# Feasibility of Solar-Assisted Refrigerated Transport in Australia

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## ABSTRACT

Research carried out in the United Kingdom in the late 1990s demonstrated the feasibility of using photovoltaics to minimise the use of diesel generators in refrigerated transport. Several years ago, UK supermarket chain Sainsbury's began to trial the use of PV modules mounted on trailers to provide the energy needed to keep the trailer contents refrigerated. This has proven to be very successful and reasonably economical.

Solar electricity can be economically viable in such applications because it competes with the price of electricity generated off-grid. The UK experience is compelling. The Australian situation differs due to higher levels of solar insolation, but also high levels of diesel subsidies for commercial users. This paper presents an analysis of the economics of Australian supermarkets using PV for displacing the diesel used in conventional refrigerated trailers.

The key finding is that such a system is capable of displacing a very significant proportion of diesel, but requires a more level playing field (such as a carbon price and elimination of subsidies) to be competitive with existing systems.

**Keywords: refrigeration, transport, photovoltaics, economics.**

## Introduction

Research carried out in the late 1990s demonstrated the feasibility of using photovoltaic (PV) modules to minimise the use of diesel generation in refrigerated transport. Subsequently, UK supermarket chain Sainsbury's began to trial the use of PV modules mounted on trailers to power the refrigeration unit. This has proven to be reasonably economical, given the high cost of diesel fuel in the UK. This report investigates the merit of retrofitting a PV system to assist refrigerated trailers in Australian conditions.

Conventional refrigerated trailers can be configured to carry either chilled (4°C) or frozen (−18°C) goods. It is impractical for a supermarket chain to own two different types of trailer, so each trailer is designed to carry goods at either temperature. Trailers are equipped with an integrated diesel-powered refrigeration unit. Power is generated on the trailer, which allows it to be disconnected from the prime mover. The diesel engine drives the refrigeration compressor directly, but AC power (240V) may be supplied while the trailer is parked at the dock to save fuel. A simplifying assumption is made that the refrigeration unit possesses control logic to suspend the diesel engine when electrical power is applied and, conversely, to fail over to the diesel generator when electrical power is cut.

The major supermarket chains trading in Australian cities replenish their stores from nearby distribution centres. In a larger city, a number of distribution centres are located around the city to service a set of supermarkets. A simplifying assumption has been made that Canberra supermarkets will be replenished from a distribution centre in Canberra. By constraining the movement of the trailer to a single city, the assessment of the solar resource and ambient temperatures is simplified.

This paper describes a feasibility study in PV-assisted refrigerated transport. An assessment of the solar resource in the Canberra region is performed. The electrical power required is estimated based on the requirement to keep goods frozen at -18°C. The thermal load is estimated using a simple thermodynamic model based on a control volume. A PV system design is specified to meet as much of this demand as practical. An economic analysis investigates the cost savings that can be achieved with PV assistance.

## Solar resource assessment

The only practical way to mount PV modules on a moving trailer is flush with the roof. Average daily irradiation data (by month) for a horizontal collector in Canberra was obtained from the ANU PVPanel web applet and is given in Table 1.

| Month | Irradiation ($kWh/m^2$) | Month | Irradiation ($kWh/m^2$) |
|---|---|---|---|
| January | 7.87 | July | 2.16 |
| February | 6.48 | August | 3.36 |
| March | 5.56 | September | 4.60 |
| April | 3.58 | October | 5.76 |
| May | 2.76 | November | 7.28 |
| June | 2.35 | December | 6.98 |

Table 1: Global irradiation data for Canberra (horizontal collector).

| | External (m) | Internal (m) |
|---|---|---|
| Length | 14.5 | 14.15 |
| Width | 2.6 | 2.4 |
| Height | N/A | 2.7 |

Table 2: Typical dimensions for a trailer.

# Load analysis

To analyse the load, it is necessary to specify how the trailer will be operated. A plausible requirement is for the trailer to store goods at a near-constant temperature of −18°C for 18 hours per day on any day of the year. Reliability is important in refrigerated supply chains. If the trailer contents exceed strict temperature controls, the entire load will spoil. This is costly and must be avoided.

## Trailer thermal characteristics

Typical dimensions for a trailer are listed in Table 2. It is assumed that the trailer is insulated with a material such as extruded polystyrene. This provides a thermal conductivity of 0.03 W/mK. Insulation in refrigerated transport plays a critical role in reducing the cooling load required, but there is a tradeoff to be made with the reduction in trailer volume. Sandia National Laboratories have considered the use of vacuum panels to achieve much better insulation and this would be worthy of more investigation (Bergeron 2001). Given the trailer dimensions, the total area of the trailer panels is calculated at $157.4m^2$.

A typical refrigerated trailer is capable of carrying 20 tonnes of food. Due to the high water content of perishable food, most food products have a specific heat capacity of approximately 75% that of water (American Society of Heating, Refrigeration and Air-Conditioning Engineers 1994). The trailer load is therefore modelled as having the thermal mass of 15 tonnes of water (with a specific heat capacity of 4.2kJ/kg°K).

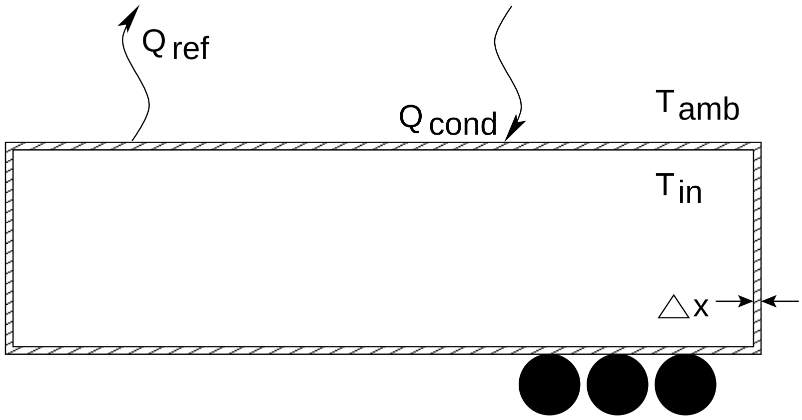


Figure 1: Basic thermodynamic model of the trailer.

## Refrigeration load

The sources of heat ingress into the trailer are radiation, conduction and convection. Heat gain is limited to conduction through the insulation, as the trailer skin will be close to ambient temperature and radiation heat exchange is limited by the conduction resistance. The contribution from conduction is:

$$Q_{cond} = kA\frac{\Delta T}{\Delta x} \tag{1}$$

where $\Delta x$ is the thickness of the insulation, $k$ is the thermal conductivity of the insulation, $A$ is the total area of the trailer walls and $\Delta T$ is the difference between the internal and ambient temperature. Modelling the trailer as a control volume (see Figure 1), the energy balance is given by:

$$kA\frac{(T_{amb} - T_{in})}{\Delta x} - Q_{ref} = mc_p\frac{\Delta T}{\Delta t} \tag{2}$$

where $Q_{ref}$ is the thermal power of the refrigerator, $m$ is the mass of the trailer contents, $c_p$ is the specific heat capacity of the trailer contents and $\Delta T/\Delta t$ is the rate of temperature change within the trailer. In Figure 1, $Q_{cond}$ is the rate of heat gain due to conduction, $T_{amb}$ is ambient temperature and $T_{in}$ is the internal temperature of the trailer. The energy balance equation can be re-stated in a discrete form:

$$kA(\frac{T_{amb} - T_{in}}{\Delta x}) - Q_{ref} = mc_p\frac{(T^{t+1} - T^t)}{\Delta t} \tag{3}$$

Rearranging this equation for $T^{t+1}$, the temperature inside the trailer at the next $\Delta t$ time step can be calculated. The thermal load for 18 hours is calculated at one minute intervals for the average ambient temperature. A one minute time step was chosen

| | Temperature (°C) | | | |
|---|---|---|---|---|
| Month | 9am | 3pm | Max. | Avg. |
| January | 18.4 | 26.9 | 28.5 | 24.6 |
| February | 17.8 | 26.4 | 28.1 | 24.1 |
| March | 16.3 | 23.5 | 24.7 | 21.5 |
| April | 12.1 | 19.1 | 20.1 | 17.1 |
| May | 8.3 | 14.9 | 15.8 | 13.0 |
| June | 5.1 | 11.4 | 12.3 | 9.6 |
| July | 3.9 | 10.6 | 11.5 | 8.7 |
| August | 5.9 | 12.6 | 13.5 | 10.7 |
| September | 9.8 | 15.1 | 16.2 | 13.7 |
| October | 13.3 | 18.3 | 19.6 | 17.1 |
| November | 15.2 | 22.0 | 23.5 | 20.2 |
| December | 17.3 | 24.8 | 26.3 | 22.8 |

Table 3: Long-term temperature averages for Canberra (Bureau of Meteorology 2008).

to limit the computational effort and proved to be adequate, given the high thermal mass of the trailer contents. Average ambient temperatures for Canberra are listed in Table 3. The average ambient temperature for an 18 hour operating day in each month is calculated by taking the average of the 9am, 3pm and maximum temperatures for that month.

In a trailer of this size, an 8kW refrigeration unit is typical. Electrical power of 4.8kW is assumed based on an average COP value at the target temperature. The model simulates running the refrigerator for a one minute interval if the temperature of the trailer rises above the target temperature. It does not attempt to model hysteresis. From the thermal load figures, the daily electrical load figures were calculated and these are shown in Table 4. The daily load has been scaled up to incorporate inverter, battery and cabling losses. Figure 2 shows how solar electricity is well suited to refrigeration, providing maximum output when demand is greatest.

# PV system design

The PV system has been designed to cost-effectively reduce diesel use. The intention is not to design a system that has high PV system availability at high cost. In a retrofit situation, diesel generation will always be available and can be used for backup. The system has been sized to meet the summer cooling requirement.

It makes little sense to carry battery storage all year long to handle a seasonal shortfall. The additional weight of batteries would sacrifice valuable cargo by adding to the vehicle gross weight and would increase the fuel consumption of the truck, countering any benefits. Although the thermal load is lower in winter due to lower ambient tempera-

| Month | Thermal load (kWh/day) | Electrical load (kWh/day) |
|---|---|---|
| January | 36.8 | 28.64 |
| February | 36.8 | 28.64 |
| March | 35.2 | 27.39 |
| April | 31.2 | 24.28 |
| May | 28.0 | 21.79 |
| June | 24.8 | 19.30 |
| July | 24.0 | 18.68 |
| August | 25.6 | 19.92 |
| September | 28.0 | 21.79 |
| October | 31.2 | 24.28 |
| November | 33.6 | 26.15 |
| December | 36.0 | 28.01 |

Table 4: Thermal and electrical load for frozen goods.

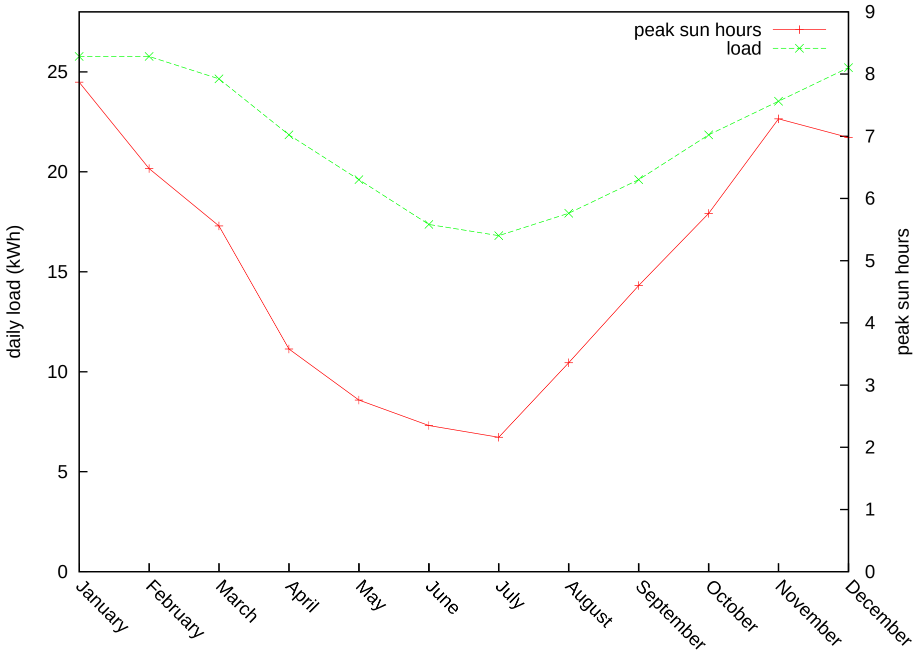


Figure 2: Energy generation and refrigeration demand for each month of the year.

| Month | De-rated Power (W) | Month | De-rated Power (W) |
|---|---|---|---|
| January | 73.6 | July | 78.6 |
| February | 73.8 | August | 78.0 |
| March | 74.6 | September | 77.0 |
| April | 76.0 | October | 76.0 |
| May | 77.2 | November | 75.0 |
| June | 78.3 | December | 74.2 |

Table 5: De-rated module maximum power.

tures, a winter shortfall occurs as a consequence of low solar insolation, the horizontal mounting of the PV modules when the sun is so low in the sky, and the relatively warm daytime temperatures in much of Australia. A benefit of sizing the system for exactly the summer demand is that the energy shortfall will be concentrated in winter, giving the diesel generator the potential to run less intermittently (Wenham et al. 2007).

As the trailer roof area is limited, high efficiency 90W, 12V PV modules were chosen and are operated at the maximum power point. An estimate of the de-rated power output of these modules for each month is shown in Table 5. In January, the trailer experiences the maximum load, requiring 28.64 kWh per day. Daily irradiation for January is 7.87 peak sun hours per day. The maximum power required from the PV array is therefore 28.64 / 7.87 = 3.64 kW. In January, the de-rated module output is 73.6W. The load requires 49.5 modules, which is rounded up to 52. This gives about 5% oversizing to compensate for any shading.

A total of 52 (13 × 4) modules are required. The dimensions of the PV modules is 1038mm × 527mm. Lower wattage panels were chosen to reduce the physical dimensions of the modules and improve the packing efficiency of the modules on the roof. The dimensions of the trailer roof permits 52 modules to be arranged in a 13 × 4 matrix, leaving a small amount of roof space. Table 6 shows the expected daily generation and energy deficit for each month. In general, there is a very small excess in November and January and a shortfall in the months with lower insolation.

A battery bank is specified to store charge for one 18 hour working day. This permits the system to operate smoothly in the summer and shoulder months when there is reduced insolation. In turn, this will allow the refrigeration unit to continue to operate without failing over to the diesel engine until the battery is discharged for the day.

The balance of system components are:

- 48V 250Ah flooded lead acid deep cycle batteries (225Ah at C20 discharge rate) for daily storage. Three batteries connected in parallel are required to obtain 675Ah storage;
- 80A solar charge controller; and

| Month | Load | Generation | Deficit |
|---|---|---|---|
| January | 28.64 | 30.13 | -1.50 |
| February | 28.64 | 24.86 | 3.77 |
| March | 27.39 | 21.57 | 5.83 |
| April | 24.28 | 14.14 | 10.14 |
| May | 21.79 | 11.08 | 10.71 |
| June | 19.30 | 9.56 | 9.74 |
| July | 18.68 | 8.82 | 9.85 |
| August | 19.92 | 13.62 | 6.30 |
| September | 21.79 | 18.42 | 3.37 |
| October | 24.28 | 22.75 | 1.53 |
| November | 26.15 | 28.38 | -2.24 |
| December | 28.01 | 26.93 | 1.09 |

Table 6: Daily load, generation and deficit (kWh/day).

- 5kW 48V sine wave inverter.

## Economic analysis

Table 7 outlines the relevant costs. As the PV system is intended to be retrofit to an existing diesel-powered refrigeration unit, the two systems being compared are the unit with and without PV assistance. Therefore, the capital cost of the unit (the same in both systems) is omitted from the calculations. If the unit requires replacement or repair, it must be paid in both cases. Diesel fuel consumption was calculated at the rate of 0.4 L/kWh. The price of diesel was taken at $1.46 per litre.

Costs in present value terms are given in Table 8. For present value calculations, a system lifetime of 25 years and a discount rate of 7% has been assumed. The present value of the recurring cost of battery replacement ($5,700 every five years) is $10,501.

Predicting the future price of diesel fuel is difficult, so the calculation for the annual costs are based on a diesel fuel price of $1.46 per litre, and subject to discounting. This may be too optimistic, as the price of diesel may rise faster than inflation in the coming decades because of continued strong global demand for oil. The substantial reduction in diesel operation in the PV-assisted system allows the annual servicing costs to be reduced from $1,000 to $500.

As can be seen in Table 8, despite an 85% reduction of diesel fuel used by the trailer, the cost of operating the PV-assisted system is greater than the cost of operating the diesel refrigeration unit alone. Over the term of the previous federal Government, road transport became increasingly subsidised in the form of various fuel excise rebate schemes (Productivity Commission 2008). Further, the eligibility criteria for these subsidies were

| Diesel | | Diesel with PV assistance | |
|---|---|---|---|
| Item | Cost | Item | Cost |
| Diesel refrigeration unit | $34,000 | Diesel refrigeration unit | $34,000 |
| | | 90W PV modules (52) | $38,480 |
| | | 250Ah batteries (3) | $5,700 |
| | | Framing | $2,000 |
| | | Charge controller | $1,395 |
| | | Inverter | $4,540 |
| | | Wiring and circuit protection | $300 |
| | | Installation labour | $2,000 |
| *Recurring costs* | | | |
| | | Batteries (5 yearly) | $5,700 |
| *Annual costs* | | | |
| Diesel servicing | $1,000 | Diesel servicing | $500 |
| Fuel (6668 kWh, 2267L) | $4,400 | Fuel (977 kWh, 391L) | $645 |

Table 7: Capital, recurring and annual costs for diesel-only and PV-assisted systems.

| Diesel | | Diesel with PV assistance | |
|---|---|---|---|
| Item | Cost | Item | Cost |
| | | Capital costs | $54,415 |
| | | Battery replacement | $10,501 |
| Maintenance | $11,654 | Maintenance | $5,827 |
| Fuel (2,267L) | $45,380 | Fuel (391L) | $6,649 |
| Total | $57,034 | | $77,392 |

Table 8: Present value costs for diesel-only and PV-assisted systems.

progressively relaxed, such that any truck over 4.5 tonnes that moves freight on public roads is currently eligible for a fuel tax credit of 18.51 cents per litre. This tax credit also applies to the use of fuels for auxiliary power generation on these vehicles (Australian Taxation Office 2008).

When this work was carried out, the retail price of diesel was $1.65 per litre, however when the fuel tax credit is applied, this is reduced to $1.46 per litre. This subsidy gives a substantial advantage to diesel generation when total system costs are considered. When the subsidy is removed the total cost, in present value terms, becomes $78,257 with PV assistance and $62,940 without.

Australia is planning to introduce an emissions trading scheme in 2011. If the permit price was hypothetically $35 per tonne of $CO_2$, the costs, in present value terms, become $78,687 with PV assistance and $65,877 without. The carbon price does not have a substantial impact on the total system cost for the diesel-only case – adding about $3,000 to the total cost over 25 years.

A sensitivity analysis with the diesel subsidy removed and a $35 per tonne price on carbon, indicates that a diesel price of $2.14 per litre is required to make the system favourable. However, there are other considerations that may make the PV-assisted system viable at a lower diesel price, such as lower PV system prices, reduced noise, greater reliability and the public relations benefits of using non-polluting fuel sources.

## Conclusion

When using PV in refrigerated transport applications, there are some physical constraints that make a greater contribution from PV impractical. The trailer roof area limits the available power. Further, transport applications may be sensitive to the weight of system components, such as batteries. Additional weight reduces fuel economy and reduces the amount of cargo that may be carried.

Nevertheless, the proposed PV system is capable of displacing 85% of the diesel used to refrigerate the trailer down to -18°C. The economics of this system are unattractive at present in Australia because diesel is relatively inexpensive compared to the capital costs of PV. The situation for Sainsbury's in the UK is quite different, where diesel fuel costs are higher—currently over AUD2.30 per litre.

## Biography

Ben Elliston is a practising computer engineer and a postgraduate student at the ANU, completing a Master of Engineering with a focus on sustainable energy systems. Dr Mike Dennis is a Senior Research Fellow in the Department of Engineering, ANU.

## References


American Society of Heating, Refrigeration and Air-Conditioning Engineers (1994), *ASHRAE Handbook: Refrigeration*, ASHRAE.

Australian Taxation Office (2008), 'Fuel tax credits', World Wide Web electronic publication.
**URL:** *http://www.ato.gov.au/corporate/content.asp?doc=/content/76594.htm&page=4&H4*

Bergeron, D. (2001), 'Solar powered refrigeration for transport application'.
**URL:** *http://www.sandia.gov/pv/docs/PDF/Solus%20SAND1.pdf*

Bureau of Meteorology (2008), 'Canberra climate averages', World Wide Web electronic publication.
**URL:** *http://www.bom.gov.au/climate/averages/tables/cw_070282.shtm*

Productivity Commission (2008), *Trade & Assistance Review 2006-07, Annual Report Series*, Productivity Commission, Canberra.

Wenham, S. R., Green, M. A., Watt, M. E. & Corkish, R. (2007), *Applied Photovoltaics*, 2nd edn, Earthscan.