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Storing Wind Power in Ice

For: Energy, smart grid and refrigeration industries

In this report we propose a new way of storing wind power energy at grid-scale. It is cheap, relatively high efficiency and most importantly it can store days' worth of energy. We put forward the concept of storing days' worth of chilling energy in ice, making use of the latent heat of freezing in a wide range of industries and applications.

We have decided to publish this under open source licence terms XYZ with the aim of promoting debate and interest.

1.0 PREFACE AND WHY OPEN SOURCE

In mid 2013 Oswald Consultancy Ltd won a funding award from the Technology Strategy Board (TSB) to investigate the energy storage work explained here. That award was to investigate the use of buildings as means of storing several days' worth of wind energy. Buildings as energy stores has been considered before (ref P.Boait) but storing many day's worth is highly challenging as stores, such as batteries or hydro electric dams become very large and very expensive when day's worth of energy is involved. We had promised the TSB to particularly focus on refrigerated warehouses as we have some previous experience with their energy consumption patterns, have some data on them and assumed their operators would be content to cope without electricity for prolonged periods of time.

Quite early in the project we realised that curtailing power to industrially refrigerated warehouses would not work in practice: temperatures in the warehouses would soon rise to levels that compromise their food contents and operators would rightly refuse. However, we did realise that there is some potential in storing energy in the latent heat of frozen blocks of ice. Frozen latent heat, as I will call it, has high energy density, is cheap to make (e.g. water and glycol), has low energy losses (heat transfer through thick, simple insulation) and could therefore, in theory, store day's worth of refrigeration energy from wind power.

1.1 Challenges of wind power

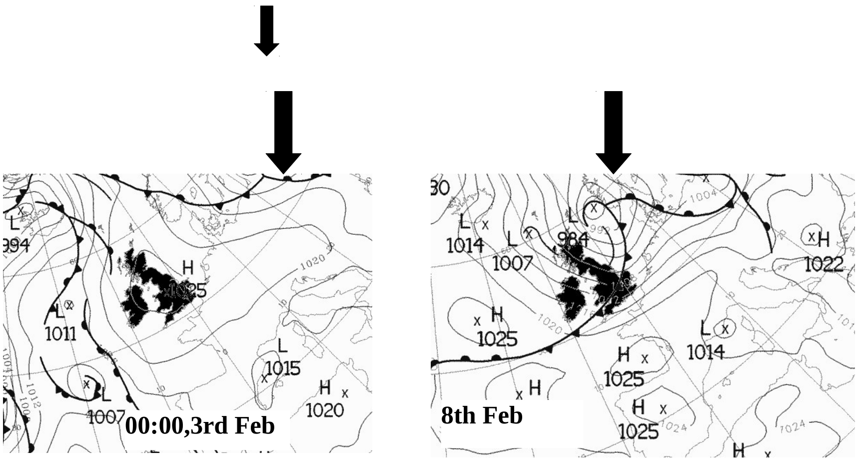
Wind power has very serious limitations to its efficacy and in 2008 we published our research findings and comments on the impact large scale wind (25GW) would have on the UK grid. (Oswald reference) The volatility of wind was the central theme we discussed, its dependence on the highly varying weather patterns of the UK and to be polite, but clear to readers that wind is simply dreadful in comparison to traditional power generation sources:

- Wind power output can't be controlled up or down as electricity demand varies
- Wind power doesn't provide grid frequency control (as above: you cannot vary power output)
- It does not provide inertia to the grid system since most, if not all, wind generators are not synchronised to the grid.
- It gets preference on the grid, thereby reducing the utilisation of conventional plant to times when it is not windy and reduces the return on investment of conventional plant
- It effectively has no capacity credit

We find this last point the most damning. In simple terms it means that for every 1000MW of wind power you install you will need another 1000MW of dispatchable plant (typically controllable fossil fuel) for when the wind does not blow. You need to build 2000MW of capacity; 1000MW wind plus 1000MW traditional. This point is most clearly illustrated in the UK, when, in the depths of winter, electricity demand reaches its moment of annual peak and wind power simultaneously collapses because a high pressure wind system sits over the UK and its neighbouring countries. Our paper used the following graph of measured wind power output for UK, Germany and Ireland to make the point:

Plotted as a five-point moving average

18:00, 2nd Feb 06



The moment of peak annual demand in 2006 is shown: 2nd February at 18:00 hours. The simultaneous weather chart shows the high pressure system sitting over Western Europe, and this explains the collapse of wind power. For the same moment we tabulated the wind farm load factors (expressed as a percentage of 100%) for neighbouring countries:

Location/Source	Load Factor % 2006-02-02 18:00
Britain (National Grid data, 16 wind farms) [a]	- 0.1
Ireland [b]	10.6
Germany [c]	4.3
Spain [d]	2.2
UK model	0

As can be seen, the wind farm outputs collapses simultaneously in the UK, Ireland, Germany and Spain. This is simply down to absence of a low pressure weather systems caused by the presence of the high pressure weather system (often referred to as a blocking system by meteorologist).

Since 2008 governments have reacted by seeking energy storage technologies to fill this wind power void. But as the graph shows you need a storage vessel, which will store a nation's worth of electricity for 150 hours to be sure of getting through the worst of the weather. We have always remained very interested in this field, but it is only with the advent of the Technology Strategy Board that we find small engineering consultancies like ours can receive any funding to develop creative solutions to this pressing challenge.

As explained in the discussion report below, we think we have possibly found a large, cheap, way in which a nation can store 5 days worth (Oswald reference)of electrical energy and at a scale which is nationally significant to grid operators. We should be clear this is not a storage method which converts stored wind energy back into electricity but a storage method which stores the end product which is ice, for subsequent use in cooling big consumers of coolth. By storing the final end product (in this case cooling) we avoid the subsequent conversion losses other energy storage techniques have in reconverting energy back into electricity.

This subject deserves more design and development work. We would love to do some of that work (particularly advanced heat exchangers required) but we don't believe, in practice, we shall have the resources and energy to lead this proposal from this initial concept study through to project delivery on our own. On that basis, and in the spirit of the modern Internet age, we have decided to open source all of our work on this subject: invite debate and comment on this possible area for energy storage, and see where it leads us. I hope you find it interesting, and have some further ideas on how to store 5 days worth of energy in refrigerated warehouses.

J.Oswald Nov 2013

Frozen Warehouse

2.0 ICE STORAGE – CONCEPT INTRODUCTION

We propose constructing ice storage vessels at sites with industrial refrigeration loads, which can be ‘charged’ with coldness when wind energy is abundant, and discharged to carry out refrigeration when electricity supply is limited. Facilities such as chilled and frozen food warehouses, supermarket chillers and even air conditioning systems are appropriate for this energy storage technology, made possible with the use of novel ices that freeze between 0 and -50C.

Ice Store

Commercial refrigeration loads account for around 3% of UK electrical consumption load (Carbon Trust Carbon Trust- Commercial & Retail Refrigeration Equipment), so the benefits of large scale ice storage as a demand management tool could be nationally significant.

A useful storage duration to absorb the challenging variations in wind power output is around 5 days, as shown by the wind-output chart below. We show in this report that ice stores of this duration take up very little space, can be operated efficiently and are likely to be considerably cheaper than alternative energy storage methods at this scale.

6 days of low wind across Europe:Refrigerate from ice stor

4 days of high wind across Europe:Charge ice storesConsume excess electricity

By synchronising the charging times of ice stores with wind power generation (or other network needs), reliable chilling can be provided to refrigerated facilities whilst the capacity margin of the national grid is maintained. The requirement for duplicated generation capacity to fill the wind energy ‘gaps’ is also reduced. High capacity dispatchable loads (ice charging compressors) that are geographically distributed could reduce the curtailment of wind generation, and play a valuable role in local network balancing.

Put simply, we consider ice stores a promising method for smoothing the increasing intermittency of electricity supply in the UK and abroad, and welcome responses and views from related industries.

2.1 National and international benefits

We believe in the UK a comprehensive programme of energy storage through ice could release 1GW of detachable load with a storage capacity of 5 days. Such a level of energy storage makes a useful contribution to the days of no wind power in the depths of winter which consume the UK and neighbouring countries. Success with this would allow the system to claim capacity credit where today wind power can claim none. In the UK the country experiences a peak in electricity demand in the cold winter months when the reader might justifiable assume refrigeration warehouse consumption is low. We have empirical data from refrigerated warehouses and this, surprisingly, indicates little reduction in electricity consumption when the weather is cold.

The ice energy storage system proposed may have higher benefits in hotter countries than the UK where cooling loads are generally higher and yet wind power is similarly volatile. (Reference??) For example, we understand both China and the USA have volatile wind power production and a summer electricity peak. Data from xxx shows that the USA electricity consumption for cooling is much high proportion than the UK (7% rather than 3%). (we will need fill hard reference through out if we use this argument)

Spain have increased their wind capacity substantially over the past x years and are noiw suffering regular curtailments as a result (reference news) due to transmission and consumption constraints. We expect cooling loads comprise a higher portion of Spanish consumption, adding to the case for time-shifting cooling loads by ice storage.

3.0 THE 5 DAY CHALLENGE

Can we store 5 days worth of refrigerated warehouse energy in the form of frozen ice using wind power efficiently, cost effectively, sensibly? For our test case we consider a large refrigerated warehouse requiring a control temperature of -25°C which typically consumes 300kW of power, on average. There are many of these warehouses situated across developed nations and many more buildings with similar cooling requirements, from supermarkets to heavily air conditioned spaces.

4.0 WHY STORE ENERGY IN ICE?

Ice or frozen ice/glycol mixes are a very dense method storing thermal energy. This is because the latent heat of energy (the energy required to convert liquid molecules to frozen rigid lattice modular array) is high. For example, if we compare the thermal characteristics of pure water in its different phases to store the same amount of energy in figure xx below. (Ref. Perry, section 2-151 on latent heats.)

Per kg water:

- Specific heat capacity of ice = 2.1 kJ/kg-K
- Latent heat of fusion of ice = 334 kJ/kg
- Specific heat capacity of water = 4.2 kJ/kg-K

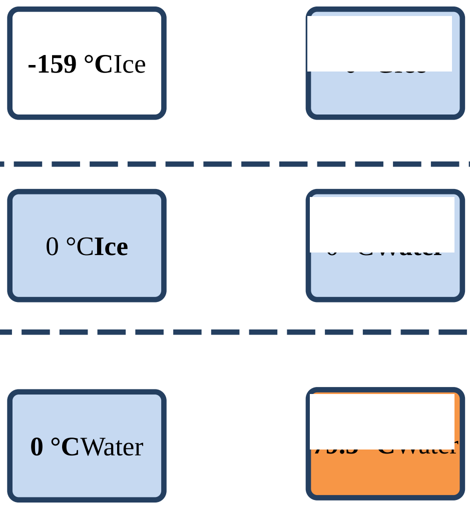


Fig XXX

So per kg of water the same energy can be stored in freezing pure water as in raising water temperature from 0°C to 79.5°C. At first glance this might suggest that a hot water store, in say a domestic house at 79°C has similar useful value as storing ice, but that is not true. A domestic house hot water store has an end deliverable of serving hot water at approximately 55°C and so to store the same amount of energy you would need to raise the temperature to 134°C (55 + 79) as this allows the store to cool to the delivery temperature of 55°C. However that requirement clearly exceeds the boiling point of water and secondly the losses to atmosphere are directly proportional to the difference in temperature between the store (say 134°C) and ambient temperature (say 20°C) which is considerably higher than between water ice at 0°C and ambient. From this we can see that storing energy in ice is not only very dense per unit of mass but is very practical in terms of heat losses.

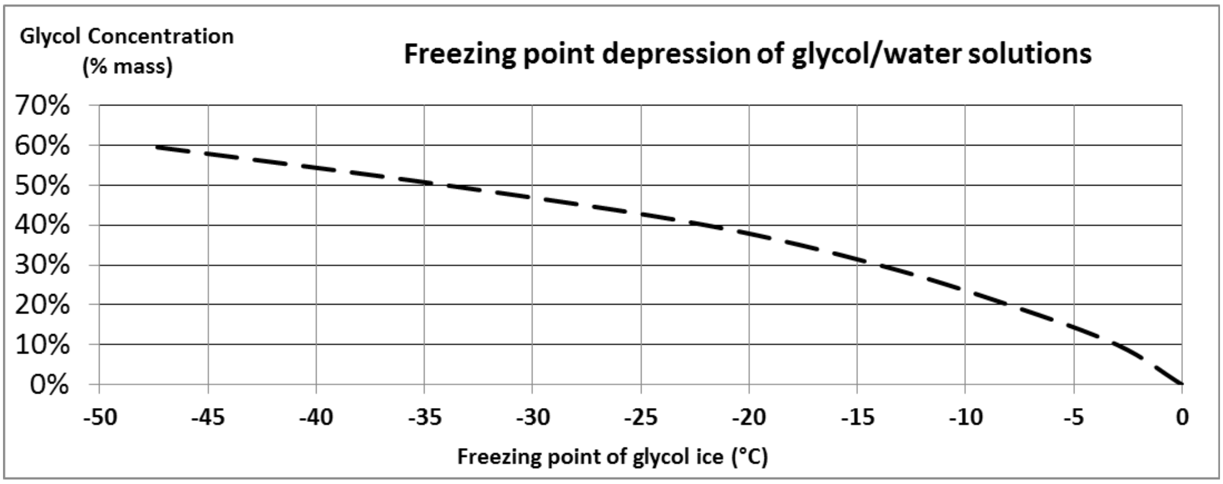
In this paper, our test case is to consider industrial warehouses at -25°C for which we shall design a store of glycol/ice mix to freeze at -35°C. We may also discuss less demanding cooling loads where pure water at 0°C is suitable for use. The temperature of freezing is designed at the start of any project. For simplicity of reporting we may call all these frozen ice/glycol mixes: ice.

4.1.1 Designing ices for your application

Designing the water mix for your application is fairly straight forward, but can reduce the energy density of the stored energy per unit volume below that of pure water. Pure water freezes at 0°C and adding large quantities of salt to water can depress its freezing temperature as low as -20°C whereas some water-glycol solutions freeze as low as -50°C. We are aware of pure ice energy stores used in the USA to cool air conditioned buildings (University building, Ice bear, glycol balls…) or cool the intake to gas turbines (Adrian name of plant? Or Evapco) on hot ambient days, but we are not aware of any thermal storage designs that exploit sub-zero ice properties, and we see this as a new opportunity to store renewable power.

Both ethylene glycol and propylene glycol are commonly used as heat transfer fluids in sub-zero applications when mixed with water. Propylene glycol may be preferable due to its advantages of being non-toxic and freezing at slightly lower temperatures than ethylene glycol when mixed with water. The graphs below show how the latent heat (energy density) of propylene glycol mixes as concentration is varied.

For our warehouse test case at -25°C we choose an ice frozen to -35°C which figure xx1 shows requires a 50% glycol/water mix to form the ice. The latent heat of fusion is thereby 250kJ/kg (Equation from paper) which is noticeably lower than pure water (334 kJ/kg) figure xx12



REFERENCE (Engineering toolbox / higher quality please!

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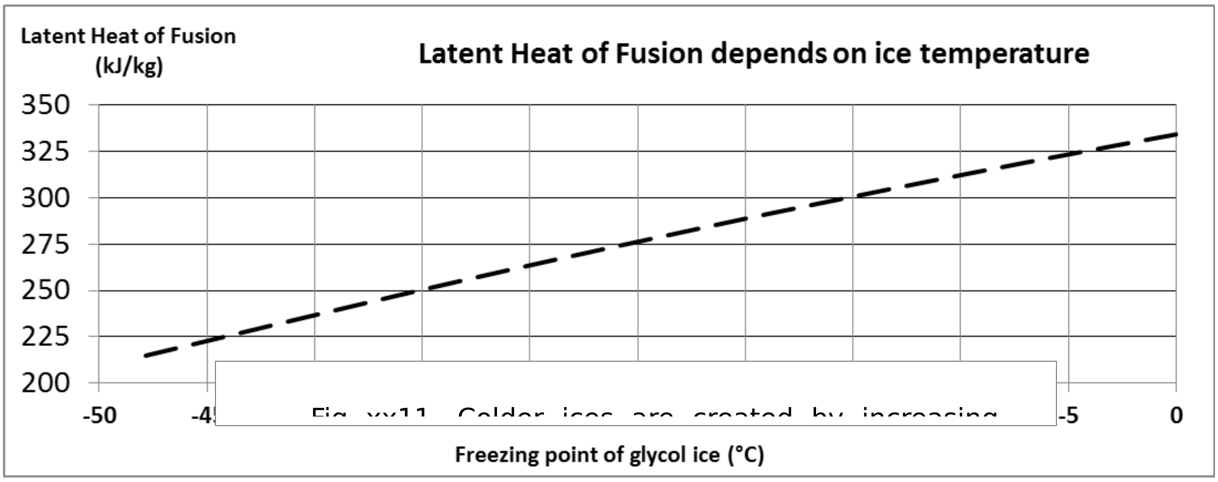


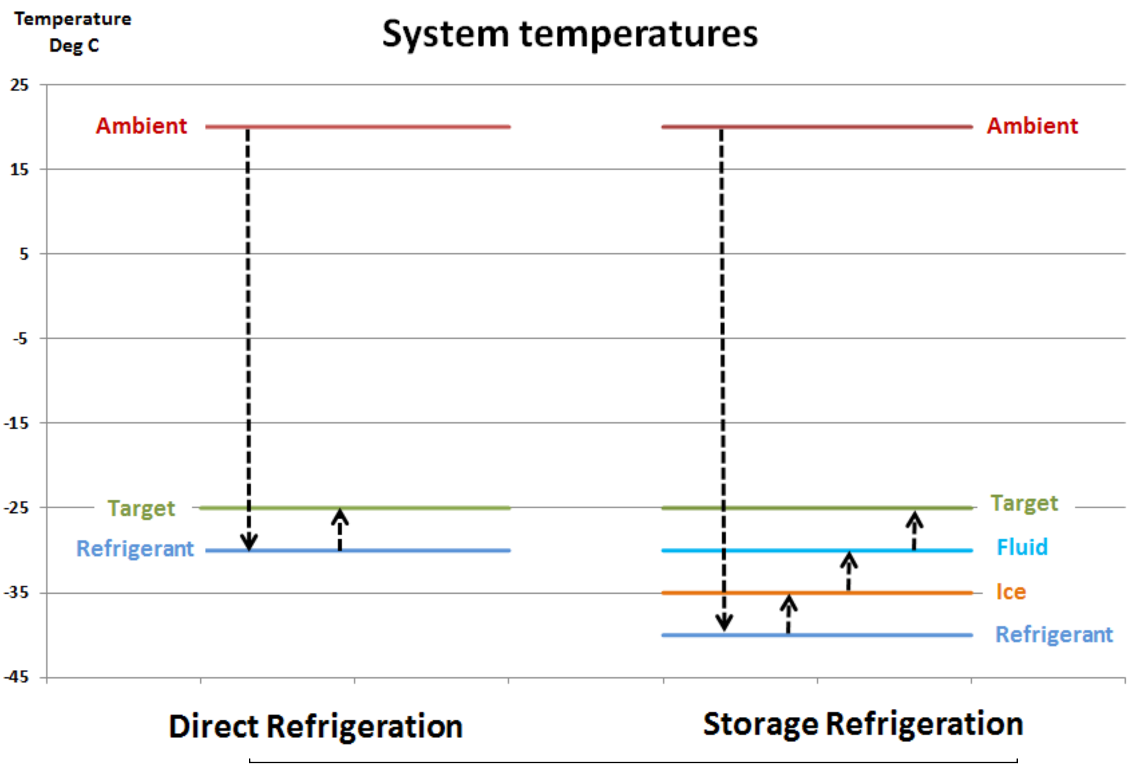
Fig. xx11. Colder ices are created by increasing

5.0 ENERGY THERMODYNAMICS OF REFRIGERATED COMPRESSION

In determining the power and efficiency of the compressors and size of heat exchangers you have to choose design temperatures for the various stages of the refrigerant as it passes through the circuit. We have chosen to set all the heat exchanger temperature differences e.g. the temperature between the

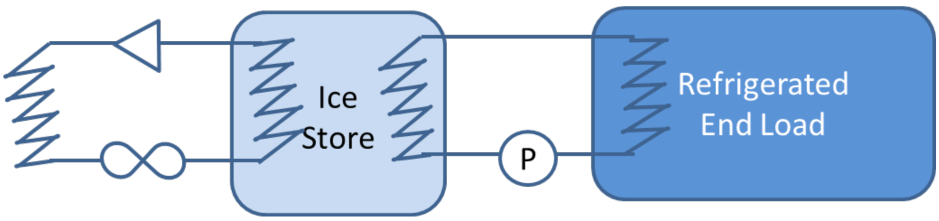
Figure XX12. Colder glycol ices have less latent heat of refrigerant and ice to be 5°C. Because the refrigerant has to deliver a colder end temperature, the refrigerant compressor has to work harder and to higher pressures than a normal refrigerant compressor. This means it consumes more energy than ordinary warehouse cooling per unit of cooling. These extra energy 'losses' can be seen as the inefficiency of storing wind power as ice. However, all energy storage has inefficiency and we think this method compares very well. (Reference table on next page?)

The heat exchanger temperatures of the loop are thereby set as illustrated below.



Pictorially the design temperatures are illustrated below

Jeremy to label with temps at each node...



5.1 Compressor work and system efficiency

To design a refrigerant system, we use Pressure Enthalpy characteristics in our calculations. From first principles of thermodynamic calculations we calculated the system thermal performance using Excel and have summarised the results in the following chart (fig zzz). We often carry out thermodynamic optimisation of gas vapour cycles for gas turbines, and refrigerated system design is a similar design calculation. These thermodynamic calculations are well known to engineers and we shall not explain them here, but suffice it to say that using these pressure enthalpy charts allows us to define the work, pressures, temperatures and efficiency of the refrigerant system.

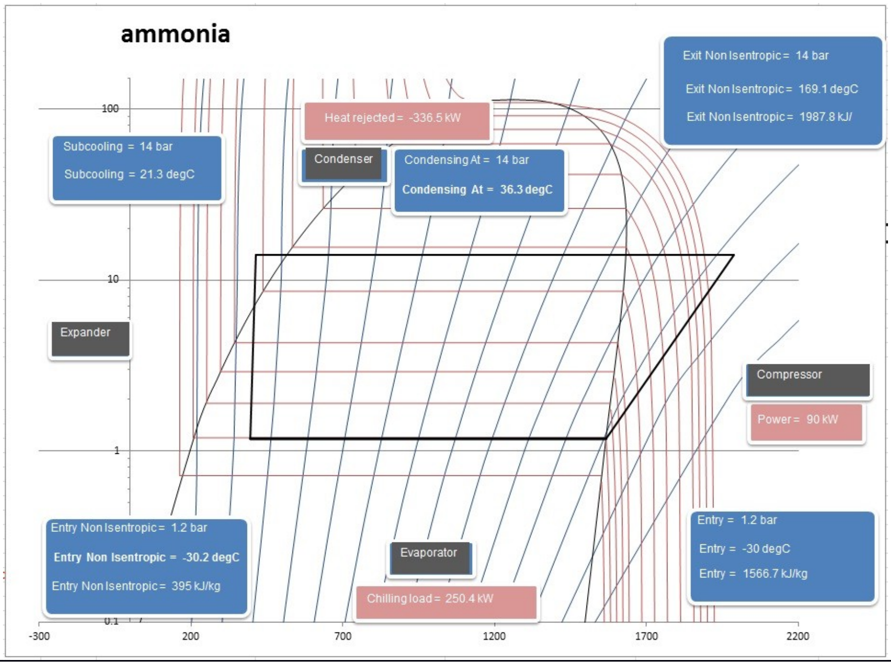
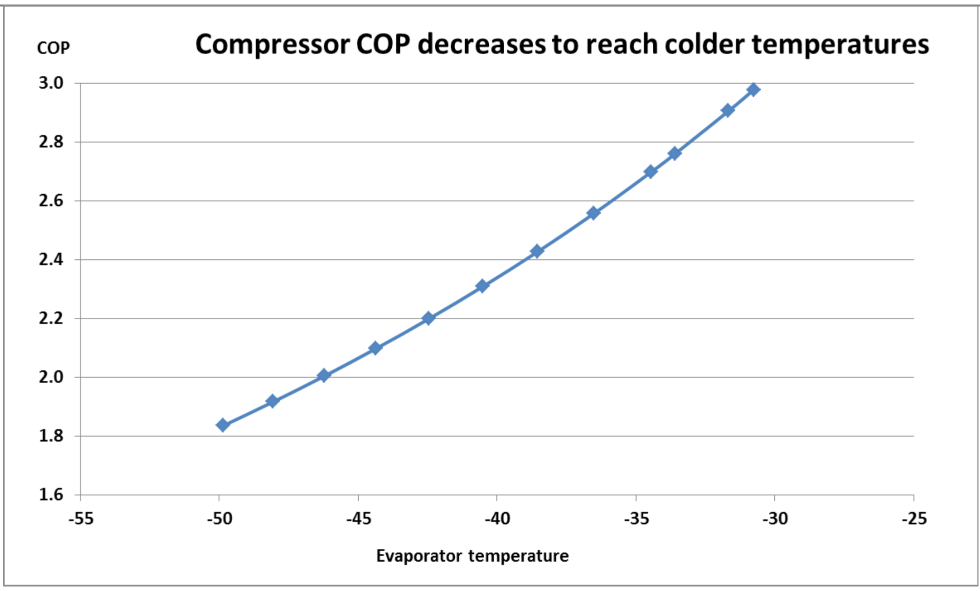


Figure zzzz

Strictly speaking the efficiency of a refrigerant system is not the correct term; the correct term is coefficient of performance (COP) which is the ratio of cooling energy achieved divided by the work done energy to achieve the cooling. This is a ratio of energies and therefore has no units. Chart xxx shows our coefficient of performance results, calculated using our models of pressure and enthalpy. As can be seen, the COP gets worse (you need more energy for quantity of cold energy) as the target temperature reduces. For our warehouse case we have a design cold temperature of -35°C which has a COP of 2.6 whereas direct cooling to -25°C has a COP of 3.2. The ratio of 2.6 to 3.2 is 81%, showing that 19% of energy is wasted compared to directly cooling the warehouse at time of electrical generation.

This is the amount of waste or inefficiency and why storing energy as ice will consume more total energy than directly refrigerating the test case warehouse. However, energy storage is carried out to store energy when it is in high supply and defer its final use until a later time, when electricity is in short supply. All energy storage methods consume additional energy compared to consuming the energy immediately and this ice method compares favourably, as discussed below.



5.2 Efficiency comparison to other energy storage techniques

In terms of efficiency, storing energy as ice appears favourable when compared to alternative energy storage methods. To be clear, ice stores only provide cooling and not electricity as is the case with most other energy storage technologies such as batteries, pumped hydro, fuel cells or compressed air energy storage. This might be seen as a disadvantage as rejuvenated electricity can be used for any purpose. However, ice has a very high value to the uses of cooling. There business aim is to cool products and they buy electricity for that purpose; they could equally buy cooling or ice as the business aim is still met. It is quite reasonable to store ice adjacent to a refrigerated warehouse as we know the cooling load is definitely going to be consumed by the warehouse and by storing the energy as 'end use' we are avoiding efficiency losses of energy conversion (from say electricity to hydrogen back into electricity).

In terms of efficiency, ice storage appears competitive as shown in table xx:

Energy storage technology	Storage efficiency
Ice Storage	70-80%
Li-ion batteries	80-90%
Lead Acid batteries	50-90%
Pumped Hydro	75%
Compressed air energy storage	30-90%

Table xx can we discuss these quantities please, (try and push ice higher)

5.3 Size of ice store

The challenge was store 5 days worth of cooling energy as frozen ice, and in our industrial warehouse test case we calculated this as requires 2% additional warehouse volume. (Add calcs in appendix?)

Using a figure of 300kW continuously for 5 days with a COP of x, our warehouse requires XX kJ of energy to produce zz kJ of cooling. The same energy can be stored in VV m3 of ice mix of a box x by x by m. The warehouse is approximately zzz m3 of storage volume today and therefore we would required an additional 2.5% of volume. (Revise numbers)

We consider it best to place the ice inside the warehouse as this has two strong advantages. Firstly standing losses are eliminated since energy loss through heat transfer from the ice is delivered as useful cooling to the warehouse, and secondly it increases the reliability and availability of cooling over and above todays practice of having compressors delivering cooling directly. This later point may make the market particularly interested in adopting the concept.

5.4 Comparison of cost

We have not produced a detailed cost estimate of ice energy storage, but a simple consideration indicates that it is very cost competitive: refrigerated warehouses already own and operated electrically driven refrigeration plant, ice storage vessels are small and low cost.

Achieving a 5 day energy store in say electrical batteries or hydrogen is expensive as it requires the storing of large quantities of chemicals, pressurised or toxic. By comparison ice is benign and compact. Equally storage of 5 days of electrical energy through hydro electric schemes requires large scale geographic terrain of the right scale and location; by comparison ice storage is compact and local and is placed adjacent to existing warehouses with sizeable grid connections.

Many of the components in an ice storage system are also required for direct refrigeration, so the marginal cost of ice storage as an addition to a refrigeration facility is low. Compressors, heat exchangers, controls etc. are required in either case. An insulated ice storage tank, ice-melt heat exchangers, pumps etc. are the additional components required for ice storage, none of which are particularly expensive to produce at scale once mature designs are established.

We believe there may be a cost saving through ice storage as it offers higher availability of cooling to the end user. Instead of an industrial cooled warehouse buying duplicate refrigeration plant to cater for plant breakdown, the warehouse can be fitted with ice stores, which release heat for several days whilst the main refrigeration plant is repaired.

So whilst we have not carried out a full cost estimate, we consider that by comparison to many other energy storage techniques proposed we think 5 days of ice energy storage is favourably competitive.

5.5 Cooling reliability and availability

Warehouse customers are very demanding of system reliability of the cooling plant; their primary business objective is not save energy or be useful to wind farm operators or provide generation capacity to the national grid, but to protect the frozen assets they are custodian of. By placing the frozen ice energy inside the warehouse it can be argued that cooling availability and reliability is improved because even in a full electrical power loss occurs the insulated ice store can still be engineered to provide cooling to the warehouse without the need for electricity (for example, by transferring the heat through heat pipes or other means that do not require electrically driven pumping).

Storing the ice energy inside the refrigerated warehouse may also provide a subtle benefit for operators of refrigerated assets as at any point in time they can monitor the level of ice stored and therefore know the energy in reserve should any element of the plant fail. This assurance reduces the need for duplicate compression plant to cover for failure of the refrigeration units.

5.6 Development costs

We believe the proposition put forward here: to store 5 days worth of wind energy as frozen ice is a new energy storage concept which can have national benefits to a countries electricity system, however, we consider it requires little new engineering component of system technologies. Ice storage has already been developed in hotter countries than the UK although we believe these operate at 0°C. The new system operating with water/glycol mixes could require new heat exchangers which require the ice to be scraped from the surface of the heat transfer surface or other solidification method, and this is an engineering technology the authors remain interested in designing and developing. The refrigeration and control equipment is really an extension of know refrigeration technology. There is newness in the market: how the electricity market performs and functions and how readily refrigeration customers with large cooling loads would take to the proposition. Overall we see the engineering risks as modest compared to alternative renewable energy stores and therefore the developments costs of demonstrating the system are modest.