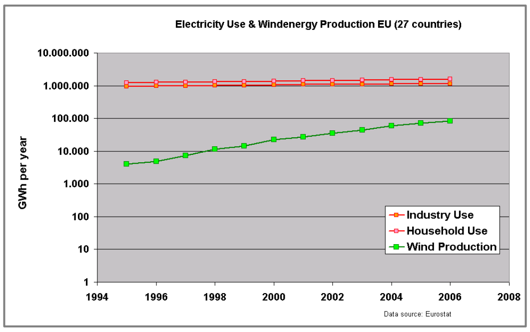
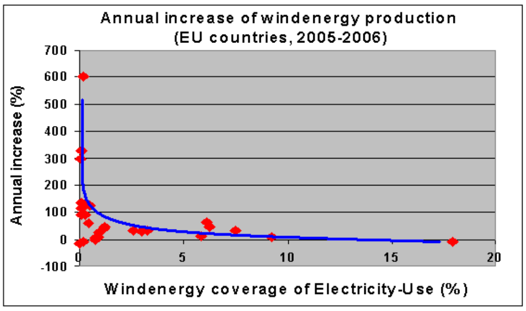
Cold Storage of Wind Energy – Night Wind

1 Introduction

There has always been a need to store electrical energy in "giant batteries" – but the costs are simply too high. A new concept, Night Wind, has proven the possibility to store electrical energy produced by wind generators in existing cold stores: at low costs.

The integration of wind power into the national or EU energy supply systems is becoming relatively more problematic with increasing installed capacity and production, especially due to a mismatch of supply and demand of energy. The wind energy is produced at rather random times, whereas the energy use pattern shows distinct demand peaks during day time and office hours, and low levels during the night.





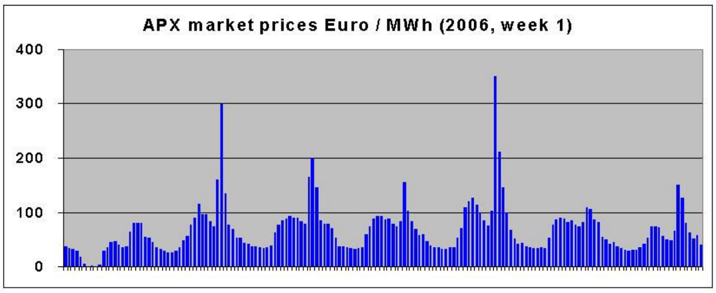
The goal for wind energy share in total electricity production in the EU-15 was set at 40 GW by 2010 (EU White paper, 1997). The actual share is growing rapidly and reached 2,9% in 2006 (EU 27 contries, see above graph). However, the graph on the left suggests that with higher wind energy share in the production, the annual growth in capacity decreases. At high installed capacity, the mismatch between supply and demand becomes bigger, and the price for produced wind energy drops – demotivating investments in extra capacity.

It is not a simple option to put supply and demand in equilibrium by changing the production capacity of conventional energy suppliers, like coal fired power plants. Running coal fired plants at "off design" conditions would lead to an increase of CO2 emissions, rather than the reduction of CO2 emissions which is desired. Trading a surplus of wind energy with neigbouring countries is also not always an option, due to the limited capacity of the grid.

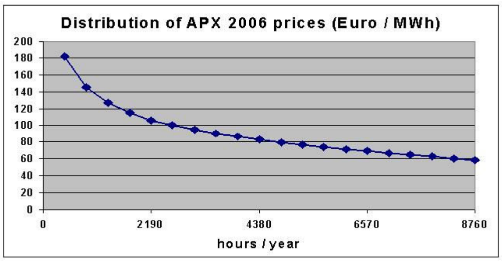
In order to accommodate the random production of wind energy in the grid, it would be most convenient when alternative (renewable and conventional) electricity producers could balance out the difference between production of wind energy and electricity demand by storing electricity. The Night Wind project aims to store wind energy produced at night in refrigerated warehouses, and to release this energy during daytime peak hours.

2 Economics

The economics for wind energy storage are directly related to price fluctuations on the free energy markets, such as the APX (Amsterdam Power Exchange). Prices range anywhere from 0,01 €/MWh to 900 €/MWh. Wind energy production costs currently are in the order of 60 €/MWh.



When the wind energy producer has no storage possibilities, he must sell at the current price, which on average will be close to the production costs (60 €/MWh). On local grids with a high percentage of wind power, the price may even fall due to a consistent surplus in supply at high wind velocities.

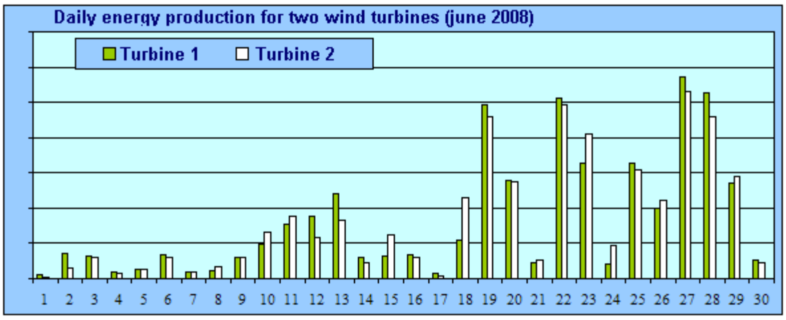


But when energy storage is available, and it becomes possible to sell only at selected hours, a better price can be reached. When the yearly production is sold during the 50% best priced hours, the average price received is € 83/MWh[1]. When selling during the 25% best priced hours, the average price received becomes € 106/MWh.

For wind turbine operators who receive a (constant) Feed in Tariff, there is no advantage in storing wind energy. The energy distribution company to whom the energy is supplied however, may benefit from differences in prices by using (large scale) energy storage.

The energy production of a wind turbine varies daily, as shown in the figure on the right. The daily production is on average 20% of the installed capacity.

To store one night's production of wind energy, a capacity is needed half the size of the daily production, equalling 10% of the installed wind power capacity.



Total wind power installed in the EU (27 countries) at the end of 2006 is 48.062 MW (source: EWEA). The total wind energy production in the EU 27 reached 81960 GWh in 2006 (Eurostat).

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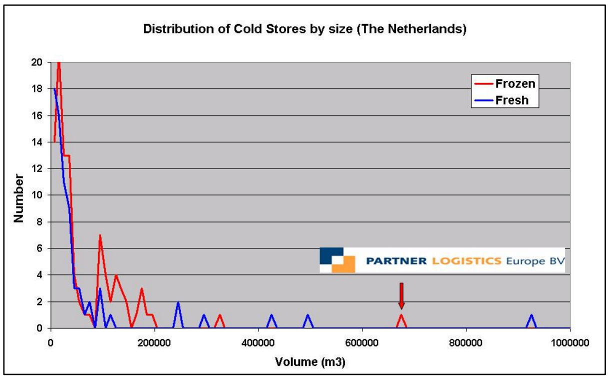
[1] Price levels according to APX 2006



The total cold store capacity in 14 EU countries equals 63 million m^3 (source IARW 2008), of which 12,6 million m^3 are located in The Netherlands. The figure on the left shows the size distribution of cold stores in the Netherlands, showing many small cold stores and some very large cold stores. Small cold stores have high values for energy consumption per m^3 and installed power per m^3 compared to large cold stores.

Cold Stores 2008	Million m3
Austria	0,8
Belgium	2
Denmark	1,9
Finland	1,8
France	8,5
Germany	13,4
Great Britain	5,6
Greece	0,9
Ireland	1,7
Italy	3,5
Netherlands	12,6
Portugal	0,8
Spain	8,2
Sweden	0,9

Based on an analysis of installed power and energy consumption for the Dutch cold stores, an estimate has been made for the situation in the EU (27 countries).

The total capacity of cold stores in the EU (27 countries) is estimated at 4.300 MW (installed electrical maximum capacity), which indeed roughly equals 10% of the installed wind power capacity.
Alike the situation with Windmills, the stated capacity of a cold store is the maximum capacity, and not the capacity in normal operation. On average in operation, the capacity is at 60-70 % of maximum capacity.

When the cold store operates above average capacity, the temperature in the cold store drops and the products are cooled down. In other words, the additional energy supplied to the cold store is transformed into thermal energy (lower product temperatures). The “battery” is being charged.

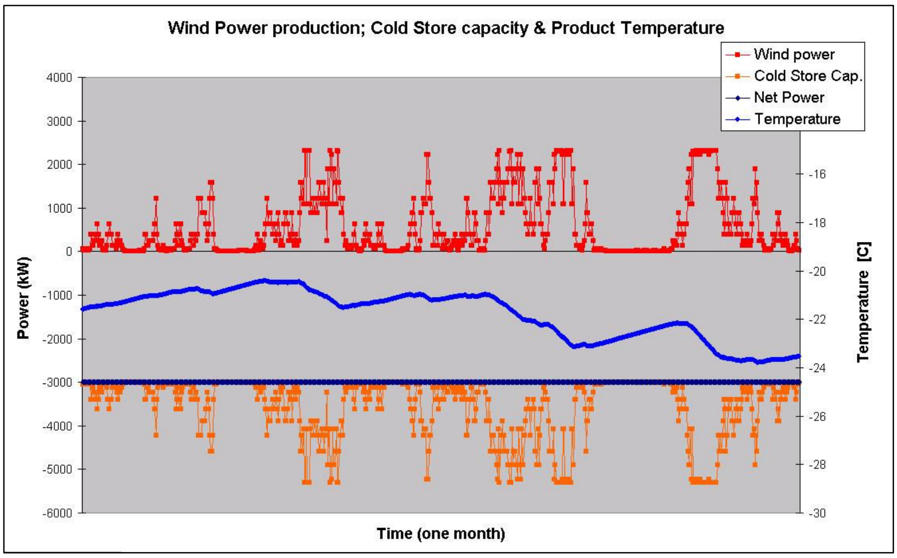
When the cold store operates below average capacity, the temperature of the products rises. The thermal “battery” is discharged. There is no “real” electricity produced in this discharging process. More precisely, the electricity that would have been required to keep the cold store at constant temperature is now available for other purposes, and is thus virtually produced.

The process of charging and discharging the cold store “battery” is almost free of losses. The comparison concerns the energy efficiency when running of the refrigeration machine for half an hour at -16 °C plus half an hour at –20 °C, versus running for one hour at -18 °C. This difference in efficiency is less than 1 %, and thus the overall efficiency is above 99 %.
For comparison, storing energy in a water reservoir by first pumping it up at an efficiency of 75% and then letting it flow out through a turbine at an efficiency of 40% has an overall efficiency of only 30 %.

Last but not least, there are no investment costs for the cold store “battery”: existing cold stores can be used. The only investment is for a change in the software of the refrigeration control system, by now using the Night Wind Control System software (NWCS).

3 Simulation

The general interest of the Night Wind cold store “battery” operation is to create a more constant load on the grid, as compared to the irregular load caused by wind turbines alone. Simulations based on the yearly wind data on an hourly basis and a wind turbine power curve show the hourly wind power production. When combined with the varying cold store capacity, the total electrical load on the grid is produced. The cold store capacity cannot influences the product temperature, and the upper (-18 ºC) and lower (-27 ºC) admitted product temperatures set the boundary conditions for the capacity variations.



The simulation result shown in the graph on the left represents a situation where the cold store capacity exacly compensates the wind power production. This gives a perfectly flat electrical load on the grid year-round. The following characteristic data wer used for this simulation:

- ENERCON E_{70} power curve
- Cold store capacity = 250 %
  (of wind turbine capacity)
- 1,5 ºC/day product cooling
  (at full cold store capacity)

In practice, the cold store capacity is smaller than the wind turbine capacity in which case it is not possible to produce a perfectly flat grid load line year round. Of course it is not require to produce a flat grid load curve year round, the Night Wind control system is used in practice to to avoid peak loads on the grid and to avoid excess (net) generation of wind power. For this purpose smaller cold stores suffice.

4 Food quality

The idea of using Cold Stores as “battery” for wind energy is interesting, as the cold stores are already in existence and only minor investments (in NWCS control software) have to be made. However, the primary function of the cold store is to store products, and this primary function must not be imperished. Therefore it is necessary to certify that the Night Wind “batttery” operation has no averse effect on the quality of the stored products.

Parallel tests have been conducted with 10 different food samples of identical type, shape and size, stored during 8 months at constant and variable temperature regimes. The samples – meat (bacon), fish (smoked Mackerel fillet), bakeries (fruit pie), fruit (strawberries), vegetables (tomatoes, melons and

peppers), potatoes (blanched/semigrilled French fries) and ice cream have been wrapped in plastic bags and boxes, evacuated and frozen at a constant air temperature of –19 °C as well as at a variable temperature (with day-night cycles) ranging from –16/–18 °C down to –26/–28 °C.

After 3 days, and 2, 4, 6 and 8 months of frozen storage, the samples have been thawed in air ambience up to a temperature in the product centre of 20-22°C. Thus, a number of quality attributes have periodically been evaluated – texture (by penetrometric measurements), colour (by the method of Gardner) and drip losses. Sensory evaluation has also been carried out (with the aid of a taste panel) to estimate the product appearance, colour, flavour and consistency.

The obtained data revealed that quality attributes of foods stored in frozen state at a variable temperature regime (involving freeze-thaw cycles) are comparable but generally inferior than the attributes of products maintained frozen at a constant temperature with no substantial temperature fluctuations.

5 The Night Wind Control System (NWCS)

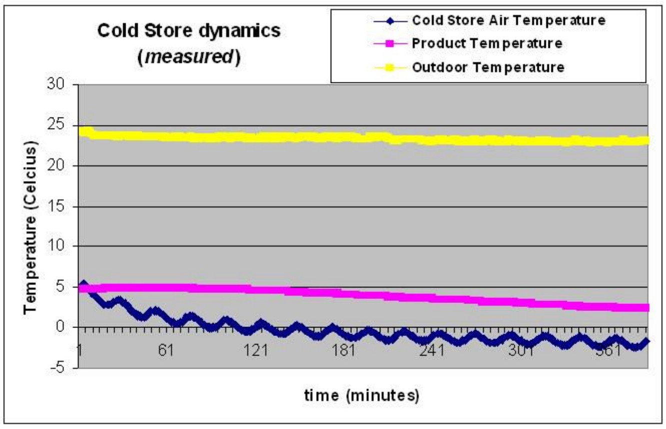
A new control system for the refrigeration capacity of the cold store is needed to operate a cold store as a “battery” in the Night Wind concept. The NWCS control system must perform the following tasks:

- Online input of wind energy predictions (3 days forward)
- Online input of energy cost predictions (24 hours forward)
- Calculate optimum capacity time-series for lowest costs or optimal grid capacity control
- Predict air temperature in the cold store and product temperatures
- Control the capacity of the cold store refrigeration compressors
- Measure air- and product temperatures (and cross-check those with the predicted values)
- Adjust the dynamic cold store model in order to optimize (future) temperature predictions

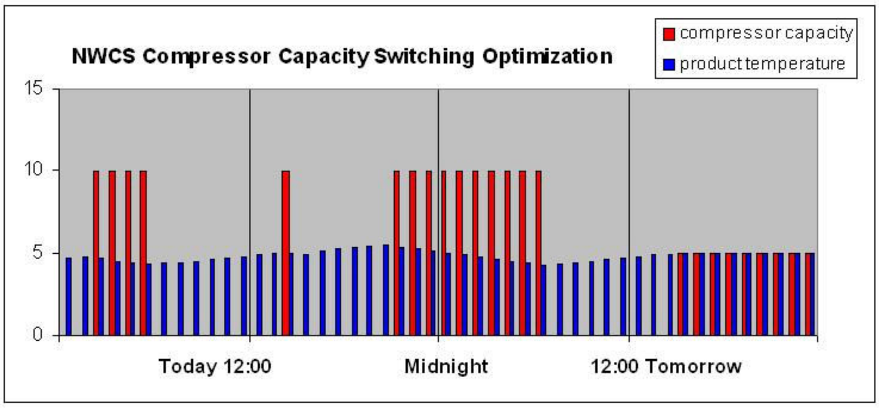
Within the EU FP6 Night Wind project, an effort was made to create such a control system. However, a working control system was not developed. Preliminary tests showed that the optimization of compressor capacity time-series took several hours to perform, mainly because of the differences in the time-scales of the air temperature dynamics (minutes) and the product temperature dynamics (days).

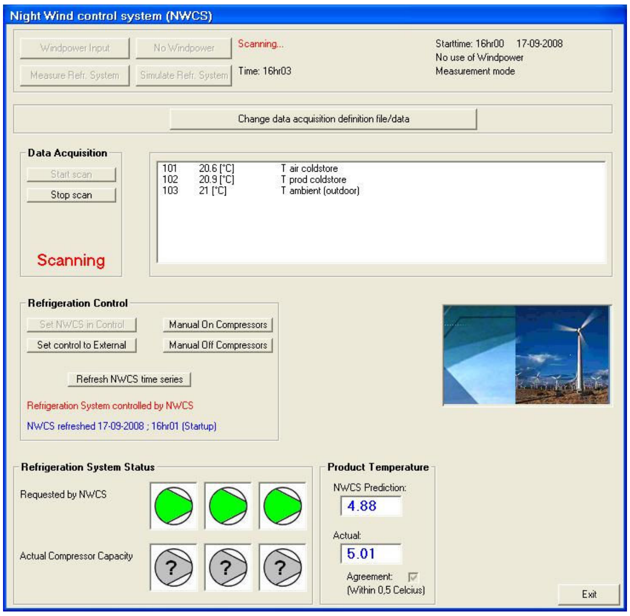
After the EU Night Wind project was concluded in June 2008, the challenge to develop a working control system for Night Wind was picked up by the Dutch company Saint Trofee.

Saint Trofee designed a new optimization routine for the capacity time-series. This routine includes a dynamic cold store model, but is nevertheless capable of producing an optimized time series in only 2-3 minutes.



The NWCS makes use of automated online acquisition of (APX) energy price forecasts, for the coming 24 hour period.
The compressor capacity time-series is optimized for the coming 24 hours, and takes account of the product temperature limits. The graph on the right shows the results for a cold store at +5 ºC





Scanning...

Time: 16hr03

Starttime: 16hr00 17-09-2008
No use of Windpower
Measurement mode

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101     20.6 [°C]       T air coldstore
102     20.9 [°C]       T prod coldstore
103     21 [°C]         T ambient (outdoor)
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Scanning

Refrigeration System controlled by NWCS

NWCS refreshed 17-09-2008 ; 16hr01 (Startup)

NWCS Prediction: 4.88

Actual: 5.01

Agreement: ☑
(Within 0,5 Celcius)

The wind energy forecast for specified turbines for the coming three days is prepared daily, and is automatically read-in by the NWCS program.

Data acquisition and control of the refrigeration system is performed by means of an Agilent data acquisition / switch unit. The NWCS provides the desired capacity for the compressors. The standard PLC compressor control remains in place, taking care of thermal and pressure overload conditions of the refrigeration system.

The NWCS program logs the measured temperatures and controller settings for later reference in an Excel log-file.

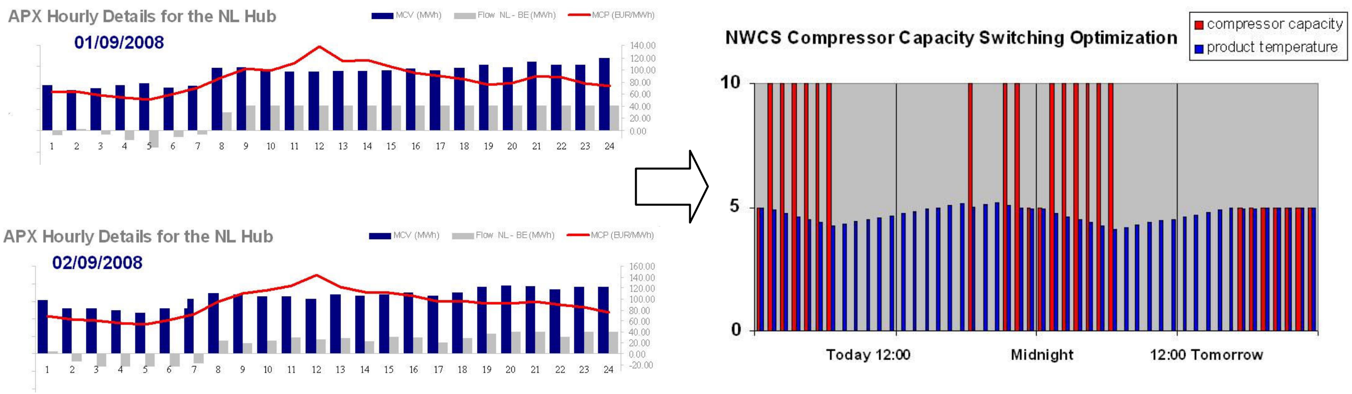
6 Contractual issues

The possibility to exploit the Night Wind concept on a national or regional scale, depends on the cooperation of cold stores. The concept must therefore be profitable for the cold store, which can only be assured when the cold store can make use of the variability of the energy price. Energy contracts with fixed day- and night tariffs are usual in the sector, but must be exchanged for contracts with (market) energy prices on an hourly basis. The Partner Logistics cold store, participating in the Night Wind project, makes use of such an energy contract.

7 Results

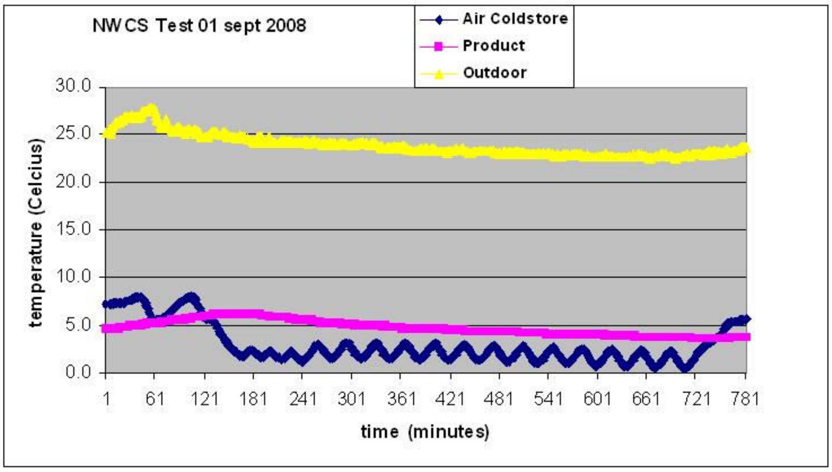
The Night Wind control system was tested on the 1st and 2nd September 2008 on a refrigerated storage space with a temperature setting of + 5 ºC. In this test, it was possible to measure the product temperature directly in a standardized test package according to European Standards (EN 441 / EN 153). Storage space temperature and outdoor temperature were measured with thermo-couples, and the compressor of the refrigeration system was directly connected to the NWCS control system.

The first action of the Night wind Control System NWCS , when it’s switched on, is to determine the optimum compressor capacity switching sequence from the APX data acquired online and the predicted wind energy for the coming days.



The capacity switching time series is determined taking into account the product temperature, where the product temperature is supplied by the dynamic cold store model for each step in the optimization routine. When the product temperature would run out of it’s boundaries (either at the “hot” or “cold” side) the optimization outcome is rejected. Based on the optimized capacity switching time series and modeled product temperatures, the NWCS is then ready to actually control the refrigerating system.

The test was started at 20:00 p.m. at a moment when according to the optimized time series the capacity demand is zero for the next two hours. The product temperature is then allowed to rise slightly in these two hours. At 22:00 the time series dictates that the compressor is switched on, and the product temperature will decrease. Due to the inertia in the product temperature, the measured product temperature starts to decrease after half an hour.



It can be seen from the test results that the product temperature performs as required: when the NWCS demands an “unloading” of the system (from 20:00 to 22:00), the product temperature rises. When the NWCS requests a “loading” of the system (from 22:00 to 07:00), the product temperature drops steadily.

What can also be seen from the test results is that temperature of the air in the cold store fluctuates. This is due to the fact that the compressor in this case was “on/off” regulated. When the NWCS demands the compressor to be “on” it runs at full capacity, and the air temperature drops to a value below the lower boundary. When this happens, the compressor temporarily cuts out, until the air temperature has risen. In a large refrigerating system the compressor is not “on/off” regulated, but continuous.

In a large refrigerating system, the capacity will not be set to “zero” but to a minimum value which will keep a steady air temperature while the product temperature rises. It will also not be set to “full capacity” but to a maximum value that keeps the air temperature constant and allows the product temperature to drop. The exact locations of the minimum and maximum capacity depend on the dynamics of the specific cold store.

When evaluating the “battery function” of a cold store in the Night Wind concept, the minimum and maximum capacity as intended above (i.e. in steady state) must be taken as basis for the determination of the power that can be sourced or delivered. The total amount of energy that can be delivered is related to the amount of products stored in the cold store, and the temperature change allowed in these products:

$E = m.C_p.\Delta T$

M = mass [kg]
C_p = specific heat capacity [kJ / kg. ºC]
ΔT = temperature change [ºC]
E = Energy [kJ]

Many products contain a large amount of water, and therefore often the C_p value of water is used in calculations (4,2 kJ / kg ºC). When 1 cubic meter of water is allowed to drop 5 ºC in temperature, the energy associated with that is 21.000 kJ or 5,8 kWh. This means that for every 1000 m^3 of products in the cold store the energy that can be stored with a 5 ºC temperature change equals 5,8 MWh - which in turn equals full power of a 1 MW wind turbine for almost 6 hours.