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Development of Concepts for a Zero-Fossil-Energy Greenhouse

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Abstract

Dutch government and greenhouse horticultural practice aim for strongly reduced fossil energy use and of environmental loads in 2010 and energy neutral greenhouses in 2020. This research aims to design a greenhouse concept with minimal use of fossil energy and independent of nearby greenhouses. The concept is called the zero-fossil-energy-greenhouse. This paper presents a theoretical design study and analysis to assess the viability of a zero-fossil-energy-greenhouse concept. The greenhouse was designed for Dutch circumstances and relies on available state-of-art technologies. Nine concepts were generated and evaluated by a panel of experts. Although, none of the concepts was unanimously selected, one of the concepts received on-average highest votes. It uses an aquifer for long term heat and cold storage. Geothermal heat and a heat pump connected to the warm pit of the aquifer are used to heat of the greenhouse. Electricity need is covered by green-electricity. Cooling and dehumidification of the greenhouse is realised by a heat pump combined with the cold aquifer pit. This concept was more thoroughly evaluated in a simulation study that assessed design consistency and evaluated greenhouse performance in view of design requirements. From the simulations it was concluded that a combination of geothermal heat and a heat pump/aquifer can cover the heat demand of the greenhouse with help of heat buffers, but a fully closed greenhouse concept is not manageable in the summer season. With given technology the chosen concept was not able to cool and dehumidify greenhouse air to target temperature and humidity. A semi closed greenhouse solves this problem.

INTRODUCTION

The Dutch horticultural industry has committed itself to improve energy efficiency by 65% in the year 2010 compared with consumption levels of 1980 (Bot, 2001). Also in light of the Kyoto treaty CO_2 emission levels should be reduced by 6% in the period 2006-2010 compared with emission levels in 1990. Designing a minimum fossil energy greenhouse aims at tackling both objectives. Additionally, there is a focus on producing energy neutral greenhouses in 2020. This research aims to design a readily available greenhouse concept with minimal use of fossil energy that contributes to Dutch aims. This greenhouse must have a neutral energy balance on a yearly basis. Transport of low temperature heat is ineffective and the system should be applicable for as many greenhouses as possible. The concept is called the zero-fossil-energy-greenhouse. This paper presents a theoretical concept design study and analysis to assess the viability of such a greenhouse concept. The greenhouse was designed for Dutch circumstances and relies on currently available technology.

MATERIALS AND METHODS

In this research a systematic design procedure was employed (e.g. Kroonenberg and Siers, 1999; Cross, 2001). The design procedure roughly contains the following steps:

0. Preliminary research resulting in definition of the design objective.
1. In a brief of requirements specifications and design limits are stipulated, for instance

costs limitations and performance targets.
2. A systems analysis will reveal the necessary system functions.
3. Derivation of alternative working principles for each function.
4. Concept development stage. During this stage working principles are combined into several different conceptual designs. Effective combinations prevail with one working principle per function but if relevant also more working principles can be combined.
5. Design alternatives evaluation and bottle-neck assessment. During this stage the various conceptual designs are evaluated in view of the design requirements. Design evaluation is based on expert assessment (quick scan) and on quantitative simulation of promising concepts using mathematical models. Also at concept level bottle-necks and contradictions in the design can be identified and removed which may lead to (minor) changes in the proposed concept. One or two conceptual designs are chosen.
6. Improving details. For the conceptual design(s) chosen, each working principle has to be worked out in more detail. Each level of detailing, from system to part level, may show bottle-necks and design contradictions that require solution.
7. The final design is materialised into a prototype or pilot and tested in view of the design requirements.

In most cases the above design procedure will have an iterative nature. Iteration is possible from each step to any of the earlier steps. The analysis up to step 6 is performed interactively using expert knowledge and databases and as a desk study using design software, analysis software, simulation models and CAD. Step 6 may include small experiments on particular working principles, but not before step 7 the design is realised.

In this research, nine alternative concepts of a zero-fossil energy greenhouse were generated. The merits of these nine concepts were evaluated in a qualitative way by three experts with different background and viewpoint. Although a unanimous best concept was not obtained from this expert forum, one concept yielded on average the best marks with clear distance from the other concepts. This concept was subjected to an in depth simulation analysis with GTa-tools (Van 't Ooster, 2007). Various alternative scenario's were calculated to assess the merits of this concept in a quantitative manner.

RESULTS AND DISCUSSION

The Methodological Generation of Alternative Concepts

The methodological approach to designing a zero-fossil-energy greenhouse is illustrated up-to step 5 of the design procedure, the evaluation of the concept.

1. Step 0 – Definition of the Design Objective. Design a readily available concept for a zero-fossil-energy greenhouse, that is a greenhouses that uses no or minimal fossil energy. This greenhouse is not dependent of conventional greenhouses nearby to close the yearly energy balance and contributes to the objectives on improvement of energy efficiency and CO_2 emission reduction.

2. Step 1 – Definition of the Brief of Requirements. The brief of requirements included amongst other the following main requirements: 1) The greenhouse should have a size of 4ha and produce at least 50kg·m^{-2} of tomatoes, 2) Greenhouse climate: Temperature must lie between 17°C (night) and a maximum of 27°C (day) with normal DIF 2°C. An acceptable range for relative humidity is 60-85%. CO_2 concentration must be economically optimized between 360 and 1000ppm, 3) Soil based energy storage systems must be energy balanced on a yearly basis, 4) Energy sources must be sustainable but if inevitable use of fossil energy exists it must be compensated by the production of a surplus of sustainable energy. 5) The vents must be closed as much as possible (to prevent losses of heat and CO_2 and to harvest energy in the warm season), 6) CO_2-emissions must be reduced to 35% of current values or less, 7) The system must be economically feasible, 8) Production must be economically competitive with standard greenhouses.

3. Step 2 - Definition of Required Functions. To satisfy the requirements, functions were derived. Functions included are energy production, energy storage, heating, cooling and dehumidification of the greenhouse air, CO_2-enrichment, prevention of energy losses through the greenhouse cover as well as shading of sunlight. These functions are the minimum set of functions to operate a zero-fossil-energy greenhouse. Internal transport, labour, cultivation systems etc. are assumed to be fixed. Also the greenhouse construction is of a standard Venlo-type and not subject to design optimization.

4. Step 3 - Definition of Working Principles. For each of the functions alternative working principles were derived as shown in the morphological chart (Fig. 1) along the horizontal direction for each function. For example, cooling could be achieved with state-of-art functions like natural ventilation, a fog system, heat exchangers with outdoor air or soil optionally combined with a heat pump. More working principles are given in Figure 1.

5. Step 4 - Derivation of Conceptual Designs. Conceptual designs were developed by combining working principles, as illustrated by the lines in Figure 1. 9 different promising designs were derived by experts, of which the 2 best are shown in the figure. The number of designs generated is arbitrarily and limited by the number of combinations that satisfy the design objectives and requirements only. More designs increase the effort needed for the remaining design steps. The designs generated reflect expert opinions on promising combinations of working principles. The best concept selected in step 5 is described below. Concept 1: So-called green electricity produced by sustainable energy sources like wind mills and hydropower, was used as external power source. Deep geothermal energy combined with an electrically driven compression ground source heat pump using long term heat stored in an aquifer as heat source, was used for heating the greenhouse. For cooling the greenhouse air, a heat exchanger either alone or in combination with a heat pump was used. This system uses long term cold stored in an aquifer as cold source and the warm aquifer pit as heat sink. Industrial carbon dioxide was used for enriching the greenhouse air. The greenhouse cover consisted of a single cover and solar radiation energy input was controlled with a shade screen outside the greenhouse. A closed greenhouse or a semi closed greenhouse concept should be applied.

6. Step 5 - Evaluation of Conceptual Designs. Evaluation of the nine concepts consisted of two steps. First a qualitative assessment was done by experts. Secondly, the best concept was evaluated in more detail using simulation.

Expert assessment of all nine concepts. In a quick-scan all designs were evaluated by experts in view of a set of criteria including: expected production level, input of fossil fuels, production of energy, efficiency of CO_2-enrichment, independent of outdoor weather conditions, humidity control, effectiveness of energy storage, light transmission and insulation of the cover, labour conditions, operating costs for heating, cooling, dehumidification, energy storage and CO_2 enrichment. With each criterion a weighing factor was associated to express the relative importance of the individual criterion for the zero-fossil-energy concept. One set of weighing factors was created to assess technical feasibility and one to assess technical and economical feasibility. Each criterion was evaluated on a scale of 1 to 4. Using this procedure, concept 1 was chosen as most promising on both technical feasibility alone and on technical plus economical feasibility. Figure 2 gives details on the winter and the summer season operation of concept 1.

Simulation assessment of the best concept. Concept 1 was implemented in a simulation model and its performance studied. The evaluation focussed on crop production and energy conservation potential, emission of CO_2 and yearly operational costs.

Simulation Results

For reasons of comparison a standard boiler heated greenhouse was simulated as a reference. Carbon dioxide enrichment was optimised to the point where marginal crop yield equals marginal CO_2 costs. Available CO_2 sources are combustion gasses and industrial CO_2. Secondly to indicate the effect of applying geothermal energy at minimal costs (€.GJ^{-1}), a standard greenhouse was simulated in which the energy need was partially covered by geothermal energy. The geothermal energy source (6.7MW) is a 2 to 2.5km deep well delivering 80°C water at a maximum rate of $150 m^3.h^{-1}$ combined with a source dedicated heat buffer (3600 m^3). Maximum unload flux of the combination is

300m^3.h^{-1} and the water is cooled down with about 40°C. A trade-off in operational costs and investment costs and economic competition between heat (and CO_2) sources resulted in an optimal share in the geothermal energy source of 34 and 40% for this configuration at gas prices of 18 and 30 €cts.m^{-3}. Thirdly, the fossil-zero-energy greenhouse was simulated. For this concept the optimal share in the geothermal energy was 35%.

Of all three greenhouses, crop production, demand and supply of energy and CO_2, required and realised dehumidification and cooling, surplus heat production and electricity use and costs are listed in Tables 2 and 1, respectively. Cost and resource use was calculated for a natural gas price of 18 and 30 €cts.m^{-3}. For the zero-fossil-energy greenhouse variants with a closed greenhouse concept (alt 1) and a semi closed greenhouse concept (alt 2, 3a and 3b) were simulated. Figure 3 shows the cumulative frequency distribution of the energy demand for both the reference greenhouse (right) and for the closed greenhouse alternative on the zero-fossil-energy greenhouse (left) and of the coverage of the energy demand by the selected heat sources. The simulations revealed that under Dutch circumstances the use of fossil energy could be excluded. The calculations also showed that short term energy storage is mandatory for covering peak loads in the energy consumption and to manage heat demands under minimum capacity of the heat pump. Because the design does not use fossil energy sources CO_2 originates from an external source. CO_2 production and enrichment demand are equal and depend on the leakage ventilation of the greenhouse (0.25h^{-1}). CO_2 use was reduced to around 30% of the use with standard horticultural practice.

With respect to the summer period the simulations revealed that, as illustrated in Figure 4 and Table 2, natural ventilation or other cooling sources than cold water from the aquifer or heat pumps are needed to cover the dehumidification and sensible cooling load of the greenhouse. Simulations also revealed that an optimal share in the geothermal heat source and the closed greenhouse concept do not lead to synergy because heat pump based heating is short on cold production for summer cooling/dehumidification demand and summer heat production is too high for winter heat demand which results in a design contradiction on these components. Only a semi closed greenhouse with moderate use of heat pump and aquifer and with natural ventilation support in the summer season leads to synergy with no fossil energy input, low CO_2 demand and no surplus heat production (as warm water with temperature of about 50°C). Although at current energy price levels, a standard greenhouse will be economically more attractive than a zero-fossil-energy greenhouse, calculations indicate that a standard normally ventilated greenhouse heated with geothermal energy and peak heating with a central boiler is already economically feasible at current energy price, but does not meet the energy nor the CO_2 emission objective. If geothermal heat is applied to a higher share with use of industrial CO_2, the objective could be realised at higher costs. This is not evaluated.

Economic feasibility of the zero-fossil-energy greenhouse depends largely on the income out of unused surplus heat and on the electricity price. Avoiding surplus heat production and balancing the energy storage in the aquifer on a yearly basis (alt 3b), the semi-closed zero-fossil-energy greenhouse shows about 10% higher costs for climate realisation than the standard greenhouse at a gas price of 0.3 €.m^{-3} and about 2% more crop yield. The crop growth target was realised in all simulations. Use of an external shade screen reduces growth but this reduction is more than compensated by a better CO_2 regime in the greenhouse. The performance of design alt. 3b does not fully meet requirements on greenhouse temperature and humidity, but it is not worse than the thermal climate in the reference greenhouse. Electric energy demand of the zero-fossil-energy greenhouse is relatively high and a major cost factor, both (green) electricity sources and energy use efficiency need more attention to improve the design.

CONCLUDING REMARKS

In this research a successful concept for a zero-fossil-energy greenhouse was developed. Simulations show that zero use of fossil energy and consequently a strong reduction in the emission of CO_2 is possible. The use of geothermal heat led to an energy unbalance in the aquifer or a large heat surplus when combined with aquifer based cooling/dehumidification and a closed greenhouse. A technically sound design concept was realised with a semi-closed greenhouse with moderate use of cooling and dehumidification in the summer season. At current price of natural gas this concept is not yet economically feasible, but the results suggest that the ongoing increase of the energy price will make this concept feasible. Another result of the simulations is that a standard greenhouse with application of geothermal heat at minimal cost per GJ also drastically reduces use of fossil energy and CO_2 emission and is economically feasible, but it does not meet all requirements of the zero-fossil-energy greenhouse. Finally use of the design method combined with expert and model assessment of concept solutions proved to be a strong procedure to come to promising concepts for the zero-fossil-energy greenhouse.

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Tables

Table 1. Annual costs[1] for heating and CO_2 supply of a standard greenhouse with and without geothermal heating (6.7MW source) and the zero-fossil-energy greenhouse.

		Standard greenhouse		Standard grh with geothermal energy		Zero-fossil-energy grh.		
						Alt 2	Alt 3a	Alt 3b
Gas price (€/100m^3)		18	30	18	30		no effect	
Geothermal source (%)[2]				34	40		35	
Fixed costs (€.m^{-2})	boiler	0.28		0.24	0.22		-	
	buffer (100 m3/ha)	0.17		-			0.17[3]	
	eq. CO_2 supply	0.12		0.12			0.12	
	eq. geothermal energy	-		6.41	7.14		6.53	
	heat pump	-		-		1.60	1.30	1.30
	aquifer	-		-			1.37	
Var. costs (€.m^{-2})	natural gas	9.39	15.64	2.82	2.00		-	
	geothermal energy	-		1.26	1.57	1.24	1.24	1.32
	CO_2	2.32	3.83	2.84	3.89	3.55	3.55	3.72
	heat pump	-		-		11.54	6.35	4.78
	aquifer	-		-		0.63	0.63	0.68
External shade screen		-		-			1.49	
Total costs (€.m^{-2})		12.28	19.59	13.67	14.94	28.24	22.75	21.49
€.GJ^{-1} heat (excl. CO_2)		5.73	9.40	6.26	6.38	8.35	8.35	7.95
€.GJ^{-1} cooling/dehum.						20.04	20.65	32.32

[1] Interest rate 4.5%; depreciation and maintenance according to Van Woerden (2006); price industrial CO_2 0.11€/kg; price electricity 0.11€/kWh. [2]Optimal share in the source capacity

Table 2. Comparison of crop yield (round tomato) and use of resources in a standard greenhouse with and without geothermal heating and in the zero-fossil-energy greenhouse with 3 alternatives evaluated (see footnote [3] and [4]).

	Standard greenhouse		Standard + geothermal en.		Zero-fossil-energy grh.			
					Alt 1 [3]	Alt 2 [4]	Alt 3a [4]	Alt 3b [4]
Gas price (€/100m^3)	18	30	18	30	no effect			
Heat demand (MJ.m^{-2})	1712		1712		1414	1462	1549	1533
geothermal heat (MJ.m^{-2})	0		1197	1493	1180	1213	1271	1262
heatpump+aquifer(MJ.m^{-2})	-	-	-	-	246	262	293	286
natural gas cons.(m^3.m^{-2})	52.2	52.1	15.7	6.7	-			
CO_2 (kg.m^{-2}) demand[1]	37.3		37.3		10.1	32.3	34.0	33.8
gross production[2)]	109.2	121.6	50.3	46.7	10.1	32.3	34.0	33.8
industrial CO_2	16.3	28.8	22.4	34.8	10.1	32.3	34.0	33.8
Crop production (kg.m^{-2})	54.6		54.6		60.1	58.4	57.0	55.8
Dehumidification (kg.m^{-2})	V		V		D	V/D	V/D	V/D
realised heat pump						216	118	67
Cooling (MJ.m^{-2})	V		V		C	V/C	V/C	V
realised heat pump						97	57	0
Unused heat (MJ.m^{-2})	-		-			654	220	0
Aquifer balanced	-		-		N	N	N	Y
Electr. heating (kWh.m^{-2})	pm		pm		43	46	49	48
cooling/dehumidification						86	41	26

[1] based on CO_2 optimisation and central boiler heating, [2] including industrial CO_2 intake, [3] closed greenhouse with ideal climate (target), [4] semi closed greenhouse, ventilation support when realised dehumidification or cooling is insufficient, simulated climate. Alt1= targeted closed greenhouse concept (required dehumidification (kg.m^{-2}) 462 (ext. shade screen), 490 (no ext. shade screen); required cooling (MJ.m^{-2}) 127 (ext. shade screen), 197 (no ext. shade screen)), Alt2 and 3= greenhouse cooled and dehumidified by a 20W.m^{-2} (alt 2) and a 10W.m^{-2} (alt 3a) compressor capacity with use on demand and a 10W.m^{-2} capacity with limited use (alt 3b). V,C and D indicate: V= realised by ventilation, D by dehumidification, C by active cooling.

Figures

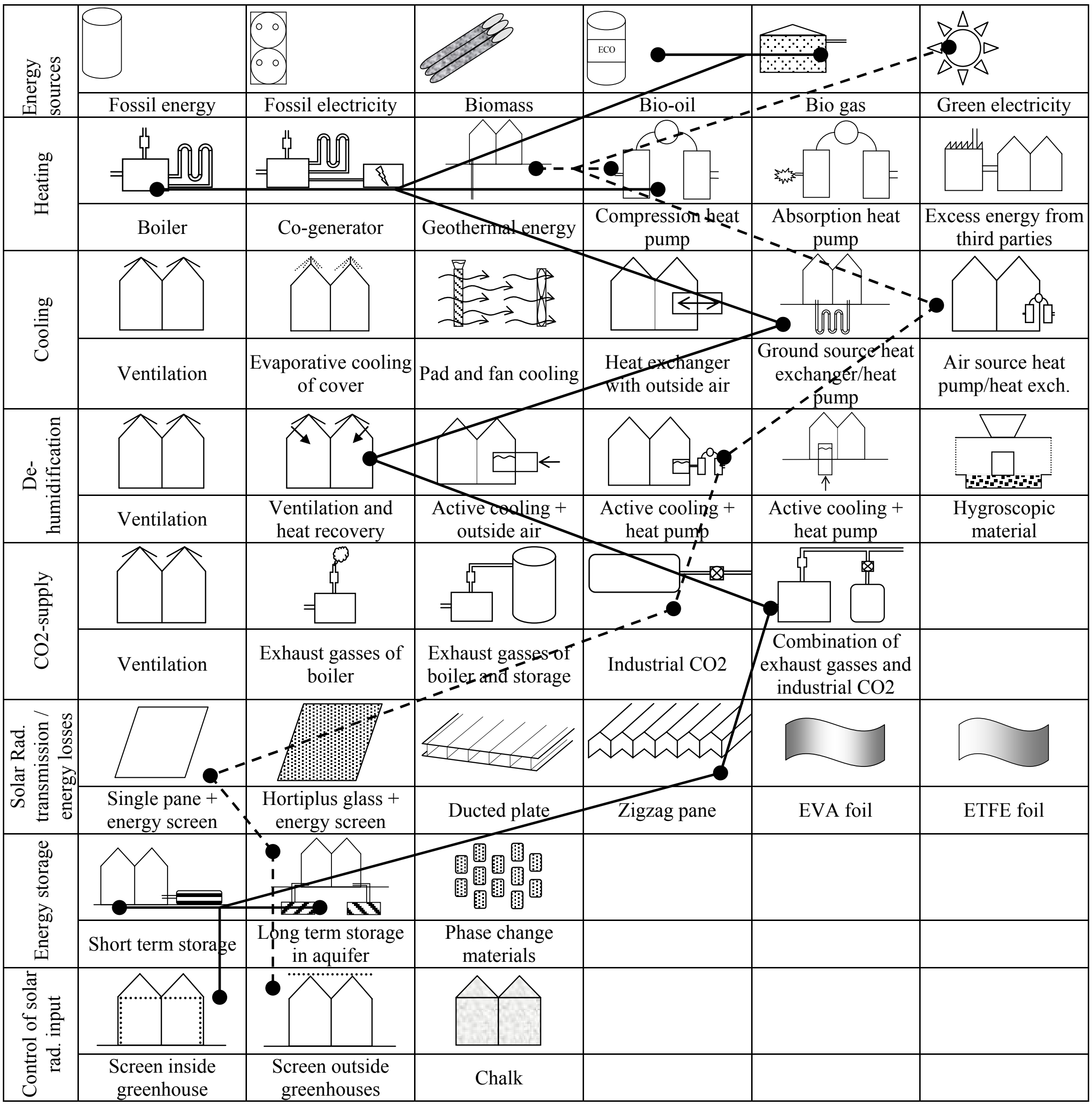

Fig. 1. Morphological chart of the zero-fossil-energy greenhouse; concept 1 (dashed line) and concept 2 (solid line).

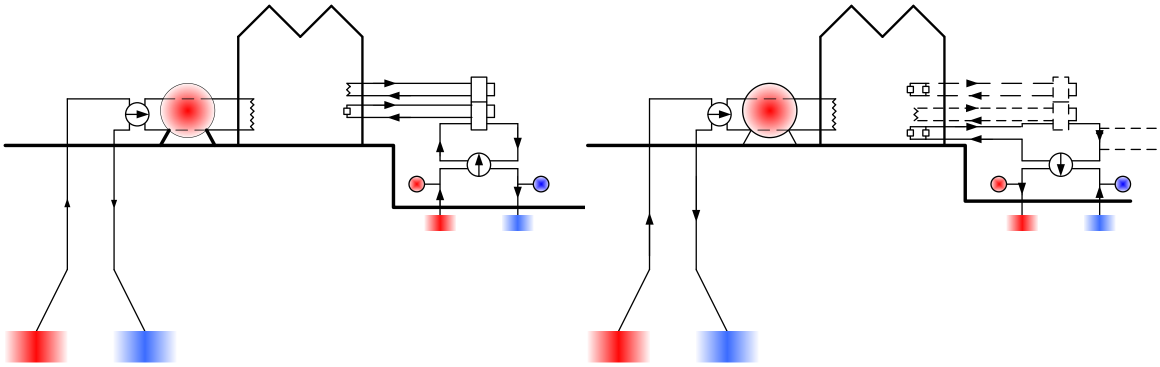

Fig. 2. Fossil-zero-energy greenhouse concept. Winter (left) heating demand covered by geothermal energy and a heat pump with aquifer. Dehumidification with cold storage. Summer (right) heating demand covered by geothermal energy, dehumidification and cooling demand covered by heat pump/aquifer with heat storage. Options cooling and dehumidification: (a) heat pump, (b) aquifer only and (c) surplus heat to third parties.

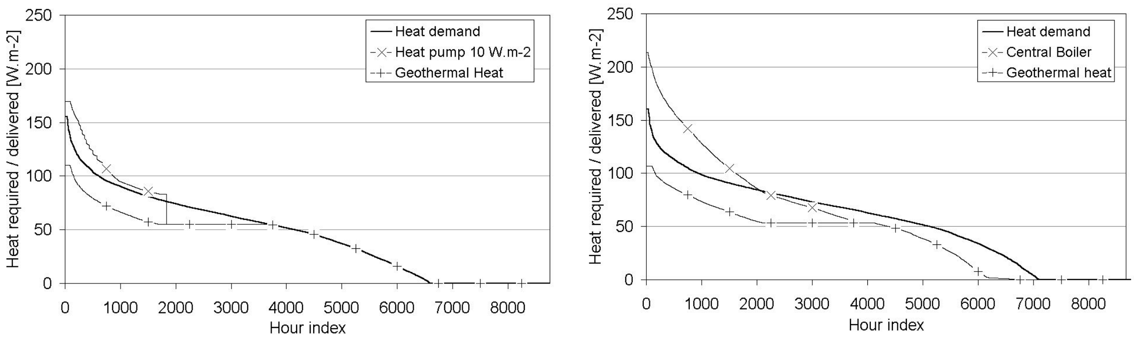

Fig. 3. Annual heat demand of the zero-fossil-energy greenhouse (left – closed greenhouse concept) and of the reference greenhouse (right). Contribution energy sources: geothermal energy, heat pump/aquifer combination ($10W.m^{-2}$ compressor capacity) and central boiler (reference greenhouse). A heat buffer ($100m^3.ha^{-1}$) balanced supply and demand.

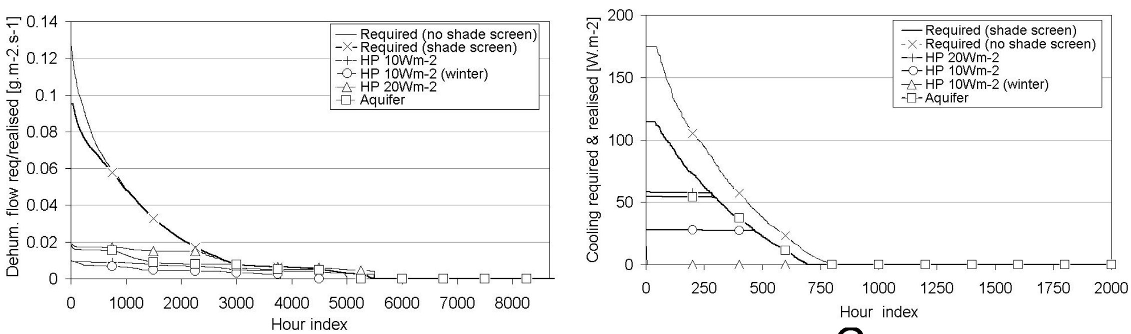

Fig. 4. Dehumidification (left) and cooling (right) demand of fossil-zero-energy greenhouse (closed greenhouse concept) with and without external shade screen (40% shade at R_e>500 $W.m^{-2}$). Contribution of alternatives on heat pump/aquifer/heat sink combination with compressor capacity $20W.m^{-2}$ (alt 2), $10W.m^{-2}$ maximum use (alt 3a), $10W.m^{-2}$ with restricted use (alt 3b) and with use of cold aquifer water only.