m^{-2}.

Detailed knowledge of the spectral, optical performance of the module is of importance for more general and theoretical parameter analyses and discussions concerning PAR and total light transmission. A spectroradiometer (Licor-1800 monochromator) has been used to study the spectral and the total transmission for the absorber and the complete roof. The monochromator, working in the wavelength range 300-1100 nm, is driven by a precision step motor controlled by an internal microcomputer. The radiation intensity was measured for spectral intervals of 2 nm.

Fig.6. Laboratory experiment with the solar desalination module at the Department of Building and Energy, Technical University of Denmark.

Fig.7. Field experiment with a greenhouse system including water desalination at the National Institute for Research on Rural Engineering, Water and Forestry (INRGREF) Tunisia.

Field experiments

System description

The roof module was installed in a greenhouse roof at the experimental site of the National Institute for Research on Rural Engineering, Water and Forestry in Tunis (figure 7). Here, it was used for studies of crop growth, water production and demand. As an important part of the focus was the effects on growth and water demand caused by the light attenuation in the desalination roof even a case with a conventional roof was studied in these experiments.

These experiments were carried through in a greenhouse oriented east-west. It contains two separated compartments (a) and (b) with single glass walls. Both have the floor area about 2 m^2 and compartment (a) with a single glass roof represents the reference system while (b) is equipped with the desalination module in the roof. The sloop of the roof is about 18^o in the north-south direction. A lettuce crop was planted in both greenhouses.

The desalination roof is connected to a pipe system for water supply and collection including storage tanks for brackish and fresh water. The lettuce crop was transplanted with 10 plants per m^2 of floor and arranged in 5 rows with 30 cm between the rows and 30 cm between the plants.

Measuring methods

During 14 weeks of experiments, from November to March, measurements of the crop growth, the water production and demand and of the greenhouse and outdoor climate conditions were carried through.

Crop measurements

Three randomly selected plants, from each compartment, were harvested with a regular time interval during the experiment period. Fresh and dry weights of both roots and shoots were registered for each plant. The used electronic balance has a capacity of 620 gr and the accuracy is ±0.001gr. The dry weight is obtained after oven drying at a temperature of 105°C for 24 hours. The plant leaf area was also measured with a leaf area meter.

Climate measurements

Figure 8 shows the measurement arrangements for the indoor and ambient climate parameters. The measurements of the indoor climate included air temperature and humidity in the two compartments at the level between the top and bottom leaves of the plants. These were performed with instruments for continuous temperature and humidity measurement. Sensors used for the registration are Drum hygrographs for relative humidity and platina resistance thermometers for temperature. The accuracy is ±1% (absolute) for the relative humidity and ± 0.5°C for the temperature sensors.

Global solar radiation in the horizontal plane in the two compartments, just above the plants, was measured with pyranometers with accuracy of ± 3%.
The leaf temperature for the middle leaves of the plant close to the hygrometers was measured with copper-constantan thermocouples (Type T) with an accuracy of ± 0.5°C. This sensor type was also used for measurement of external and internal surface temperatures of the roof and the floor surface temperature.

For the ambient climate, the solar radiation, air temperature, and relative humidity were measured with the type of sensors described above. The wind velocity was measured with a wing anemometer with an accuracy of ± 0.1 m s^{-1}.

All these sensors were connected to a data recording system and data were stored every 5th minute during the experiment. The temperature sensors were calibrated before and after the experiment period.

Water demand and production measurements

The water temperatures indicated in figure 8 were measured with copper-constantan thermocouples with an accuracy of ± 0.5°C in the interval 5° C to 90 °C. The daily water consumption was evaluated through registration of the weight change of the plants. The used electronic balance has a capacity of 6000 gr and an accuracy of ± 0.1 gr.

Before supplied to the tank, the daily fresh water production was collected in a graded glass container with capacity of 3000 ml and graded with 200 ml resolution. In order to obtain a high measurement precision the daily water quantities were weighted with the electronic balance specified in the previous paragraph.

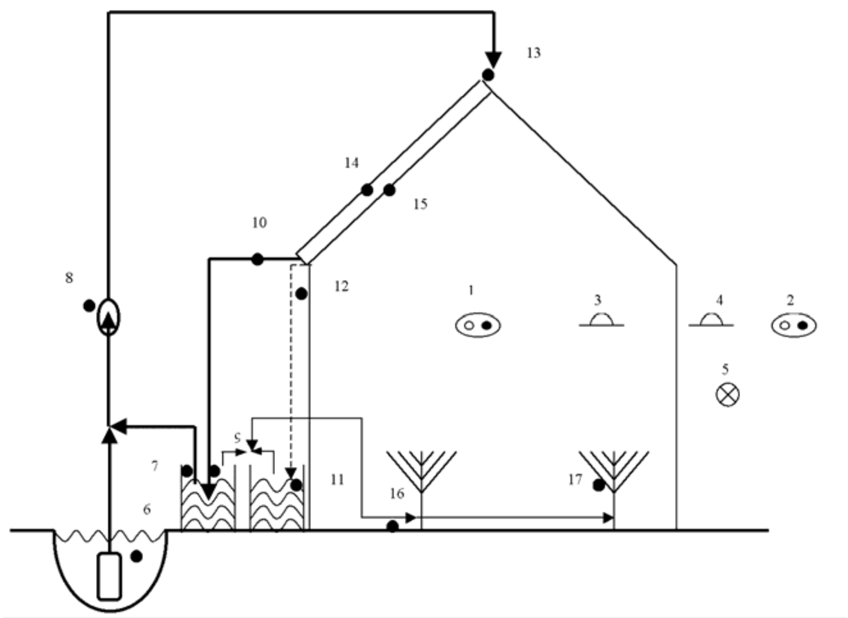

Fig.8. Measured parameters and sensor locations for field experiments in desalination greenhouse. 1-2: Air temperature and humidity, 3-4: Solar irradiation, 5: Wind velocity, 6-13: Water temperature, 14-17: Surface temperature.

Economic methods

The economic analysis has been carried out for climate and market conditions as typical for countries like Tunisia (Paper VI). Three solar powered desalination technologies are included:

- Greenhouse-integrated system
- Single effect process with heat pipe solar collectors
- Multiple condensation /evaporation cycle process with flat plate solar collectors

The first step of the analysis includes water cost evaluations and the second step is focused on evaluations of final revenues for commercial growers. For the greenhouse integrated concept crop yield reductions are regarded in relation to the yield for the conventional greenhouses which are supposed in combination with the freestanding solar collector concepts. The method used for the water cost evaluation is based on a cost-benefit ratio where the cost is the present value of the maintenance and personnel cost during the plant lifetime added to the investment cost and the benefit is the total quantity of water produced over the lifetime (Kasper & Lior, 1979; Chaibi et al. 1991; Klaiss & Meyer, 1988). Here the water quantity is the produced fresh water mixed with brackish water in the ratio 1:1.

The grower revenue has been evaluated for two production schedules including low value vegetable and fruit crops and for one schedule with a high value ornamental flower crop. This revenue is calculated considering the annual market value of the production, the greenhouse cost, the water cost, the labour and maintenance costs and finally the marketing and transport costs. The typical annual yield levels and market values of the products are based on the most relevant and actual information found and documented (S.A.N, 1985; Doorenbos & Kassam, 1980; Jolliet, et al.; 1986; Patrik & Kaija, 2000). Yield levels corresponding to well qualified greenhouse growers are assumed.

The yield reduction for the greenhouse integrated system is estimated from the correlation between this parameter and the light reduction for the crop (Paper IV) A glass type for the absorber with optical properties similar to solar protection glasses on the commercial market for building glass has been assumed.

In an analysis with a future perspective the revenues have been compared for a desalination greenhouse equipped with an absorber glass type which gives very low yield reductions and the other technologies with reduced solar collector costs.

Results and discussions

Survey of solar desalination technologies.

The survey work presented in Paper I shows that solar energy could make a substantial contribution to remote arid areas for fresh water supply in domestic or agricultural fields. The included state of art description of the field of solar desalination presents appropriate physical and economic models for the main solar desalination processes.

Concerning the economic use of solar desalination, Paper I shows that this technology requires a relatively large capital investment per unit of capacity and a minimum of operation and maintenance costs. The fresh water production cost depends primarily on still productivity, plant life, capital cost of the installation, cost of the land, operation cost, depreciation time and interest rate. Practical conditions in which solar desalination could be the most economic alternative for fresh water supply compared to other methods of desalination is limited to sites in remote areas with sunny climates and relatively low water requirements and high fuel costs.

Furthermore, short surveys are made of specific problems relevant to this technology, such as construction materials, operation difficulties (vapour leakage, heat absorption, salt and organism accumulations), reliability and lifetime of the installations.

Three major aspects are found to govern the future development of solar desalination technologies. These aspects are about the main parts included as the collectors, heat storage arrangements and the desalination process unit.

As concerns the first item, glass has proven to be an excellent and durable material, but it is often very costly contrary to the plastic films which often are used as a low cost alternative. Films, on the other hand, frequently are subject to wind and rain damage during use. Several types of rigid and semi-rigid plastic sheets have been used for covering the solar still. These covers present the advantages of being light weight, able to be formed into self-supporting shapes and to have a higher impact strength compared to glass. On the other hand, these have certain disadvantages as the low thermal conductivity, high cost and low availability in some arid countries. Research and development with the aim to improve the collector efficiency should concentrate on thermal insulation materials and geometries, thermo-optical properties of surface structures and coatings related to manufacturing technologies and proper sealing of the joints between the covering materials and the frames.

The second main research field is the heat storage. The possibility of operating at night-time here is assumed to perhaps double the economic advantages of a solar desalination plant compared to a conventional plant. Research should be directed towards the identification of new chemical reaction storage systems and more general storage system studies.

The third research field should concentrate on the solar desalination plant as a whole where thermal insulation of container volumes for evaporators, saline and hot water etc, geometry and orientation of the collectors, reliability and lifetime and design aspects should be studied more extensively.

System performance theories and model development

The simulation model, developed in Paper II provides a large number of outputs concerning the hourly production of fresh water, the efficiency of the solar still, the temperatures of the brackish water and of the roof cover and the total light transmittance of the integrated roof.

The first part of the simulation analyses was a comparison between different absorber materials concerning the fresh water production capacity and the corresponding solar radiation transmission through the roof. Included material examples are selective glass (typical solar protection glass for buildings) and a double layer plastic material (rigid polycarbonate sheet). The roof slope is assumed to be 23^{o} with south orientation which is a common slope in traditional greenhouses.

For typical summer conditions in Tunisia with the highest solar irradiation levels, the calculated daily water production is 1.8 kg m^{-2} and the solar radiation transmission is 44% for the plastic material absorber. For the selective glass the water production is a factor 1.5 higher but the radiation transmission is reduced to 33%.

The absorber material should be selected with respect to crop water demand for irrigation as well as required light levels for the greenhouse cultivation. Compared to estimated water demands for efficient irrigation management both the presented alternatives have a sufficient water production capacity.

However, the tasks concerning required radiation transmission levels also means a more complex optimization problem which is extensively analyzed in Paper IV, V and VI. For the main parameters with impact on the water production capacity, sensitivity studies are carried through (Paper II). Included parameters are the water flow rate, the inlet water temperature and the slope of the roof. The assumed location and ambient climate conditions are the same as above.

The water flow rate has an important influence on the water production capacity which decreases with increasing flow rate. If the flow rate is increased from 1 to 50kg h^{-1} m^{-2}, the water production decreases by 50% which is related to considerably lowered brackish water temperatures during the day. The production is further related to a shorter operation period during the day for a case with high flow rate.

However, to assure stable operation conditions a certain minimum flow rate has to be maintained in order to wet the entire surface of the absorber uniformly. Earlier studies by others and also the present studies (Paper III) indicate that a minimum flow level of about 10 kg h^{-1} m^{-2} is required for this.

The influence of the brackish water inlet temperature on the water production has also been studied for a fixed flow rate of about 10 kg $h^{-1}m^{-2}$. Here, cases with fixed inlet water temperature are compared to a case with variable temperature in a closed loop system. In the later case the water volume in the roof is heated up through solar heat absorption during the day. Water production levels were considerably higher for the closed loop system compared to the cases with fixed inlet temperature. For a fixed inlet temperature of 15, 20 and 25°C the calculated production was reduced by 35, 30 and 25% compared to the daily production in closed loop system.

Concerning the roof slope, higher slopes than selected (23^o) in the previous examples would increase the water production for winter conditions and decrease the production for summer conditions. For instance, the winter increase is 9% and the summer decrease is 6% for the roof slope 45^o. Taking typical winter and summer production capacities into account the optimal roof slope is around 35^o.

The model was used even for simulation of temperature conditions in the roof material layers. The variation of the top glass, brackish water, absorber and the internal roof surface temperature is presented in Paper II. Results show that the brackish water and the absorber temperatures, i.e. the highest roof temperatures, are very close. This is due to the efficient heat transfer from the absorber to the water.

This simulation analysis has illustrated that the temperature of the absorber, the brackish water flow rate and the inlet water temperature are the most important parameters affecting the fresh water production capacity.

The validation of the simulation model, focused upon these parameters is presented in Paper III. Also included is a short analysis of the effect of the heat storage volume on the water production.

Results of the investigations illustrate the similarity between the simulated and measured absorber and water temperatures. These are simulated with average temperature deviations of about 1.5 °C above the measured values for several hours of continuos operation.

For these conditions the real, accumulated water production is at the level of 80% of the calculated production. The main factor behind this is supposed to be the mentioned temperature deviation. Further explanations behind the observed deviations probably are dropwise condensation on the cover glass and also re-evaporation of the drops near the outlet to the collector for condensed water. Another source of error is probably also parts of the absorber area not completely covered by the water layer.

Variations with the water flow of the hourly water production as well as the absorber and water temperature are simulated in good agreement with measurements for the different absorber types included. This is observed for water flow rates from 10 to 100 kg m^{-2} h^{-1}.

The influence of a water storage volume connected to the roof on the storage temperatures and the hourly water production is simulated with high accuracy. The average deviation between the calculated and measured production is around 5% and the calculation results are overestimated. This accuracy has been significantly improved due to the higher water temperature used during the experiments. These simulation results have been useful in the later studies (Paper V) including short-term heat storage tasks for systems with combined daytime and night-time operation.

The simulations indicate a good agreement with measurements with a high influence of the inlet water temperature on the hourly water production. The results show that the hourly water production is more than three times higher for an inlet water temperature of 55 °C compared to 25 °C.

Based on results presented in Paper III, more extensive model validations have been performed in the later studies including field evaluations under real and more varied weather conditions. The main purposes of these studies have been to develop the model into a general design and analysis tool for desalination system concepts integrated in greenhouses.

Optical performance and crop growth

A theoretical study of the spectral and total transmission for the absorber materials is related to the measurements during the laboratory experiments with the roof module under artificial solar irradiation. The absorber material chosen for this detailed optical analysis is a single glass coated with solar protection film with a total light absorptance of around 56%. Here, the water flowing on the absorber is assumed to have the form of perfect continuous layer with uniform layer thickness. The results were derived under the assumptions of an average extinction coefficient for glass of 16 m^{-1}which corresponds to a modest glasss quality. Typical extinction coefficients for the saline water are taken for each wavelength band as determined by Kanayama & Baba (1988) and Mertins (1970).

The optical study is focused especially on the PAR–light transmission. The measured PAR light transmission of the absorber is about 23.5% including blue light, green/yellow light and red light transmission of 19.8, 24.9 and 25.7%, respectively. The spectral transmission measurements (300-1100 nm) and simulations with and without water flow on the absorber are presented in Paper IV.

The results are mainly that the spectral PAR and NIR transmission for the complete roof is simulated with high accuracy. Also illustrated is a small transmission increase of about 2 %, in the interval between 300 to 700nm with water layer compared to the case without water on the absorber. However, a transmission decrease of about 5 % is shown for the NIR wavelength range (above 700 nm). These results are confirmed by Pollet & Pieters (1999), Pieters (1996), Jaffrin & Morisot (1994), and Morris et al. (1958)

A more general evaluation of the effect of the extinction coefficient of the top glass on the PAR light transmission and crop growth capacity is presented in Paper IV. The analysis shows that a nominal extinction coefficient for a modest glass quality used in a desalination roof with water should be reduced by about 5 m^{-1} in order to get relevant PAR transmission simulation results. This can be explained by the presence of the water layer on the absorber which represents a medium with a refractive index value between the value of the absorber glass material and the air which reduces losses through partial reflection at the upper glass surface.

An analysis of the reductions in lettuce crop growth for complete roofs with reduced PAR transmission is presented in Paper IV. The analysis was based on a model developed by van Henten (1994) for total dry weight simulation. The used model gives a simulated crop growth which closely follows the general trend of the experiment measurements with an inaccuracy of about 3-4% (figure 9). These experiments also clearly show that for the reference greenhouse compartment the higher transmission level of solar radiation gave a cumulative and constant increase in the dry weight production compared to the solar desalination greenhouse Also clearly showed is the importance of high light intensity for the production of a high quality lettuce crop with a high number of leaves and a compact morphology which is confirmed by Benoit & Ceustermans (1990) and many authors in the crop science field.

These simulation results are based on a measured value of the final leaf area to weight ratio used in the simulation model as a constant for the whole cultivation period. However, higher simulation precision during the whole cultivation period for crop types in general must consider a very exact variation of this crop parameter.

More general simulation analyses focused on the relations between the crop yield and the PAR transmission or absorption of the roof are presented in Paper IV and V. These have illustrated the distinct sensitivity of the seasonal plant yields to light reductions in the greenhouse (figure 12). Also shown is that the relative impact on yield levels of the top glass quality from the optical point of view is quite marginal compared to the greenhouse climate conditions. For instance, a combined elevation of the greenhouse temperature by about 4°C and a CO_2 concentration elevation of 0.6 times the natural level for the desalination case would result in about the same yield level as for a conventional greenhouse case.

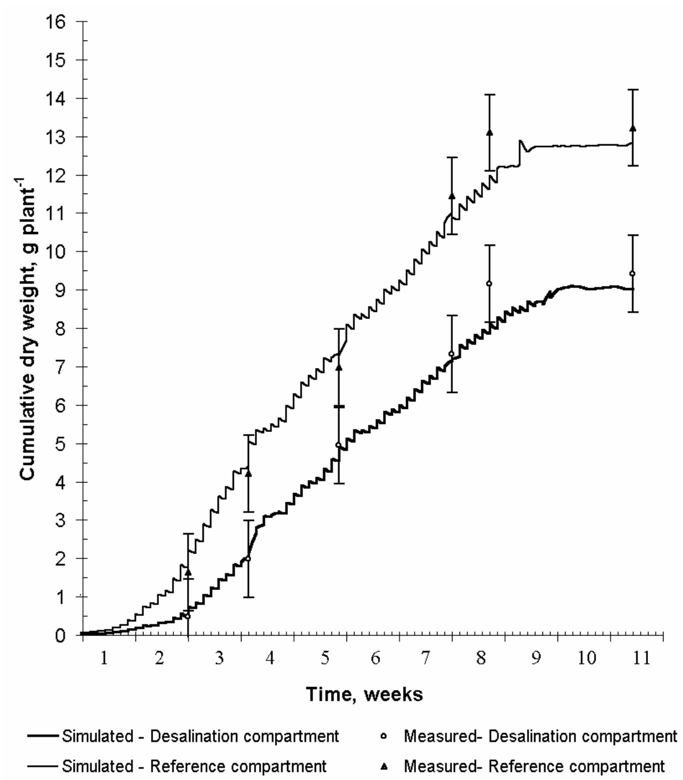

Fig.9. Simulated compared to measured lettuce crop growth in the desalination and reference greenhouse compartment during the crop growth experiments in Tunis (20th December to 4th March). The vertical bars indicate the 95% confidence limits of the mean values of the measurements.

System design and performance

Greenhouse climate analysis

Two chosen days during the field experiments have been selected in order to analyze the influence of the external climate on the climate conditions of the experimental greenhouses. The first day represents a typical winter day in Tunis where the LAI of the juvenile lettuce crop in the greenhouse is on the level 1.5 and the second one represents a typical spring day with mature crop and LAI about 4.2.. The simulated climate conditions, presented in Paper V, are in good agreement with measured. Compared to measured values, the simulated air temperature is underestimated by 1°C while the relative humidity and transmitted solar radiation is overestimated by 1% (absolute) and 3% (relative), respectively.

These greenhouse climate evaluations illustrate the advantages of the desalination greenhouse concept under sunny day conditions. Here, the temperatures in this greenhouse are kept under 28°C in contrast to the overheating in the conventional greenhouse up to levels around 35 °C. Consequently, this could sharply reduce the ventilation demand and maintain humidities on higher levels in desalination greenhouses compared to conventional greenhouses. This is supposed to have a positive impact on the plant growth conditions and reduce stress risks.

An extended climate analysis was carried through in order to illuminate the sensitivity of the greenhouse climate conditions for variations in the ambient climate. Of particular interest are variations in solar irradiation and wind velocity. Variation levels assumed for the analysis are ±10% in solar irradiation (e.g. related to local variations from site to site) and between 0.5 and 2 times in wind velocity. These variations are related to measured parameters during the periods given in table 1.

The practical situation could for instance be a system design task where the performance of one specific system is well evaluated and documented but local deviations or perhaps slightly inaccurate climate data from weather statistics is available for a site considered for the erection of a new greenhouse facility. The matter could also be to analyze the impact of how essential details in a system simulation model are related to parameters of certain interest for variation. One example is the correlation based expression for natural ventilation air exchange rate included in the simulation model used in this work (Paper V). Here, both wind and temperature difference induction of the ventilation is represented why the complex and combined influence of two ambient climate parameters is in the focus. In this situation perhaps an alternative ventilation model has to be considered and evaluated if for instance the input data are too limited.

In table 1 a summary of the simulated results is given for the experiment period with juvenile crop between 7th to 11th December and the period with mature lettuce crop between 21st to 25th February . It is found that an increase during daytime periods in solar irradiation by 10% increases the greenhouse temperature with about 1°C. As shown in table 1 a wind velocity increase up to 2 times the reference velocity will decrease the greenhouse temperature with around 3 °C.

This illustrates that the wind variation impact on the greenhouse temperature could be more heavy than the solar irradiation variation impact.
It is also noticed that the greenhouse humidity also is affected, particularly by the wind velocity variations.

Table 1. *The mean variation for daytime periods of the greenhouse climate with respect to variations in solar irradiation (I) and wind velocity (v) compared to the average values simulated for the early experiment period in December and the late period in February in the reference and desalination compartment.*

Period	Variable	I+10%		2 v	
		Reference	Desalination	Reference	Desalination
7th- 11th December	Tai (°C)	1	0.8	-3	-2.5
	Hai (%)	3.5	2.5	-8.3	-7.6
21st – 25th February	Tai (°C)	1.6	0.95	-3.7	-3.1
	Hai (%)	2.3	1.8	-6.5	-5.1

Water demand and balance analysis

The simulated crop transpiration in the reference and in the desalination greenhouse has been compared to measurements. Good agreement between simulation and measurement has been found with an average inaccuracy of 5%. For the high radiation levels and under the specific conditions during the February period with mature crop the water demand in the conventional greenhouse is found to be about 60% higher than in desalination case. The water production in the desalination roof has been simulated with an inaccuracy of about 7%. Here, the production is constantly overestimated. The supposed reason is that the model not accounts for the reduced capacity owing to water drops falling back into the roof flow before reaching the collection trough and also to re-evaporation from the collected water surface where the trough is partly heated by solar irradiation.

The sensitivity of the crop water demand for the same greenhouse climate variations as described above has also been studied. Figure 10 illustrates the crop transpiration simulation for the solar irradiation variation ±10 % of the values recorded during a typical and sunny spring day in Tunis. The simulations show that the solar irradiation variation has a significant impact on the crop transpiration in the reference and the desalination compartment. Through an increase of the solar irradiation by 10% the daily crop transpiration is increased by about the same, 11%, in the reference compartment and by 8.3% in the desalination compartment.

Results from a variation analysis concerning the daily lettuce crop transpiration and fresh water production with respect to variations in solar irradiation compared to the simulated values for the real climate conditions during the early growing period in December (juvenile crop) and the late period in February (mature crop) in the reference and desalination compartment are presented in Table2. The results mainly show that the fresh water production sensitivity for solar irradiation variations is higher compared to the crop transpiration sensitivity.

However, one dimension to stress is that for a complete sensitivity analysis for a real case the impact of a combined variation of all parameters with integrated influence on all involved processes must be carried through. For crops with marked increase of the canopy size during the cultivation period (like e.g. lettuce) a more dynamic sensitivity analysis has to be performed for a real case. Here, even the influence on the crop growth of ambient climate variations and the related impact on the greenhouse climate and water demand have to be regarded.

The variations in wind velocity also seems to have a considerable effect on the crop transpiration as illustrated in figure 11. The variation in crop transpiration is in the range of 9% for an increased wind velocity up to 2 times or a decrease down to 0.5 times the reference velocity.

Table 2. *The mean variation for the daily crop water demand (lettuce) and the roof water production with respect to variations in solar irradiation compared to the average values simulated for the early experiment period in December and the late period in February in the reference and desalination compartment.*

		I +10%				I – 10%			
Period	Variable ($g\ m^{-2}$,day)	Reference		Desalination.		Reference		Desalination.	
		Abs.	Rel. (%)	Abs.	Rel (%).	Abs.	Rel. (%)	Abs.	Rel. (%)
7^{th}- 11^{th} Dec.	W_{irr}	749	6.2	652	4.9	655	-7.1	587	-5.4
	W_{prod}	-	-	1572	8.6	-	-	1325	8.5
21^{st} – 25^{th} Feb.	W_{irr}	3235	10.9	1968	9	2713	-7	1671	-7.5
	W_{prod}	-	-	3715	10.9	-	-	2937	-11.5

The main conclusion based on these sensitivity analyses for water demand and production is that a greenhouse desalination system in perfect water balance could change into a system with a demand higher than the production under the combined influence of irradiation and wind velocity changes.

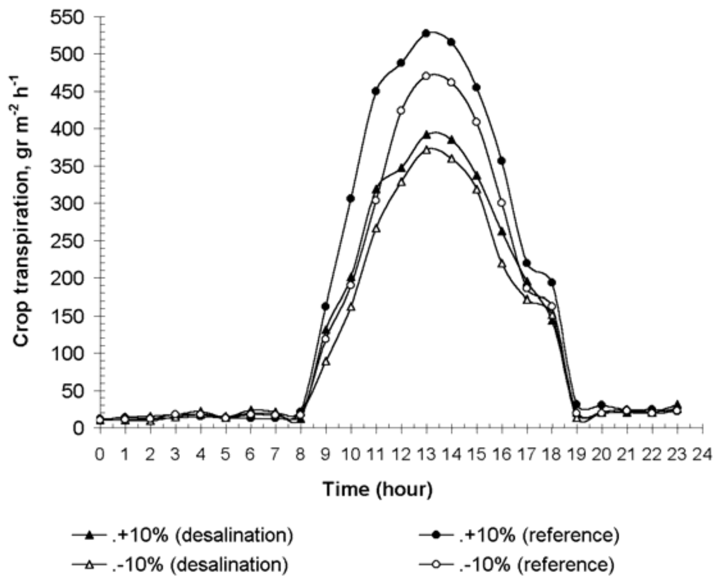

Fig.10. Simulated crop transpiration for a lettuce crop associated with solar radiation variation between +10% and −10% of the radiation during a sunny February day for the desalination and reference compartment . Mature crop with LAI=4.2.

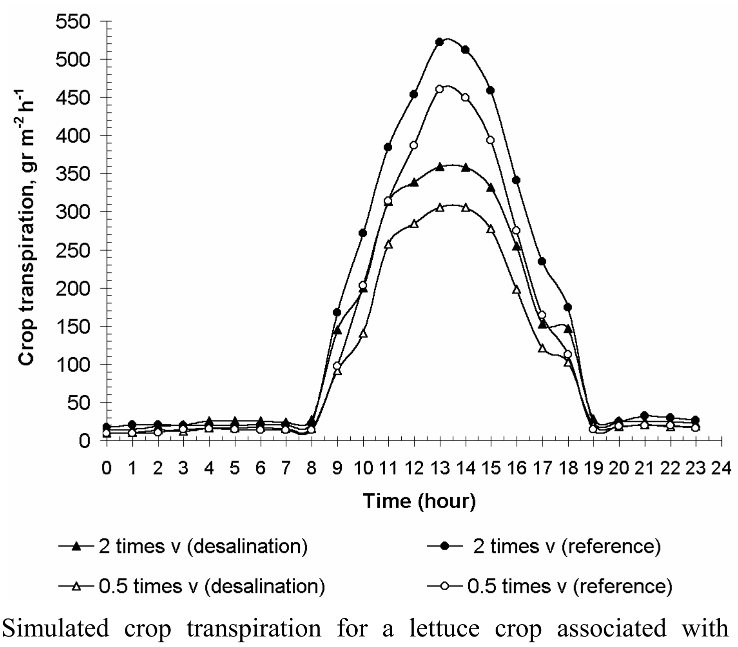

Fig.11. Simulated crop transpiration for a lettuce crop associated with wind velocity variation between 2 times and 0,5 times the wind velocity during a sunny February day for the desalination and reference compartment. Mature crop with LAI=4.2.

General performance and design

The system design and performance analysis is presented in Paper V. This analysis is based on simulated crop cultivation in typical arid climates as in Tunisia (Ghrab & Ben Alaya 1985). Results are presented for system designs with a water production capacity for a complete coverage of the annual water demand. A system equipped with seasonal fresh water storage could completely satisfy the water demand of a low canopy crop like lettuce cultivated in a symmetric greenhouse with desalination system in the south sloping part of the roof. In this case, the seasonal fresh water storage demand is about 18% of the annual production. According to crop growth simulations the corresponding lettuce yield reduction is about 25% compared to a conventional greenhouse case with single glassed roof (table 3).

In order to cover the annual water demand of a high canopy crop like tomato, an asymmetric roof design with a desalination system in the whole roof area is required. This corresponds to a yield reduction of about 18% and a required seasonal fresh water storage demand of about 12% of the annual production (Table3).

Table 3. *Simulated annual water demand, seasonal fresh water storage demand (related to total floor area) and yield reduction for lettuce and tomato cultivation in desalination greenhouses with asymmetric and symmetric roof designs. Absorber absorptance levels for cases with complete production of the annual water demand. Typical ambient climate for Tunis.*

	Lettuce crop		Tomato crop
	Asymmetric design	Symmetric design	Asymmetric design
Annual water demand (kg m^{-2} $year^{-1}$)	490	530	600
Seasonal fresh water storage demand (kg m^{-2})	85	95	70
Absorber absorptance	0.33	0.61	0.52
Yield reductions (%)[(a)]	8	25	18

[(a)] *In relation to conventional greenhouse with single glassed roof and same geometry*

Advanced material and system concept perspectives

In order to study the crop yield penalties due to the PAR radiation losses in the absorbers with various degrees of selectivity , simulations of the annual yield for the desalination case in relation to a conventional greenhouse case for varied proportion of light absorptance in the NIR spectrum have been carried through. The estimations below are related to the case with a lettuce crop and symmetric greenhouse design in table 3.

The results show that the use of absorber glasses with higher selectivity could decrease the yield reduction from 25% for conventional glass types with 50% of the absorption in the NIR spectrum down to 15% and even to 3% for glasses with NIR absorptance proportion of 70 and 90%, respectively (figure 12). However, glass materials with perfect optical properties for a desalination roof absorber are not available on the commercial market. With the use of through coloured solar protection glasses on the market today yield reductions on the level of 15% are possible to achieve.

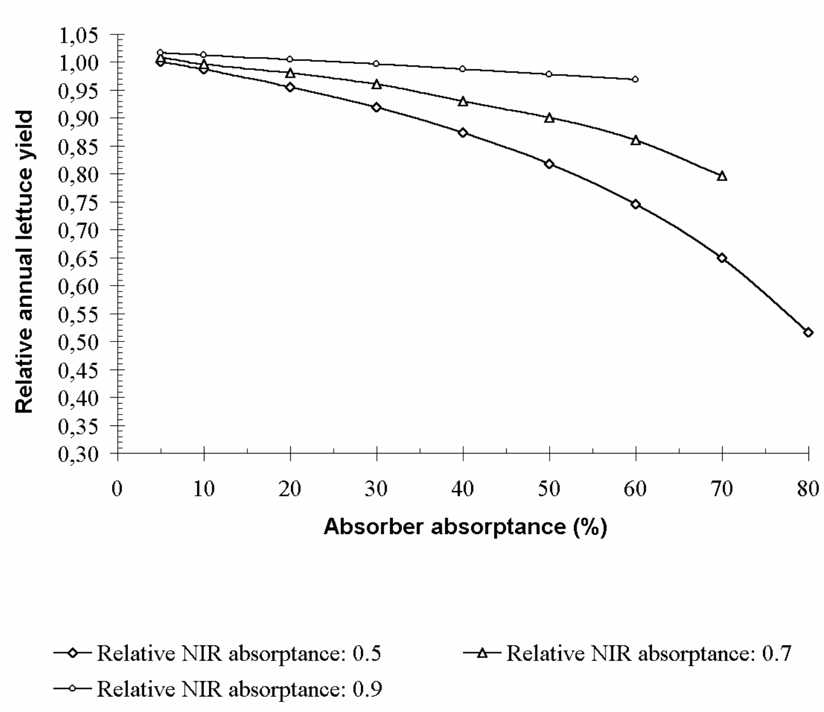

Fig 12. Simulated annual lettuce yield for a desalination case in relation to a conventional greenhouse case with single glassed roof (asymmetric roof design, Tunisian climate). Curves for varied proportion of light absorptance in the near infrared spectral band (NIR).

Glass materials with more advanced optical properties should be expected in the future. The most interesting option should be a more selective electrochromic function with a majority of the absorption in the NIR band. Electrochromic materials developed at present with absorption in the NIR-band get and keep significant absorption even in the PAR-band when switched from transmitting to absorbing state. Probably, advances in the field of more complex desalination technologies like discussed below will contribute to stronger incentives to develop more industrial manufacturing methods for such materials with practical applications and future market prospects for a wider range of applications.

In order to illustrate the performance of a system with a dynamic absorptance control in the desalination roof, the water balance of a desalination greenhouse has been simulated for a single day example. As alternatives, two operation modes are analysed. The first alternative is operation of the system during day- as well as night-time with diurnal heat storage for night operation. The second alternative is system operation during day time only and with smaller diurnal heat storage only for securing an elevated start temperature in the roof loop in the morning. For both the alternatives a perfect, diurnal water balance was assumed.

The results clearly show the sensitive impact of the variation in the dynamic absorptance control on the crop yield. This advanced material application could eliminate the seasonal storage demand and also increase the crop yield compared to the material option with static absorptance. Compared to the static case with seasonal water storage, the diurnal crop yield is found to be increased by 4.7 % for the first operation mode and reduced by 8 % for the second one. The reason for this is the higher absorptance required in the latter case in order to produce the water required for balance during daytime only.

However, a more complete evaluation of dynamic options like these compared to static options would require extensive simulations and economical analyses where investment costs for exactly specified storage arrangements and crop yield penalties based on annual system performances are taken into account.

Economic analysis

According to the water cost evaluations in Paper VI the fresh water cost is about 7$/m^3$ for the greenhouse-integrated system which is about 35% of the cost for the two included solar collector based technologies intended for small scale, rural applications. The greenhouse system also has the lowest investment cost per volume unit of water production. A comparison with reported water costs for larger and more advanced desalination plants with solar collectors (El-Nashar, 2001) indicates that the water cost for a greenhouse system with a production capacity 10 times lower is well competitive.

Also concerning the grower revenue the desalination greenhouse concept is interesting compared to the solar collector based concepts for desalination (Paper VI). For production alternatives including low and medium value crops the revenues are low for the desalination greenhouse but negative for the conventional greenhouses with solar collector based desalination. This is based on 15% yield reduction for the desalination greenhouse and corresponds to a solar protection glass available on the market today. For an alternative with a high value ornamental flower crop the desalination greenhouse competes well with the other desalination technologies. However, in this alternative the economical impact of the yield reduction is heavy why a certain reservation for a less competitive economy as a result even of quality losses is motivated.

Concerning the future prospects for the desalination greenhouse concept the following two indications are of specific interest. For this greenhouse type equipped with a more selective absorber glass for extra low yield reductions (5 %) the grower revenue for high value crops could be higher than for the other desalination technologies. In this case the desalination greenhouse could be well competitive to the other technologies even if the solar collector costs were reduced by 50 %. An internal revenue analysis for the desalination greenhouse case has given a permitted cost for the very selective glass type corresponding to 18 times the cost for the commercial solar protection glass of today.

Conclusions

The general and main conclusions which can be drawn from the research work are the following:

- A greenhouse with integrated water desalination could be designed to provide technically feasible systems suitable for arid climate conditions. The analysis of this combined design requires a very complex and interlinked technical and biological approach.
- The simulation analysis of the system is found to give very relevant performance estimations. This concerns the quantitative fresh water production and demand as well as the crop growth under various climate conditions.
- Greenhouses with full coverage of the irrigation water demand are possible to design with the concept. This is provided the use of mixed fresh water and brackish water from ground water sources with limited salinity.
- In a roof desalination greenhouse, the daytime climate variations have a less peaky pattern around noon and lower water demand compared to a conventional greenhouse. This is supposed to have a positive impact on the crop conditions and reduce stress risks.
- Diurnal operation of the system is the most favourable operation strategy as the night-time operation is found to represent a substantial proportion of the total fresh water production.
- Application of more selective absorber glass materials improves the crop growth and reduces the yield loss.
- Also of supposed interest for future performance improvements are concepts based on warmer water sources as well as combined water production for several purposes. Considered options are supply of geothermal water and combined production of irrigation and drinking water.

Conclusions, which are underbuilt on a lower level of generality but are to be regarded as clear indications, are the following:

- The greenhouse roof type and the specific crop water demand have a high impact on the yield reduction for design cases with seasonal storage and full coverage of the water demand for irrigation.
- Application of advanced glass materials with dynamic control of the light absorption could improve the system design and eliminate the seasonal storage demand for fresh water. It also could improve the crop yield compared to concepts where glass materials with static absorption are used.
- From an economic point of view, the greenhouse integrated system is found to have the lowest investment and water cost compared to solar collector

based desalination technologies. The grower revenue for a desalination greenhouse competes well with the revenue for these alternatives.

Future research

The following suggestions concerning research efforts are of a major interest for future improvements of the greenhouse system with integrated water desalination:

- Interesting prospects and potentials for desalination applications in the future are supposed for materials with dynamic and active control of the light absorption. The related system oriented research should focus on the storage demand issues and possibilities to improve the crop yield in relation to concepts with a simpler, static approach.
- An extended co-operation with the material science researchers in the field of electrochromic glass and plastic materials seems especially motivated. Interesting synergies with this field are expected concerning more advanced desalination technologies based on materials with dynamic optical performance.
- Research concerning reliability and lifetime to assess the expected degradation in the performance of the absorber materials. A particular focus should be the extremely corrosive environment caused by brine solutions.
- Development of simulation programs for the total performance of the desalination concept including the water desalination, the light transmission into the greenhouse, the crop growth and the greenhouse climate and the water balance. The interaction and coordination between these technical and biological parts should be facilitated and efficiently managed.
- Development of more general and less complex growth simulation models which are feasible for integration into the model for technical system simulation. Here, co-operation with the more applied crop science research field should be beneficial.
- In more general terms the future research about water desalination with the actual concept should be more focused on advanced and combined concepts for several purposes useful for human consumption.

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