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Decision Support for Climate Dependent Greenhouse Production Planning and Climate Control by Modelling. I. Modelling Climate

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Summary

In greenhouse production planning and control both, the greenhouse climate and cost of conditioning are of particular importance. To estimate greenhouse climate, respective plant growth and energy demand the external climatic conditions of the sites have to be processed. The suitability's of Long term normals (Ltn, long term means) and Reference years (Blümel et al. 1986) were tested. The Reference years are considered adequate to forecast the most probable climate for special periods. To derive seasonal trends Ltn are preferred. On the basis of these data and the advanced models of Rath (1992, 1994, 2004, 2007) greenhouse climate and energy demand for heating were estimated.

The models of Rath enable to parameterise *radiation* and air as well as soil *temperature* in greenhouses as a function of the climate of sites, greenhouse size and type (Venlo block, Wide span greenhouse, height of side panel), energy saving installations (single and double glass, energy screens) and set point for heating. The *energy demand* for heating (Rath 1994) is calculated on hourly basis for the respective conditions considering ventilation, heat storage in the soil and wind speed.

Key words. energy demand – energy saving installations – greenhouse size and type – greenhouse climate – long term normals – reference years – sites

Introduction

Up to the seventies of the 20th century planning and control of greenhouse production was based on long term grower experience as well as on individual experimental data, attained under the respective special basic conditions. Due to the long term experiences in general the results were satisfactory. When, however, in 1973 the energy crisis changed drastically the special basic conditions by multiple energy prices, nobody was able to give proved answers, how to react. Therewith it became evident that for flexible adaptation to changing conditions more should be known on the modes of action and interaction of the main contributing factors. Just at that time modelling approaches were developed (summarised by Bertalanffy (1968) as "General system theory") and applied to plant growth by de Witt and Brouwer 1968. On this basis first preconditions were established to build modules of greenhouse production and upgraded for greenhouse vegetable production by Krug and Liebig et al. (summarised in Krug 2002).

In complex biological-technical-economic systems, such as crop production, modelling requires simplifications. In the investigations of Krug and Liebig the major ones were:

- The climatic conditions were derived as Long term normals (Ltn), giving the levels and the seasonal trends, but neglecting fluctuations (these are only recognised by calculating for 50 single years, to derive the span and frequency of deviations by Krug and Liebig 1988).
- The climatic conditions inside the greenhouses were derived by regression functions, calculated for the small greenhouses of the institute in Hannover, that also means just for one site, one greenhouse type and size.
- The submodels for the energy demand were based on more (Vickermann 1969) or less (Damrath 1980) simplifications and both approaches neglect heat storage in the soil, an important attribute for heating in cold seasons.

In the meantime new climate basic data – Reference years – and new submodels have been developed, such as for greenhouse climate considering greenhouse construction and energy saving installations (Rath 1992) or to calculate energy demand (Rath 1994). The option of this project is to check and extend the results and recommendations of earlier investigations on the basis of more actualised submodels and to evaluate the impacts of a broader spectrum of external climatic conditions on greenhouse climate, crop growth and energy demand in greenhouses.

Material and Methods

Ambient climate data (irradiance, temperature) in the earlier experiments (Krug and Liebig 1994, 1995) were derived from meteorological statistics as Long term normals (Ltn), here daily mean temperatures and daily sums

of irradiance of Hannover in the period 1960–1990. In this investigation at first the expressiveness of "Reference years" (BLÜMEL et al. 1986) was tested for the site Hannover. Reference years represent the long term means of 14 meteorological parameters (a. o. air temperature, direct and diffuse irradiance), superimposed by statistically determined typical seasonal weather courses, by correction factors to meet the levels of Ltn and by data generated by interpolation and modelling (e.g. for irradiance). Therewith they describe most reliable courses of the weather during the whole year in hourly data for different areas with comparable climates. Reference years, however, are only derived for Germany.

Concerning Ltn three sites were elected, Hannover (52° n.l.) for a northern medium climate, Helsinki (60° n.l.) for a cool climate and Naples (41° n.l.) for a warm climate. Since for the sites outside of Germany only Ltn means for months were available, hourly and daily means/sums were generated by the climate model of RATH (2007). This model considers monthly means of the daily maxima and the daily minima temperatures, monthly sums of solar radiation of special locations (MÜLLER 1996; PALZ 1996) and a model for sun movement over earth (DAM 2001).The data were combined with cubic splines and trigonometric functions to create hourly values for every day. Special iterative algorithms were developed to assure the yearly means of temperature and radiation to be fulfilled.

The calculations are based on two types of **greenhouses**, the small span (3,2 m) Venlo-block and the Wide span greenhouse (12,55 m) block, the ground area A_g always assumed quadratic. The heights of the side panels (sp) are considered 3,0 m as standard and also 4,5 m. The cover area (A_c) was calculated according to Hortexlight (RATH 2004):

$A_c = x*A_g+(sp-1)*\sqrt{A_g}*4$ with (1)

$x = 1.9745*(A_g^{-0.0607})$ for the Venlo type (2) and (2)

$x = 2.201*(A_g^{-0.0669})$ for the Wide span type (3).

The greenhouse area was varied from 100 m² (for theoretical reasons and for comparison with earlier results) to 10,000 m². The houses were assumed to be covered by single and double glass (energy transmission factors U' = 7.56 and 4.65 W m^{-2} K^{-1}, respectively) with 4 m s^{-1} wind speed. Additionally, the effects of screens were estimated. The orientation is only north – south, according to ZABELTITZ (1986) east-west orientation will result in only small deviations.

The **climate inside** the greenhouses was calculated by the comprehensive model of RATH (2004), considering site, celestial orientation, greenhouse construction including ground area, cover material and energy loss on a hourly basis. Reduction of irradiance inside the greenhouse is assumed by the factor 0.6 for single glass and 0.5

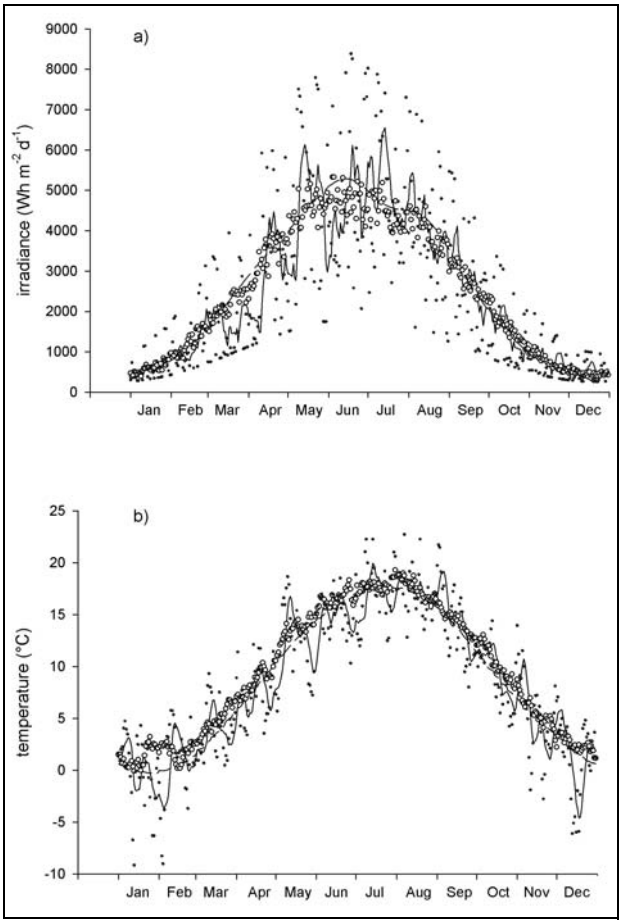


Fig. 1. Comparison of seasonal climate data of Hannover, demonstrated by daily Long term normals (1960–1990, sign o), daily data of the Reference year (sign ×, BLÜMEL et al. 1986), Reference year smoothed to 7-day-means (||) and daily means of Long term normals (- - -), generated by the climate model of RATH (2007). a) global irradiance, b) air temperature

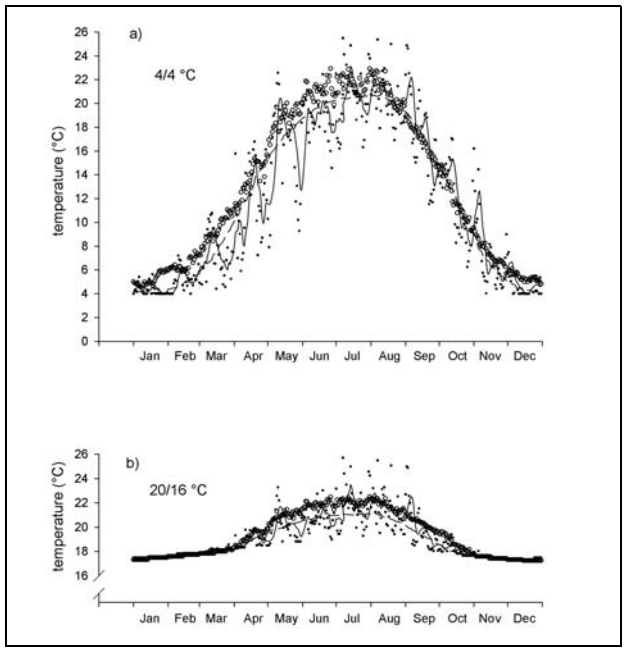


Fig. 2. Comparisons of daily means of air temperature inside a 100 m² greenhouse in Hannover, calculated with daily Long term normals, daily data of the Reference year, reference data smoothed to 7-day-means and daily means of Long term normals generated by the climate model of RATH (2007), with set points for heating of 4/4 °C and 20/16 °C, resp. (day/night, symbols as Fig. 1).

for double glass. Using energy saving screens no light reduction is assessed (open at day conditions).

Soil temperature modelling could be based on various investigations (KRUG et al. 1985, 1995, 2002, Fig. 4. 1–3; TAHA 2003), comprising various greenhouse types, seasons and set points for heating. The different approaches show distinct effects and interactions of irradiance, air temperature, set point for heating and season. These factors were more or less correlated with each other and could not be disentangled or integrated in the available data base. Therefore two equations are used:

In the spring and summer measurements of Rath in different greenhouses (unheated, TAHA 2003 and with a set point of 15 °C) on an hourly basis in a depth of 2–5 cm the excess temperature showed a linear positive correlation to irradiance (Fig. 5) and resulted in equation (4):

$$TS = (0.0002\ SP_a - 0.031)\ Q_g - (0.181\ SP_a - 3.5391) + TA_{hort} \quad (4)$$

TS= soil temperature calculated (°C), SP_a= set point air (°C), Q_g= global irradiance inside (W m^{-2}), TA_{hort}= inside air temperature calculated according to Hortex (°C). If ventilation is open, TS is at least 2 °C above external temperature.

In the winter season measurements with set points of 2/2–14/10 °C (KRUG et al. 1985) a regression equation was used with terms for irradiance and temperature on a daily basis and factors for season and soil depth resulted in equation (5):

$$TS = 21.5399 + 0.5757\ TA_{hort} - 0.00004877\ Q_g - 1889\ d + 0.0004886\ d^2 + 0.05159\ S_d \quad (5)$$

Abbreviations see equ. 4 and d = days after July 1th, S_d = soil depth in cm.

Both approaches are considered statistically realistic for their season.

The Rath-model also allows for estimating the **energy demand** for heating (RATH 1994):

$$Q = [(A_c * A_g^{-1}) * U' * (Ti - Ta) - Q_g * g * 0.7 - Q_s] * t \quad (6)$$

Q= energy demand in W h m^{-2}; A_c = cover area of the greenhouse (m^2); A_g = ground area of the greenhouse (m^2); U' = energy transmission factor (W m^{-2} K^{-1}) ; Ti = temperature inside (K); Ta = external temperature (K), Q_g = external global irradiance (W m^{-2}); g = irradiance transmittance of the greenhouse [0.6 (–)], 0.7 (–) = conversion factor from irradiance to sensible heat; Q_s = energy storage of the soil (W m^{-2}); t = simulation time (1 h steps).

The heat demand is expressed in energy units (Wh). After conversion to kWh the factor for transfer in oil is 0.0994 and in natural gas (useful heat) 0.0957. Energy saving by screens is calculated according to Hortexlight (RATH 2004) and resulted in a factor for heat loss of 0.4. All parameters are calculated for the mean wind speed in Germany (about 4 m s^{-1}). Other wind speeds are considered by the regression equation (RATH 1992):

$$U'' = U' + U' * 7.56^{-1} * (0.35 * V_w - 1.4) \quad (7)$$

U'= energy transmission factor with 4 m s^{-1} wind speed V_w; U" energy transmission factor for other wind speeds (both in W m^{-2} K).

Results and Discussion

Climate data

Reference year – Long term normals (Ltn). The **ambient climate** (irradiance and temperature) of Hannover is represented by meteorological Ltn of 30 years, by Ltn derived

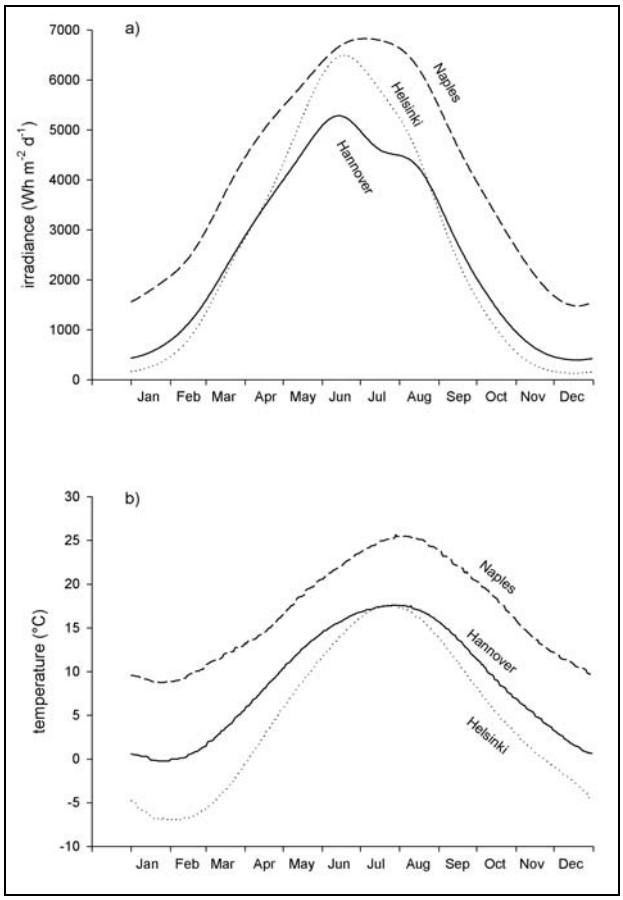


Fig. 3. Comparison of daily means of outside irradiance and temperature of three sites, derived by RATH (2007).

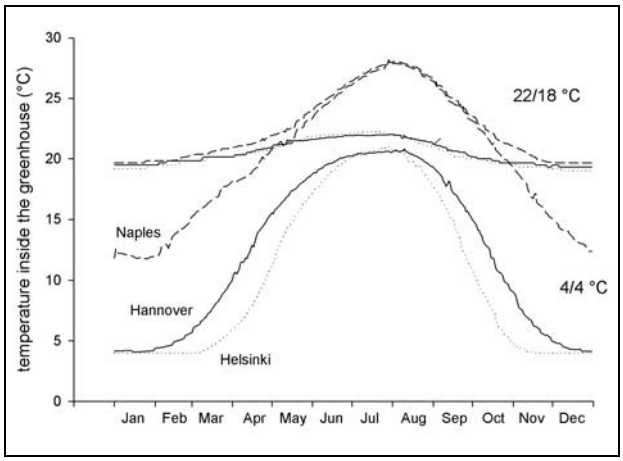


Fig. 4. Daily means of temperature inside the greenhouses (100 m^2, single glass) at three sites with set points of 4/4 °C and 22/18 °C (model RATH 2004).

Table 1. Annual temperature means (°C) and means of daily irradiance sums (kWh $m^{-2}d^{-1}$) were calculated for Hannover according to the meterological Long term normals (Ltn_{met}) 1960–1990, the Ltn_{Rath} derived from the climate model of RATH (2007) and the Reference year of Hannover were in accordance to BLÜMEL et al. (1986).

	Temperature	Irradiance
Ltn_{met}	9.60	2553
Ltn_{Rath}	8.73	2612
Reference year	8.65	2543

by the climate model of RATH (2007) and by the Reference year of the Hannover region derived by BLÜMEL et al. (1986). The annual means are summarised in Table 1. The annual daily sums of irradiance show only negligible differences. The annual temperature means of the Ltn of RATH (2007) and of the Reference year are short 1 °C cooler than the meteorological Ltn. This means a greenhouse energy difference of about 10 % (inside temperature about 20 °C).

The *annual courses* of the climate data are presented in Fig. 1. The irradiances of the Ltn of RATH (2007) are close to those of the meteorological data all the year round. The course of the values of the Reference year, however, shows considerable fluctuations, even when smoothed (Fig. 1a). Deviations of the smoothed curve are especially obvious from April to June. The fluctuations for temperature are less pronounced, they occur particularly in April–May and especially in wintertime (Fig. 1b).

The effects of fluctuations of the Reference year on the temperature **inside the greenhouses** (100 m^2, single glass) are naturally larger with low set points for heating than with high set points (Fig. 2), especially when greenhouse temperature is higher than the external temperature. Clearly marked deviations, however, occur with both high and low set points, at 20/16 °C from May to September, at 4/4 °C especially from March to June.

The physiological impacts of these fluctuations on plant growth and development are difficult to assess. Regarding irradiance investigations of LIEBIG (1989) demonstrated that in terms of fresh weight kohlrabi is able to buffer fluctuations up to 10 days via dry matter concentration. Therefore, at least short time fluctuations of irradiance will be buffered. Concerning temperature plants react more or less on-line, but daily and medium term fluctuations affect growth of most species according the long term means (LIEBIG 1989; FINK and KRUG 1998). Therefore, short time fluctuations will be buffered to a large extent by most plants. On the other hand KRUG and LIEBIG (1988, 1995) did show the large influence of extended warm and more pronounced cool weather periods on plant growth.

Due to the buffer capacity of many plant species, the smoothing effect of high set points in greenhouses and since Reference years make it more difficult to derive seasonal trends in plant growth and factor demands, daily means of Ltn are preferred to calculate plant growth. Energy costs for heating, however, are computed on a hourly basis for Ltn, multiplied with a correction factor (as a function of site time and set point) to meet the higher fuel consumption with fluctuating temperatures, as presented by the Reference year (example see Fig. 7).

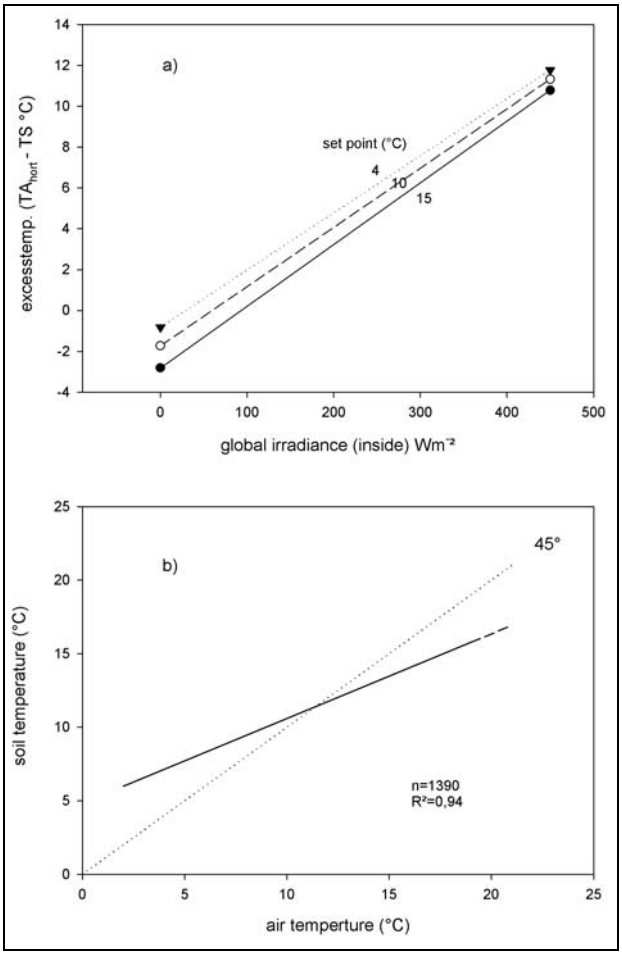


Fig. 5. Soil temperature related to a) irradiance and set point for heating during the summer season according to calculations with Hortex and equation (4) and b) to inside air temperature in the winter season according to equation (5).

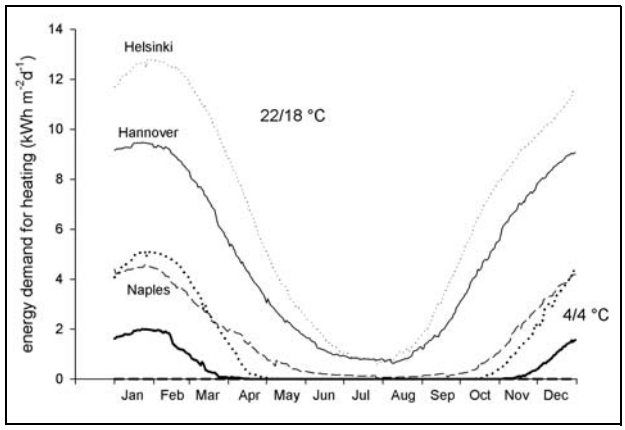


Fig. 6. Energy demand for heating a 100 m^2, single glass greenhouse at three sites for set points of 4/4 °C and 22/18 °C (model RATH 2004).

Climates of the sites. The **climatic conditions** of the three sites are presented in Fig. 3. The main differences are: All the year round Naples enjoys the highest irradiances and temperatures; concerning the northern sites Helsinki suffers lower irradiances and distinct lower temperatures in winter compared to Hannover; in summer it is favoured by noticeable higher irradiances with about equal temperatures in July. In spring and autumn in Helsinki irradiances are comparable, but temperatures are lower than in Hannover.

The meaning of the ambient climate data for the **climates inside the greenhouses** depends on the properties of the greenhouses and climate control. Since the reduction of *irradiance* is primarily caused by the cover material and its exposition and as irradiance is only controlled in exceptional cases, considerations are restricted to inside temperature.

The effects of ambient temperature and irradiance on inside temperature of greenhouses (100 m^2, single glass, Venlo) at the three sites is quantified in Fig. 4. Temperature is largely equalised by high set points, except when air temperature rises above the set point by the natural irradiance or high ambient temperature, such as in Naples in the hot summer months. The impacts of the ambient conditions increase with lower set points and then compensation only occurs during the cool season, such as in Hannover and Helsinki in December–January.

Concerning *greenhouse size* (100–20,000 m^2 ground area) inside irradiances in the approach used are considered identical. With respect to inside temperature the effects of greenhouse size must be small to negligible in the stage of heating. In the warmer season with low set points, however, in Hannover and Helsinki the 10,000 m^2 greenhouse is 1–2 °C warmer than the 100 m^2 one, especially in spring (1.9 °C), in summer (1.1 °C), and in autumn (1.2 °C) (because ventilation effects are not included into the model).

Energy saving installations: Modelling resulted in only small differences between inside temperatures with single and double glass and energy screens, except in spring time. Here double glass heats the greenhouses about 0.5 °C higher in Hannover from March to May. In Helsinki this effect is shifted somewhat more toward summer time; with the low set point more so than with the higher set point, with a maximum difference between single glass and double glass of 1.0 °C and 1.6 °C. The effect of the screen is less (maximum difference 0–0.5 °C) and the effective period is shorter. In Naples the effects are negligible. Therewith the warming effect was more apparent with cooler sites and with lower set points, when irradiance warms up the greenhouse above ambient temperature.

Soil temperature in its relation to air temperature is calculated on the basis of the equations (4) and (5). According to calculations with Hortex and equation (4), Fig. 5a presents the dominating effect of irradiance in summer climates, the intercept point for irradiance with the excess temperature of 0 °C was 93 W m^{-2} (set point 15 °C), 60 W m^{-2} (set point 10 °C) and 29 W m^{-2} (set point 4 °C). That means a warmer soil below the intercept point and warmer air above the intercept point.

For the winter season Fig. 5b demonstrates the dominating effect of inside temperature on soil temperature with almost identical regression lines for the autumn-winter season and the winter-spring season. During

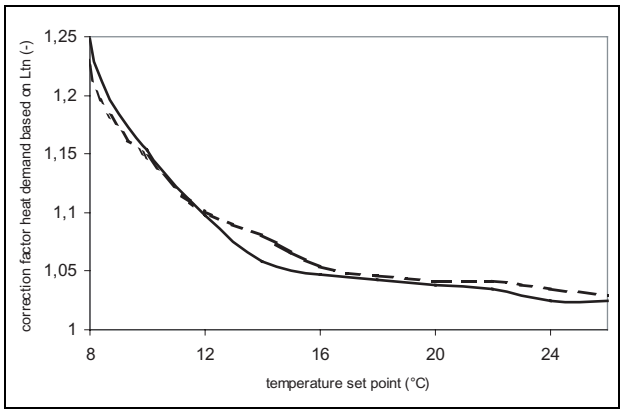


Fig. 7. Factor (U''/U') to calculate the effect of wind speed on energy demand of greenhouses for single glass (s), double glass (d) and double glass related to single glass (d/s), according to equation (7).

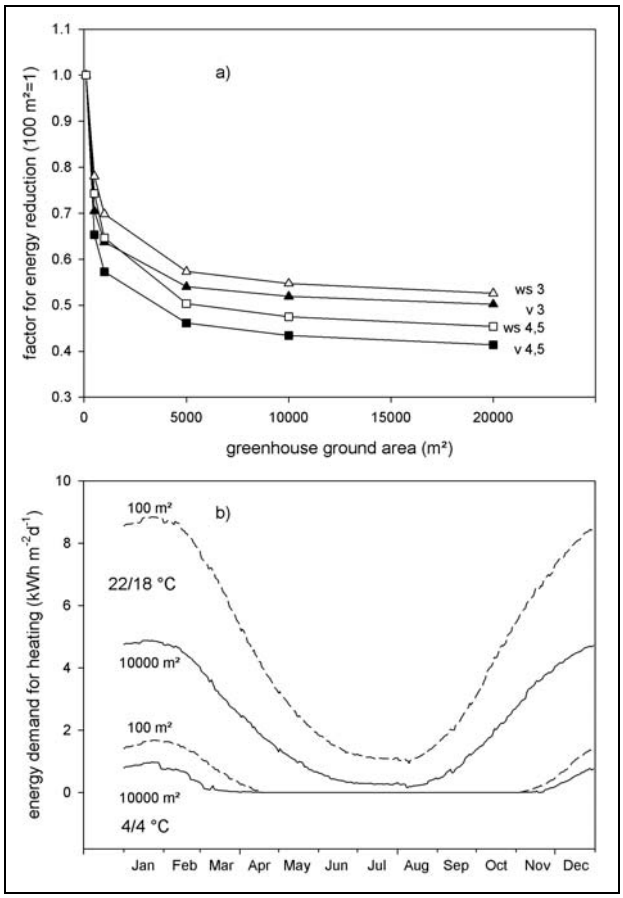


Fig. 8. Effect of greenhouse area on the energy demand for heating. a) reduction factor calculated by the cover to ground-area relationship (100 m^2 equal 1) for Venlo-blocks (v) and Wide span (ws) greenhouses with 3 m and 4.5 m side panels, respectively. b) Year round energy demand of a 100 m^2 greenhouse compared to 10,000 m^2 (single glass for a high and a low set point in Hannover (model RATH 2004).

the total winter season soil temperature increases almost linearly from 1 to 10 cm depth (0.05 °C cm^{-1}, KRUG et al. 1985), causing only small effects. With an intersection with the bisector (TS = TA_{hort}, 2 cm depth) at about 12 °C the soil is warmer than the air below 12 °C and cooler above 12 °C.

Energy demand for heating. More drastic than the site-effects on controlled inside temperature are the differences in energy demand to assure the required temperature for plant growth (Fig. 6). In February, the month with the highest energy demand, the values for a set point of 22/18 °C average out to about 4 kWh m^{-2} d^{-1} in Naples, to 9 kWh m^{-2} d^{-1} in Hannover and to 13 kWh m^{-2} d^{-1} in Helsinki. For a set point of 4/4 °C the values average out to 0,2 and 4 kWh m^{-2} d^{-1}, respectively. In July the differences are negligible.

Wind speeds deviating from the selected standard of 4 m s^{-1} can be incorporated by factors calculated for single and double glass greenhouses (equation 7). Related to the wind speed 4 m s^{-1} the factor U'/U" increases with a wind speed of 10 m s^{-1} by about 30 % and accordingly the energy demand increases as well.

Also the effect of *greenhouse size* on energy demand is striking (Fig. 8). Calculated by the cover/ground-area-relationship and the value of 100 m^2 equal to 1, the energy demand is reduced with larger ground areas according to Fig. 8a. It drops drastically up to about 2,000 m^2 greenhouse area and then slowly levels down to the largest area calculated. The reduction runs faster with the 4.5 m side panels compared to the 3 m ones and with the Venlo-block compared with the Wide span greenhouse block. A reduction by 50 % is reached at about ≥7,000 m^2. The dimensions of energy reduction are demonstrated in Fig. 8b.

Energy saving installations reduce the energy demand drastically. At all sites and with all set points the energy demand is reduced by double glass by about 40 %. The reduction by screens is caused by heat storage and radiation effects at night, and it is more variable (7–35 %, in an average 23 %), due to the different lengths of the nights – the screen saves least energy in the short, warm nights of July, most with the long cool nights.

General Discussion and Conclusions

The presented calculations demonstrate the process and the problems of modelling climates for sites, to estimate respective greenhouse climates in relation to diverse modifying factors and respective energy demand for heating. Due to the complexity some simplifications were inevitable: Greenhouse area is mostly not quadratic, the construction parameters are variable and the heating systems are manifold in construction and installation. The same is true for the energy saving installations. Basically all these variations can be considered in individual cases, but in a general view standardisation is inevitable. In spite of these constraints the approach is considered an acceptable and developable module to entangle the multivariable production system, and the calculations presented are examples for improved decision making for special situations by iteration.

Beyond the well known relationships main results are:

- *Reference years* are useful tools for production control and for estimation of factor quantities and therewith costs (e.g. heating) for special situations, but less suitable than Ltn to derive seasonal trends.
- *Larger greenhouses* when heated, they reduce the energy demand by factors up to 0.4–0.5. The reduction is more pronounced in the range of smaller greenhouse areas, with Wide span houses and with higher side panels.
- *Wind speed* has an appreciable and calculable effect on energy demand.
- *Energy saving installations*: Double glass reduces irradiance, but has only minor effects on inside temperature of greenhouses. Only in spring with low set points modelling resulted in a noteworthy daily mean temperature increase. Energy saving amounts to about 40 %. Saving is more effective in spring and at cooler sites. Screens should have almost no effect on irradiance and have a small effect on temperature. Energy saving per 24 h depends on night length and hence is more variable (7–35 %, mean 23 %) than double glass. The parameters elaborated enable to estimate the profitability of these installations for special conditions.
- Soil temperature is a function of the greenhouse climate, especially irradiance and air temperature; furthermore factors for the season and soil depth are involved. In the summer season irradiance is the dominating factor, in the winter season air temperature. This was regarded by two different equations, resulting in interceptions (air = soil temperature, lower values mean a warmer, higher values a cooler soil) of 29–93 W m^{-2} (set point 4 to 15 °C, respectively) in the summer season and about 12 °C (2/2–14/10 °C) in the winter season.
- Concerning energy demand for heating the values of the Rath-model, calculated on the basis of hourly values and 100 m^2 greenhouses exceed those of the Vickermann-model by far. The Vickermann values, however, approximate the Rath-model values for large greenhouses.

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