International Journal of Thermal Sciences 49 (2010) 202–208

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Evaluation of a heat pump system for greenhouse heating

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ARTICLE INFO

Article history:
Received 21 July 2006
Received in revised form
3 July 2009
Accepted 7 July 2009
Available online 30 July 2009

Keywords:
Greenhouse heating
Heat pump
Energy
Greenhouse gas emissions

ABSTRACT

Greenhouse heating costs for some commercial growers in southern Australia are now a significant production cost. This is particularly the case for those operators who installed heating systems using liquefied petroleum gas (LPG) when this fuel was relatively inexpensive. Heat pump systems used in various configurations have been suggested as an option for reducing energy use and costs for greenhouse heating, particularly if off-peak electricity is used. This paper investigates the financial and environmental viability of an air-to-water heat pump system for a 4000 m^2 greenhouse, located 120 km north of Melbourne, Victoria. The simulation software, TRNSYS, was used to predict the performance of the system. The heat pump system was found to have a simple payback period of approximately six years and reduce LPG consumption by 16%. Greenhouse gas emissions were 3% higher using the heat pump system, compared to the existing LPG boiler.

1. Introduction

In winter in southern Victoria, Australia, the weather can often be cool and cloudy. The long-term average minimum temperature in Melbourne, its capital city, for the months of June, July and August is 7.0 °C. As a result, in this location heating is an essential requirement for the year-round efficient production of certain greenhouse crops such as roses and tomatoes. For some years now, many growers who were not connected to natural gas pipelines have used liquefied petroleum gas (LPG) as an alternative source of heating energy. Its low price, compared to other fuels such as oil, made LPG financially attractive. However, in recent years the price of LPG has risen substantially. For example, the price rose from approximately AU \$0.26 L^{-1} in 1995 to over AU \$0.40 L^{-1} in 2000 i.e. over 50% [1] and heating now represents a significant component of production costs for some growers.

Heat pumps can offer the opportunity to reduce heating costs because of their ability to efficiently convert the heat in a low-grade energy source into heat at a more useful temperature. There are a number of possible configurations using heat pump technology and previous researchers have tested some of these systems [2–6]. This paper describes the evaluation of an air-to-water heat pump system. The overall objective of the heat pump system would be to reduce the heating costs, while at the same time not increasing greenhouse gas emissions. This paper begins with a brief review of previous attempts to use heat pump technology for greenhouse heating, both in Australia and elsewhere. A proposed installation of a heat pump is then analysed to determine the energy savings, together with the environmental and financial implications, of such a system.

2. Heat pumps for greenhouse heating

The high cost of fuels and inherent efficiency of heat pumps has resulted in a number of studies to use this technology to reduce the heating costs for greenhouses. Twenty years ago, a theoretical study in the UK investigated the effect of using a heat pump to control the relative humidity of the air within a greenhouse [2]. Excessive levels of humidity can be a problem for growers and can arise when some energy conservation measures such as reducing infiltration are applied to greenhouses. The usual method of reducing humidity is to increase ventilation levels but this increases heating costs. The study by Bailey found that if a heat pump was used to dehumidify the greenhouse air overall energy consumption (greenhouse and heat pump) was reduced by 30%.

Kozai [3] used ground water at 14 °C as the low-grade energy source for an 87 kW water-to-water heat pump system used to heat a 333 m^2 commercial glasshouse. An overnight minimum air temperature of 12 °C was maintained in the single skin PVC covered greenhouse used for carnation production. With a COP range of 1.76–2.16, fuel consumption was halved. Although no financial analysis was presented in this study, the paper reports that by 1985, 30 heat pumps were in use in commercial greenhouses in Japan indicating that local growers found the technology financially competitive.

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doi:10.1016/j.ijthermalsci.2009.07.002

Nomenclature

A_c	glazing area (m^2)
A_g	floor area of greenhouse (m^2)
D_L	daytime heat load, whenever heat losses exceed solar gains (W)
F_1	factor to allow for solar radiation required for photosynthesis and conducted through floor (0.91)
F_2	factor to allow for reflection of internal solar radiation by cover (1.04 for double glazing)
G_o	horizontal outside solar radiation ($W\,m^{-2}$)
m	heat pump mass flow rate of water ($kg\,s^{-1}$); range ($0.6\,kg\,s^{-1} < m < 1.6\,kg\,s^{-1}$)
N_L	nightime heat load (W)
t	time (h)
t_i	heat pump inlet water temperature (°C); range $30\,°C < t_i < 55\,°C$
t_a	ambient air temperature (°C); range $-10\,°C < t_a < 25\,°C$
Ta_{id}	daytime set point greenhouse air temperature (K)
Ta_{in}	night-time set point greenhouse air temperature (K)
Ta_{od}	average ambient air temperature during day (K)
Ta_{on}	average ambient air temperature during night (K)
U'	overall heat loss factor ($W\,m^{-2}\,K^{-1}$) (*5.3 for double layer polyethylene in the daytime and 3.8 for double layer polyethylene combined with a thermal screen at night*)
τ	glazing material solar transmittance (*0.6 for double glazing*)
α	absorptance of internal surfaces of greenhouse (*0.84*)

In 1989, an experimental study of a solar-assisted heat pump system was carried out at the Victorian College of Horticulture at Burnley, Melbourne [5]. Unglazed swimming pool solar collectors (36 m^2) mounted inside and outside the greenhouse were used to generate a small rise in ambient water level temperatures. This warmed water was then stored in an externally mounted low temperature heat store. A 6.5 kW water-to-water heat pump then used this source of low-grade energy to boost the outlet water temperature to heat a high temperature water store within the greenhouse itself. Although it was found that 34% of the energy was delivered to the bench heating system during the peak tariff period for only 19% of the heating power consumption, the cost savings did not justify the additional capital cost of the heat pump system.

A much larger (304 kW) solar heat pump system was installed in commercial pot plant nursery in the Netherlands [6]. In addition to the heat pump system, heat was recovered from the air dehumidifiers installed in the greenhouse and from the gas engine used to supply the company's electricity needs. Prior to the installation of the system, a conventional gas-fired boiler was used for heating. After one year of operation, the system achieved gas and electricity savings of 4.6 m^3 and 6 kWh per m^2 of greenhouse floor area per year respectively. The simple payback period, however, was 12.6 years.

Garcia et al. [4] conducted a theoretical study of several heating technologies, including an air-to-air heat pump for greenhouse heating in seven European locations. The economic feasibility of the heat pump could not be established for any location because the life cycle costs of the technology were too high. Feasibility depended on the electricity/fuel price ratio and a value of 3.0 was used in the basic analysis. The heat pump was likely to be more feasible in northern rather than in southern European climates because heating was required in summer as well as winter.

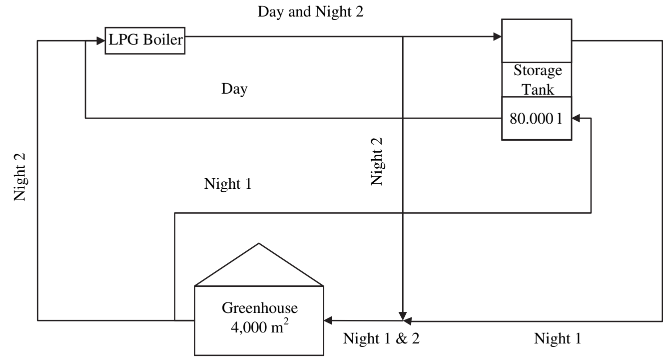

Fig. 1. Schematic arrangement of current heating system.

3. Current heating system

The commercial greenhouse in this study is located near Seymour, approximately 120 km north of Melbourne, the capital of Victoria. The owner had been investigating ways to reduce the cost of heating this 4000 m^2 greenhouse. The present heating system uses LPG and the current high fuel cost is preventing the owner from expanding his business operation. The LPG-fired boiler currently produces hot water, which is pumped when required through pipes on the floor of the greenhouse. In addition to providing heat to the greenhouse at night, the 1 MW boiler is also operated for approximately five hours per day (9am to 2pm) to produce carbon dioxide for plant growth enhancement. The hot water produced during the day is stored in an 80-m^3 uninsulated concrete storage tank. This hot water is then used for greenhouse heating at night when the demand arises. If there is insufficient heat within the storage tank, then the boiler is again used and hot water is supplied directly to the greenhouse (Fig. 1). The current system is designed to provide heat to the greenhouse during the daytime and at night if the temperature of the air in the greenhouse falls below 20 °C and 15 °C respectively. To reduce heating energy use, the greenhouse is covered with two layers of polyethylene film, inflated to provide an insulating air gap, and uses a thermal screen at night.

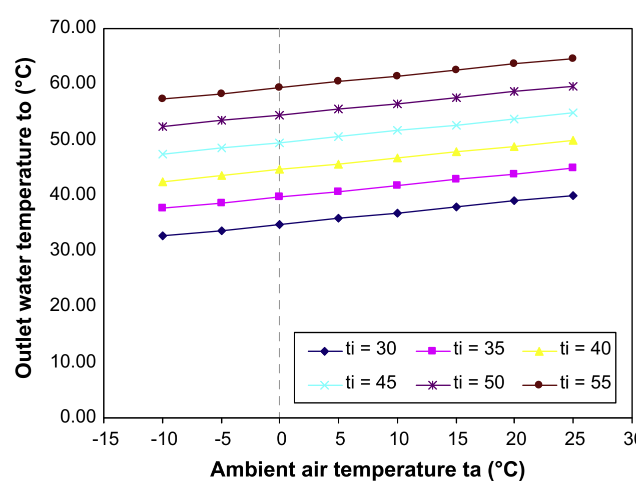

Fig. 2. Outlet water temperature (to) versus ambient air temperature (t_a).

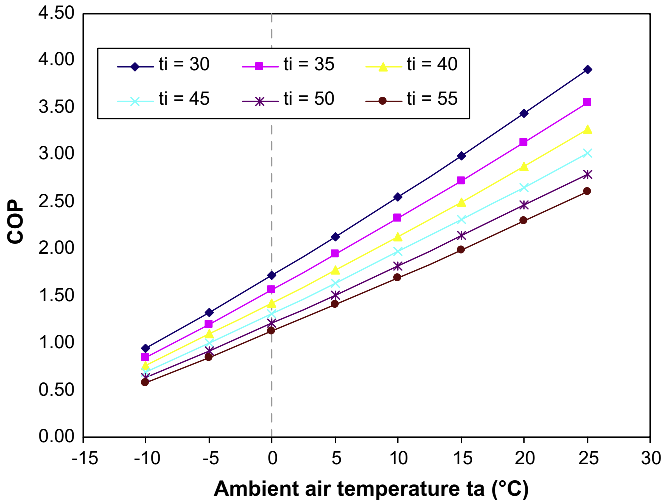

Fig. 3. COP versus ambient air temperature (t_a).

4. Heat pump system option

The heat pump configuration considered in this evaluation has two 32 kW air-to-water heat pumps to provide the additional heat required at night, if there is insufficient heat within the concrete storage tank. The heat pumps are to operate between 11pm and 7am to take advantage of off-peak electricity rates and thus hopefully provide a financially attractive alternative form of heating to the LPG. No scheduling of two heat pumps were considered since they are running full capacity most of the time. The outlet water temperature (t_o) in °C and electricity (E) in kWh consumed by the compressors were calculated using Equations (1) and (2), which are representative of the heat pump chosen for this application. It should be noted that these equations were derived from the manufacturer's measured data of a heat pump which is currently commercially available.

$$t_o = 9.37614 + (0.98392 \times t_i) + (0.208931 \times (t_a + 10)) - (5.24839 \times m) \quad (1)$$

$$E = (-2.15712 + (0.222835 \times t_i) - (0.0428957 \times (t_a + 10)) + (8.18669 \times m)) \times t \quad (2)$$

Figs. 2 and 3 show how the system outlet water temperature and the heat pump coefficient of performance (COP) vary with ambient air temperature and inlet water temperature respectively.

Table 2
Seasonal adjustments (M–S) to Melbourne TMY data used for model validation.

Use	Summer	Autumn	Winter	Spring
	January February December	March April May	June July August	September October November
Daytime load calculations	−3.0 °C	−0.9 °C	1.1 °C	−0.8 °C
Night-time load calculations	1.5 °C	8.0 °C	5.0 °C	9.0 °C

5. Methodology

The methodology adopted for the evaluation was as follows:

- Actual LPG usage between 2000 and 2002 was analysed. A total of 28 months of data over these three years was used to determine a monthly profile of gas usage.
- The differences between the local climate and Melbourne were determined so that the hourly Typical Meteorological Year (TMY) climatic data input file for Melbourne to be used in the simulations could be appropriately modified.
- The performance of the existing system was simulated and a comparison made between the actual and predicted gas consumption. The model was calibrated to produce credible predictions.
- The heat pump system was then incorporated into the model to determine the reduction in gas usage and increase in electricity usage resulting from its operation.
- The costs and carbon dioxide emissions associated with the original system and the proposed system were calculated and compared.

6. TRNSYS simulations

The computer simulation tool used in this study was TRNSYS (2000) [7]. This software was launched nearly 30 years ago and is generally recognised as the benchmark program for the dynamic simulation of solar energy systems. Over 20 upgrades of the program have occurred to the present version. This particular simulation model used the following standard TRNSYS subroutines: Types 9 and 16 to read and process climatic data; Type 14 to model the three controllers; Type 4 for the stratified water tank; and Type 25 as an output device. Fifty equations were inserted into the main TRNSYS deck file to adjust climatic data and flow rates, calculate heating loads and heat pump output, and perform various other simulation functions. The following assumptions were made in order to complete the simulations:

- the surface to volume ratio of the greenhouse was 1.2.
- the water flow rate in the heat delivery circuit was 35 640 kg h^{-1}. At a supply temperature of 55 °C, the minimum

Table 1
Long-term maximum and minimum temperatures for Melbourne and Seymour.

Melbourne	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Max Temp (°C)	25.9	26	24.1	20.6	17.1	14.3	13.7	15.1	17.2	19.7	21.8	24.1	20
Min Temp (°C)	15.1	15.5	14.1	11.8	9.5	7.2	6.5	7.4	8.7	10.3	12	13.7	11
Average	***20.5***	***20.8***	***19.1***	***16.2***	***13.3***	***10.8***	***10.1***	***11.3***	***13***	***15***	***16.9***	***18.9***	***15.5***
Seymour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Max Temp (°C)	29	29.3	26.2	21.4	16.6	13.3	12.3	14.1	16.7	20.4	24.2	26.8	20.9
Min Temp (°C)	13.7	14.2	12.4	8.8	6.2	3.8	3	4.2	5.5	7.4	9.8	11.9	8.4
Average	***21.4***	***21.8***	***19.3***	***15.1***	***11.4***	***8.55***	***7.65***	***9.15***	***11.1***	***13.9***	***17***	***19.4***	***14.7***
'Average' Diffs (M–S)	−0.9	−1.0	−0.2	1.1	1.9	2.2	2.5	2.1	1.9	1.1	−0.1	−0.5	0.9
Max Diffs (M–S)	−3.1	−3.3	−2.1	−0.8	0.5	1.0	1.4	1.0	0.5	−0.7	−2.4	−2.7	−0.9
Min Diffs (M–S)	1.4	1.3	1.7	3.0	3.3	3.4	3.5	3.2	3.2	2.9	2.2	1.8	2.6

Table 3
Monthly consumption of gas (litres) between 2000 and 2002.

Month	Use-2000	Use-2001	Use-2002	Average	Revised Ave
January		12 598	11 740	12 169	12 169
February		5976	7527	6752	11 634
March		13 602	11 900	12 751	12 751
April		25 496	13 934	19 715	19 715
May		24 353	21 199	22 776	22 776
June	13 129	20 902	25 711	19 914	23 307
July	11 001	7942	23 921	14 288	23 921
August	31 416	21 493	27 115	26 675	26 675
September	28 180	18 003	22 344	22 842	22 842
October	27 035	22 324		24 680	24 680
November	16 205	30 858		23 531	23 531
December	15 500	16 462		15 981	15 981
Total		220 011		222 075	239 982

flow rate recommended [8] is 0.045 l per second per kilowatt of heating. A design heating capacity of 220 kW was calculated for this greenhouse. The flow rate figure used represents 94% of pump specification.

- the temperature of the water returning to the tank from the greenhouse was 10 °C below the supply temperature. At a supply temperature of 55 °C, this temperature drop is slightly greater than desirable and could lead to uneven temperatures in the greenhouse. It is based, however, on the conditions produced by the existing heating system.
- the water flow rate is reduced proportionally, depending on the load and temperature of the water in the tank, to meet the load. In practice, the pump would be turned "off" once sufficient heat had been delivered to the greenhouse.
- for heating load calculations, "daytime" was defined as the hours between 9am and 6pm and "night-time" as the remaining hours.
- the boiler was set to operate between 9am and 2pm every day for CO_2 production. The output of the boiler was fixed to consume approximately 80 l of gas per hour at 90% efficiency in summer.
- the boiler efficiency was assumed to be 90% in summer, 80% in spring and autumn, and 70% in winter. This variation takes account of the changes in inlet water temperature and variations in boiler heat losses. It should be noted that the seasonal efficiency of a boiler can vary considerably depending on type, load and climate.
- the water flow rate from the boiler to the storage tank in the daytime was 26 667 kg h^{-1}.
- the heat pump operation was restricted to the hours between 11pm and 7am on weekdays and at any hour on the weekends, except when the boiler was in use for CO_2 production.
- heat pump operation was also controlled by the temperature of the water at the bottom of the tank and was allowed to operate if this falls below a supply temperature of 55 °C during off-peak hours. The temperature of the water at the top of the tank is normally used to control a conventional (in-line) auxiliary heating system. The heat pump, however, operates in parallel with the storage tank and has a much lower heating rate than a conventional auxiliary heater. Using the temperature of the top level may mean that much of the water is below the supply temperature and then more gas will be consumed if there is a sustained high (load) demand which the heat pump is unable meet. If the bottom level temperature controls the heat pump, then the system has a greater chance of meeting the load. Simulations indicated that gas savings increased by 3.9% by using the bottom water layer temperature for control purposes.
- the heat pump water mass flow rate was fixed at 4241 kg h^{-1}, which is typical for the heat pump chosen.
- the concrete storage tank was assumed to be stratified with four layers at varying temperatures.
- the concrete tank was insulated for the heat pump simulations, with a loss coefficient of 0.42 W m^{-2} K^{-1}, because an insulated tank was assumed to be part of any heat pump system installation. Simulations indicated that annual gas savings of 1.4% or 3000 l of gas (value US $900) would be achieved by insulating the tank. The heat loss coefficient was doubled when modelling the current system to account for the increased heat losses from an uninsulated tank.

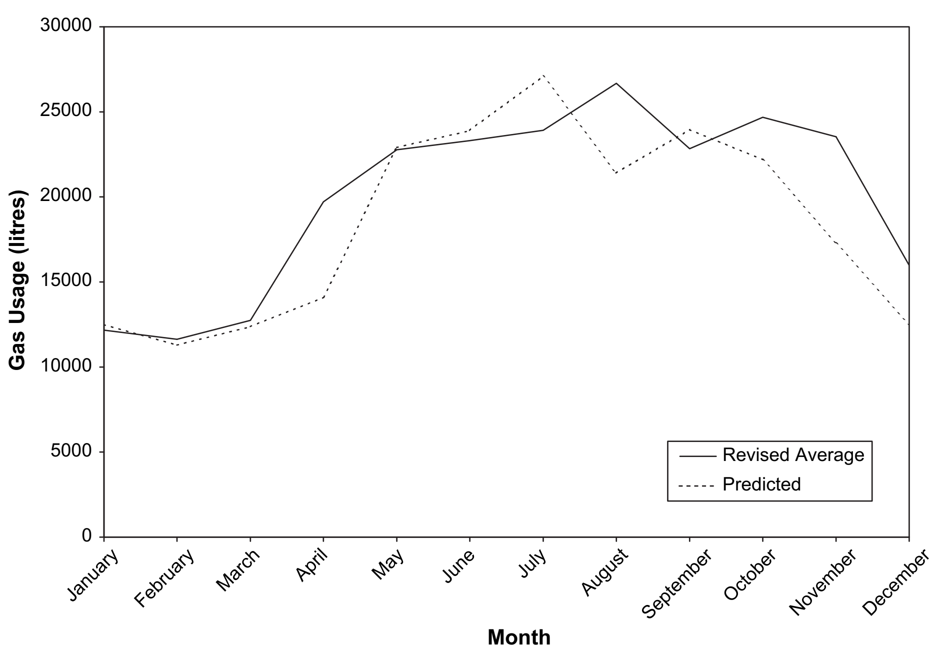

Fig. 4. Revised average and predicted gas use comparison using existing boiler system.

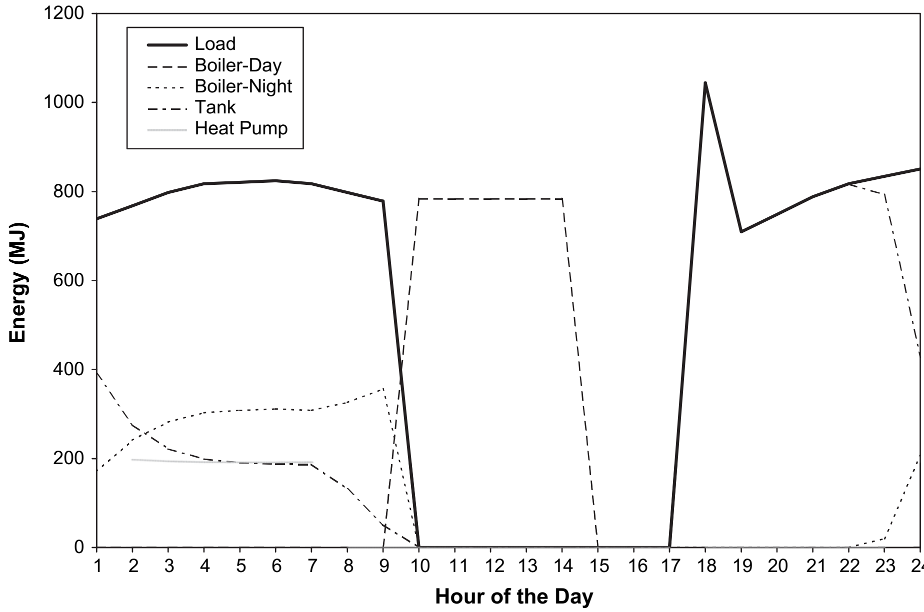

Fig. 5. Contributions to heating load from various system components in winter.

- a heat transfer efficiency of 70% was assumed between the boiler, storage tank and the greenhouse to account for heat losses in pipework etc. Long term experimental data from a solar industrial process heating system with insulated tank and pipe work, boiler and solar collectors indicated that utilization efficiency i.e. how much of the energy stored in the tank was usefully used was 71% [10].

The modified TMY data file was used to determine the daytime (D_L) and night-time (N_L) hourly heating loads using the following equations and parameters suggested by Garzoli [9].

$$D_L = \tau\alpha A_g G_o F_1 F_2 - U'A_c(Ta_{id} - Ta_{od}) \quad (3)$$

$$N_L = U'A_c(Ta_{in} - Ta_{on}) \quad (4)$$

In order to calculate the financial and greenhouse gas emissions of the existing and proposed systems the following costs and coefficients were used:

- gas cost (at time of evaluation) – 30 US cents per litre
- gross gas heating value – 25.5 MJ per litre (DRE, 1985) [11]
- electricity costs: peak 12.59 US cents per kWh and off-peak 5.27 cents per kWh
- full fuel cycle greenhouse gas emission factors used:
  - LPG (non transport) – 64.2 kg $CO_{2\text{-}e}$ GJ^{-1};
  - electricity in Victoria – 1.44 kg $CO_{2\text{-}e}$ kWh^{-1}

The full fuel cycle emission factor is the sum of the direct emission factor for combustion and the indirect emission factor for fuel extraction and line loss (transmission and distribution emissions). Detailed calculations may be found in [12]. The values of all the adjusted parameters are provided in the Nomenclature section.

7. Results

The results from the various stages of the evaluation, including climatic data comparison, gas usage predictions and the final comparison between the existing boiler arrangement and the proposed heat pump system are presented below.

7.1. Climatic data

Table 1 shows the maximum and minimum temperatures for Melbourne (M) and Seymour (S) [13] and the calculated long term monthly average differences between the maximum and minimum temperatures at the two locations. It can be seen that in winter (June, July and August) the average of the minimum temperatures for those months in Seymour is 3.4 °C below the same months in Melbourne. Similarly, in the summer months (December, January and February) the average of the maximum temperatures for those months is 3.0 °C above the same months in Melbourne.

The data in Table 1 is based on long-term averages. On individual nights and in particular years, differences in monthly figures will occur. The difference in overnight minimum temperatures, which is the key variable in determining the heating load in the greenhouse, can be much larger than the long-term averages indicate. Anecdotal evidence indicated that in Seymour overnight temperatures can be six degrees or more below those experienced in Melbourne. Accordingly, when validating the model, larger seasonal temperature differences were used (Table 2) to adjust the typical meteorological year (TMY) for Melbourne [14]. The use of these values effectively calibrated the model to calculate a heating load that would demand a gas usage similar to that experienced in the actual years analysed (shown later in Table 3).

Table 4
Seasonal adjustments (M–S) to Melbourne TMY data used for long-term performance predictions.

Use	Summer	Autumn	Winter	Spring
	January February December	March April May	June July August	September October November
Daytime performance predictions	−3.0 °C	−0.8 °C	1.1 °C	−0.9 °C
Night-time performance predictions	1.5 °C	2.7 °C	3.4 °C	2.8 °C

Table 5
Comparison of business-as-usual and heat pump system.

Parameter	Business-as-usual	After heat pump installation[a]
Gas usage ($L\,a^{-1}$)	216 785[b]	185 106
Electricity usage ($kWh\,a^{-1}$)	78 000	122 112
Total energy use ($GJ\,a^{-1}$)	5809[c]	5160
Gas costs (US $ a^{-1})	65 036	55 532
Electricity costs (US $ a^{-1})	6965	9290[d]
Total costs (US $ a^{-1})	72 001	64 822
Gas CO_2 (tonnes a^{-1})	355	303
Electricity CO_2 (tonnes a^{-1})	112	176
Total CO_2 (tonnes a^{-1})	467	479
Investment cost (US $)	n.a.	41 250
Maintenance cost (US $ a^{-1})	n.a.	n.a.

[a] Figures in this column represent the predicted new total energy and costs as a result of installing the heat pump system.
[b] Calculated using client's estimates of electricity usage, total costs and an average electricity price of 8.93 US cents kWh^{-1}.
[c] Calculated assuming a gross heating value of 25.5 MJ per litre for LPG.
[d] Sum of original total electricity costs and electricity for heat pump compressor at off-peak rate.

7.2. Gas consumption

Gas usage for 28 months between 2000 and 2002 was analysed and is shown in Table 3. Also shown in the table is the average gas usage during the three summer and winter months respectively. These figures, together with the annual total figure, were used as the three reference values to validate the model of the existing system. In summer, the gas consumed daily during the five daytime hours of boiler operation is assumed to be all for CO_2 enrichment. In winter, all the gas consumed (day and night) is considered to be used for heating.

The data in Table 3 indicates that gas consumption does not appear to be just a function of the heating load. For example, the consumption in July i.e. in the mid-winter month varies from 7942 to 23 921 l. According to the owner, no changes to boiler settings or operation occur during the year, even though the former figure is below the average amount used for CO_2 enrichment. Therefore to produce a more uniform "statistical average" year (see Revised Ave), various data i.e. those that seem unusually low have been excluded. The resulting total is approximately 8% and 9% greater than the three-year average or in 2001 respectively.

Fig. 4 shows the comparison of the "Revised Average" and the predictions of gas use from the model. Over the whole year, the model prediction is 8% lower than the Revised Average. In the winter months, the model predicts 2% lower than the Revised Average for those months. Over the three summer months, the model predicts 9% lower than the Revised Average for those months. Considering the number of unknowns e.g. greenhouse operating parameters and climatic variables, this level of agreement was considered to be acceptable and therefore the model was deemed to be suitable to evaluate the savings from the heat pump system.

7.3. LPG boiler and heat pump comparison

Using the same heating load, which generated the gas consumption shown in Fig. 5, the performance of the heat pump was predicted. However, in this case the long-term climatic differences were used in the heat pump equations (Table 4), rather than the values used when calibrating the model (Table 2) because these higher values would have disadvantaged the heat pump system. The quantity and cost of the electricity consumed by the heat pumps during their hours of operation has been added to the original electricity use and cost. No allowance has been made for additional electricity for pumping. The increase and decrease in CO_2 emissions as a result of changes in electricity and gas usage respectively has been calculated and the original figures, supplied by the owner, in the "Business-As-Usual" scenario have been adjusted (Table 5).

8. Discussion

Table 5 indicates the performance of the heat pump system in several key areas. In terms of LPG savings, reductions of 16.4% are predicted. This and subsequent figures in the Discussion section have been calculated by comparing the predictions of the boiler and heat pump systems, rather than comparing the heat pump predictions against gas usage, either the average or the Revised

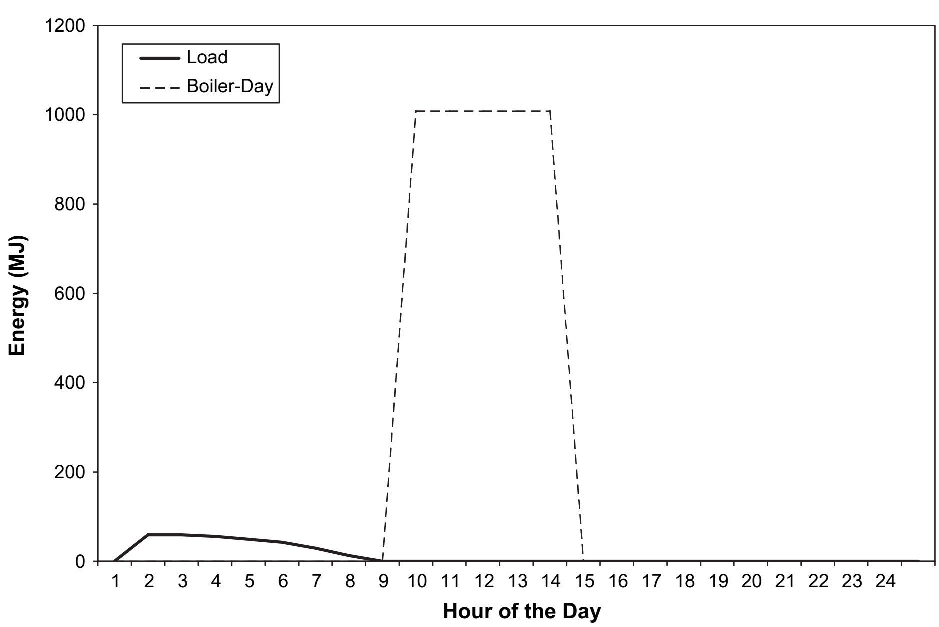

Fig. 6. Contributions to heating load from various system components in summer.

Average. Although low, this figure appears to be reasonable in light of the fact that approximately 66% of all the gas used is consumed in the daytime for CO_2 enrichment. In addition, the operation of the heat pumps is generally restricted to eight hours a night in order to use off-peak electricity. Furthermore, using the heat pumps during peak electricity price periods, in addition to the off-peak period, is unlikely to produce a significant increase in energy or financial savings. Since the water in the tank has been heated during the day, this is usually able to meet the energy demand early in the evening. Gas savings only increased from 14.3% to the current figure when the heat pump was allowed to run on an unrestricted time schedule over the weekends. Cost would almost certainly increase, however, because the peak rate is twice that of the off-peak rate.

Fig. 5 shows the contributions to the heating load from the various components of the system for a typical winter's day (July 3), chosen at random from the simulation output. In the early hours of the morning, a combination of heat from the boiler, tank and heat pump meets the load. Between the hours 0900 and 1400 the boiler is operated for CO_2 production and heats the water in the tank. When the greenhouse requires heat at hour 1800, the tank is able to supply the required energy until hour 2200. The boiler and later the heat pump supply the deficit during the remaining two hours of this day. In contrast to the operation of the system in winter, typical system behaviour in summer is shown in Fig. 6 (February 1). A small load in the early hours of the morning is easily met by the energy that has been stored in the tank the previous day during the operation of the boiler for CO_2 production. There is no requirement for the boiler to operate at night or for heat pump use.

The heat pump operation is efficient with an average Coefficient of Performance (COP) of 3.0 and a range of 1.6–4.9. The low values of COP, however, occur in winter when the ambient temperatures are low and the load is high. It should also be noted that the proposed heat pump system is not intended to be an instantaneous heater and would take 18 h to turn over the whole storage tank at the given flow rate. In fact it only operates for eight hours every 24 h during off-peak hours. The cost savings as a result of reduced gas consumption are approximately US $7,200 per annum. Based on the estimated project cost of US $41,250 this would produce a simple payback time of approximately six years. The price of LPG in Australia is benchmarked against the international price, quoted in US$. Accounting for changes in the value of the Australian currency, the current price of LPG for this customer is approximately 25% higher than it was in 2000. Assuming that project costs have only increased in line with inflation since that time, the simple payback period is almost certainly likely to have improved. Table 5 indicates that the heat pump system would produce a small (3%) increase in greenhouse gas emissions if its operation were restricted to off-peak hours.

9. Conclusions

The heat pump system, operated as described above, is predicted to save approximately 16% of current LPG useage. Depending on the expectations of the user, the system appears to be financially viable with a simple payback period of less than six years. This payback period is considerably better than those reported from most previous evaluations. In terms of greenhouse gas emissions, the proposed heat pump system produces almost the same level of CO_2 as the boiler system, so no environmental benefits or costs can be attributed to the proposed system.

A ground source heat pump would probably provide better energy efficiency than the proposed air source heat pump since the ground temperature is higher than the average air temperature in winter. A detailed simulation and financial analysis is recommended. The practice of using LPG in summer to produce CO_2 for the plant growth should be reconsidered. At a time when the reduction of carbon emissions is a global priority, efforts should be made to produce comparable yields in a more environmentally friendly way. Alternatively, a productive end-use of the heat generated as a by-product of CO_2 production in summer should be investigated.

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