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Solar Powered Refrigeration for Transport Application -- A Feasibility Study

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Solar Powered Refrigeration for Transport Applications

A Feasibility Study

Final Report

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Abstract

A feasibility study was conducted to determine if solar power could be used to offset or eliminate the diesel fuel powered refrigeration systems currently used in transport applications. This study focused on the technical feasibility and economic viability of solar for this application. A target application was selected and a moderately detailed mathematical model was constructed to predict the performance of the system based on hourly solar insolation and temperature data in four U.S. cities. An economic analysis is presented comparing the use of solar photovoltaics *vs.* diesel for this application.

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Executive Summary

As the price of photovoltaic (PV) power decreases, new opportunities for its use develop. One such potential market is the use of PV to displace power supplied by diesel engines used for transport refrigeration. This is a particularly attractive potential market for solar PV in that the relative cost of power produced by small diesel engines is high, not only in terms of operating and maintenance cost, but in terms of noise and air pollution.

This report identifies a potential transport application, models the performance of solar powered refrigeration for this application and presents an economic analysis the system. The following is a list of conclusions and recommendation based on this study.

Conclusions

- Although there are some technical challenges to developing a solar PV powered refrigeration system for transport applications, this technology is basically available for a demonstration system.
- The original goal of completely eliminating diesel powered back-up may not be quite as valuable as first thought, in that the majority of the cost of operating a diesel generator is related to the runtime, not the initial cost.
- The trade between the battery storage and PCM (phase change material) storage has significant impacts on the design of the refrigeration system and should be carefully considered. The PCM approach should offer the best long-term benefit, but will present more development effort.
- The payback analysis indicated that at the present time, the economic justification for wide-spread use of solar is moderate, but not compelling. However, as the price of diesel increases and the price of solar modules and vacuum panels decreases, the economic case will improve. These are expected trends. In addition, any new regulations impacting diesel emissions will likely favor solar.
- The extra cost of insurance is the largest single operating expense of the solar powered system (~$1,500/year)
- Other economic factors such as noise and pollution related issues may tip the scales in favor of the solar approach in some applications and some effort will be required to seek out the niche markets for this technology.
- International applications may be the early adopters of this technologies due to the higher cost of diesel fuel in these countries ($3.50 to $4.00 USD per U.S. gallon in England)
- Some form of government supported economic incentive would enhance widespread near-term commercial utilization.
- Other things being equal, transport applications with high total annual runtime will have more favorable economic returns.
- Other things being equal, operation in sunny cooler climates will have more favorable economic returns.

- Developing a good service infrastructure will be necessary and important requirement.

Recommendations

- Locate a refrigerated cargo hauling company that would consider hosting a prototype and potentially purchasing a fleet of solar refrigerated trailers.
- Remodel the system based on the known operating conditions of the host company and re-optimize the design for the host application.
- Begin prototyping a solar driven variable speed refrigeration unit that meets the efficiency requirements targeted in the new model.
- Construct a section of trailer wall with embedded vacuum panel insulation. Once this wall is tested, construct an entire trailer using the embedded vacuum panel insulation. The target UA (overall energy loss coefficient –area product) value for this trailer should be 45 BTU/Hr/°F.
- Consider the advantage of integrating an APU (auxiliary power unit) that provides back-up power to the solar refrigeration system and provides environmental control for the cabin and engine compartment (to avoid diesel idling).
- Consider how the Government might provide incentives for the trucking industry to adopt this technology.

1. Introduction

The first commercial application of this technology was developed in England in 1997. Solar PV panels mounted on the roof of a trailer were used to charge batteries that powered a refrigeration system. This application was for the delivery of refrigerated food products by a supermarket chain. Two second-generation trailers are now undergoing commercial trials in anticipation of an order for a fleet of these units. These solar refrigerated trailers are designed to maintain refrigerated conditions for a period of roughly six hours a day only, and do not haul frozen product.

The key economic factors that led to the commercial development of these units were (1) the high cost of diesel fuel in England, (2) the high cost of the diesel system maintenance, and (3) the noise generated by the diesel engines during night-time delivery in residential areas.

Figure 1. Solar PV Refrigerated Trailer

While the food distribution market appears to be a good application for PV power in England, economic factors are different in the United States. The purpose of this study is to determine the technical and economic feasibility of developing a PV refrigeration system for transport applications that would have widespread market potential in the United States.

This study includes selecting a candidate target market, developing and modeling a conceptual system design, identifying key technology development requirements, and addressing the economic trades between diesel and solar powered refrigeration systems that drive the commercialization potential.

2. Target Market

Two key conclusions were made based on the telephone discussions with several refrigerated trailer manufacturers. First, the market for road based transport refrigeration is much larger than the market for rail based transport refrigeration. The rationale for this is that the rail based refrigerated systems cannot be monitored as well during transport and the risk of loss (spoilage) is much greater. It was suggested that the market for road based refrigeration was 2 to 3 orders of magnitude greater than rail. This led the study to focus on road based systems.

The second conclusion was that if solar refrigeration was to reach the largest potential market, the unit must be able to operate at both freezer (0°F) and refrigeration (38°F) conditions. The rationale for this is that many truck haulers carry different cargo to and from their usual destinations. On many jobs, the cargo traveling one way is refrigerated and the cargo traveling back is frozen or vice versa. A trailer system that can only provide refrigeration, not freezing, would have much less market value than a system that could handle both. Because of this, it is assumed that the solar powered refrigeration system should be capable of both operating conditions, as well as simple air conditioning.

However, designing a system for freezer operation (0°F) is significantly more challenging than for refrigeration (38°F). The thermal load increases by more than 50% in hot weather and the refrigeration system efficiency drops by almost 50%, so the overall electrical energy required to maintain freezer conditions is 3 times that of maintaining refrigerator conditions. The exception to this statement is in the case of refrigerated loads that exhibit high rates of respiration (exothermic process), in which case the refrigeration load can be higher than a freezer load. The decision to design for freezer conditions generally poses a significantly increased technical challenge, but is thought to be appropriate for this feasibility study. The first market for solar powered transport refrigeration may prove to be for refrigerator operation alone (with moderate-to- low respiration loads) because of the easier requirements, but this can be determined later.

3. Current Technology

The majority of current refrigerated trailer technology includes polyurethane insulation, fixed speed Rankine Cycle vapor compression refrigeration equipment, and direct drive diesel engine power. If one were to simply replace the diesel engine with an electric motor, and power the motor from a conventional solar/battery/inverter system, this would form the basis of what we are defining as “Current Technology.”

To assess the performance of the current technology, the trailer thermal load was predicted, the refrigeration system efficiency was determined, and an estimate of the

Solar/Battery/Inverter output for various insolation conditions was made. To assess the performance of the current technology, three baseline cities were chosen -- Phoenix, Houston, and Boston.

Thermal Load

To determine the thermal load, a software package developed by Carrier-Transicold for predicting the trailer thermal loads was used. Table 1 is an example of output from the code used to predict freezer operation heat loss. The worst-case U.S. regional temperature was selected. The trailer was assumed to be 53' in length with normal-to-thick insulation for refrigeration applications.

This is a well-insulated trailer and assumes long haul conditions (limited door openings). The territory assumes the U.S., so the average ambient design condition is 101°F. It also assumes freezer operating conditions (0°F). The result is a predicted average load of 10685 BTU/Hr (3131 Watts).

Refrigeration System Efficiency

The next step was to determine the energy requirement for the refrigeration system to maintain this load condition. Refrigeration system performance data was gathered from both Carrier-Transicold and ThermoKing. System performance data is proprietary to the manufacturers and cannot be documented in this report. However, based on published compressor data, a reasonable system COP (coefficient of performance -- cooling effect/system power) of 0.6 can be assumed.

Given a system COP of 0.6 while operating at typical freezer conditions, the average power input to the refrigeration system is 5218 Watts (3131W cooling / 0.6). Based on this average electrical input load of 5218W, the total daily energy input required is 125 kWh.

CUSTOMER		DEALER	
Company	Solus	Company	
Contact	David Bergeron	Representative	
Phone	(775) 331-6600	Phone	
Fax		Fax	

BODY INFORMATION

		Insulation	
Body type	trailer		
Length	53 feet	Insulation type	polyurethane (walls)
Width	7.8 feet	Nose	4 inches
Height	8.5 feet	Roof	4 inches
Rear door type	swing	Side walls	4 inches
Side doors (Y/N)	no	Floor	3 inches
How many?		Rear doors	2 inches
What type?		Insulation type	polyurethane (rear doors)
Air curtain (Y/N)	no	**Other**	
E-tracks (Y/N)	no	Body efficiency	Standard
		Body color	light

Calculated Body UA		Manufacturers UA Rating	
Calculated UA ->	86 BTU/ft²/hr/°F	Rated UA --->	BTU/ft²/hr/°F (over-rides calculated UA)

OPERATIONAL DATA

Operating Territory		Door Openings	
Operational area	U.S. (See chart)	How many	1
Design high	112 °F	Duration	1 minutes
Design low	-26 °F	Delivery period	24 hours
Ave daily temp	101 °F (summer)		

PRODUCT INFORMATION		AIRFLOW RECOMMENDATION
Product	frozen (See chart)	Minimum unit airflow for 1 air cycle per minute
Set point	0 °F	3513.9 cfm
Product weight	35000 lb. (estimated)	

COOLING AND HEATING LOAD ESTIMATES

	Maximum Load	Mean Daily Load	
Base	9594	8609	BTUH
Solar Gain	735	735	BTUH
Degradation	1439	1291	BTUH
Recovery	52	50	BTUH
Respiration	N/A	N/A	BTUH
Total	*11820*	*10685*	*BTUH*
Base			BTUH
Degradation			BTUH
Recovery			BTUH
Total			*BTUH*

Table 1. Examples of output from code used to predict freezer operation heat loss

Solar Power Availability

Based on current commercial panel efficiency, an insolation study was conducted to determine the total available annual energy from the panels in Phoenix, Houston, and Boston. A total rated power of 5.7 kW was used, which was based on a fully covered 53' trailer roof and a very high efficiency commercially available panel (136 watts/sq.m gross panel efficiency). Table 2 summarizes the results.

Table 2. Array Energy Per Day

Location	Array Energy
Phoenix, Summer	43.4 kWh
Houston, Summer	31.8 kWh
Boston, Summer	32.5 kWh
REQUIRED	125 kWh

As can be seen, current technology is well below the required efficiency to maintain freezer conditions in a well-insulated (4" of urethane) trailer.

4. Proposed Technology Development

In order to make solar powered refrigeration feasible, technologies need to be developed to address the following necessary system improvements:

1. Reduce the thermal load on the trailer.
2. Improve the refrigeration system efficiency.
3. Select and develop an optimal energy storage technology (Battery or Phase Change Material).
4. Develop a source of auxiliary power to augment and serve as a back-up to the available solar input.

It is suggested that all four system improvements/developments be addressed.

Reduce Thermal Load

The principal thermal load on trailers carrying frozen product is thermal conduction through the trailer walls. According to the load prediction software, 99.5% of the total load is caused by conduction for long-haul trailers and 77% of the total load is caused by conduction for delivery trucks (twelve 15-minute door openings per day). The actual numbers are lower due to food insertion loads, which are not included in the model.

For the thermal load calculation, it was assumed that the trailer had an average of about 3 ½ inches of insulation. One simple way to reduce thermal load is to add extra insulation; however, this reduces the useable cargo volume of the trailer. If one were to add 5 inches of insulation to all surfaces, the usable payload volume would decrease by about 20%.

An alternative method to reducing the wall conduction is to embed vacuum panel insulation into the walls of the trailer. Vacuum panels have insulating value in the range of R-20 to R-50 per inch, where urethane has an insulating value of about R-6.5 (beginning of life). To be most effective, the vacuum panels should be placed in the walls before the urethane is poured. Techniques will need to be developed to allow the trailer manufacturers to economically embed the vacuum panels into the walls. Alternative urethanes (with lower pour temperatures) may need to be used to prevent damage to the vacuum panels. The proper pour technique will insure complete flow of urethane around the vacuum panels, leaving no air pockets.

Vacuum panels are commonly constructed using rigid, open-cell foams which are evacuated and sealed with a thin air barrier material. A small puncture hole in the vacuum panel reduces the insulation value down to approximately that of urethane. Embedding the vacuum panel in the walls will protect the panel from damage.

It is inevitable that over the life of the trailer, some panels will be damaged, so designing the panel installation for field service (panel replacement) is prudent. Making the individual panel too large will result in higher thermal losses from single individual panel failures. Making the panels too small results in lower overall insulation performance because small panel conduct more heat (conduction around the panel edges becomes a significant thermal load). It is suggested that the size of the vacuum panel be kept to no larger than 2 ft x 2 ft or 2 ft x 4 ft. Given the overall surface area of the trailer (2000 sq. ft.), about 250 to 500 individual vacuum panels will be needed per trailer.

If the overall trailer wall thickness remains the same, but that 1" of urethane is replaced by 1" of vacuum panel (R-30), the UA value of the trailer walls will drop from 86 BTU/hr/°F to 41 BTU/hr/°F. The total thermal load would drop from 3131 watts to 1512 watts. This is the most ideal case and actual performance may not consistently achieve this level. The analysis in this report will assume that a trailer UA value of 55 will be achieved with vacuum panel insulation, resulting in an overall thermal load of 2000 watts.

<u>Refrigeration System Efficiency</u>

The current technology system COP is 0.6 and is based on industry provided data. This means to achieve 0.6 watts of cooling requires 1.0 watts of power input. Given the operating temperatures of 0°F in the trailer and 101°F outside, the maximum theoretical thermodynamic COP can be determined from the Carnot Equation. In this case, the maximum theoretical COP is 4.55. The current technology refrigeration system achieves only 13% of theoretical efficiency. A variety of system losses combine to produce this result. The industry design is not flawed, but rather optimized for cost, reliability, serviceability, and weight. However, given a requirement to operate the system on much less energy, several design changes are appropriate.

First, the size of the condenser and evaporator heat exchangers must be re-optimized (enlarged) to reduce the refrigeration system lift (T cond – T evap). Enlarging the condenser and evaporator surface areas to cut the temperature differentials in half would improve the system efficiency by 35%.

Second, a look at 2-stage compressor technology would be appropriate. The inherent Rankine cycle loss using a single-stage compressor for these operating conditions is about 28%. About half of this loss can be recovered using a two-stage compressor. Two-stage compressors are more complicated, but they are commonly used in many stationary applications. Other more advanced technologies are possible to further reduce the inherent Rankine cycle loss.

Third, a review of candidate refrigerants for this application should be performed. R-134a has a high theoretical efficiency under these operating condition and has a reasonable density and compression ratio. Other refrigerants should be considered. Some have a lower theoretical efficiency, but will allow the compressor to achieve a higher isentropic efficiency, which may result in overall improved system efficiency.

Finally, reducing the fan power consumed by the evaporator and condenser fan motors is an important and potentially productive area of improvement. These improvements can be made by using higher efficiency motors and reducing the static pressure drop across the coils (which should occur automatically with the large heat exchangers recommended above). The energy saving potential of the fan motor cannot be determined within the scope of this effort, but something on the order of 10% to 15% is reasonable to assume. Making use of natural convection and the "natural" forced convection available when the truck is moving can also be an important area of investigation.

Energy Storage Technology (Battery vs. Phase Change Material)

The decision between electrical storage (Batteries) and thermal storage (PCM) is an extremely important and driving technical decision for PV refrigerated transport application. If the selection is battery storage, there is less technology development required. If PCM is selected, more development is needed, especially in the area of variable speed refrigeration technology[1].

Pros and Cons of Battery Storage

+ Battery technology is well defined for this application and provides excellent operational flexibility. PCM systems freeze at one operating point so they are optimized for one operating condition. The battery storage system seamlessly adapts to various trailer operating temperatures.

+ With the battery system, the compressor can operate more hours per day, allowing for a small compressor, evaporator, and condenser (save weight/cost). This also tends to improve the overall operating efficiency of the system (constant lower speed operation). The batteryless design (PCM) can operate only when the sun is shining and must be a larger capacity system to produce the same total daily cooling in a shorter time period.
+ The battery design also provides a stable input voltage to the motor drive electronics, which will allow for a wider range of potential vendors for this device.
+ Two-stage compressor designs (or other advanced cycle designs) may be easier to implement using a fixed speed system, which battery storage allows.
+ If battery storage is selected, it may be easier to harness engine power during truck operation to supply the "Auxiliary Power" needed to maintain trailer temperature. With the battery system, any time the truck is running, the batteries can be charged, while in the PCM approach, auxiliary power can only be used when the refrigeration system is running. With the battery approach, truck operation and refrigeration system operation do not have to coincide.

- However, batteries lose energy in the charge/discharge cycle. Round trip efficiency is estimated at 75% to 80%
- Batteries self-discharge over time and if allowed to become completely discharged, cause permanent damage to the cells.
- Batteries must be periodically charged to the maximum charge voltage to maintain good capacity and long life. This process requires a significant amount of wasted energy.
- Battery maintenance will be required every 3 to 9 months. This maintenance includes inspecting cells for low water, adding water as required, and cleaning the battery terminals.
- Additionally, battery replacement will be required 3 to 5 times over the 20-year life of the trailer.
- Finally -- and perhaps the most substantial drawback of the battery approach -- is the weight of the battery as compared to the equivalent weight of thermal storage. For this application, the battery system will likely weigh ~3,000 lbs, where the PCM system will provide the same equivalent cooling with about 1,000 lbs (see analysis in the following section).

Pros and Cons of PCM Storage

+ Less weight for the same equivalent thermal cooling effect (see analysis below).
+ If the PCM is located inside the trailer, the PCM has no thermal loss mechanism equivalent to battery round trip efficiency or self-discharge.
+ A good PCM storage system design should require much less maintenance than a battery system.
+ The PCM will mostly likely be non-toxic and environmentally safe.
+ Depending on the final design of the PCM, natural convection can be used to reduce fan power

- Knowing the state of thermal reserve of the PCM is currently more difficult to determine than knowing the state of electrical reserve of a battery.
- The evaporator will need to operate at a lower temperature (reducing efficiency) because the PCM needs a ΔT between it and the trailer compartment, and the refrigerant needs a ΔT between it and the PCM, so two heat exchanger steps are required.
- Defrost procedure is complicated with PCM systems. A secondary loop of glycol/water will likely be required to separate the air heat exchanger from the PCM compartment to facilitate defrost operation. Defrost is typically required several times per week.
- Because no electrical energy is stored, anytime the compressor is not running during the day, the PV power is lost. This typically occurs at low sun conditions.
- Also, because no electrical energy is stored, anytime the PV power is greater than the powered used by the compressor, the PV power is lost. This can occur in full sun conditions when the compressor is operating at maximum speed, yet there is more available PV power.
- Anytime the solar power is intermittent (clouding weather or other shadows) the compressor is subject to wide speed changes and even shut-downs. These speed changes and shut-downs cause the system to operate in transient conditions which typically reduces refrigeration system efficiency (refrigerant imbalance between evaporator and condenser).
- Not using a battery drives the design of the refrigeration system to variable speed operation. This is discussed in the next section. Variable speed systems will require more initial engineering. Operating a compressor at variable speed and maintaining high compressor efficiency is a significant technical challenge.
- Some amount of battery storage will be required to operate pumps and fans at night to maintain temperature. It is conceivable that a natural convection system could be designed to eliminate the need for active fan power at night.
- The PCM design would benefit from a compressor development effort that resulted in a compressor with a very wide operating range (at least 6:1). The battery design will operate fine with many existing production compressors.

As mentioned above, one important advantage that the PCM system has over the battery system is in the area of weight. Table 3 shows the ratio of battery mass to thermal storage mass for freezer and refrigerator operating conditions. The energy stored in a battery can be converted into a cooling effect, given the efficiency of the refrigeration system. For this calculation, a large flooded lead-acid battery was assumed with a 50% DOD (depth of discharge; that is, no more than 50% of the battery capacity is discharged in each cycle). The freezer and refrigerator cases are treated separately because the system cooling efficiencies and the choice of PCM materials is different. Based on the assumptions in this table, the PCM thermal storage approach has only about one-third the weight of the battery approach. Given the amount of expected storage required for this application, the weight savings from the PCM approach is about 2,000 lbs.

Table 3. PCM vs. Battery Weight Trade

	Freezer	Refrigerator	Units
Battery Capacity	498	498	amp-hr @ 12 hr rate
Battery Weight, (2 V Cell)	80	80	Lbm
Battery Energy	996	996	Watt-Hr (electric)
Allowed DOD	50%	50%	DOD
Battery Specific Energy	6.2	6.2	W-Hr/lb (electric)
Refrigeration Efficiency	1.5	2.5	COP
Battery Specific Cooling	9.3	15.6	W-Hr/lb (cooling)
Battery Specific Cooling	31.9	53.1	BTU/lb
PCM Specific Cooling	100	125	BTU/lb
PCM Weight/Battery Weight	32%	42%	Ratio

PCM and Variable Speed Operation

If PCM is selected as the primary energy storage, the use of variable speed refrigeration technology becomes an important feature. This has significant implications for the design of the refrigeration system. PV power is variable during the day and highly variable during cloudy or partly cloudy days. In order to maintain good efficiency, the refrigeration system must be able to efficiently adapt to varying power levels. This requires the use of a variable speed compressor and a control system that will allow the refrigeration system to maintain maximum efficiency at both high and low operating speeds as well as during the transient conditions between power levels. These are two separate issues -- variable speed compressor technology and refrigerant management technology.

If the compressor is unable to operate at variable speed, it will not operate when the sun is low in the sky or will waste power when the available solar power is more than what the compressor needs. This is illustrated in Figure 2.

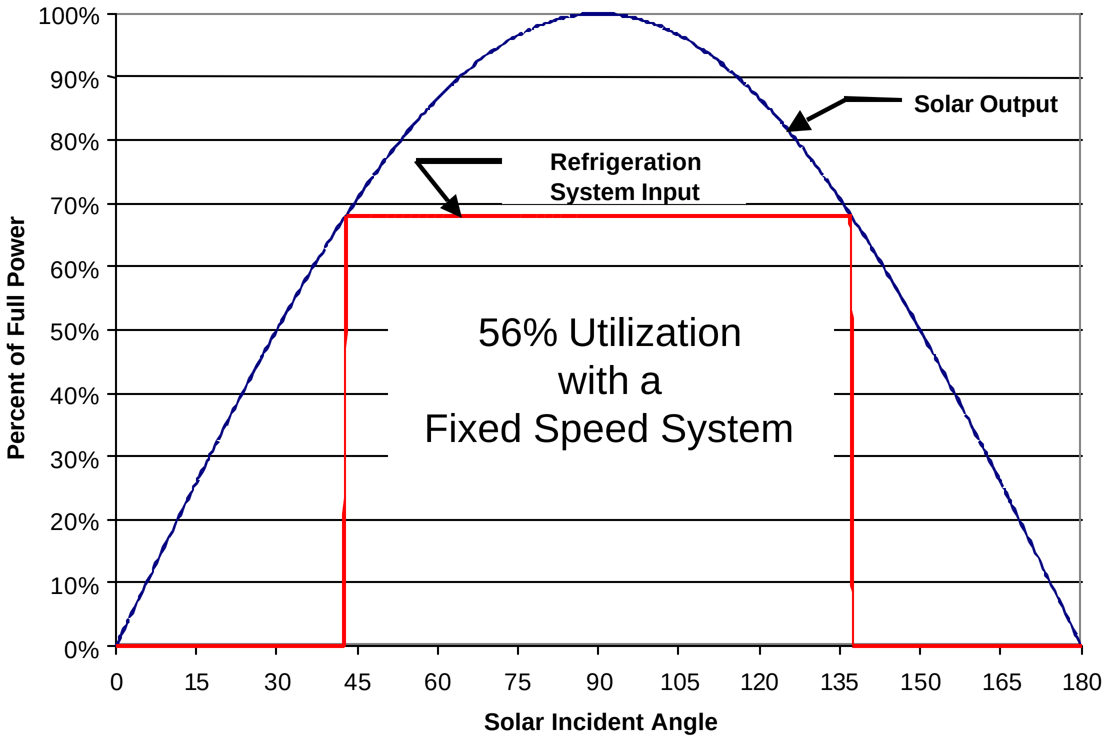

Figure 1. Fixed Speed Solar Utilization

Under the most ideal conditions a fixed speed compressor will only utilize 56% of the available solar energy. In practice, the utilization is less because the compressor power and available solar input are rarely matched well enough to reach 56% utilization. Variation in compressor power requirement (operating conditions) and variations in solar input (seasonal/weather) cause poor solar utilization the vast majority of the time.

In order to capture much of the available solar output, the compressor (and entire refrigeration system) must be capable of variable capacity operation. This can be accomplished via variable speed operation or some other load shedding capability. However, if a load shedding technique is employed, it is not sufficient to simply reduce power input, as with some capacity reduction methods, but the load shedding method must provide for continued high efficiency operation in low load conditions.

If the compressor is able to vary its speed over a 1.5:1 speed range (e.g. 2000 to 3000 rpm), the solar utilization can improve to a maximum of 77%, as can be seen in Figure 3.

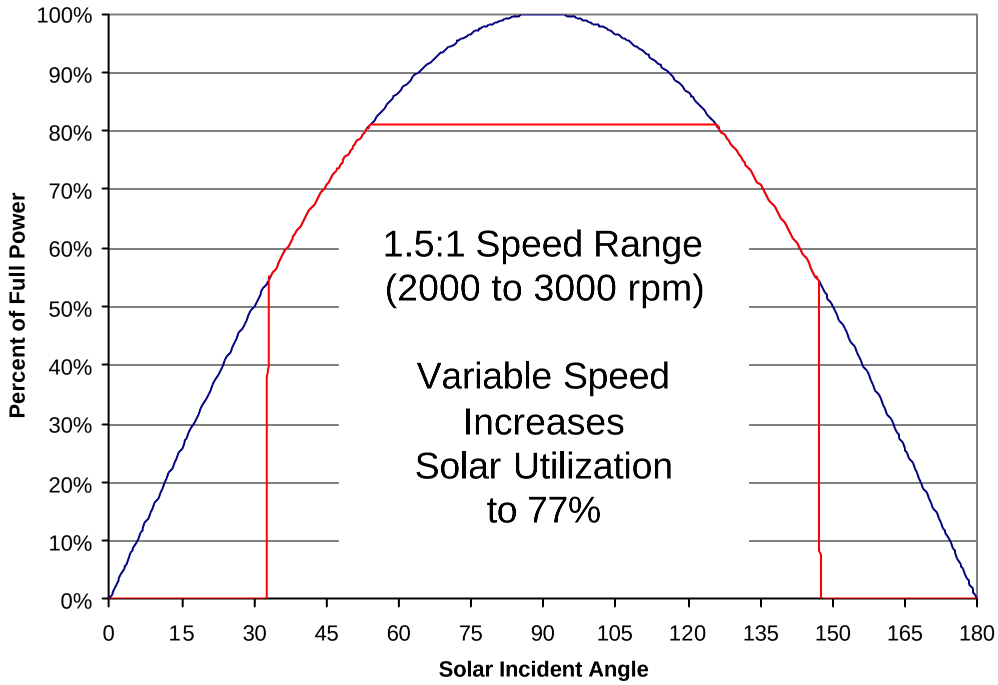

Figure 2. Solar Utilization with 1.5:1 Speed Compressor

As the speed range of the compressor increases, the maximum theoretical solar utilization continues to improve and is illustrated in Figure 4.

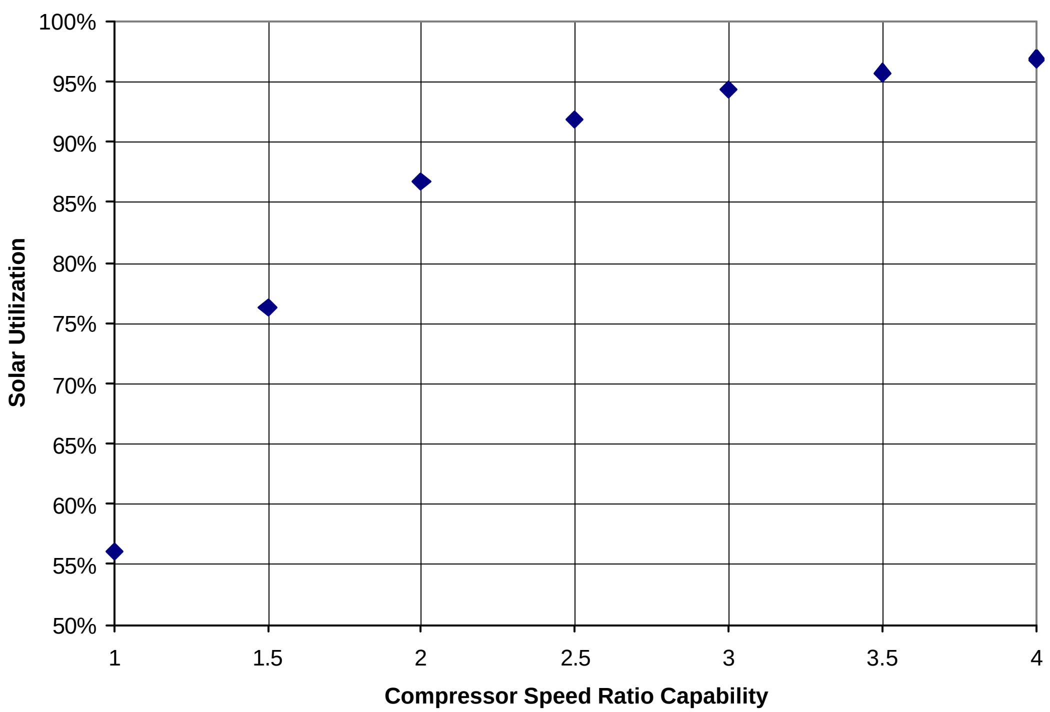

Figure 3. Solar Utilization with Different Speed Ranges

Most types of standard refrigeration system compressors can operate over a range of at least 2:1, resulting in a best-case solar utilization of about 87%, but this requires a variable frequency motor drive. The limiting factor for most compressors is the oil circulation system within the compressor. Below about half speed (30Hz), many oil pumps do not pump enough oil to lubricate the piston and crank bearings. Modifying the oil lubrication system to allow for a wider operating range is an important potential technology for solar direct operation. The automotive compressors that do allow for a wide speed operating range are not efficient enough for this application.

An alternative way to improve the solar utilization is to use a compressor that can vary its capacity by off loading cylinders or reducing the volumetric throughput by some other means. These techniques are typically not as efficient as varying the compressor speed, but they are available features on some compressors, and when used in conjunction with speed control can allow the system to achieve a solar utilization above 90%.

Another way to efficiently improve solar utilization is to use 2 parallel compressors, which can be operated separately or together. If one compressor has twice the capacity of the other (1/3 + 2/3 = 100%), and both can operate down to 50% speed, the overall speed range would be 6:1.

Assuming the compressor speed/capacity problem is resolved by using one of the above-mentioned techniques (or some other), the next technical challenge is refrigerant management. To maximize refrigeration system efficiency during variable capacity operation, the refrigerant balance between the condenser and evaporator must be maintained. It is suspected that traditional refrigerant controls (capillary tube or expansion valve) may not respond quickly and correctly to changes in pressures and flow rate to maintain ideal conditions in heat exchangers (condenser and evaporator). A more responsive and intelligent control may be required to maintain efficient operation. This can be accomplished via the use of an electronically controlled expansion valve and proper instrumentation in the evaporator to insure wetted but not flooded conditions are maintained.

Performance of Improved System

Given the reduced thermal load and the improved system efficiencies proposed here, the overall system energy balance is much improved. Figure 5 illustrates the solar input and required power for this proposed system. The data in this chart assumes no auxiliary power input.

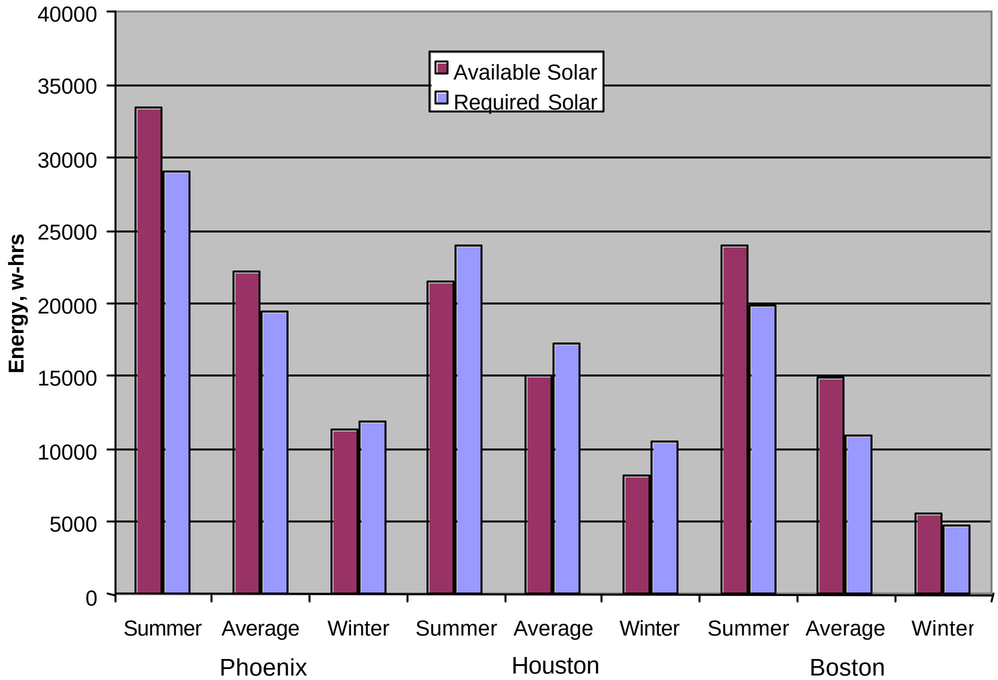

Figure 4. Energy Margin in Three U.S. Cities

As shown, the system has positive annual margins in several of the location/season combinations. However, daily or weekly weather patterns may not allow adequate cooling in some cases even though the annual margin is positive. A more detailed analysis of the operation of the system is presented in the modeling section of this report. The annual margin calculations were based on the information in Table 4.

Table 4.   Calculation Assumptions

Season	Phoenix Summer	Phoenix Average	Phoenix Winter	Houston Summer	Houston Average	Houston Winter	Boston Summer	Boston Average	Boston Winter	
Trailer Overall R	52.4	52.4	52.4	52.4	52.4	52.4	52.4	52.4	52.4	BTU/Hr/F
Trailer Temp	0	0	0	0	0	0	0	0	0	Deg F
Ambient	93	73	54	83	68	50	74	51	29	Deg F
Delta T	93	73	54	83	68	50	74	51	29	Deg F
Daily Load	4873	3825	2830	4349	3563	2620	3878	2672	1520	BTU/hr
Daily Load	1428	1121	829	1275	1044	768	1136	783	445	Watts
Daily Load	34278	26906	19903	30592	25064	18429	27275	18798	10689	Whr
Evap dT	15	15	15	15	15	15	15	15	15	Deg F
Cond dT	25	25	25	25	25	25	25	25	25	Deg F
COP	1.18	1.39	1.67	1.28	1.45	1.74	1.38	1.72	2.27	W/W
Design Margin	0	0	0	0	0	0	0	0	0	Whrs
Required Solar	29048	19372	11921	23975	17247	10568	19812	10899	4699	Whrs
Solar Input	41840	29582	16197	30684	23169	13640	31891	21352	8583	Whrs
Solar Utilization	0.8	0.75	0.7	0.7	0.65	0.6	0.75	0.7	0.65	Multiplier
Useful Solar	33472	22187	11338	21479	15060	8184	23918	14946	5579	Whrs
Auxiliary Input	0	0	0	0	0	0	0	0	0	Whrs
Total Input	33472	22187	11338	21479	15060	8184	23918	14946	5579	Whrs
Energy Margin	4424	2814	-583	-2497	-2187	-2384	4107	4047	880	Whrs
Margin	**15%**	**15%**	**-5%**	**-10%**	**-13%**	**-23%**	**21%**	**37%**	**19%**	%
PCM H of F	101	101	101	101	101	101	101	101	101	BTU/lbm
Duration	48	48	48	48	48	48	48	48	48	Hrs
Load	233914	183610	135821	208762	171034	125760	186125	128275	72941	BTUs
PCM	2321	1822	1347	2071	1697	1248	1846	1273	724	lbm

Auxiliary Power

Even with these improvements in overall system efficiency and reductions in thermal load, the solar input will not likely be able to maintain freezer conditions 100% of the time in all weather conditions. Some form of auxiliary input power will be needed, at least in the near term. The optimal source for this power is dependent on the amount of power required and frequency of use. Several candidate sources of power are available.

1. Engine Driven Alternator/Generator. An enlarged engine mounted alternator/generator could be used periodically to provide power to drive the refrigeration system. In many cases, this may be available naturally from the normal operation of the truck. But in some cases, the truck engine may need to be idled only for the purpose of providing this back-up power.

2. Auxiliary Power Unit (APU). Several companies promote small diesel generator products that mount on the tractor. This unit provides environmental control for the engine and tractor cabin. This unit could be operated to supply auxiliary power to the refrigeration unit during periods of cloudy weather. Since the use of an APU also benefits the tractor (avoids main engine idling), this dual use technology could be an optimal system approach.

3. Plug Connection. Another alternative is to provide an electrical input to the refrigeration system, but the truck driver would be required to find such available power (likely 220VAC) and to stop the truck for "charging." This may only be

feasible for specific truck operations that are commonly near available grid power. This is not likely feasible for long haul operations.

An important factor in determining the choice of auxiliary power is whether to mount the device on the tractor or trailer. A trailer-mounted device has the added benefit of allowing the trailer refrigeration system to operate 100% independent of the tractor. Option 2 and 3 allow this scenario.

5. Conceptual System Design

Based on the technological improvements recommended in this report, a simple conceptual design of a PV refrigerated trailer is presented (Figure 6). The trade between battery energy storage and PCM energy storage is yet to be resolved. However, this system concept shows a design based on PCM storage.

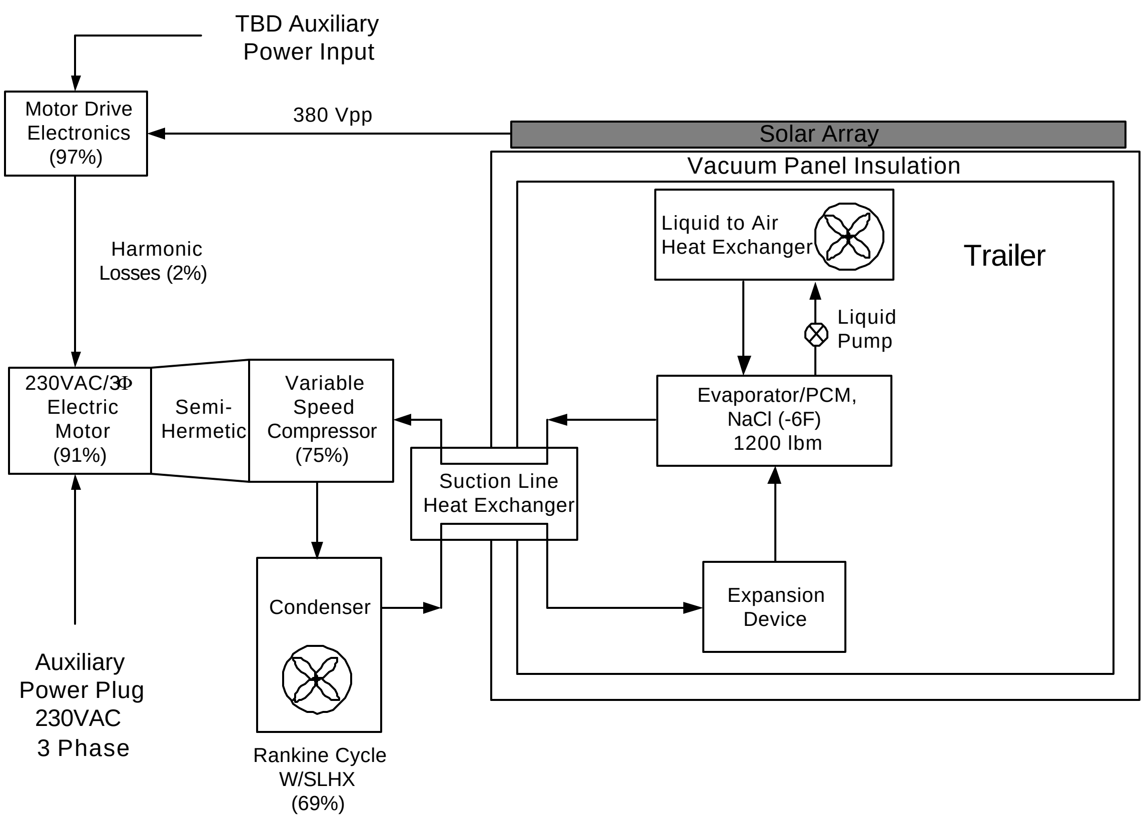

Figure 5. System Schematic

(figures in parentheses indicate component efficiency)

This system is composed of a high efficiency variable speed induction motor compressor and a thermal storage system. The proposed thermal storage system uses a 23% NaCl aqueous eutectic solution, which has a freezing point of –6°F. The compressor is a variable speed unit that allows for operation under a range of solar insolation levels. The compressor motor is a 3-phase induction type motor driven by a high efficiency variable frequency inverter that matches compressor speed to solar input. The array voltage is wired for 380 Vpp to avoid any DC to DC conversion losses. The motor drive electronics is ideally suited to 380VDC to operate a 230VAC 3-phase motor. The PCM is sized for 18 to 24 hours of trailer cooling (without any compressor operation).

6. Performance Modeling

In order to better understand the performance of this system, a math model was constructed in an Excel spreadsheet to predict real time performance of the system and to allow for technical trades between different subsystem performance levels. These trades were for the purpose of understanding the relationship between such factors as the amount of PCM, the amount of auxiliary power use, the insulation quality of the trailer, the efficiency of the refrigeration compressor and electronics, etc. The model used hourly insolation and temperature data for four U.S. cities: (1) Phoenix, (2) Houston, (3) Boston, and (4) Reno. The model used this hourly data over a period of one year in order to make a reasonably accurate and detailed prediction of the performance of this system.

The following charts show the results of the modeling for the four U.S. cities (Figures 7 through 22). The assumptions used in the model are listed in Table 5 and represent the best estimate of the performance that can be realistically achieved with a modest amount of technology development. Freezer operations (0°F) were assumed.

Table 5. Modeling Assumptions

Input Data	Value	Units	Comment
City	HOUSTON		TMY2 Database
Trailer UA	60	BTU/Hr/ °F	Industry Software
Trailer Temp	0	°F	Design Assumption
Temp Margin	3	°F	Design Margin
Compressor	40%	100% = 06DR337	Model Variable
Array Nominal	5760	Watts	Model Variable
Nominal Temp	77	°F	Model Variable
Temp Factor	-0.18	% /°F	Model Variable
Panel dT	30	°F	Engineering Estimate
Electrical Eff	93%		Vendor Data + Wire Loss Estimate
Motor/Comp Eff	60%		Manufacturer's Data
Cond dT	20	°F	Engineering Estimate
Evap dT	10	°F	Engineering Estimate
Comp Min	50.0%		Standard Limit = 50%
2-Stage Compr	0	1=Yes	Model Option
Max EER	18		Engineering Estimate
PCM	1200	Lbm	Model Variable
H of F	100	BTU/lbm	23% NaCl/Water Solution
PCM Cp	1	BTU/lbm/°F	23% NaCl/Water Solution (Est.)
Trailer Cp	300	BTU/°F	Rough Estimate
Fan Power	25%	of Total Input	Engineering Estimate
Use Aux Power	10000	if reserve below	Model Assumption
Aux Power	2500	Watts	Model Variable
Min Solar Util.	80%		Engineering Estimate

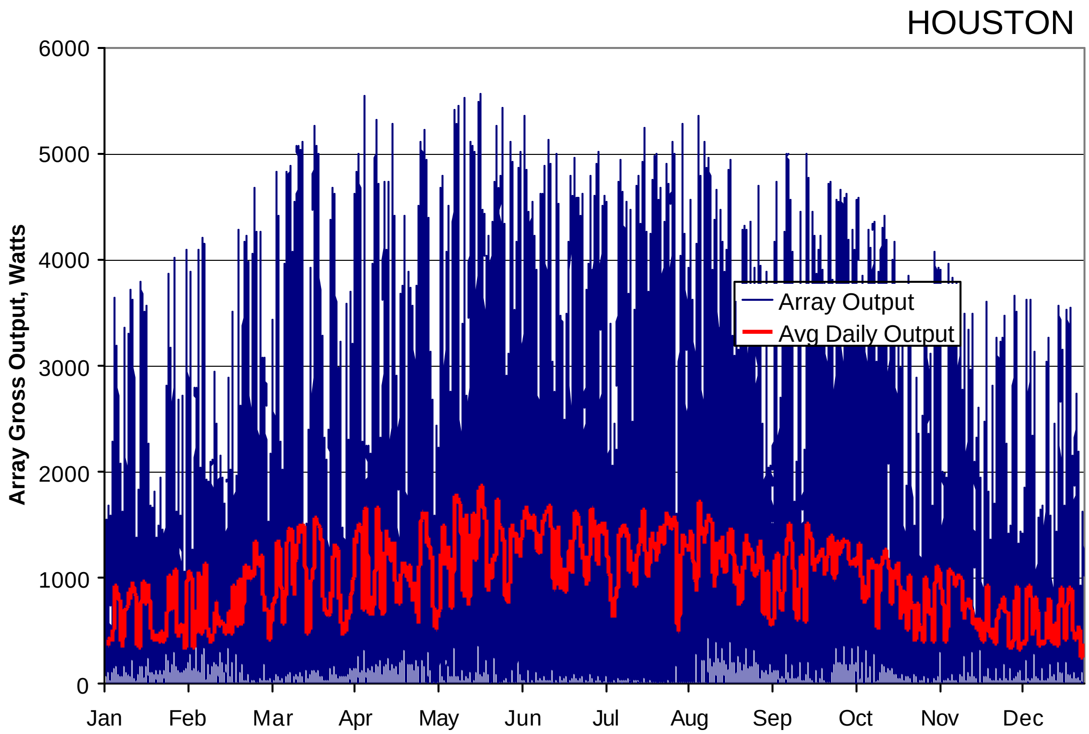

Figure 6. Solar Array Output (Houston)

A 53' trailer with a 5760 watt (nominal) roof mounted array was assumed. 5760 watts assumes the top of the trailer to be fully populated with high efficiency, but not exotic solar modules. The lower line represents the average power collected over a 24 hour period. For Houston, the annual average array output is almost exactly 1 kW. (8.8 MW-Hrs)

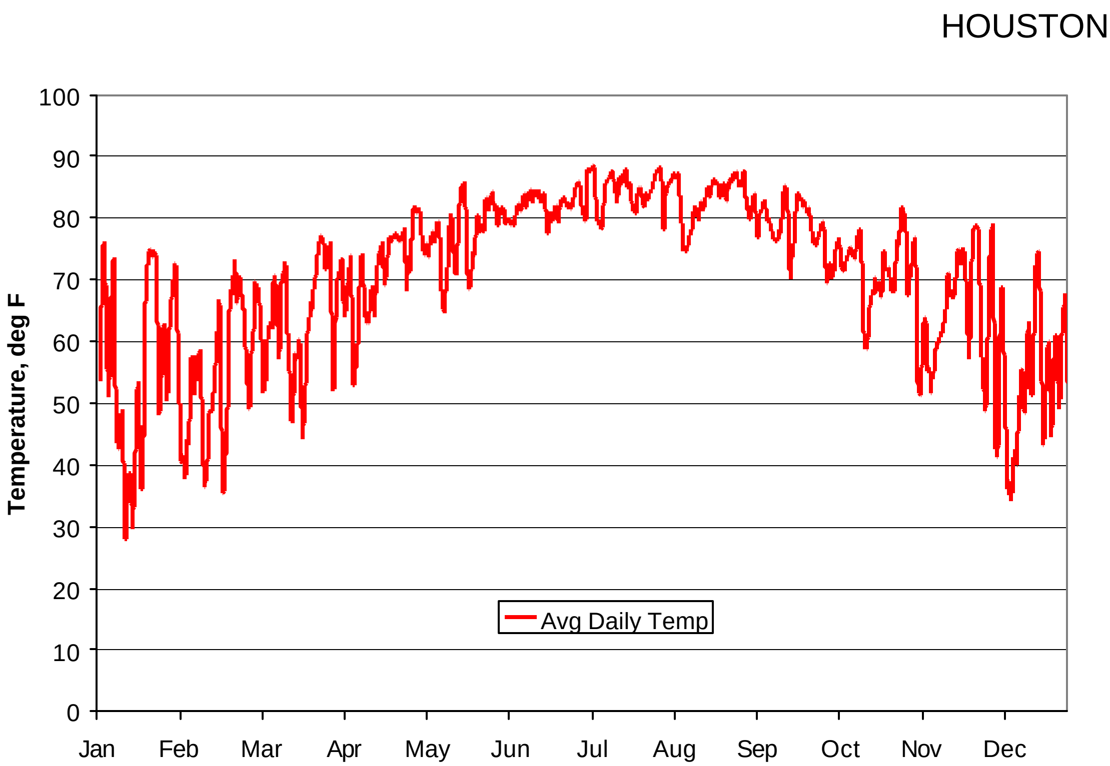

Figure 7. Ambient Temperature Data (Houston)

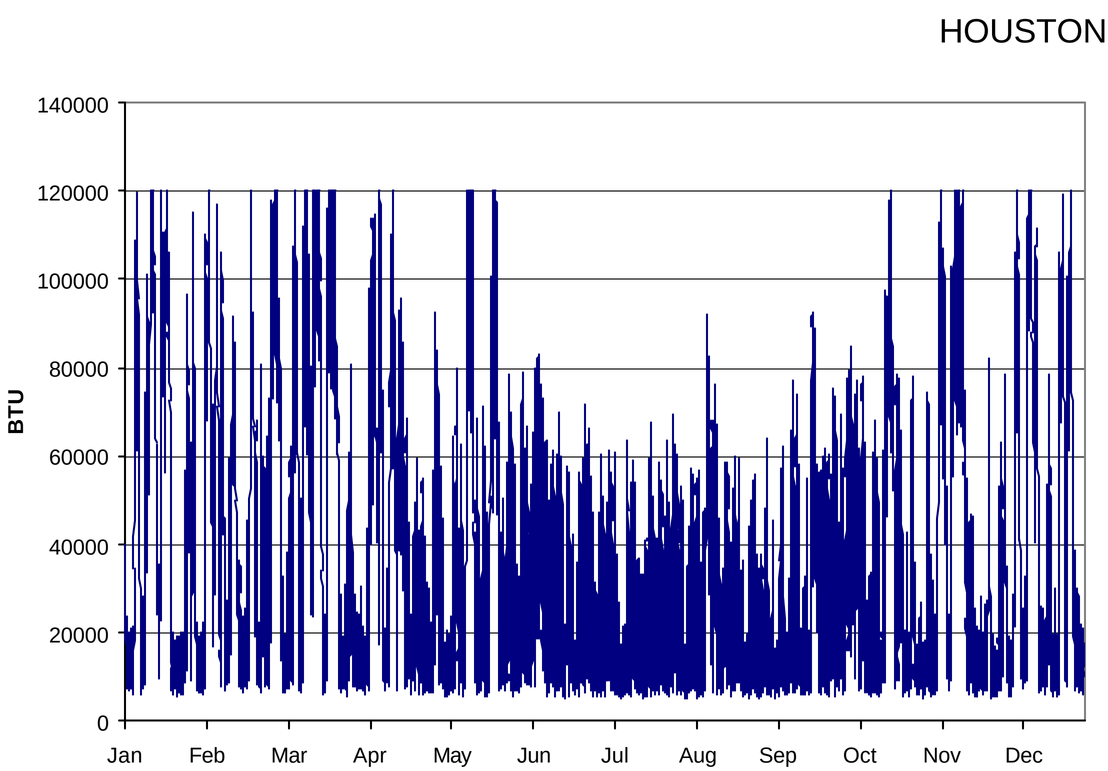

Figure 8. Thermal Reserve Status (Houston-Freezer)

From the thermal reserve chart, it can be seen that the maximum reserve (120,000 BTU) is not achieved too often. The minimum reserve observed on the chart of about 7,000 BTUs is the point at which the auxiliary power is switched on, so the reserve does not dip below this level. The actual auxiliary power unit use profile is seen on the following chart. It tends to run more often in the summer months, as expected. In this case the APU runs 980 hrs per year.

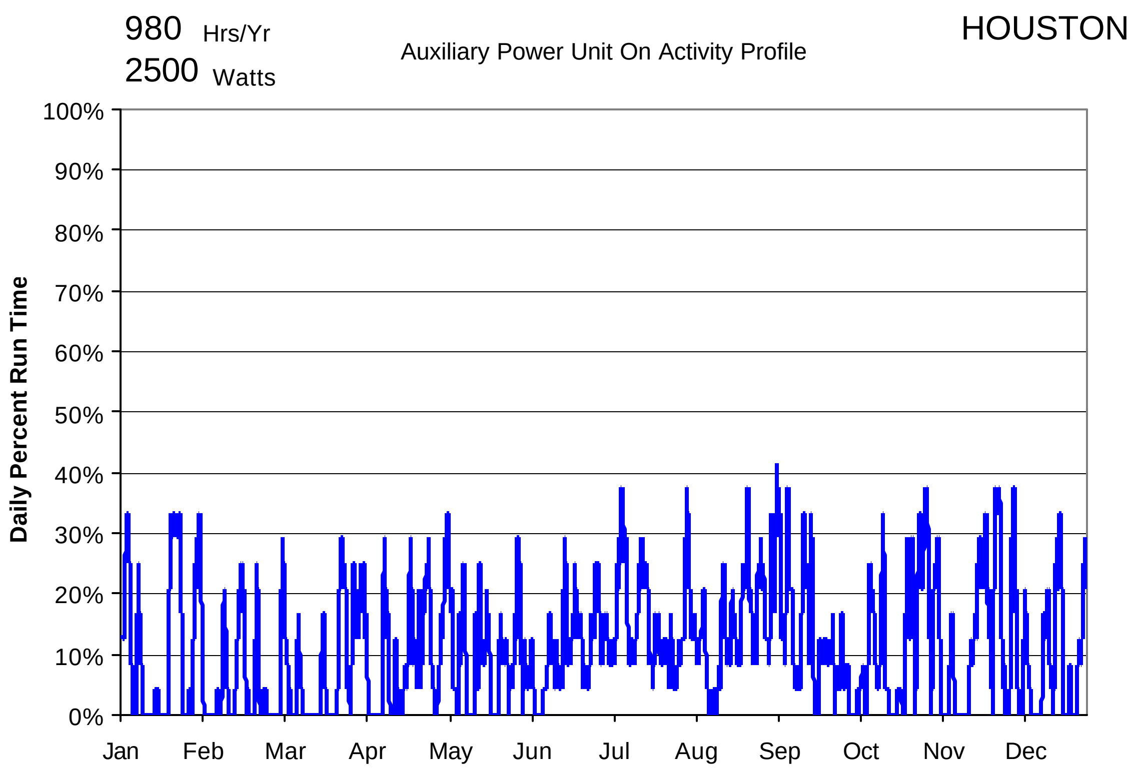

Figure 9. Auxiliary Power Use Profile (Houston-Freezer)

The same data are now presented for the other cities modeled in this analysis.

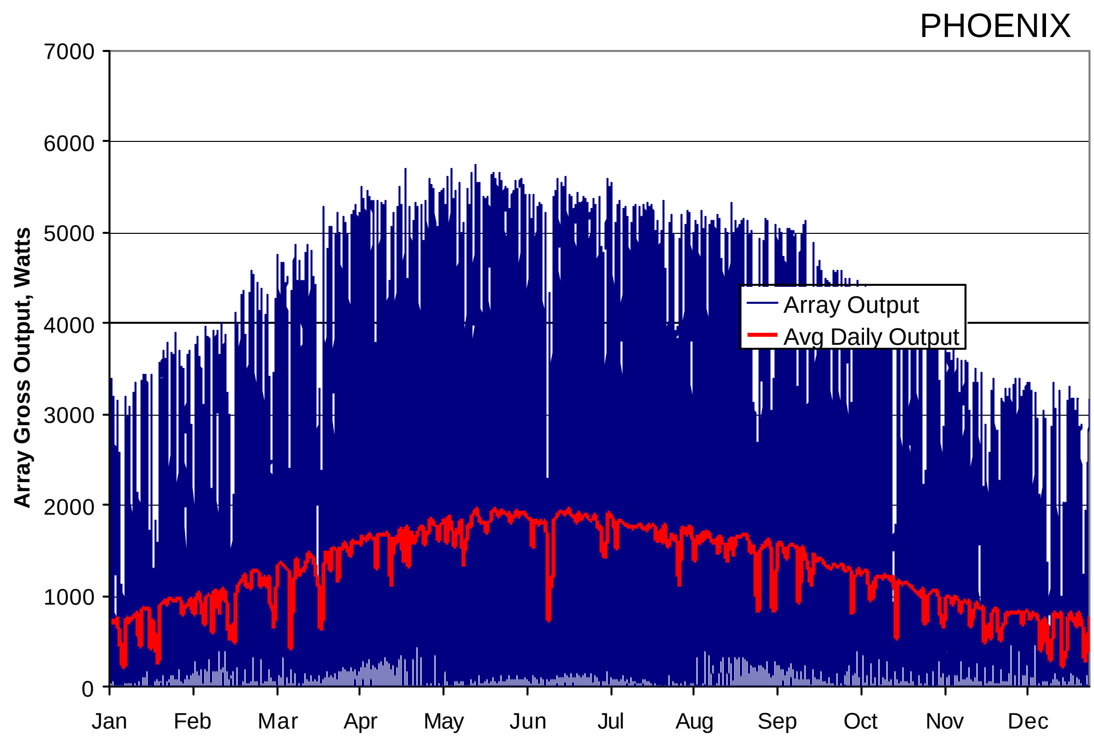

Figure 10. Array Output - Phoenix

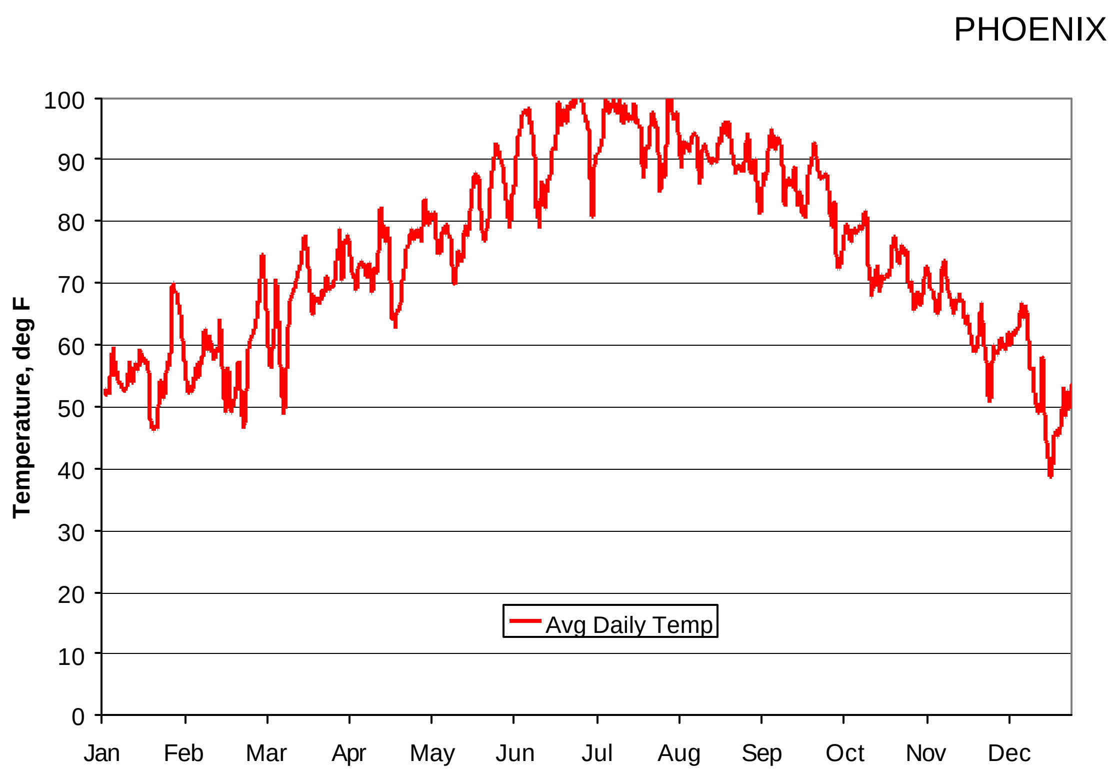

Figure 11. Ambient Temperature - Phoenix

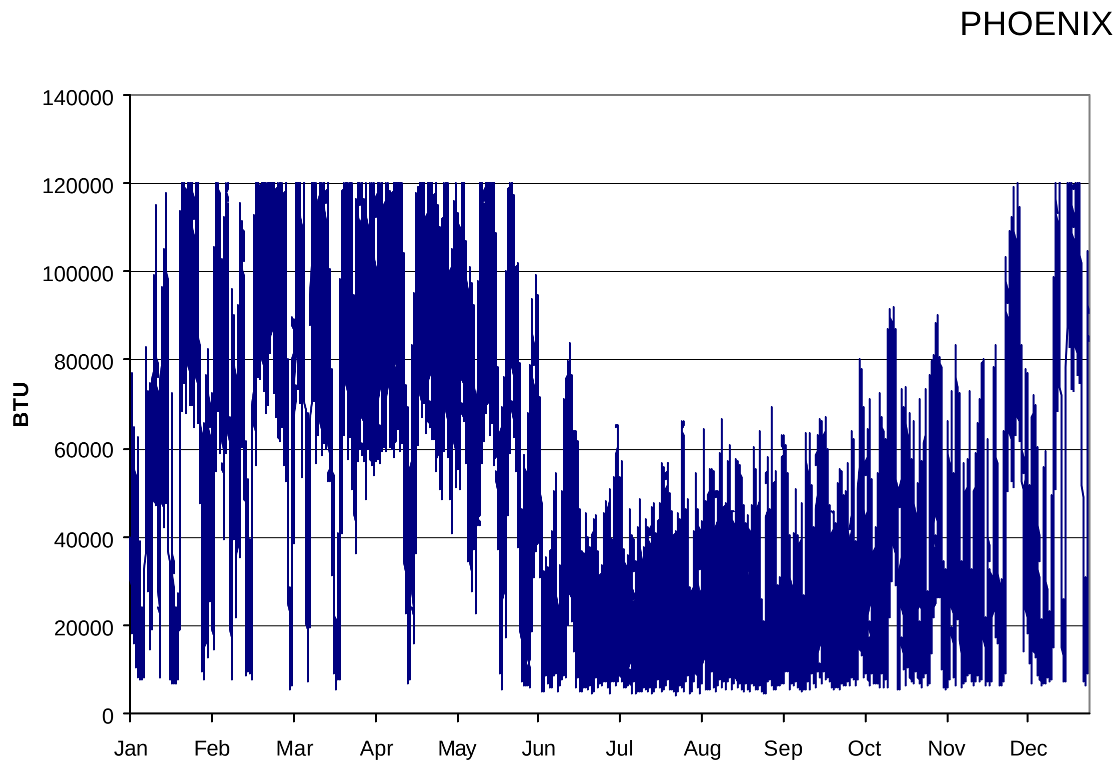

Figure 12. Thermal Reserve Status - Phoenix

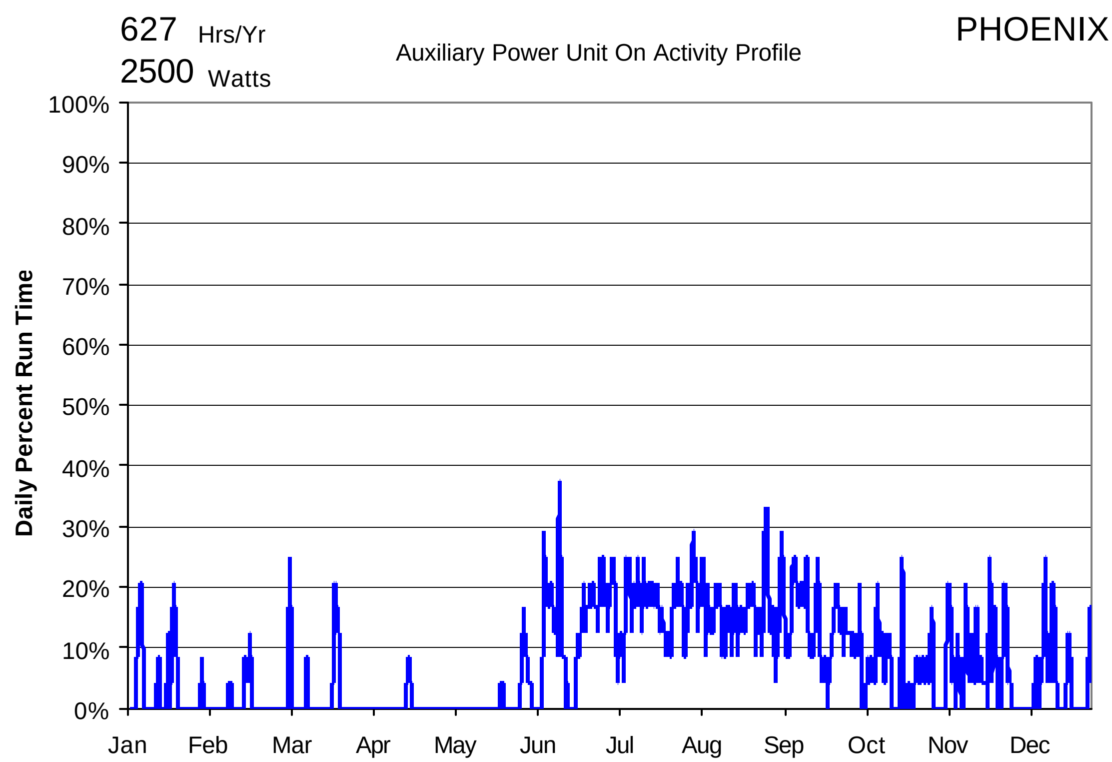

Figure 13. APU Activity - Phoenix

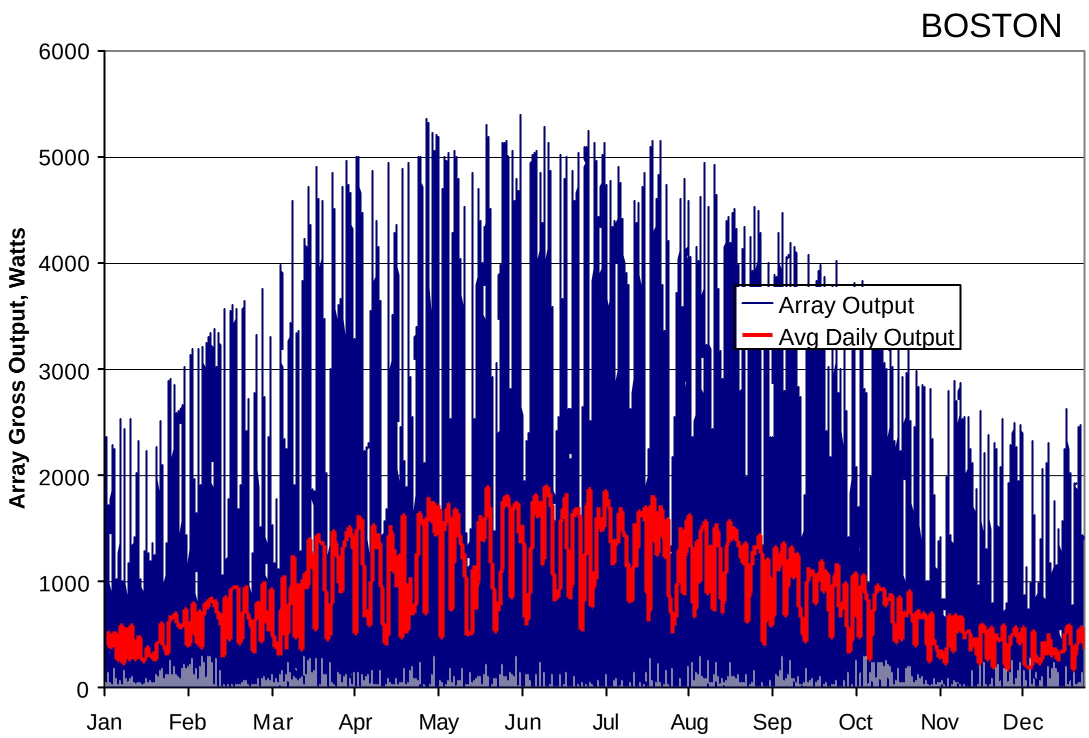

Figure 14. Array Output - Boston

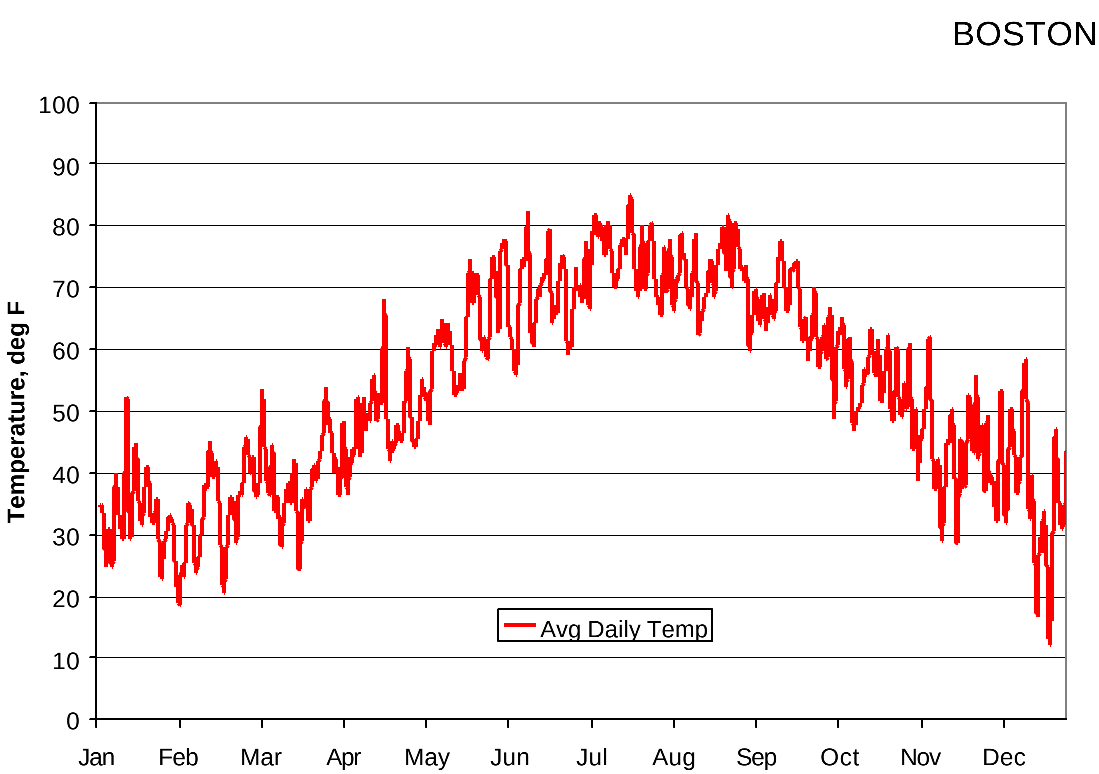

Figure 15. Ambient Temperature - Boston

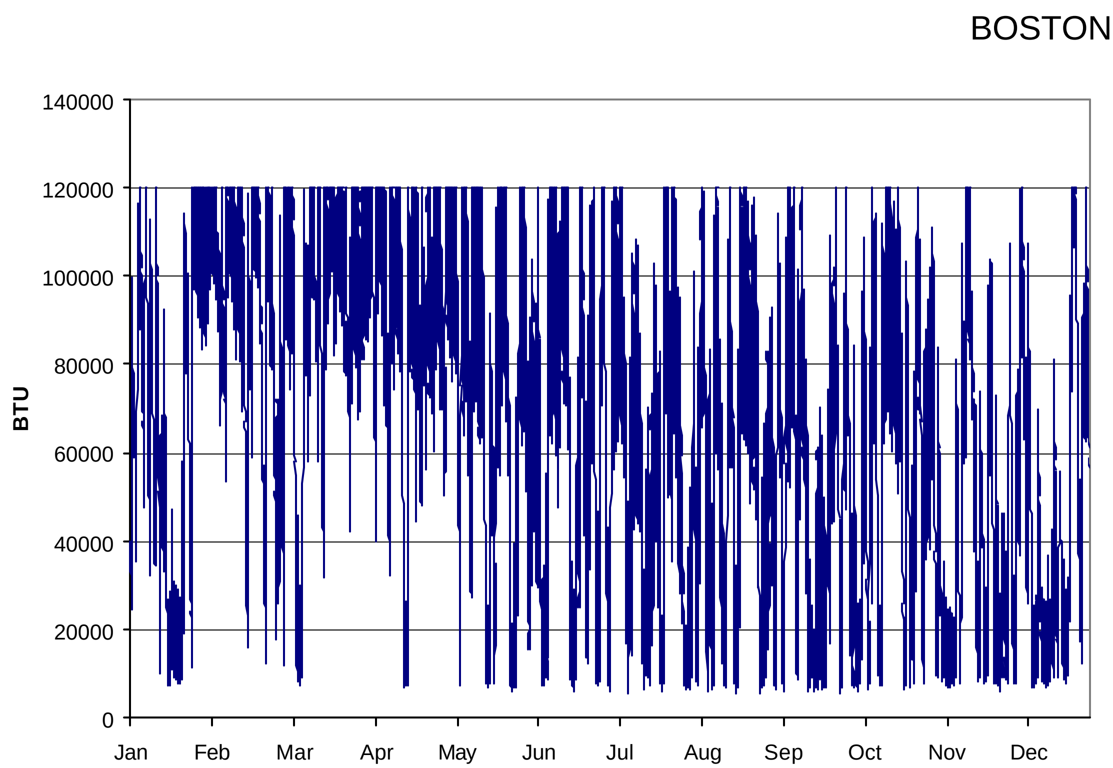

Figure 16. Thermal Reserve - Boston

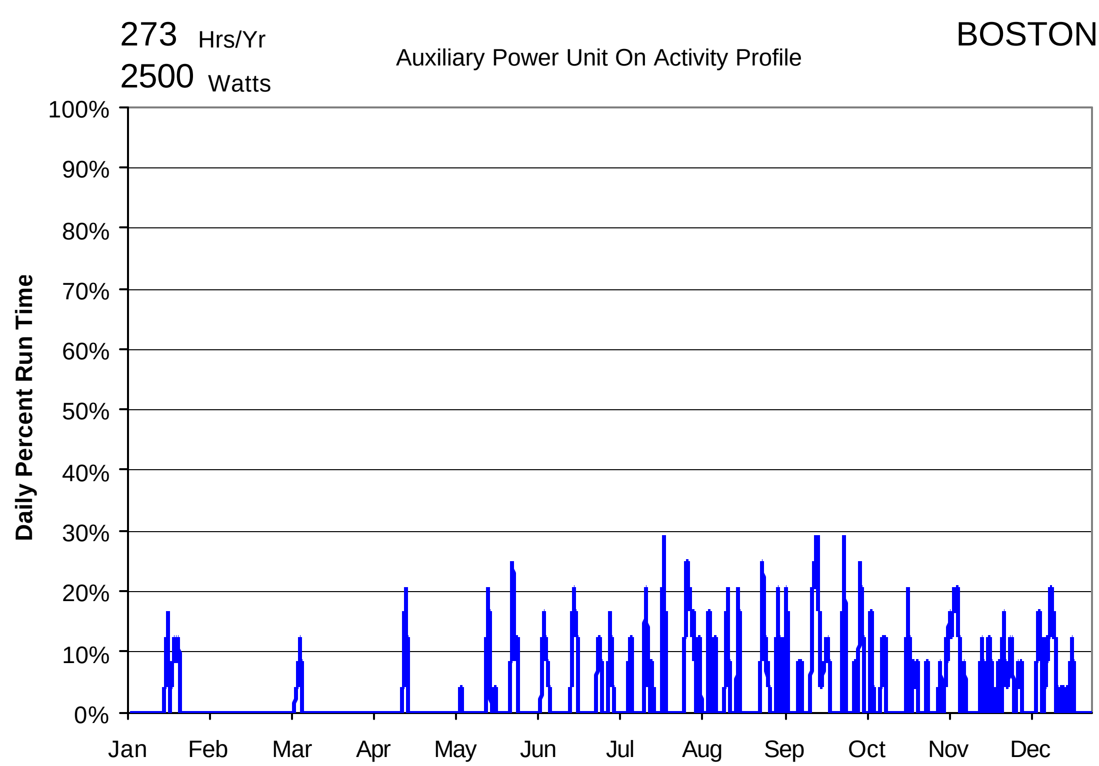

Figure 17. APU Activity - Boston

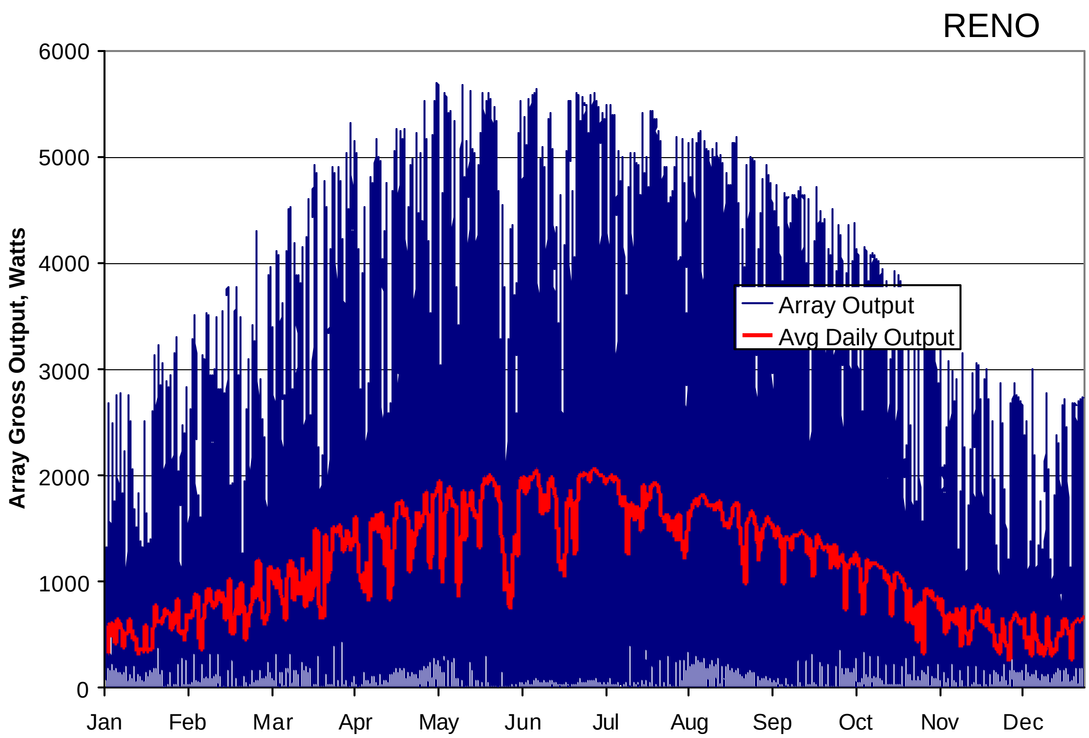

Figure 18. Array Output - Reno

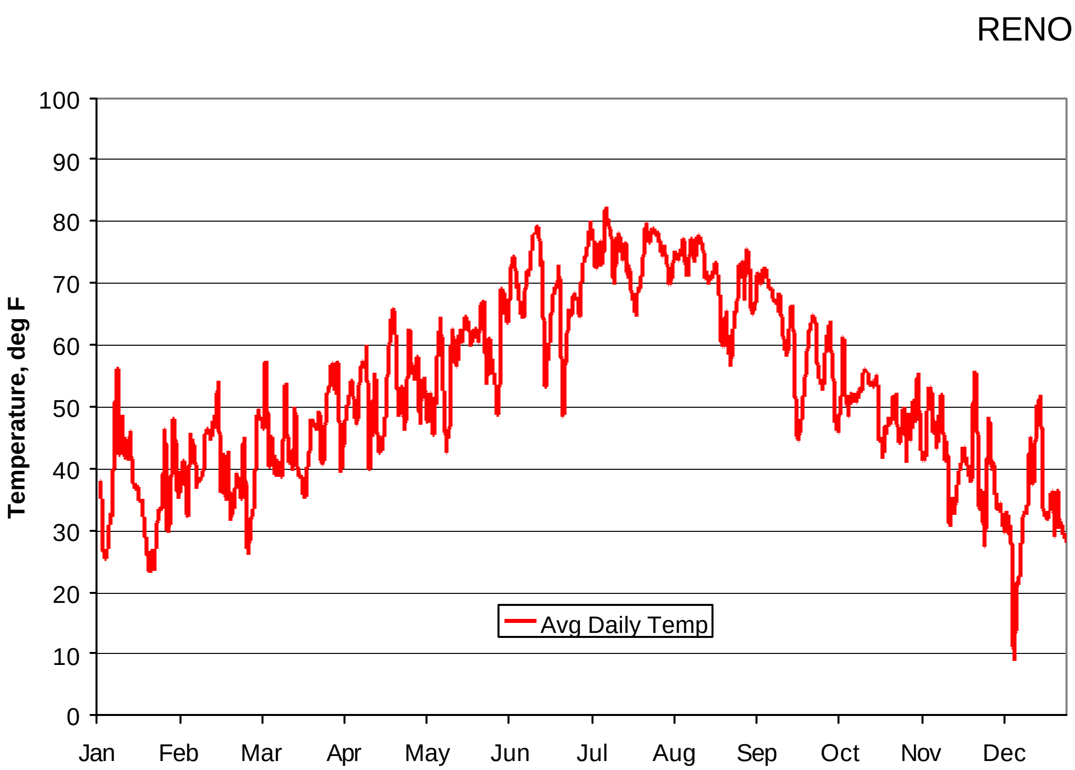

Figure 19. Ambient Temperature - Reno

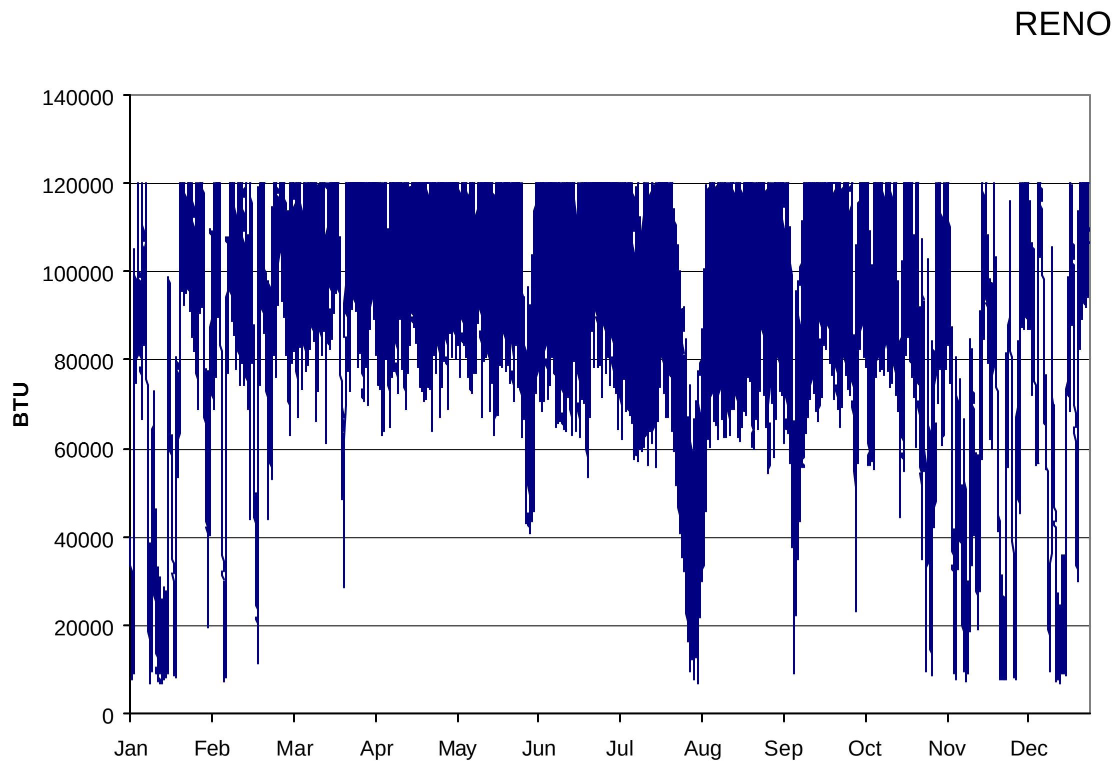

Figure 20. Thermal Reserve - Reno

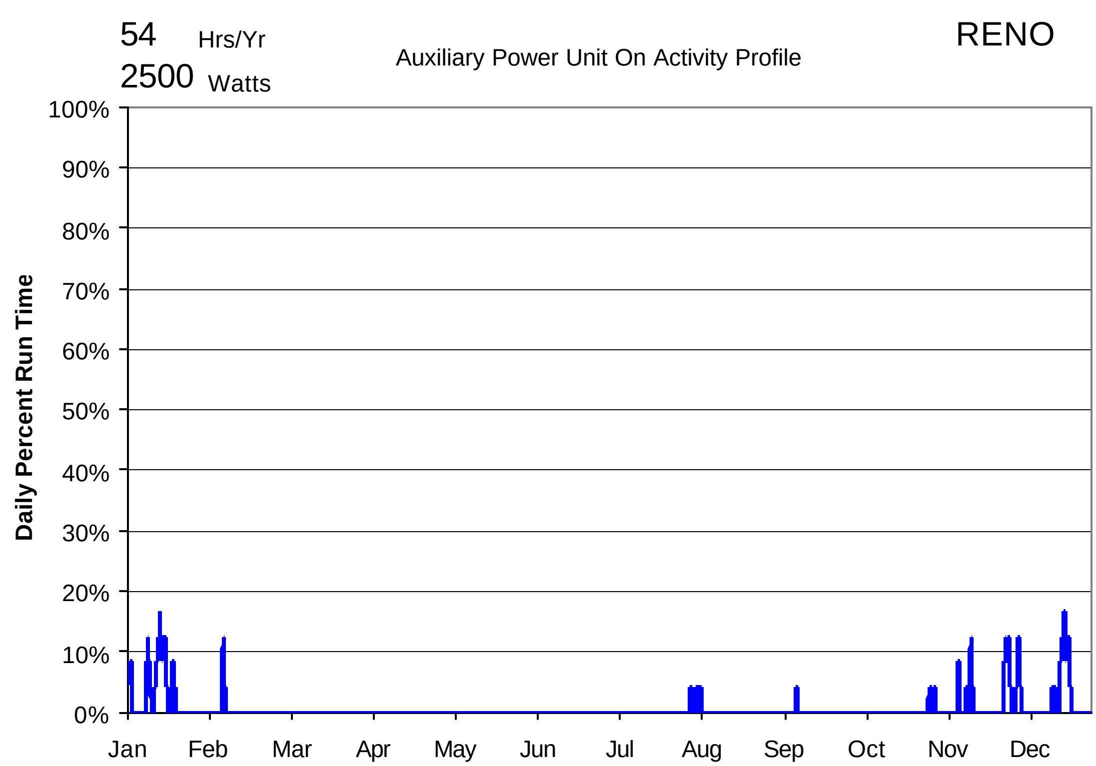

Figure 21. APU Activity - Reno

A simple analysis of refrigeration operation (38°F) was also modeled, and the results for Houston are shown in Figure 23. Accurately modeling a refrigeration load is more complex than modeling a freezer load because the respiration loads generated by different refrigerated products vary considerably.

Fresh vegetables are living tissues and have a continuing need for oxygen for respiration. During respiration, sugars in the vegetables convert to heat energy. For example, 20,000 lbs of asparagus cooled to 39°F can produce enough heat of respiration to melt 7,900 lbs of ice during a cross-country trip[2]. Asparagus has an unusually high respiration rate. The average refrigerated produce has only 15% of the respiration rate of asparagus.

The respiration rate of asparagus and several other types of produce can generate thermal loads 2 to 3 times greater than the basic wall heat load of the trailer. Therefore, to accurately predict the performance of a solar cooled trailer carrying refrigerated produce, the type of produce must be known. This level of analysis in the modeling was not performed. However, based on the levels of respiration observed in these common vegetables, some refrigerated cargo may present a greater thermal load than the freezer modeling conditions.

The modeling results for Houston are much improved if the assumed load is refrigeration, and the produce has no or low respiration loads (e.g. butter, cheese, eggs, apples, celery, carrots, or potatoes). The APU run-time decreased from 980 hours per year to 75.

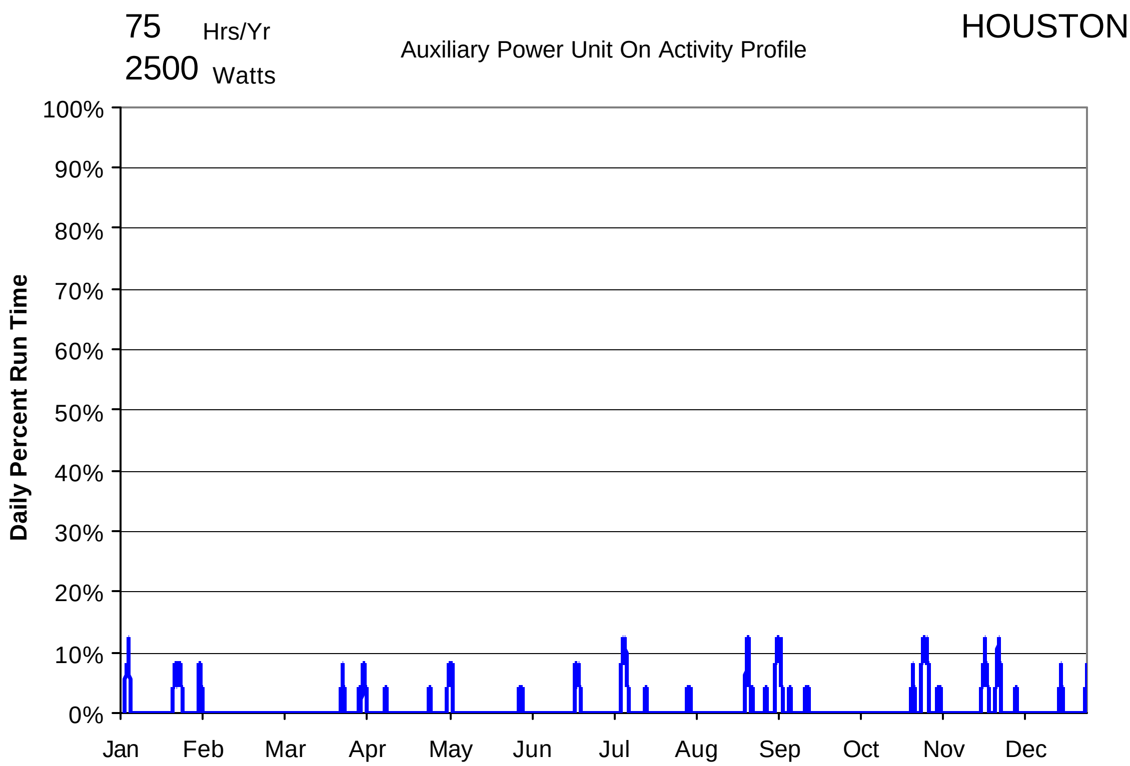

Figure 22. Auxiliary Power Use Profile

(Houston, Refrigerator, No/Low Respiration Load)

7. System Trades

The system model allows for trade studies to be performed in order to see the effect of the performance of one design element on some aspect of the performance. For instance, as the insulation value of the trailer changes, how does this effect run time of the auxiliary power unit, or, how does the quantity of phase change material effect the run time.

Trades were performed to understand the relationship between a given engineering variable and the run-time of the Auxiliary Power Unit. The following charts (Figures 24 to 30) illustrate these trade-offs.

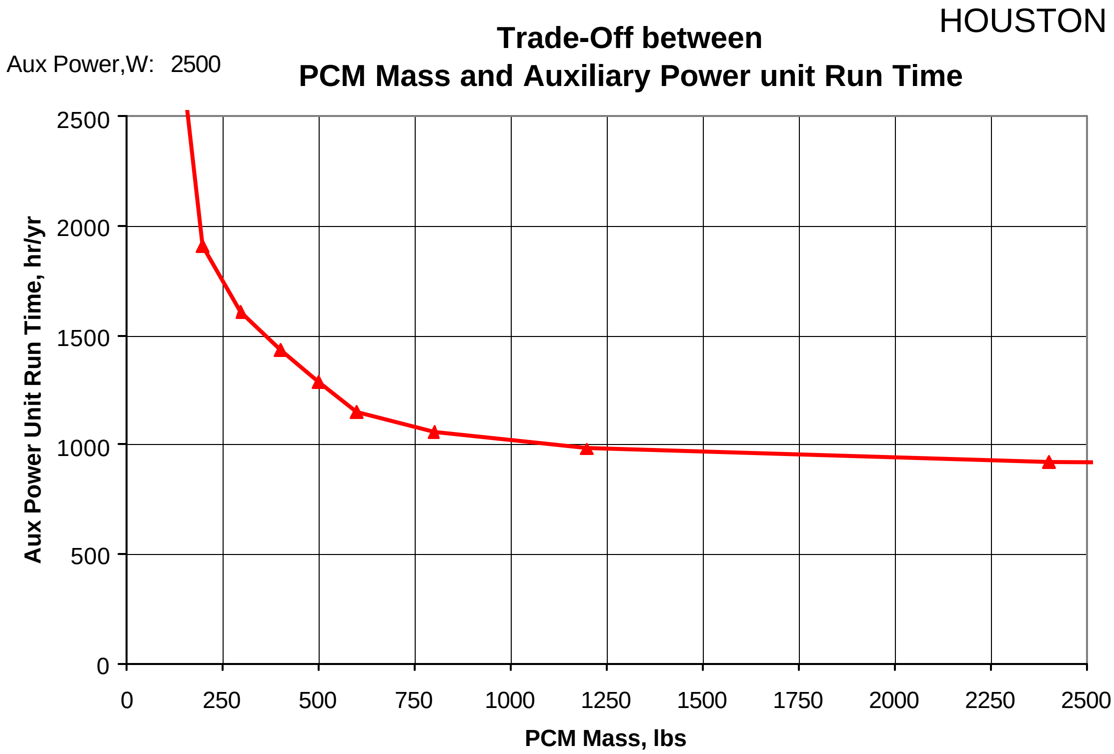

Figure 23. PCM Mass vs. Run Time (Houston)

As can be seen, the more PCM mass that is used, the less often the auxiliary power unit must run. From the general shape of the curve, for Houston, it would seem that PCM mass levels above 800 lbs do not significantly reduce the APU run time. If the cost of operating the APU were estimated on an hourly basis and the cost of the PCM mass were known (initial and operational cost), an economic break-even could be determined. Future work might address this economic break-even.

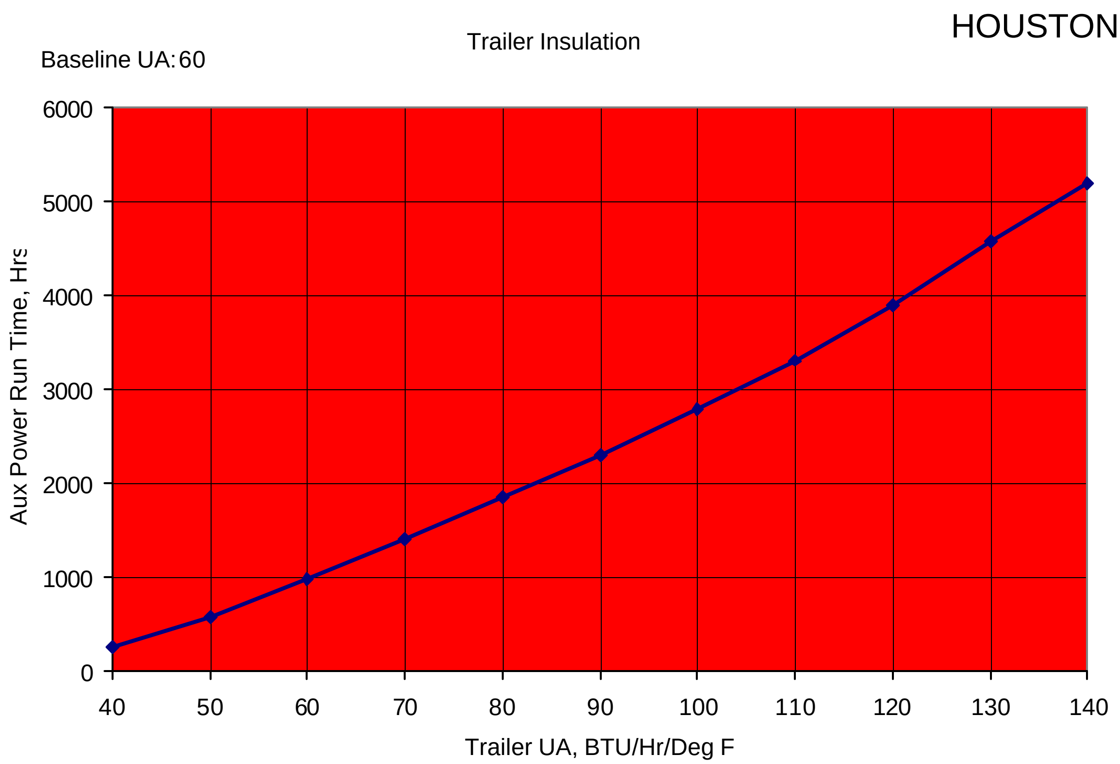

Figure 24. Trailer UA vs. Run Time (Houston)

As can be seen, the better the trailer insulation, the less the APU is required to operate. Current trailer insulation technology achieves a UA value of about 90. The estimated performance with vacuum panel insulation is 60. Continued improvements in the insulation of the trailer seem to have a strong impact on the run time of the APU. Achieving a UA of 60 or less would be an important goal of a development effort.

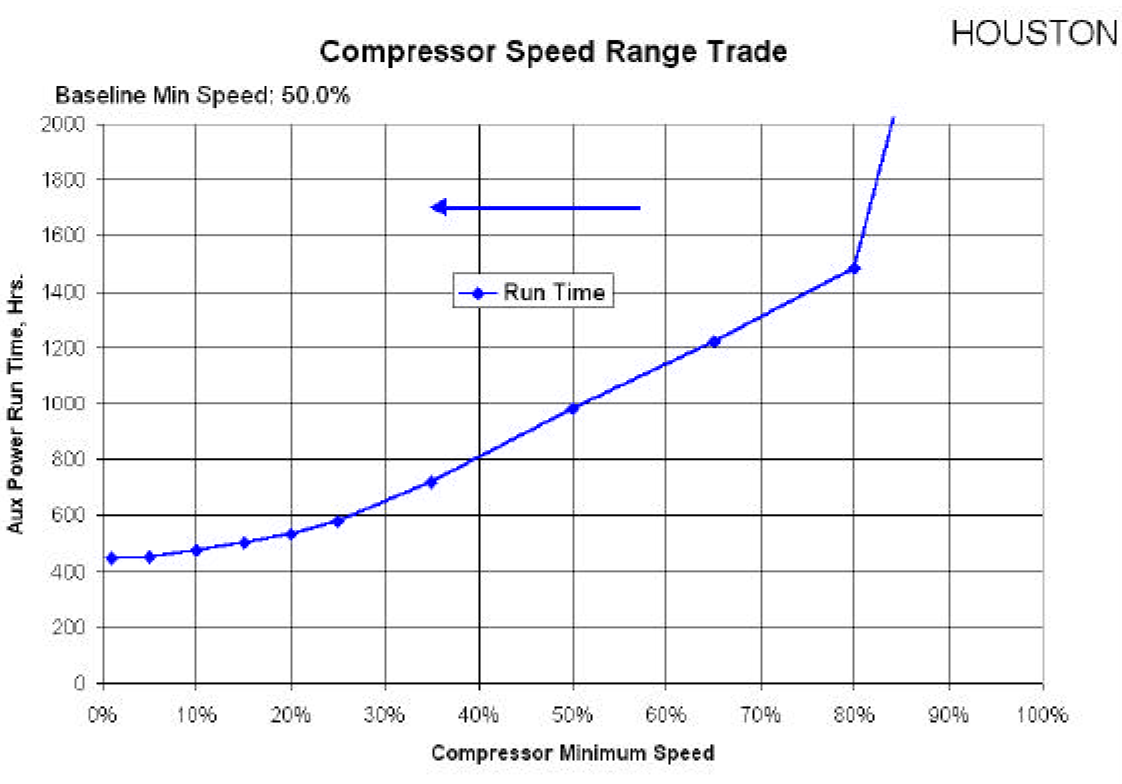

Figure 25. Compressor Speed Range vs. Run Time (Houston)

Given a PCM based design, it is important for the compressor to have a wide operating speed range. This allows the compressor to operate in low sun conditions and make better use of the overall available solar energy. This chart illustrates the reduction in APU run time afforded by extending the operating speed range of the compressor. Most compressors can operate over a range of 2:1 (50% minimum speed). Increasing the operational range of the compressor has a strong positive impact on the overall performance of the system. In this case, a compressor speed range down to 25% of full speed has a strong positive impact on reducing APU runtime.

Of course, if battery storage is selected as the primary energy storage, variable speed is much less critical a feature.

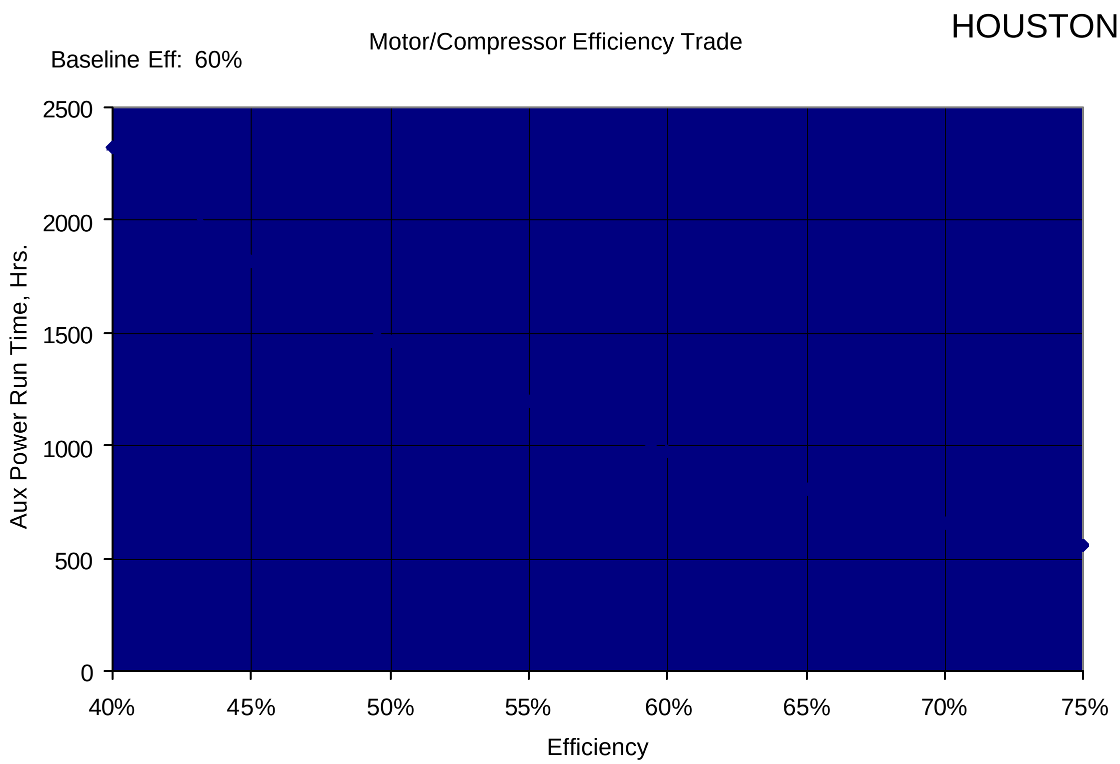

Figure 26. Compressor Efficiency vs. Run Time (Houston)

This chart illustrates the relationship between the efficiency of the compressor and the run time of the APU. It is reasonable to assume a motor/compressor combined efficiency of at least 60% will be achieved. The estimate of 60% was determined by assuming a motor efficiency of 91% and a compressor isentropic efficiency of 80%. The motor isentropic efficiency estimate is based on R-134a operating at freezer conditions (10:1 pressure ratio). This represents very good current reciprocation or scroll technology (no technology improvements). This motor compressor efficiency combines to 71% (80% x 91%). However, this is achieved only near the design points of the motor and compressor. Given the highly variable speed operation, an overall compressor efficiency of 60% should be reasonable and achievable. The system may achieve higher overall efficiency than 60%. The increases in efficiency afforded by the use of more exotic compressor technologies must be balanced with the increased cost associated with their use.

Higher efficiency motor and compressor technologies are available, but some development effort may be required, and the service infrastructure for radically different compressor technologies is not developed. This lack of service infrastructure may be a significant practical impediment to market acceptance.

However, if further analysis indicates that improvements in compressor performance are important, the development of a linear compressor for this application would be ideal. Linear compressor technology can offer better efficiency, lighter weight, and outstanding variable capacity range and performance, but currently no linear compressor is developed for this size application.

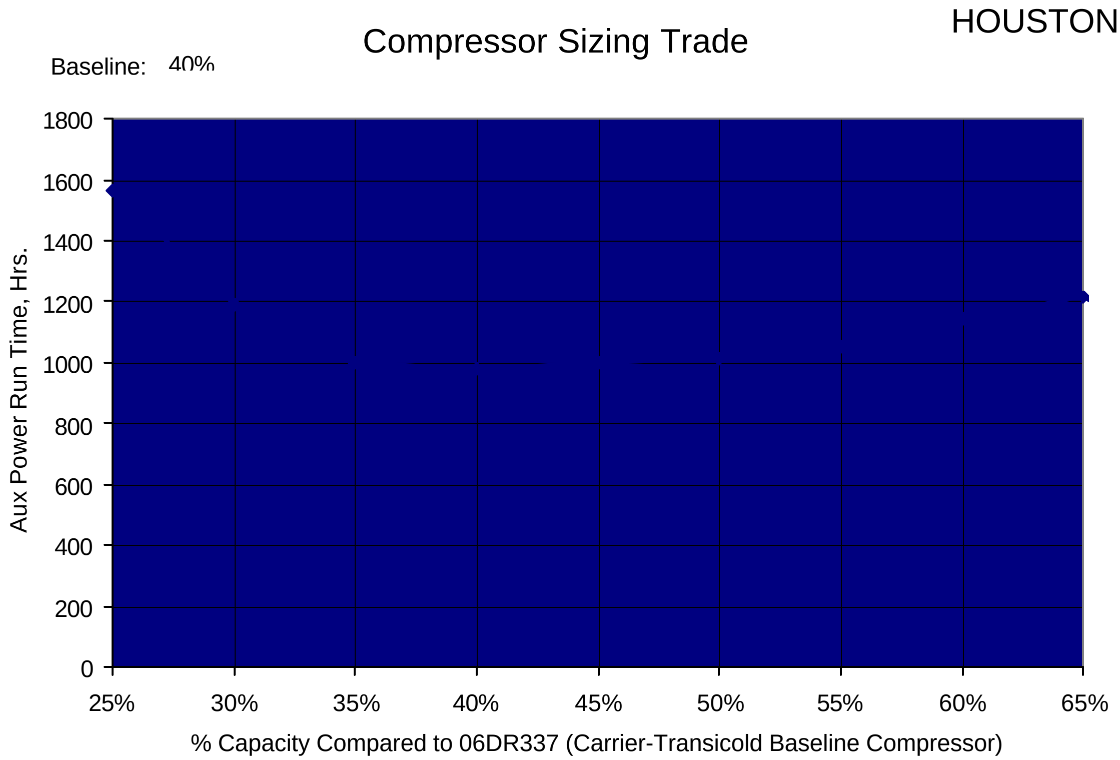

Figure 27. Compressor Size vs. Run-Time (Houston)

In the case that PCM technology is used, it is important to match the compressor power to the amount of power produced by the array. If the compressor is too large, it will not be able to operate at low solar insolation levels. If the compressor is too small, it will reach full speed early in the day and higher solar power levels will not be used. This study indicated that a compressor that has about 40% of the capacity of an industry standard 37 cfm compressor would be a good match for a freezer application.

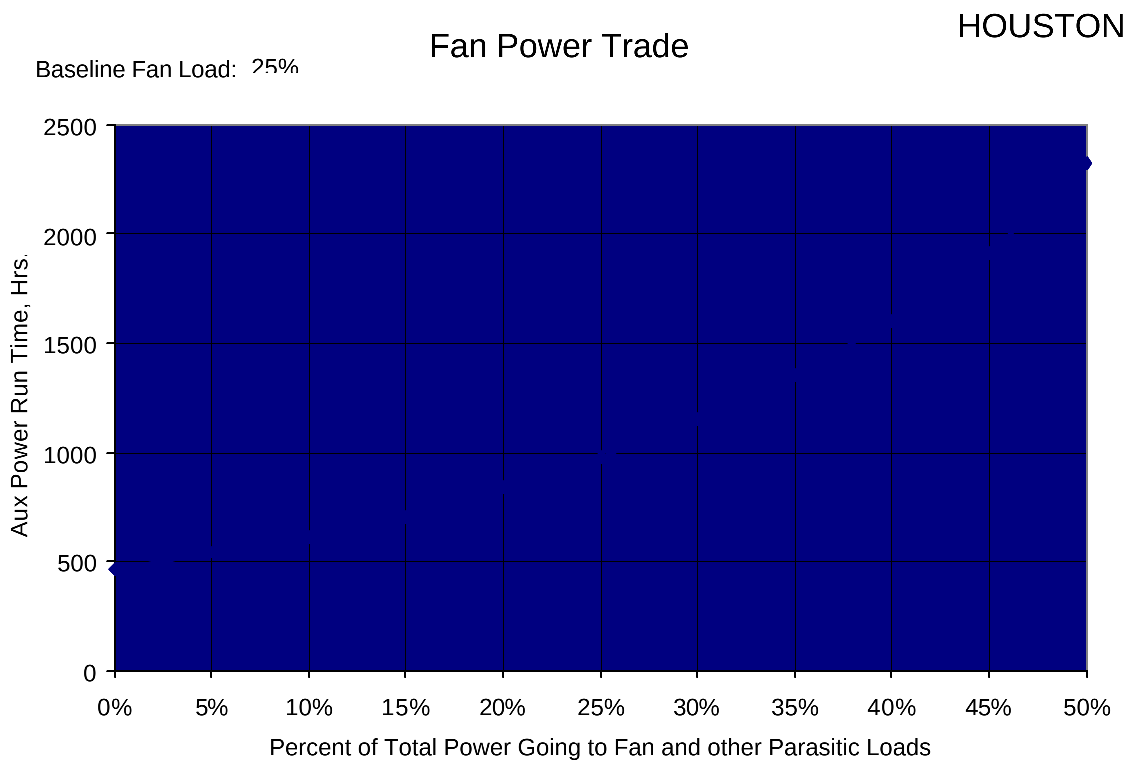

Figure 28. Fan Power vs. Run-Time (Houston)

Some fraction of the available solar input will be required to drive the fans and other parasitic loads. A value of 25% was selected based on typical HVAC equipment which was somewhat optimized to reduce fan power. Additional reduction in the parasitic power draw provides for a notable improvement and should be pursued.

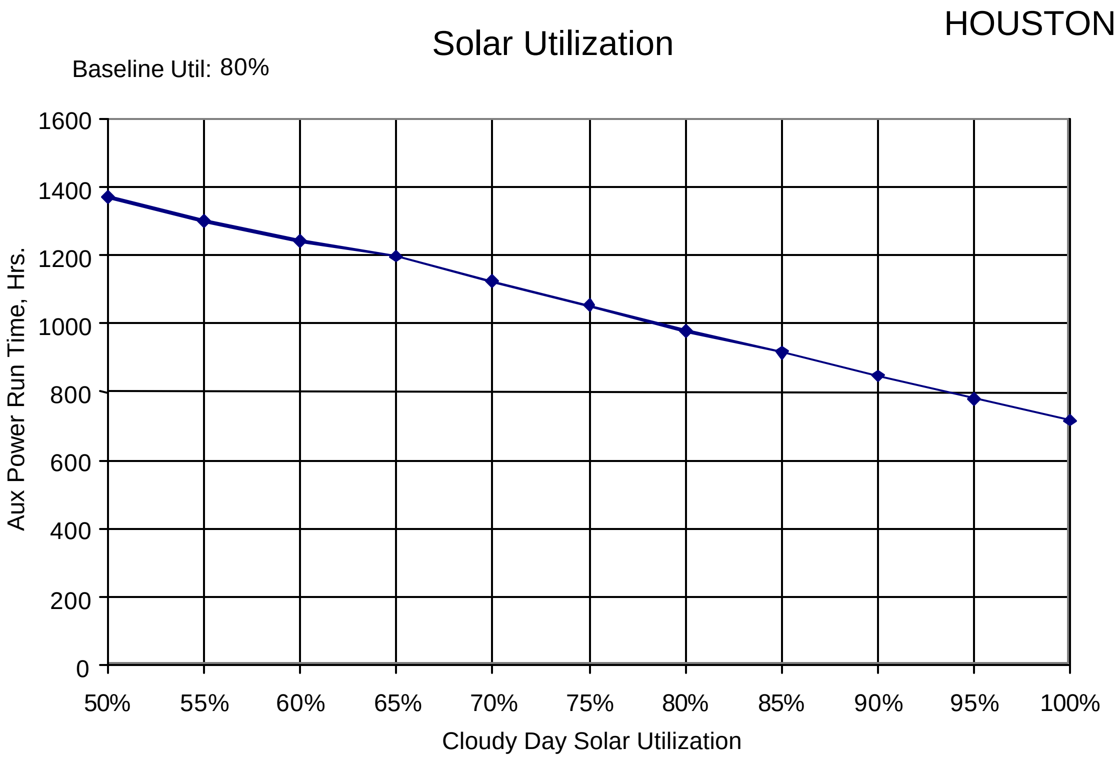

Figure 29. Solar Utilization vs. Run Time (Houston)

This "Solar Utilization" term is used to estimate the loss in system performance that typically occurs on cloudy days which is related to the stopping and starting of the refrigeration system. On cloudy days, the refrigeration system operates more frequently in a transient state, changing speed and even starting and stopping. This transient operation causes the refrigeration system to operate at a lower overall level of efficiency than would have been achieved under steady state conditions and the same average power level. Based on past observation of the impact on this effect and based on the improved transient efficiency that this system should be able to achieve with a modest amount of development, a baseline target of 80% is assumed. This means that on a sunny day the solar utilization is assumed to be 100%. On a completely cloudy day the solar utilization is assumed to be 80%. Since the transportation application will likely have more fluctuations in power input, designing the system for high efficiency during transient operation is important. 80% utilization should be achievable with a responsive motor drive and a responsive expansion valve. There are also fundamental refrigeration system design attributes that will help achieve good transient performance, such as oversizing the evaporator volume and designing to eliminate gravity induced refrigeration flow from the evaporator back to the condenser while the compressor is off.

Conclusions

During the development of the trade study, it became apparent that the most important design change from the initial work was in the area of PCM storage quantity. The initial work assumed 48 hrs of storage (~2,500 lbs). The trade studies indicted that a PCM quantity of more than 800 lbs does not reduce the APU run time significantly.

Mass and Volume Impact of PV System

The weight and volume of the PV refrigeration system is greater than the current Diesel systems. This additional weight will reduce the useful payload carrying capacity of the trailer. Tables 6 and 7 show the estimated payload weight and volume losses.

Table 6. Mass Impact

Nominal Tractor/Trailer		Solar Tractor/Trailer	
Tractor	19,000	Tractor	19,000
Trailer	15,000	Trailer	15,000
Refrig	1,610	Elec Refrig	800
Tank & Fuel	292	Solar Panels	1,050
Payload	**44,098**	Panel Mounts	210
Total	80,000	Vacuum Panels	750
		Electronics	75
		PCM	1,200
		Payload	**41,915**
		Total	80,000

5% Payload Mass Loss

Table 7. Volume Impact

• Standard 53' Trailer	• 53' Trailer	3,625
• 2.5" Insulation	• 4.0" Insulation	-231
• 3625 Cu.Ft.	• PCM	-38
	• Lower Roof	-37
	• Total	3,319

8.5% Payload Volume Loss

8. Estimated Development Cost

For the development cost estimate, it was assumed that the thermal storage system was the selected design approach.

Several major system components will need to be purchased and modified for the development effort. Table 8 summarizes these items. The cost estimates in this table include the basic equipment purchased plus an estimated cost for modifications. For example, a standard electric refrigeration unit costs about $11,000, however several modifications are expected. These modifications would likely include installing a non-standard compressor, an enlarged condenser and evaporator, alternate fan motors, and a secondary oil pump to allow for low speed operation. These modifications will require substantial engineering effort.

Table 8. Estimated Development Cost

Item	Cost Estimate	Comments
Solar Panels	72,000	5.7 kW Thin Profile Panels (Installed)
Vacuum Panels	10,000	2000 sq.ft.
Electric Refrig. Unit	20,000	Custom requirements
Aux Power Unit	15,000	W/3.5 kW Generator
PCM Container	15,000	800 lb PCM
Motor Drive Electronics	5,000	3-Phase Drive, DC Input
Trailer	40,000	53' With some Modifications
Labor (2.5 FTE)	300,000	Engineering, Assembly, Test
TOTAL Cost Est.	$477,000	

The labor estimate is based on experience developing systems of similar complexity. The PV system, trailer, refrigeration, electronics, and vacuum panels are based on telephone and written quotations. The PCM cost is an extrapolation from similar, but smaller capacity tanks. The auxiliary power system cost is a budgetary estimate in that no particular system concept has been base-lined.

9. Estimated Production Cost

An estimate of the production cost of the solar components is presented in Table 9. This estimate is based, to some extent, on the premise that the cost of PV panels and vacuum panels will decrease 20% to 30% over the next 3-4 years. The production cost of the panels is based on achieving $5.00/watt installed cost. Current costs are in the range of $6 to $10/watt installed. The electric powered refrigeration system is based on a current vendor quotation of $10,750 plus a margin for system enhancement. The vacuum panel cost is based on $4/sq.ft. The current retail price for R-30 panels is about $5/sq.ft. The thermal storage system cost is a budgetary estimate and will be somewhat dependent on the manufacturing approach taken to produce the container. The motor drive electronics assumes about $0.45/watt output power. In order to achieve these target production costs, it is assumed that quantities in the range of at least 100 units will be required.

Table 9. Estimated Production Cost

Item	Est. Cost	Comments
Solar Panels	28,500	5,700 @ $5/watt installed
Vacuum Panels	8,000	2000 sq.ft. @ $4/sq.ft.
Electric Refrigeration Unit	12,000	Variable Speed System
Del: Diesel Unit	-19,000	Typical for 53' Trailer
Aux Power Unit	2,500	3.5 kW Generator
PCM Container	2,500	Estimate
Motor Drive Electronics	2,250	Estimate
Total	36,750	

10. Estimated Operating Cost (Solar vs. Diesel)

Diesel Operating Cost

Two approaches were used to estimate the cost of operating the diesel powered refrigeration system. The first was based on generic industry estimates and the other estimate was based on actual experience with a local produce hauler.

A period of 20 years was assumed based on the estimated life of the trailer and solar powered refrigeration equipment. Solar panels are now available with warrantee periods of 20 to 25 years. Although it is common for fleet managers to sell the trailers after 7 years of use, the value of the solar system will add to the resell value of the trailer, so assuming only a 7-year life for the economic analysis is not valid.

- Estimate #1 (Generic Data)

Based on telephone discussions with manufacturers of diesel powered refrigeration equipment, the following estimates of fuel, scheduled maintenance, unscheduled maintenance, and major service event were made. This data is presented in Table 10.

Table 10. Estimate Operating Cost of Diesel System

Item	Calc/Info	Annual Cost	20-Yr Cost
Fuel	2000g/y @ $1.50/g	$3,000	$60,000
Scheduled Maintenance	Fuel, Oil, and Air filters	$250	$5,000
Unscheduled Maintenance	Alternator, etc.	$600	$12,000
Replace Engine	20,000 hr, life	N/A	$6,000
			$83,000

- Estimate #2 (Actual Data)

The second estimate was based on actual data collected by a local produce hauler[3]. This produce hauler typically operates refrigerated 48’ trailers that moved produce between San Diego, Los Angeles, Fresno, Phoenix and Reno. The total of fuel and maintenance averaged $2.71 per hour of system runtime. Based on 2200 hours per year and a 20-year life, this results in a total 20-year cost of $119,240. (44% higher than the generic industry estimate.

Solar Operating Cost Estimate

The estimated operating cost of the solar powered refrigeration system should be significantly lower than that of the diesel system. The major maintenance/cost items on the solar powered system will be:

- Refrigeration system service
- Electronic system component replacement
- Auxiliary Power Unit fuel/service
- Insurance
- Other

The refrigeration service estimate is based on one major overhaul after 10 years. The electronic component estimate is based on one motor controller replacement in 20 years (main system component). The APU fuel/service estimate is based on the $2.71/hr total system operating cost data less an amount for the smaller, simpler design. This APU will use less fuel when running as compared to the diesel powered refrigeration unit, and has only a motor and alternator. The 500 hr/year runtime estimate is based on the average of the four cities modeled in the simulation model.

Since the refrigerated trailer is more valuable than a standard trailer, the cost of trailer insurance will be increased. Trailer insurance typically cost about 4% per year of the value of the trailer[4]. Based on an increased value of about 37,000, the additional insurance cost will be about $1480/year or about $29,600 over 20 years. As the equipment ages and its value decreases, the insurance cost should decrease.

In addition to the basic trailer insurance, "refrigeration breakdown" insurance can be purchased. The extra insurance is not always purchased, as is the case with the local produce hauler, who chooses to "self-insure." The long-term reliability may be such that the solar-based system is more reliable than the diesel system because the solar system has less moving parts. If this proves to be the case, the cost of "refrigeration breakdown" insurance may be less for the solar-based system. Refrigeration breakdown insurance adds 10% to 25% to the basic trailer insurance cost. The refrigeration breakdown insurance is not included in the cost analysis, because it is not known if this cost will go up or down relative to current technology.

In order for the insurance carrier to provide refrigeration breakdown insurance the following items will need to be provided (and approved) by the insurer:

- Technology Description
- Fail Safe System
- Test Data / Product literature

An "other" category was created to provide some margin in this overall estimate.

The following table summarized the estimated cost for each of these items. These numbers are only estimates, however, the largest two costs item in this table, Insurance and APU Fuel/Service have a good basis of estimate.

Table 11. Estimated Operating Cost of Solar Powered System

Item	Calc/Info	Annual Cost	20 Yr. Cost
Refrigeration Service	$100/year	$100	$2,000
Electronics Component Replacement	$100/year	$100	$2,000
APU Fuel/Service	1.25/hrs @ 500 hrs	$625	$12,500
Insurance	36,500*4%	$1,460 (decreases)	$18,104
Other	$100/year	$100	$2,000
Total		$2,385 (decreases)	$36,104

<u>Rate of Return Analysis</u>

A present value analysis was performed using these cost assumptions and an implied internal rate of return was calculated. The diesel operating cost estimate was based on the data from the local produce hauler. Both the diesel and solar operating cost estimates were spread evenly over the entire period of 20 years. The cost of insurance was assumed to decrease linearly over the period from 100% (year 1) to 24% (year 20).

The results indicate a 10% internal rate of return.

11. Conclusions

- Although there are some technical challenges to developing a solar PV powered refrigeration system for transport applications, this technology is basically available for a demonstration system.
- The original goal of completely eliminating diesel powered back-up may not be quite as valuable as first thought, in that the majority of the cost of operating a diesel generator is related to the runtime, not the initial cost.
- The trade between the battery storage and PCM storage has significant impacts on the design of the refrigeration system and should be carefully considered. The PCM approach should offer the best long-term benefit, but will present more development effort.
- The payback analysis indicated that at the present time, the economic justification for wide spread use of solar is moderate, but not compelling. However, as the price of diesel increases and the price of solar modules and vacuum panels decreases, the

economic case will improve. These are expected trends. In addition, any new regulations impacting diesel emissions will likely favor solar.

- The extra cost of insurance is the largest single operating expense of the solar powered system (~$1,500/year)
- Other economic factors such as noise and pollution related issues may tip the scales in favor of the solar approach in some applications and some effort will be required to seek out the niche markets for this technology.
- International applications may be the early adopters of this technologies due to the higher cost of diesel fuel in these countries (3.50 to 4.00 US$/gallon in England)
- Some form of government supported economic incentive would enhance widespread near-term commercial utilization.
- Other things being equal, transport applications with high total annual runtime will have more favorable economic returns.
- Other things being equal, operation in sunny cooler climates will have more favorable economic returns.
- Developing a good service infrastructure will be a necessary and important requirement.

12. Recommendations

- Locate a refrigerated cargo hauling company that would consider hosting a prototype and potentially purchasing a fleet of solar refrigerated trailers.

- Remodel the system based on the known operating conditions of the host company and re-optimize the design for the host application.

- Begin prototyping a solar driven variable speed refrigeration unit that meets the efficiency requirements targeted in the new model.

- Construct a section of trailer wall with embedded vacuum panel insulation. Once this wall is tested, construct an entire trailer using the embedded vacuum panel insulation. The target UA value for this trailer should be 45 BTU/Hr/°F.

- Consider the advantage of integrating an APU which provides back-up power to the solar refrigeration system and provides environmental control for the cabin and engine compartment (to avoid diesel idling).

- Consider how the Government might provide incentives for the trucking industry to adopt this technology.

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[1] Ewert, et al., "Development of a Battery-Free Solar Refrigerator," ISES Forum 2000.
[2] ASHRAE Handbook of Refrigeration 1998.
[3] Communication with Dennis Vermilion at Bonanza Produce, Reno, Nevada.
[4] Communication with Tracy Motley at Scottsdale Insurance Company, Arizona.