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Evaluation of the Feasibility of Alternative Energy Sources for Greenhouse Heating

J. L. García; S. De la Plaza; L. M. Navas; R. M. Benavente; L. Luna

Departamento de Ingeniería Rural, Universidad Politécnica de Madrid, E.T.S.I. Agrónomos, 28040, Madrid, Spain

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Four greenhouse heating systems were compared by computer simulation in seven European locations: a conventional fossil-fuel system and three hybrid systems, in which part of the heating demand was covered by solar collectors, a heat pump and a cogeneration system, respectively. Flat solar collectors were found to be of no interest for greenhouse heating. There were possibilities of economic feasibility for heat pumps in northern European countries with electricity/fuel-price ratios (when buying electricity from the grid) of between 2·1 and 3·0 (or lower). Cogeneration systems were found to have the best possibilities, especially in northern European countries with electricity/fuel-price ratios (when selling electricity to the grid) of between 2·3 and 3 (or higher). Heat storage improved the economical performance of the cogeneration systems: life-cycle costs decreased by about 4%. The electricity/fuel-price ratios are calculated with the prices of electricity and fuel which give the same amount of energy.

1. Introduction

The interest in alternative energy sources for greenhouse heating is currently high, owing to the large heating loads and the relatively high price of fossil fuels. Important alternative sources of energy are solar collectors, heat pumps and cogeneration systems.

Although solar energy is available and free of charge, the practical use for greenhouse heating still presents technical and, above all, economic problems. Many systems have been developed but most of them were too expensive for practical use.[1,2] In practice, only passive systems, using transparent polyethylene tubes placed on the soil of the greenhouse, have been installed by some growers.[3] Flat collectors are the most widely used systems for general purposes, but the payback period of these systems seems to be very long when used for green house heating. Seasonal storage of solar energy performs poorly compared with daily storage.[4]

Heat pumps have been studied by many researchers in terms of thermal performance[5] and economic feasibility.[6] The relatively high cost of electricity has usually precluded its use as a fuel for greenhouse heating, but in some cases electric heat pumps have proved to be economically feasible. Due to the high investment costs, a pump has to work for many hours at full capacity. This is only possible when the heat pump supplies the base load as well as a large part of the annual heat consumption.[7] If the heat pump uses a source which varies in temperature with the seasons, it can deliver during mild periods three to four times more heat energy than it uses as electric energy itself; but during periods of extreme cold, both the efficiency of the heat pump and its output capacity decline dramatically.

Cogeneration is considered the most important alternative energy source for greenhouses.[8,9] At present, some Dutch growers use cogeneration units, also called total energy units.[10] Some studies have shown that cogeneration is feasible without connection to the public grid, especially if supplementary lighting is used;[11] but electricity companies are presently required to buy surplus electricity from private cogenerators, and this seems to provide promising alternatives for the greenhouse sector. Cogeneration units in individual holdings may be owned by the grower or by a public utility company. If the grower were the owner, heat and electricity would be used by himself, and part of the electricity might be sold to the public grid. Technically, there are no big problems, but the economic feasibility of the system is as yet not clear.

The object of this study was to determine the economic feasibility of solar collectors, heat pumps and cogeneration systems to heat a simulated greenhouse in different European weather conditions and with different economic frameworks.

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2. Materials and methods

2.1. *Weather model*

Simulations were carried out in seven European locations: Aliartos (Greece), Almería (Spain), Bedford (United Kingdom), Braunschweig (Germany), De Bilt (The Netherlands), Milan (Italy) and Montpellier (France). The monthly average, mean maximum and mean minimum air temperatures of these locations are available.[12] Monthly mean values of solar irradiation on a horizontal surface, data not included in the above publication, were obtained from a commercial database.[13]

Based on these data, hourly values of temperature and solar radiation were calculated for each hour of an average day of each month, with the following assumptions (*Fig. 1*). The daily minimum temperature occurs 1 h before sunrise (for a good adjustment of the curve); the daily maximum temperature occurs 2 h after solar noon; the mean temperature occurs 3 h after sunset; and the temperature profiles from each mentioned point to the next are described with a sine function (three sine curves for three periods each day). The three equations must have common values at their common points.

Hourly values for solar radiation were generated from daily means by assuming that solar radiation versus time of day follows a sine function, taking into account the length of the day.

Similar methods were used previously.[14] The weather data obtained were used to calculate the greenhouse thermal needs. For this reason, the accuracy of the described method for calculating heating demands was checked for Bedford (1972) and Madrid (1995). In these specific years, the hourly data of temperature and radiation measured for the whole year were available; the hourly thermal needs were calculated with actual hourly climatic data and the greenhouse thermal model ($365 \times 24 = 8760$ calculations). The total sum was the annual thermal needs. On the other hand, the monthly average, mean maximum and mean minimum air temperatures and average radiation were calculated from the actual hourly climatic data; these monthly average values were used to generate the hourly values of an average day of each month, with the described method. Then monthly and annual thermal needs were calculated with the data generated and the greenhouse thermal model ($12 \times 24 = 288$ calculations). Results of both procedures were compared.

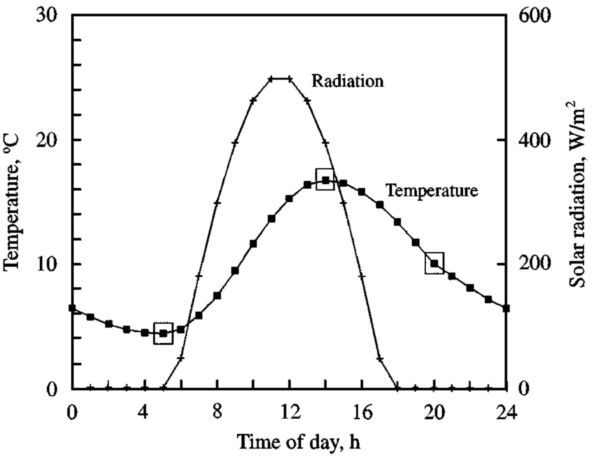

Fig. 1. Generation of weather data. Values of temperature were calculated for each hour of an average day of each month, using the monthly average, mean maximum and mean minimum air temperatures (values in rectangles). The three values were joined by sine functions. Hourly values for solar radiation of the average day of each month were generated from the monthly average by assuming that solar radiation follows a sine function

2.2. *Greenhouse thermal model*

A stepwise steady-state model, in which the time step was 1 h, was used to calculate the thermal needs (H, W/m^2) required in a simulated greenhouse. This type of model is commonly used:[15]

$$H = U(T_{ia} - T_{out}) - b\tau S \tag{1}$$

where U is the greenhouse heat-transfer coefficient in W/K m^2 greenhouse ground area, T_{ia} the temperature setpoint at the hour in question (°C), T_{out} the hourly outside-air temperature (°C), b is the percentage of solar radiation which contributes to sensible heating, τ is the transmissivity of the cover (dimensionless) and S the hourly value of solar radiation on a horizontal surface (W/m^2).

In this study, it was assumed that $U = 8 W/m^2 K$, $T_{ia} = 22°\text{C}$ (day) and 16°C (night), $\tau = 0{\cdot}75$ and $b = 40\%$ (Marsh and Singh[6]). The day and night were defined as hours with $S > 0$ and $S = 0$, respectively. If the calculated heating energy H was negative then H was adjusted to equal zero, since no heating was required under these conditions.

2.3. *Description of the energy systems and operational modes*

Simulations were carried out with four heating systems, a conventional fossil-fuel system and three hybrid systems, in which part of the heating demand was covered by solar collectors, a heat pump and a cogeneration system, respectively.

Average energy prices of 15 European countries in 1995 are available in a Eurostat publication.[16] The electricity price varied from 0·053 (Ireland) to 0·135 ECU/kW h (Germany) for a consumption of between 20 and 1250 MW h/yr. The night consumption of greenhouses can decrease the price since a different tariff is charged for electricity used at night, as compared with that used during the day. The price of natural gas varied from 0·013 (Ireland) to 0·069 ECU/kW h (Denmark) for a consumption of between 35 and 11 625 MW h/yr; the price of heating gas–oil varied from 0·017 (United Kingdom) to 0·068 ECU/kW h (Italy).

As for greenhouse production, Marsh and Singh[6] used prices of 0·032 ECU/kW h for electricity and 0·014 ECU/kW h for fossil fuel (United States, 1994); Meijaard[7] and Van der Velden[9] reported values from 0·006 to 0·014 ECU/kW h for natural gas (The Netherlands, 1989) and Vilarnau[17] indicated values of 0·025 ECU/kW h for gas–oil and 0·024 ECU/kW h for natural gas (Spain, 1994). The average prices used in the present work were 0·06 ECU/kW h for electricity and 0·02 ECU/kW h for fossil fuel.

Equipment prices were obtained from commercial companies and also from the literature.[6,18] For all the systems, mean costs with reference to a greenhouse ground-surface area of 10 000 m^2 were used.

For the basic set of simulations, the conventional fossil-fuel system was based on the following characteristics.

Heater costs: 10 ECU m^2 of greenhouse ground area (except Almería, 5 ECU/m^2)
Maintenance costs: 0·1 ECU/yr m^2 of greenhouse ground area
Fossil fuel costs: 0·02 ECU/kW h
Heater efficiency: 80%

The conventional heater was assumed to be able to cover all the thermal needs of the greenhouse. Almería has much lower energy needs than the rest of the locations, so heater costs were considerably lower because less heating capacity was needed. It is important to note that the same conventional heater was used in the three hybrid systems, since the heater may have to supply the full heating load when any of the supplementary systems are unavailable or the electricity prices are not suitable. Besides, the alternative systems were designed only to cover the base load.

Simulations were carried out with flat collectors, the most usual system for general purposes, with the aim of determining under what conditions these systems would become feasible. Costs were obtained from commercial companies and from the literature. Leigh[19] used a value of 120 ECU/m^2 for collector costs and 480 ECU/GJ for storage costs (United States, 1989); the Commission of the European Communities[20] indicated values from 170 to 280 ECU/m^2 for collector costs in 1994. Total investment must include collectors, storage, pipes and pumping. On the other hand, Santamouris[1] cited values from 0·05 to 0·32 for the ratio collector surface/greenhouse surface. From this information, the following parameters were chosen in our work:

Solar system costs: 380 ECU/m^2 collector = 19 ECU/m^2 of greenhouse ground area
Installed collector surface area: 0·05 m^2 collector/m^2 of greenhouse ground area
Operating costs: 0·25 ECU/yr m^2 of greenhouse ground area

In the model used, the efficiency of the collector (μ) was a simple linear function

$$\mu = a_0 - b_0\,(T_c - T_{out})/S_{col} \qquad (2)$$

where the coefficient a_0 represented the ability to capture and convert solar radiation ($a_0 = 0{\cdot}8$) and b_0 represented the heat losses from collectors ($b_0 = 7$ W/m^2 K); T_c was the mean water temperature of the collectors (estimated as an average value of 30°C); T_{out} was the hourly outside-air temperature (°C) and S_{col} the hourly solar radiation on the inclined surface of the collector (W/m^2). This kind of model is commonly used.[21] The values of the coefficients a_0 and b_0 were supplied by a commercial company; product performance data usually include these values.

On the basis of these parameters, the solar energy (S_E, W h/m^2) collected every hour per m^2 of greenhouse ground area was the following:

$$S_E = 0{\cdot}05 \times 0{\cdot}9[a_0 S_{col} - b_0(T_c - T_{out})] \qquad (3)$$

where 0·05 is the collector surface per m^2 of greenhouse ground area, 0·9 the coefficient used to take into account storage losses of 10% and $[a_0 S_{col} - b_0(T_c - T_{out})]$ is the collected energy per m^2 of collector surface, according to Eqn (2).

The hourly solar radiation on an inclined surface (S_{col}) was calculated on the basis of the hourly solar radiation on a horizontal surface (S) using a conversion parameter.[22] The inclination of the collectors was the latitude plus 15°; this inclination is typical for collectors used for heating. When the calculated collected S_E was negative, S_E was adjusted to equal zero. It was assumed that a heat-storage system, included in the cost, would allow the energy stored in the day to be used during the night.

Heat pump prices were obtained from commercial companies and also from the literature. Marsh and Singh[6] used a value of 250 ECU/kW for heat pump costs (United States, 1994); Meijaard[7] indicated values from 4·8 to 9·6 ECU/m^2 glass for the same parameter (The Netherlands, 1989). The heat pump characteristics considered in the analysis were as follows:

Heat pump costs:	250 ECU/kW = 5 ECU/m^2 of greenhouse ground area
Maintenance costs:	0·15 ECU/yr m^2 of greenhouse ground area
Mean electricity costs (buying from the grid):	0·06 ECU/kW h
Nominal heating capacity:	0·02 kW/m^2 of greenhouse ground area
Actual heating capacity:	$2\,H_P/3 + H_P T_{out}/48$ (if $T_{out} < 16$) H_P (if $T_{out} > 16$)

where T_{out} is the hourly outside air temperature, °C and H_P the nominal heating capacity, kW/m^2.

Using these equations, the actual heating capacity is the nominal heating capacity H_P when the outside-air temperature is 16°C or higher, and it is $2H_P/3$ when the outside-air temperature is 0°C. With air temperatures from 16 to 0°C, the actual heating capacity takes intermediate values according to the linear function. This empirical relationship is typical in commercial heat pumps with sources with varying temperature.[6] It was assumed that the outside air was the heat source of the heat pump; the outside-air temperature T_{out} was obtained from the weather model,

Coefficient of performance (COP) $2{\cdot}4 + 0{\cdot}05\ T_{out}$

depended also on the outside-air temperature. Using this equation, the value of the COP was 3·2 when the outside-air temperature was 16°C and 2·4 with 0°C. This type of behaviour has been previously reported.[6]

In the hours in which the heat pump did not work at full capacity, COP was considered to be lower,[23] since the switching on and off process decreased the efficiency of the system.

The simulation established that whenever heating was needed, the heat pump always worked covering the base load, except when the outside temperature decreased below 0°C. Under these conditions, the COP was considered too low to be of interest, and all the heating needs were covered by the conventional system.

Cogeneration costs were obtained from commercial companies and also from the literature. Meijaard[7] and Verhaegh and Vernooy[10] indicated values from 480 to 720 ECU/kW for the investment costs (The Netherlands, 1989); Bailey and Ellis[11] reported that a cogeneration unit could generate electricity with an efficiency of 27% and provide 53% of the energy as recoverable heat. The characteristics of the cogeneration system established in the analysis were the following:

Cost of the cogeneration unit:	640 ECU/kW = 6·4 ECU/m^2 of greenhouse ground area
Maintenance costs:	0·3ECU/yr m^2 of greenhouse ground area
Fossil-fuel costs:	0·02 ECU/kW h
Mean electricity costs: (selling to the grid)	0·05 ECU/kW h
Nominal electrical output:	0·01 kW/m^2 of greenhouse ground area
Efficiency for electrical production:	27%
Efficiency for heat production	53%

The grower is assumed to be the owner of the system, and all the electricity produced is sold to the grid. The assumed electricity price received by the grower is higher than the usual price with conventional generation, since many countries have special conditions for the electricity produced by cogeneration.

The operating mode would depend on the system of tariff rates. In some systems, a basic price is applied except for peak-load hours, when the rate is increased. Under these conditions, it is usual to produce electricity continuously, not only in peak-load hours. The simulation established that the cogeneration system worked 11 months without interruption and stopped only for maintenance. Therefore, the operating mode was independent of the heat load; heat was produced continuously and used in the greenhouse when heat was required.

Heat-storage systems were not used in the basic set of simulations. However, daily storage can improve energy management in periods in which there are thermal needs at night and not in the day. An additional set of simulations was carried out with heat storage, using a water tank of 10 l/m^2 of greenhouse ground area (with a delivery capacity of about 850 kJ/d m^2 greenhouse) at a cost of 2·5 ECU/m^2 of greenhouse ground area.

2.4. *Energy and cost analysis*

Using all the parameters mentioned, the total thermal needs, the part covered by the alternative energy systems and the life-cycle costs of the four heating systems were calculated for each location. Life-cycle cost is the sum of all the costs associated with an energy system (in this case, investment, fuel, electricity and maintenance) during its lifetime at today's prices. The financial parameters used in this analysis were the average inflation rate (5%), market investment rate (10%) and lifetime (15 yr) with no salvage value at the end of the 15 yr.

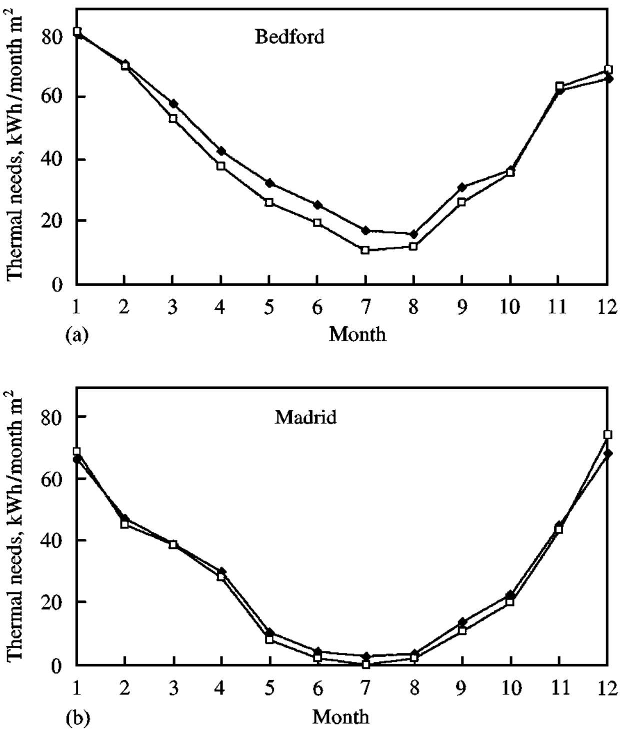

Fig. 2. Thermal needs (kWh/month m² of greenhouse ground area) calculated from hourly climate data (–◆–) and from monthly values (–□–) in (a) Bedford (1972) and (b) Madrid (1995). Simulations with monthly values showed lower annual thermal needs than calculations with hourly climate data (a difference of 6·4% in Bedford and of 3·4% in Madrid)

The life-cycle costs obtained were highly dependent on certain parameters (for example, fuel or electricity prices) so an additional analysis of break-even points was performed. Break-even points are the fossil fuel prices which would make no difference to life-cycle costs when conventional or hybrid systems are used. They were calculated for each location and with various electricity prices.

3. Results and discussion

3.1. *Weather model*

Thermal needs calculated from hourly climatic data were compared with thermal needs obtained from monthly values in Bedford (1972) and Madrid (1995), as shown in *Fig. 2*. Simulations with monthly values showed lower annual thermal needs than calculations with hourly climatic data; annual differences were 6·4 and 3·4%, respectively. The accuracy was considered appropriate for simulation studies. The advantage of using monthly values was that only four values were required every month instead of the 1440 necessary when hourly values are used.

3.2. *Energy and cost analysis*

The thermal needs of the seven European locations were calculated with monthly climatic data and are given in *Fig. 3*. The percentage of energy covered by the alternative systems is shown in Table 1. In northern European climates, heat pumps and cogeneration systems covered higher heat requirements in absolute values, since heating was also necessary in the summer. For this reason, such alternative systems, designed to cover the base load, proved to be more feasible in northern than in southern climates.

For each European location, the life-cycle costs of conventional and hybrid systems are shown in Table 1 and the break-even points in Table 2. The economic parameters of the solar system studied showed that it is of no interest at present: flat collectors, the system most widely used, will only be feasible in greenhouse heating when fuel prices are three or four times higher than today (Table 2, solar system column; reference fuel price, 0·02 ECU/kW h). This result points to the fact that other systems should be used instead of flat collectors; some of them, such as soil polyethylene tubes, seem to be feasible. However, the analysis with flat collectors shows the economic problems of using solar energy for greenhouse heating.

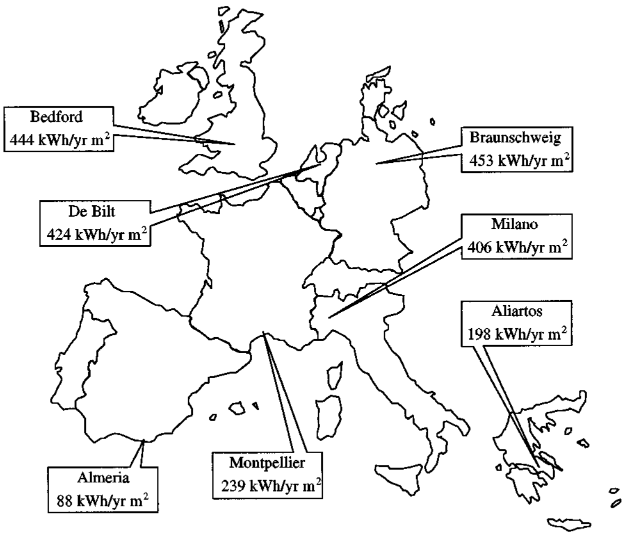

Fig. 3. Annual energy needs (kWh/yr m² of greenhouse ground area) calculated for a standard greenhouse in seven European locations. The greenhouse parameters used in the simulation were the following: greenhouse heat-transfer coefficient, $U = 8$ W/K m² greenhouse ground area; daily and nightly temperature setpoints, $T_{ia} = 22$ and 16°C, respectively; percentage of solar radiation contributing to sensible heating, $b = 40\%$; transmissivity of the cover, $\tau = 0{\cdot}75$. Simulations performed with monthly climatic data

Table 1

Energy needs (E_n, %) covered by the alternative energy systems, using per m^2 of greenhouse ground area 0·05 m^2 of collectors (solar system), 0·02 kW of heating capacity (heat pump) and 0·01 kW of electrical output (cogeneration), and life-cycle costs (LCC) of the conventional and hybrid systems. Absolute values of energy needs are shown in *Fig. 3*

		Solar		*Heat pump*		*Cogeneration*	
Conventional	*LCC ECU/m^2*	*E_n %*	*LCC ECU/m^2*	*E_n %*	*LCC ECU/m^2*	*E_n %*	*LCC ECU/m^2*
Aliartos	65·7	13	80·6	32	69·5	37	78·5
Almeria	30·4	26	45·8	49	35·0	53	50·5
Bedford	133·8	4	150·4	23	136·8	28	133·0
Braunschweig	136·3	5	151·6	21	139·6	26	137·0
De Bilt	128·2	5	144·8	23	131·2	28	128·5
Milano	123·3	4	139·9	16	127·5	23	130·6
Montpellier	77·0	10	92·3	27	81·2	31	89·4

The economic feasibility of the heat pump could not be established at any location. In the basic simulation, the life-cycle costs of the heat pump were higher than the costs of the conventional system at all seven locations (Table 1, conventional system and heat pump columns). Obviously, the feasibility depended on the electricity/fuel price ratio, with a value of three in the basic analysis. Table 2 (heat pump column) shows that the system may be of interest in Bedford, Braunschweig and De Bilt with electricity/fuel price ratios of between 2·1 and 3·0 (or lower). The electricity/fuel price ratios are energy-based; they are calculated with the prices of electricity and fuel which give the same amount of energy. It has to be pointed out that the COP was always higher than 2·4 in the simulation since the heat pump is switched off when the outside temperature is lower than 0°C. If this action is not taken, the reduced COP renders the system uneconomical.

As regards the cogeneration system studied, its life-cycle costs were virtually identical to costs of the conventional system in Bedford (Table 1, conventional system and heat pump columns) and close to those in De Bilt and Braunschweig. Again the feasibility greatly depends on the electricity/fuel price ratio, in this case for selling electricity to the grid. The system proved to be of interest in Bedford, Braunschweig and De Bilt with electricity/fuel price ratios of between 2·3 and 3 (or higher). The heat-storage systems improved their performance (*Fig. 4*); when heat storage was used in De Bilt, the annual energy substitution increased from 28 to 35% and life-cycle costs decreased from 128·5 to 123·0 ECU/m^2. The analysis showed that in some cases heat storage can make cogeneration feasible.

The analysis was performed with constant values of heat transfer coefficient (U) and contribution of the solar radiation (b). The use of variable values increased or

Table 2

Fossil-fuel prices (ECU/kWh) with no difference in life-cycle costs when using conventional or hybrid systems (break-even points), calculated for the described solar collectors, heat pump and cogeneration system, using different electricity prices. The alternative systems are feasible if the present fuel price is higher than the break-even point (solar and heat pump) or lower than the break-even point (cogeneration). Prices are for electricity bought from the grid in the case of the heat pump, and for electricity sold to the grid in the case of cogeneration

		Heat pump			*Cogeneration*		
		Electricity price, ECU/kWh			*Electricity price, ECU/kWh*		
	Solar	*0·03*	*0·06*	*0·10*	*0·03*	*0·05*	*0·07*
Aliartos	0·061	0·016	0·024	0·036	0·008	0·015	0·022
Almeria	0·068	0·019	0·027	0·038	0·007	0·013	0·020
Bedford	0·084	0·013	0·022	0·033	0·010	0·021	0·031
Braunschweig	0·067	0·014	0·023	0·034	0·010	0·020	0·029
De Bilt	0·078	0·013	0·022	0·034	0·010	0·020	0·030
Milano	0·085	0·016	0·025	0·037	0·009	0·017	0·025
Montpellier	0·065	0·016	0·025	0·036	0·008	0·015	0·023

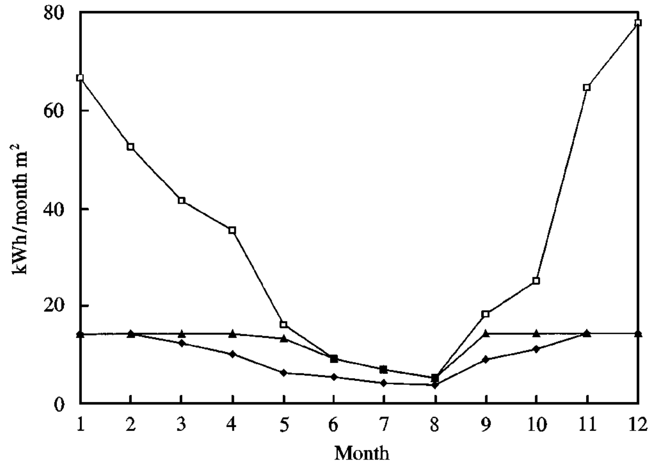

Fig. 4. Energy substitution achieved with a cogeneration system (using a nominal electrical output of 0·01 kW/m² of greenhouse ground area) with and without energy storage. Simulation performed in De Bilt (The Netherlands) using a water tank of 10 l/m² ground area (with a delivery capacity of about 836 kJ/d m² ground area) as a storage system, with a cost of 2·5 ECU/m² ground area. When storage is used, annual energy substitution increased from 28 to 35%, and life-cycle costs decreased from 128·5 to 123·0 ECU/m². Thermal needs, −□−; substitution with storage, −▲−; substitution without storage, −◆−

decreased the heating needs, with slight changes in the cost analysis. However, the main factors involved were the energy prices and the number of months with functioning of the heating systems (depending on climate variables); in southern countries, with heating demands only in winter, systems with high investments are not feasible.

On the other hand, the cost analysis was made with average prices for all locations. The results were expressed as electricity/fuel price ratios to be useful as a general guide in comparing a number of different locations. To improve accuracy, the method should be used with values appropriate to specific localities.

4. Conclusions

1. Greenhouse energy needs can be calculated using monthly climatic data instead of hourly data. The resulting simulation error was around 5% and this was considered to be acceptable for such studies.
2. The heat pump and cogeneration systems studied, designed to cover the base load, proved to be more feasible in northern than in southern European climates, since heating was also necessary in the summer.
3. Flat solar collectors were economically feasible in greenhouse heating only with fuel prices three or four times higher than today. Cheaper systems than flat-plate solar collectors are needed.
4. With average European prices, heat pumps were found not to be feasible in the seven locations studied. There was a possibility for them in northern European countries with electricity/fuel price ratios of between 2·1 and 3·0 (or lower).
5. With average European prices, cogeneration systems were found to be feasible in one of the locations studied (Bedford) and close to feasibility in two other locations (Braunschweig and De Bilt). The best possibilities are in northern European countries with electricity/fuel price ratios of between 2·3 and 3 (or higher). Heat storage improved the economic performance of the system: life-cycle costs decreased about 4%.

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References

[1] **Santamouris M I** Active solar agricultural greenhouses. The state of the art. International Journal of Solar Energy, 1993, **14,** 19–32

[2] **Von Zabeltitz C H R** Effective use of renewable energies for greenhouse heating. Renewable Energy, 1994, **5**(I), 479–485

[3] **Mavrogianopoulos G N; Kyritsis S** Analysis and performance of a greenhouse with water filled passive solar sleeves. Agricultural and Forest Meteorology, 1993, **65,** 47–61

[4] **Kurata K; Takakura T** Underground storage of solar energy for greenhouse heating. II. Comparison of seasonal and daily storage systems. Transactions of the ASAE, 1991, **34**(5), 2181–2186

[5] **Kozai T** Thermal performance of an oil engine driven heat-pump for greenhouse heating. Journal of Agricultural Engineering Research, 1986, **35,** 25–37

[6] **Marsh L S; Singh S** Economics of greenhouse heating with a mine air-assisted heat pump. Transactions of the ASAE, 1994, **37**(6), 1959–1963

[7] **Meijaard I D** The economic evaluation of energy reduction and substitution techniques. Acta Horticulturae, 1989, **245,** 520–529

[8] **Van der Klaauw D** Masterplan for combined heat and power in greenhouse horticulture in The Netherlands. Acta Horticulturae, 1992, **312,** 45–53

[9] **Van der Velden N J A** Economic aspects of greenhouse horticulture; energy efficiency and CO_2 emission in the Dutch glasshouse industry. Acta Horticulturae, 1992, **312,** 87–94

[10] **Verhaegh A P; Vernooy C J M** Electricity costs of a self producing TE-installation. Acta Horticulturae, 1989, **245,** 587–589

[11] **Bailey B J; Ellis R G** The potential for using combined heat and power (CHP) in greenhouses. Divisional note, DN 1523, AFRC Institute of Engineering Research, Silsoe, May 1989

[12] **Statistical Office of the European Communities** Eurostat Publication on Agricultural Meteorology, 1990

[13] **Censolar Studies Group** International H-World^R Database. Censolar, 1993

[14] **Marsh L S; Albright L D** Economically optimum day temperatures for greenhouse hydroponic lettuce production. Part I: a computer model. Transactions of the ASAE, 1991, **34**(2), 550–556

[15] **Bakker J C; Bot G P A; Challa H; Van de Braak N J** Greenhouse Climate Control. Wageningen: Wageningen Pers, 1995

[16] **Statistical Office of the European Communities** Eurostat Publication on Energy Prices, 1995

[17] **Vilarnau A** Energía sí, pero más limpia (Cleaner energy). Horticultura, 1994, **99,** 23–26

[18] **Bredenbeck H** The use of waste heat from a power plant for greenhouse heating in commercial application in Germany. Acta Horticulturae, 1992, **312,** 29–35

[19] **Leigh R W** Optimal design of solar energy systems with uncertain data. Journal of Solar Energy Engineering, 1989, **111,** 10–15

[20] **Commission of the European Communities** The European-Renewable Energy Study. Altener programme, DG XVII, 1994

[21] **Bourgues B; Rabl A; Leide B; Carvalho M J; Collares-Pereira M** Accuracy of the European solar water heater test procedure. Part 1: measurement errors and parameter estimates. Solar Energy, 1991, **47**(1), 1–16

[22] **Duffie J A; Beckman W A** Solar engineering of thermal processes. New York: Wiley Interscience, 1991

[23] **Parken W H; Kelly G E; Didion D A** Methods of testing, rating and estimating the seasonal heating performance of heat pumps. National Bureau of Standards, US Department of Commerce, Washington, DC, 1980