VALUING THE BENEFITS OF INSULATED BATTERY ENCLOSURES FOR STAND-ALONE PHOTOVOLTAIC SYSTEMS IN COLD CLIMATES

Michael M. D. Ross
Energy Diversification Research Laboratory
CANMET -- Natural Resources Canada
1615, boul. Lionel-Boulet
Varennes, Québec J3X 1S6
Tel: (514) 652-5278
Fax: (514) 652-5177
michael.ross@nrcan.gc.ca

Dave Egles
Soltek Solar Energy Ltd.
2-745 Vanalman Avenue
Victoria, B.C. V8Z 3B6
Tel: (250) 727-7720
Fax: (250) 727-2135
soltek@soltek.ca

ABSTRACT

In most Canadian remote-area power supplies, lead-acid batteries are used to store the energy generated by photovoltaic arrays, wind turbines, and gensets. Unless the batteries are installed in an insulated and/or heated enclosure, the temperature of the batteries at a given point in time will be roughly equal to the average ambient temperature over the previous day or several days. As a result, at most Canadian sites the batteries will be very cold during winter; this significantly affects the battery's performance, and reduces its useable capacity.

This paper examines the various effects of cold temperatures on lead-acid batteries and outlines several options for protecting the batteries from extreme cold, including insulated enclosures, phase change materials and resistive heating by photovoltaic panels.

A qualitative assessment of the importance of variables associated with the choice of battery, the site, and the design of a system is followed by a quantitative case study, in which various insulated battery enclosures are compared. Thermal protection permits smaller battery banks to offer the same reliability as large, uninsulated battery banks. It is shown that for all but the warmest Canadian sites, a 15 cm envelope of insulation is cost-effective for battery banks larger than about 1.5kWh of minimum useable capacity. This is conservative, since it does not account for the heat generated by the batteries themselves on charge and discharge; it is demonstrated that this significantly affects minimum battery temperatures, especially for large battery banks. Enclosures using phase change material (PCM), which can guarantee a minimum year-round battery temperature, and enclosures using PCM and heating provided by power from the array when the battery is fully charged are even more cost-effective than insulated enclosures when batteries are relatively expensive and voluminous or the site is relatively cold, e.g., in Northern Alberta. In addition, it is demonstrated that the deeper cycling caused by reducing the battery bank size will not shorten battery lifetime in typical Canadian PV systems.

1. INTRODUCTION

In Canada, stand-alone photovoltaic systems that are required to operate during the winter must have comparatively large battery banks, for two reasons. First, much less solar energy is available during the winter than during the summer, and a large battery ensures that sufficient energy is stored to meet the power requirements of the winter months. Second, the cold winter temperatures negatively affect the performance of the battery.

Cold temperatures reduce the useable capacity of a lead-acid battery, the battery most commonly used in Canadian PV systems [Ross, 1996]. As it discharges, the freezing point of the battery's electrolyte rises dramatically; when fully discharged, the freezing point may be just below 0 ºC. Thus, to avoid freezing the electrolyte, which will prevent the battery from operating (at best) or cause it permanent damage (at worst), the depth-of-discharge must be restricted. In addition, cold temperatures decrease the rate at which electrochemical reactions and electrolyte diffusion can occur; this is manifested as an increase in the internal resistance of the battery. This also limits the useable battery capacity, since on discharge a given voltage cutoff will be reached at a higher state-of-charge. The elevated internal resistance also lowers the battery efficiency and makes full charging of the battery difficult or practically impossible: on charge, the higher internal resistance leads to higher voltages, resulting in premature gassing (electrolysis of water into hydrogen and oxygen gas).

Since the battery constitutes a significant portion of the cost of a typical stand-alone PV system, reducing the battery bank size is a promising avenue to reducing the system cost. One way to decrease the battery bank size without lowering the reliability of the system is to raise the minimum temperature reached by the battery in a "worst-case" winter.

2. THERMAL PROTECTION FOR BATTERIES

There are a number of ways to raise the minimum wintertime battery temperature. The most obvious of these is to insulate the batteries in order to retard the heat loss from the battery. In this way short, cold periods will not cause the battery temperature to drop drastically; rather, the battery temperature will tend to approximate the average temperature over the preceding several days or weeks. In addition, insulating the battery amplifies the effect of battery self-heating, the generation of heat by the batteries due to inefficiencies during charge and discharge. Batteries have an energy efficiency of around 70 to 75 % [Linden, 1984, p. 13-21]; if hydrogen and oxygen escape from the enclosure, however, much of the energy associated with electrolysis will escape from the enclosure with the gas. Nevertheless, it can be assumed that at minimum 10 to 15% of the electrical energy intended for charging will eventually be liberated as heat within the battery. It should be noted that batteries are much less efficient at high states-of-charge and low temperatures.

Battery self-heating can be augmented by heat from another source. One of the simplest and most reliable methods is to pass current from the PV array through a resistance heating element. The PV array is usually sized on the basis of the worst-case availability of sunshine during November, December, and the early part of January. If the electrical load is constant there will be excess PV power available for heating prior to and following this period. When the batteries are fully charged, the system controller diverts power to the resistance heater. In systems designed for very high reliability, the array is sufficient to maintain the battery at a full state-of-charge for all but a brief period during the winter. If the thermal mass of the battery bank is high, the battery temperature will not drop significantly during this period. Furthermore, the coldest time of the year tends to be out of phase with the period of least insolation: during December, the state-of-charge drops, but the coldest period of the year comes in January or even later. If the battery has been fully recharged by this time, PV power will be available for heating.

Another approach is to place the batteries in an enclosure containing a large mass of phase change material (PCM) with an appropriately chosen freezing point [Baer, 1989],[Strickland]. At the onset of winter, when the temperature inside the enclosure drops to the PCM's freezing point, the PCM begins to freeze. The PCM will hold this temperature until it is completely frozen. If a sufficient quantity of PCM is contained in the enclosure, the PCM will never completely freeze, and the batteries will never drop significantly below the freezing point of the PCM. In this way, the PCM establishes a guaranteed floor temperature, below which the battery temperature will not fall: this is a significant advantage over simply heating the enclosure, which does not guarantee a floor temperature, although simulation can reveal a good estimate of the minimum temperature. An obvious choice of PCM is water, which has a high latent heat of fusion, meaning it will liberate a great deal of heat while freezing. Additionally, its freezing point is attractive: useable battery capacity is relatively high at 0 ºC, but drops significantly at temperatures below this.

The above approaches can be combined to good effect. For instance, it makes little sense to use PCM in an uninsulated enclosure; likewise, using surplus heating with PCM, which provides security for the period when the battery state-of-charge drops below 100% is often more effective than using either PCM or heating alone.

3. IMPORTANT FACTORS

Although the concept of insulating and heating the batteries is very simple, determining all the cases where a certain type of thermal enclosure makes sense is difficult. This difficulty stems from the large number of factors affecting the performance of the enclosure and its cost: there are ten relevant external variables, two of which are vectors of time-series data. Assessing the influence of each using just three values for each variable would involve over 6000 simulation runs. Many of the variables have a nonlinear influence, making generalizations about their importance difficult. Furthermore, there are additional variables associated with the particular manner in which the enclosure is constructed: the type of insulation used, the thickness of insulation, how efficiently the enclosure's space is used, costs of materials, etc. For this paper, the relevant variables will be discussed qualitatively first, and then the influence of several variables examined in the form of a case study.

Type of Batteries: Whether or not a thermal enclosure makes sense depends greatly on the batteries that will be placed inside of it. The *cost per unit capacity* of the batteries has direct bearing: the higher the cost, the greater the incentive to employ thermal protection, including PCM. If the batteries have a high *volume per unit of capacity* then thermal protection, especially the use of PCM, will be attractive since reducing the capacity greatly reduces the size of the enclosure. GNB Absolyte IIP and Varta Bloc have especially high volume per unit capacity, while Global Yuasa tubular batteries and most RV batteries have a low volume per unit capacity. *Sealed batteries with recombination*, such as gell cells and absorbed glass mat batteries, will generate more heat than flooded batteries, since the heat of electrolysis and recombination will not be lost in the form of gas escaping from the enclosure. These are therefore better suited to enclosures with thermal protection, with or without PCM. Batteries with a high *energy density*, such as the Global Yuasa tubular battery, will have a high thermal mass and therefore benefit less from the use of PCM, although this variable plays a minor role. Another variable of minor importance is the *shape* of the battery. If the battery bank (plus PCM, if any) approximates the shape of a cube (or better yet, a sphere, though this is generally impractical), heat loss will be minimized. Batteries with a high *temperature derating for useable capacity* will derive greater benefit from thermal protection; most batteries used in Canada have roughly similar temperature deratings, however.

Site: The site determines the ambient air temperature and the solar availability, both of which impact the thermal performance of an enclosure. Sites with long winters and low average winter temperatures-- that is, with a large number of *degree seconds below the freezing point of the PCM*-- will require large quantities of PCM, diminishing its attractiveness. The exception to this is an Arctic site so cold that the battery temperature, even in a well-insulated enclosure, would be so low that lead-acid batteries would not be appropriate. If the PCM enclosure permits lead-acid batteries to be used in the place of ni-cadmium batteries, which are three to ten times more expensive, even very large enclosures will be attractive. The size of the enclosure can be lowered by using surplus heating; dedicated PV heating may also make sense, since it ensures that some heating will be available even when the batteries are at a low state-of-charge. On the other hand, a site with reasonably high average temperatures but with severe *cold snaps* lasting for a week or longer will not require much PCM; enclosures without PCM will tend to have a low minimum battery temperature. Such sites are well-suited to PCM. Unless a very large array is used, northern sites and other sites with very little *insolation during the winter* are poorly suited to heating by surplus power from the PV array if no PCM is used, since they will tend to lack surplus power for an extended period of time. On the other hand, surplus power heating plus PCM is an excellent combination for these sites, since the PCM will maintain the battery temperature for the period of low insolation, and there will be plenty of surplus power to maintain the temperature for the rest of the winter and early spring. Mountain sites subject to *rime icing or extended periods of fog or cloud* are poorly suited to surplus heating or dedicated PV heating, since the array may be unable to provide power for an extended period of time; PCM, which will maintain the battery temperature regardless of icing on the exterior, is well-suited to these sites.

System Size and Design: The batteries in systems with large *loads* will generate more heat due to inefficiencies, and will benefit from insulation. The required *reliability* of the system will determine the *size of the battery bank*, in terms of the number of days of autonomy at 25 ºC, N, and the *array-to-load ratio*, R_{AL}. An infinite number of combinations of N and R_{AL} achieve a given desired loss-of-load probability; thus these variables are not independent. Multiplying N by the load yields the absolute battery size. A large battery bank (greater than 5 to 10 kWh) will have a high thermal mass, suggesting that insulating the batteries will raise the minimum temperature significantly, especially if there is considerable battery self-heating. The battery self-heating will be more pronounced when N, the number of days of autonomy, is low, since it suggests that the load (related to the heat gain) is large in comparison with the size of the battery bank (related to the heat loss). When the array is sized conservatively-- that is, R_{AL} is large compared with the ratio of the average wintertime insolation to the load-- surplus heating will make sense, since the period of low battery state-of-charge will be short, and before and after this period there will be significant surplus power available.

4. COSTS AND BENEFITS: A CASE STUDY

The effect of basic thermal protection in the form of insulation can be seen in Fig. 1, which shows simulated minimum battery temperatures (ignoring battery self-heating) for a variety of battery banks and enclosures in Montréal, based on actual hourly weather data from 1953 to 1989 [Environment Canada, 1993]. Adding 5cm of high quality (polyisocyanurate) insulation raises the minimum battery temperature roughly 7 ºC; adding another 10 cm of insulation increases the temperature by another 5ºC.

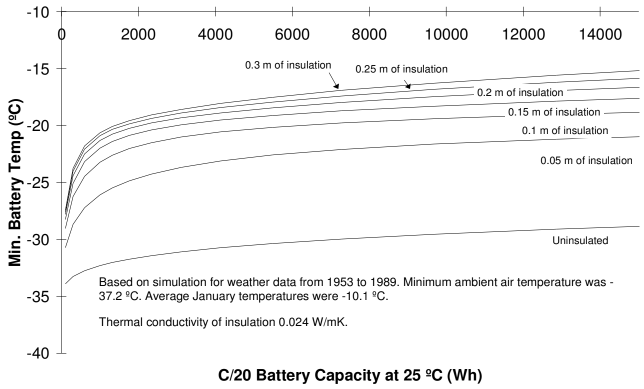

Fig. 1 Minimum Battery Temperatures for Various Insulated Enclosures in Montréal, Not Accounting for Battery Self-heating

A similar analysis can be done for other Canadian locations. The minimum temperature of a 10000 Wh battery bank is representative of a wide range of battery banks; this temperature is listed for a number of Canadian cities in Table 1.

Table 1. Simulated Minimum Battery Temperatures for a 10 kWh (at 25 ºC and C/20 Rate) Battery Bank: Uninsulated Enclosure versus Enclosure w/ 15 cm of Polyisocyanurate Insulation, Not Accounting For Battery Self-Heating. Figures in parentheses refer to battery capacity derating.

City	Uninsulated	Insulated
Vancouver	-14ºC (32%)	-5ºC (21%)
Shearwater, N.S.	-20ºC (40%)	-10ºC(26%)
St. John's, Nfld.	-20ºC (40%)	-11ºC(28%)
Toronto	-22ºC (46%)	-13ºC(30%)
Montréal	-30ºC (64%)	-17ºC(36%)
Winnipeg	-37ºC (74%)	-26ºC(55%)
Prince George, B.C.	-38ºC (76%)	-26ºC(55%)
Grande Prairie, Alta.	-42ºC (81%)	-32ºC(67%)
Yellowknife, NWT	-45ºC (86%)	-37ºC(74%)
Hall Beach, NWT	-50ºC (93%)	-41ºC(80%)

The useable battery capacity decreases as the minimum battery temperature drops. Since insulated enclosures keep the batteries warmer than uninsulated enclosures, a smaller battery bank will achieve the same minimum useable capacity. The ratio of the nominal battery capacity required for an insulated enclosure versus an uninsulated enclosure, given a certain desired minimum useable capacity, is shown in Fig. 2.

The insulated enclosure permits a smaller battery bank to be used, thus reducing the battery cost; the insulation and the larger enclosure cost more, however. The retail cost of an average battery has been estimated at $0.25/Wh of 25 ºC, C/20 capacity; more expensive batteries such as the GNB Absolyte IIP cost up to $0.60/Wh and often require more volume per unit capacity. For a well-insulated aluminum enclosure, the cost of the aluminum shell has been estimated as $200/m^2, and the insulation, $400/m^3, both including labour. These costs can be used to compare insulated and uninsulated enclosures (Fig. 3). While 15 cm of insulation doesn't make sense for anything but the largest enclosure in warm climates like Vancouver's, it is well-suited to just about any battery bank exceeding about 1500Wh of minimum useable capacity in colder climates, such Montréal and Yellowknife. This is especially true for more expensive batteries, (e.g., the Absolyte IIP).

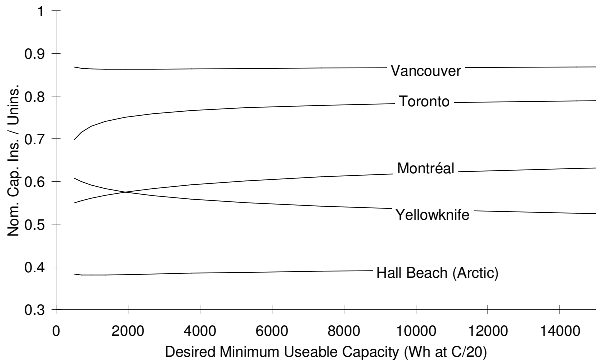

Fig. 2 Reduction in Nominal Battery Bank Capacity Required for a Given Minimum Useable Capacity: Enclosures with 15 cm of Polyisocyanurate Insulation versus Uninsulated Enclosures

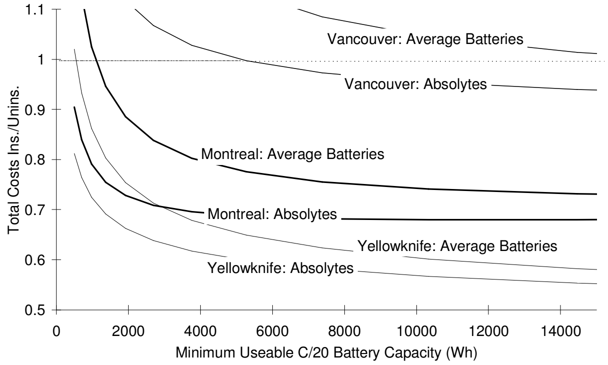

Fig. 3 Total Cost of Batteries and Enclosure: Insulated versus Uninsulated

These estimates of battery temperature for insulated enclosures are very conservative, since they do not account for battery self-heating. If it is assumed that 10% of the energy used for charging and 5% of the energy liberated on discharge are dissipated as heat in the enclosure, the minimum battery temperature rises significantly. This is seen in Fig. 4, which shows simulated minimum battery temperatures for various insulated enclosures in Montréal and Grande Prairie, a site north of Edmonton. This means that Fig. 3 actually underestimates the benefit associated with insulated enclosures. Fig. 4 also demonstrates the impact of using surplus power from the array to heat the enclosure. The influence of battery self-heating and surplus heating is more pronounced for larger battery enclosures, since with the number of days of autonomy (N) fixed, the heat gain is roughly proportional to the volume of the battery bank while the heat loss increases only in proportion to the 2/3 power of the volume. Both surplus heating and battery self-heating significantly raise the enclosure battery temperature.

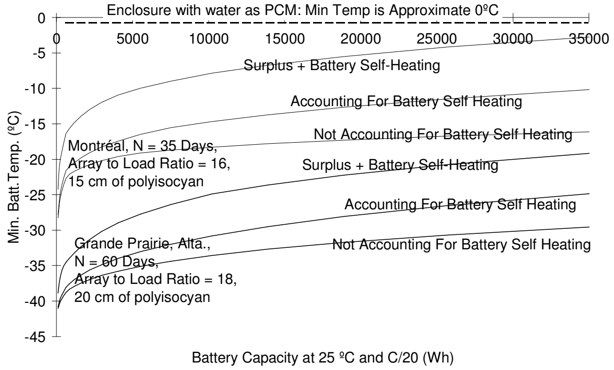

Fig. 4 Simulated Minimum Battery Temperature, Montréal and Grande Prairie, Insulated Enclosures with Heating and PCM

Fig. 4 also shows the minimum temperature of an enclosure using water as a PCM: it is fixed at 0ºC regardless of the battery bank size. While this can significantly reduce the battery bank size and provide excellent freeze protection, a substantially larger enclosure may be required. Fig. 5 shows the amount of water that needs to be incorporated into these enclosures, based on the worst-case (combination of coldest and least-sunny) winter from 1953 to 1989. It has been assumed that only 75% of the free space of the enclosure has been filled with water. As a first approximation, the amount of water required, not accounting for battery self-heating, is shown. Just as this underestimates the minimum temperature of an insulated enclosure, ignoring battery self-heating overestimates the water requirement for these enclosures, as seen by the "Battery Self-Heating" trace. For the Grande Prairie site, the water requirement assuming surplus heating is also shown-- significantly less PCM is required.

An attempt to weigh the benefits of a smaller battery bank versus the costs of a larger enclosure is given in Fig. 6, for Montréal, and Fig. 7, for Grande Prairie. In addition to the previously stated assumptions about cost, it was estimated that the containers holding the water cost $1 per litre of water, the additional cost of a controller capable of diverting surplus power to a heating cable is $200, and that the heating cable itself has a cost in dollars equal to the square root of the nominal battery capacity. For both Grande-Prairie and Montréal, the enclosures containing PCM are the most cost-effective option for all enclosures having a minimum useable capacity exceeding 4kWh for the average battery and 2 kWh for the expensive, voluminous battery. The benefit of PCM is more pronounced, as would be expected, for more expensive batteries and for colder sites. For a system requiring around 6kWh of minimum useable battery capacity, the cost reduction is only about 5% (or $180) for average batteries in Montréal, but is 36% (or $4200) for the expensive batteries at Grande Prairie. However, even less-expensive batteries would benefit from PCM at Grande-Prairie: holding all other costs constant, PCM with surplus heating would be the preferred option for a 6kWh (minimum useable capacity) battery bank with batteries as cheap as $0.12 per Wh (nominal). For enclosures without PCM, surplus heating made sense at both Montréal and Grande Prairie; in combination with PCM it was marginally more cost-effective at Grande Prairie than relying on PCM and battery self-heating alone.

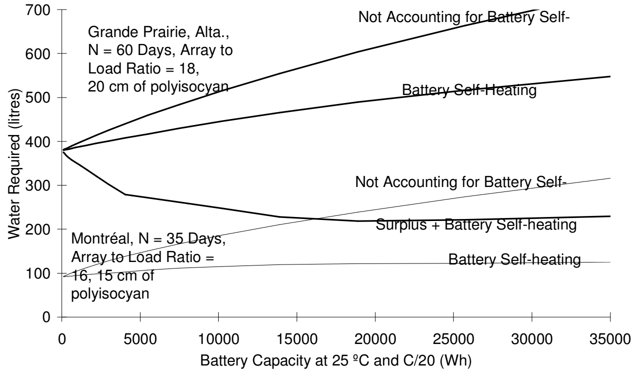

Fig. 5 Water Required for Insulated PCM Enclosures at Grande Prairie and Montréal

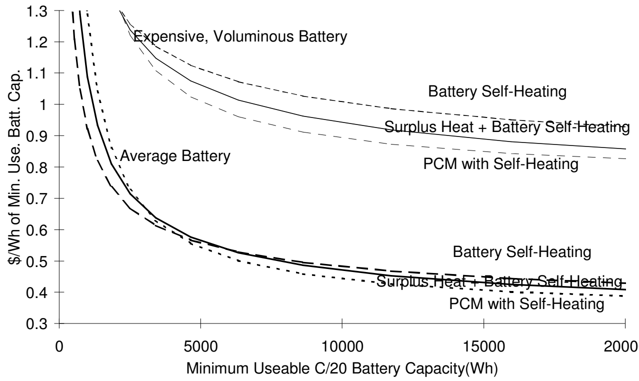

Fig. 6 Cost per Unit Minimum Useable Battery Capacity for Montréal

6. EFFECT ON BATTERY LIFETIME

Battery manufacturers commonly state that cycling a battery more deeply reduces its lifetime; at first glance, this might suggest that thermal enclosures will have a negative impact on battery lifetime. In fact, this should not be the case. Cold-climate PV systems that are required to power the same load year round are sized on the basis of the insolation available in the winter. Since much more sunshine is available during spring, summer and autumn, the battery is kept nearly fully charged at all times, except during the middle of winter. Furthermore, in the high reliability systems for which thermal protection would be well-suited, it is only in especially dark winters that the battery state-of-charge drops significantly. Cycling is not an important cause of ageing in such batteries; rather, ageing can be attributed to the corrosion characteristic of float operation, and possibly to sulphation due to the battery being left at partial state-of-charge in the middle of winter. It should be noted that decreasing the battery size does nothing to lengthen the time that the battery spends at a partial state of charge-- this is purely a function of the array size and the load.

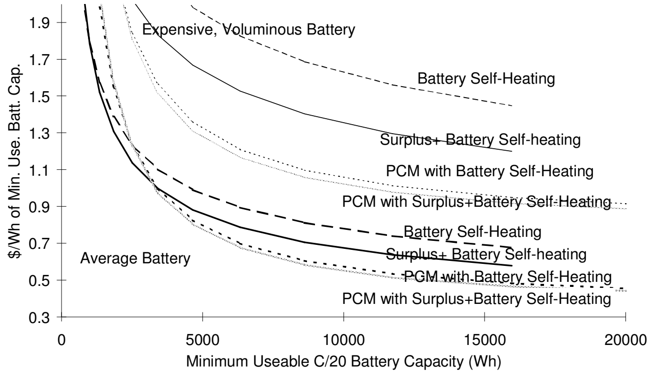

Fig. 7 Cost per Unit Minimum Useable Battery Capacity For Grande Prairie, Alta.

The fact that cycling is not an important cause of ageing in high reliability PV systems can be demonstrated quantitatively [Spiers et al., 1996]. For example, assume that a battery can provide 500 cycles to a 80% depth-of-discharge (which is conservative for high quality batteries). This suggests that over its lifetime at least 400 times the battery's nominal capacity can be discharged from it-- once again, a conservative assumption, since most of the cycling will be at a high state-of-charge. If such a battery is used in a system with only 20 days of autonomy (capacity at 25 ºC divided by average load), then the maximum possible daily discharge is 5% of the battery's capacity. Dividing 400 by 5% yields a lifetime of 8000 days, or over 21 years. Clearly, PV batteries do not last 21 years in the field, so cycling is not the factor causing ageing. [Spiers et al., 1996] suggests that for systems with an autonomy greater than 6 days, other factors are always responsible for ageing.

7. CONCLUSIONS

The large number of factors affecting the costs and benefits associated with thermal protection for batteries in PV systems makes it difficult to generalize about the applications in which they are cost-effective. Despite this, it is clear that for all but the smallest systems and the warmest Canadian sites, insulating the battery bank is cost-effective. When the battery is expensive and voluminous and/or at sites that are particularly cold, phase change materials are very attractive. Although reducing the battery bank size through the use of a thermal enclosure will increase the maximum depth-of-discharge, this will not affect the battery lifetime in Canadian PV systems, since cycling is not a prime cause of ageing.

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