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Evaluation of a heat pump system for greenhouse heating

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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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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.

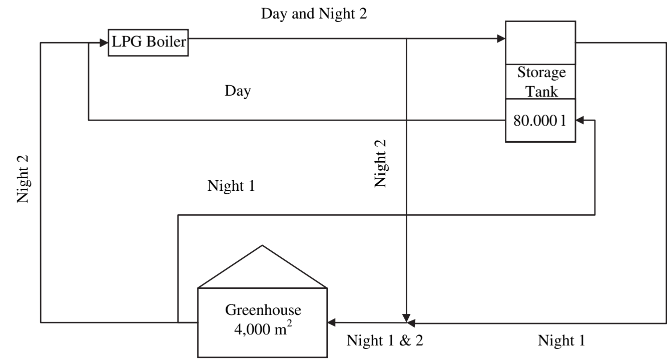

Fig. 1. Schematic arrangement of current heating system.

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.

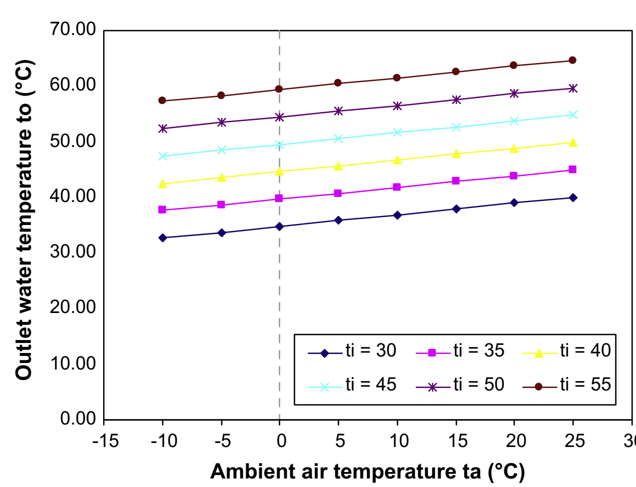

Fig. 2. Outlet water temperature (to) versus ambient air temperature (t_a).