

FREELY AVAILABLE COLD STORE ENERGY MODELS

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ABSTRACT

User friendly, free, spreadsheet based numerical models were developed for the ICE-E (Improving Cold storage Equipment in Europe) project. These models were developed to enable end users to simply calculate how to save cold store energy. Two models were developed; these were called the 'simple' and 'complex' models. The 'simple' model predicts the steady state energy usage. For the 'complex' model, weather data are imported and the energy is calculated every day, such that yearly energy consumption is predicted. The 'complex' model also offers the ability for the daily heat loads to be exported and imported into Pack Calculation, a model developed by IPU Technology Development (Denmark). This model allows a more sophisticated refrigeration prediction to be made than the 'simple' model allows. The 'simple' model was compared with metered energy readings from a privately owned small cold store located in Northern Italy and shown to be accurate to 10%.

1. INTRODUCTION

Cold store facilities generally store food at chilled temperatures (typically between -1 and 5°C) or frozen temperatures (typically below -18°C) to maintain quality and safety of the food. For some specialised products ultra low temperatures (some fish, and specialised foods) or modified atmosphere storage (fruits and vegetables) are used. Cold stores can be owned by retailers, food producers or by private companies (often termed 'public cold stores').

Refrigeration is one of the most energy-intensive technologies used in the food supply chain. Refrigeration poses a number of sustainability-related challenges related to energy consumption and to loss of refrigerants, many of which are high GWP (Global Warming Potential) greenhouse gases. Refrigeration accounts for about 35% of electricity consumption in the food industry (Guilpart, 2008). Worldwide this equates to a consumption of about 1300 TWh per year. The cold chain is believed to be responsible for approximately 2.5% of global greenhouse gas emissions through direct and indirect (energy consumption) effects. Studies have shown that leakage of refrigerants may be higher than 17% in industrial plant (Clodic and Palandre 2004).

There are estimated to be 1.5 million walk-in cold rooms in the EU (Lot 1, 2011). In 2002 Duiven and Binard estimated that cold stores use between 30 and 50 kWh.m⁻³.year⁻¹. Cold store operators are often reluctant to install new equipment without sufficient information on savings that can be achieved.

Currently few cold store operators have the tools to be able to identify the most appropriate energy saving options, e.g. energy efficient fans, low energy lights, strip curtains etc. Most energy saving options are only selected and then installed after a case has been made for a relatively short payback period. This often requires a greater level of knowledge than most cold store operators have available. Therefore it is often difficult for cold store operators to obtain a clear and unbiased view on whether energy saving options are worthwhile in terms of carbon and financial savings.

This paper presents two user friendly tools that can be used by cold store operators and technicians to identify energy savings. The models are intended to provide cold store operators with a means to simply identify whether a technology is appropriate for their cold store and whether it is likely to achieve suitable benefits. The models are Microsoft Excel spreadsheets and are freely available at the ICE-E website <http://www.khlim-inet.be/drupalice/models>. Both models are available in English, Italian, Dutch, Czech, Bulgarian and Danish languages. The models have been validated against data measured at a cold store during an extensive energy audit.

2. SIMPLE MODEL

The following paragraph details the assumptions used in the model.

The model is steady state, therefore all heat loads are averaged over one day. The shape of the cold store is a rectangular box. There is only 1 door and the cold store is otherwise fully sealed. The cold store has enough thermal mass such that door openings do not change the temperature in the cold store. The temperature of the ambient outside the cold store is not changed by the door openings. There is only one layer of insulation on the walls, roof and floor. Any metal cladding is ignored as the resistance to heat transfer from this is considered negligible. The luminous flux from the lights is divided by the area of the floor and walls to give a uniform luminance. In reality there will be more lumens near the lights and shadows from racking etc. Some of the lumens will illuminate the ceiling and some will be absorbed by product and reflectors. The thermal mass of the trucks are ignored. Therefore if they move from a warm environment into the store, they do not give up this heat to the store. There is no energy from charging battery trucks given up to the store. Any product which changes temperature when loaded into the store does not have a latent load (e.g. freezing and thawing) only a sensible load. Respiration is included for all vegetable and fruit product above 0°C.

The user inputs data about their cold store into a spreadsheet. The layout of the spreadsheet is shown in Figure 4. The inputs include;

- Information about each wall (including ceiling and floor) of the cold store, e.g. face area, whether it is in the sun, outside ambient or internal and the type and thickness of the insulation.
- The size of the door, its opening schedule, whether it is protected (e.g. by strip or curtains), amount of traffic through the door and the outside conditions.
- The refrigeration system, refrigerant, type of condenser, condenser ambient, efficiency of compressor and number of stages.
- Heat loads inside the store, forklifts, lights, personnel, product, defrosts, evaporator and condenser fans.

From these data a steady state heat load is calculated for the cold store. An electrical energy of the compressor is derived from the heat load using a calculated COP. The energy of the compressor E_{comp} is calculated using the formula given in Cleland (1992) (eq. 1).

$$E_{comp} = \frac{[Q \cdot (T_c - T_e)]}{[(273 + T_e)(1 - \alpha \cdot x)^n \mu_c]} \quad (1)$$

Where Q is the total heat load on cold store, T_c is the condensing temperature, T_e is the evaporating temperature, α is an empirical constant for different refrigerants, x is the fractional vaporisation on expansion from liquid to saturation at discharge, n is the stage coefficient and μ_c is the isentropic efficiency of the compressor

The electrical power of the condenser and evaporator fan motors, E_{motor} is given in eq. (2).

$$E_{motor} = \frac{N_{motor} P_o}{\mu_{motor}} \quad (2)$$

Where N_{motor} is the number fan motors, P_o is the output power (shaft) of fan motor and μ_{motor} is the efficiency of the fan motor.

For electric defrosts, the electrical power of the defrost heater is given in eq. (3).

$$E_{def} = \frac{1}{\mu_D} \frac{\{[m_{DO} \cdot (X_o - X_i) \cdot L_f \cdot D_{DO} \cdot N_{DO}] + (m_{WL} \cdot L_f)\}}{(24 \cdot 3600)} \quad (3)$$

Where m_{DO} is the mass flow through an open door, X_o and X_i are the concentration of water air outside and inside the cold the store, L_f is the latent heat of fusion for water, D_{DO} is the duration of each door opening, N_{DO} is the number of door openings per 24 hours, m_{WL} is the weight loss from product and packaging and μ_D is the defrost efficiency. Where the defrost was either hot gas or natural then $E_{def} = 0$.

The electrical power of the lamps E_L is given in eq. (4).

$$E_L = L \cdot \frac{A_f}{e_L} \quad (4)$$

Where L is the Luminous flux required, A_f is the floor area and e_L is the efficacy of the lamps.

If floor heating, E_f , uses recovered heat then $E_f = 0$

This electrical energy is added to all other electrical energies from fans, lights, defrost heaters, floor heating etc.

The total calculated heat load is presented along with a pie chart showing the individual heat loads from transmission, infiltration (door opening), defrost, lights, fork lift trucks, personnel, product, evaporator fans and other heat loads.

The total electrical energy is presented along with a bar chart showing the individual electrical loads from the refrigeration compressor, defrosts, condenser and evaporator fans, lights and floor heating.

The output sheet (Figure 1) recommends potential ways to improve energy. Another worksheet allows the cold store to be improved, for example by fitting more energy efficient lights or fans. The output sheet displays a comparison of both cold store energies showing the energy saving of the improved store. The output sheets are updated automatically and in real time every time a modification is made.

3. COMPLEX MODEL

The complex model is based on the simple model but has some enhancements. Energy consumption is calculated every hour for a whole year. The parameters which change every hour are the ambient temperature, relative humidity (RH), ground temperature, wind speed and solar radiation and the position of the sun in the sky. All other parameters are fixed throughout the year. This allows a yearly profile of energy consumption to be evaluated. The model uses Visual Basic macros accessed by 'user friendly' buttons.

The uses worldwide hourly weather data imported from the U.S. Department of Energy, Energy Plus Energy Simulation Software, weather data

(http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm).

The daily heat loads for the 12 months of the year are shown as a bar graph. The hourly heat loads during the day for the months of the year are shown as a line graph. A similar output is then presented for electrical consumption and power (Figure 2).

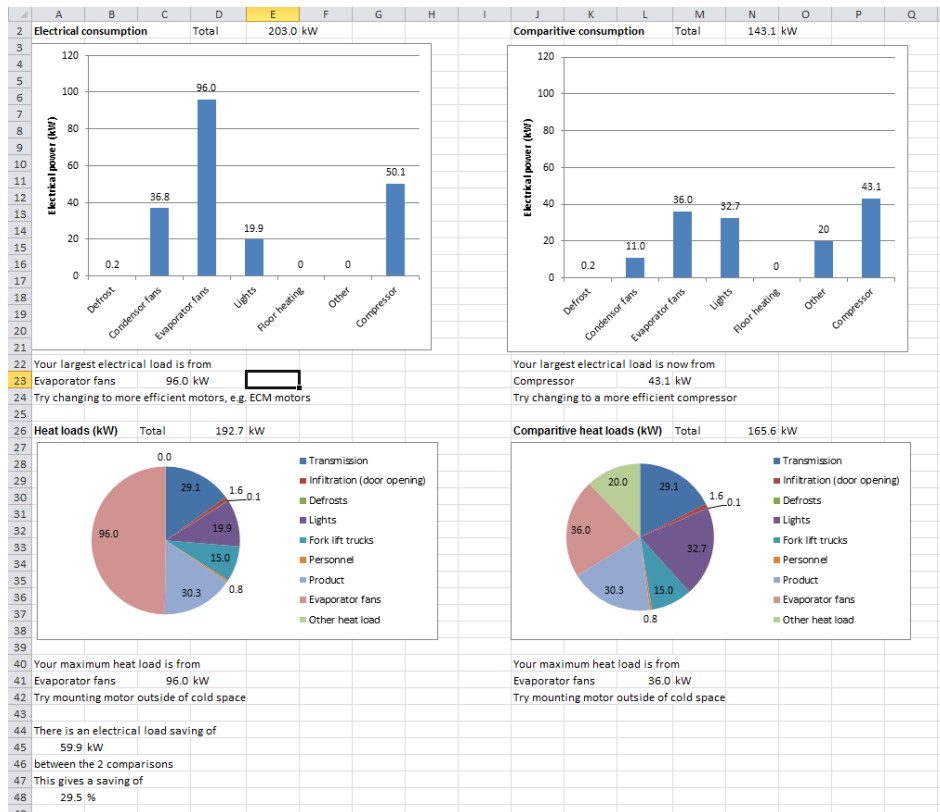


Figure 1. Output screen for the simple model

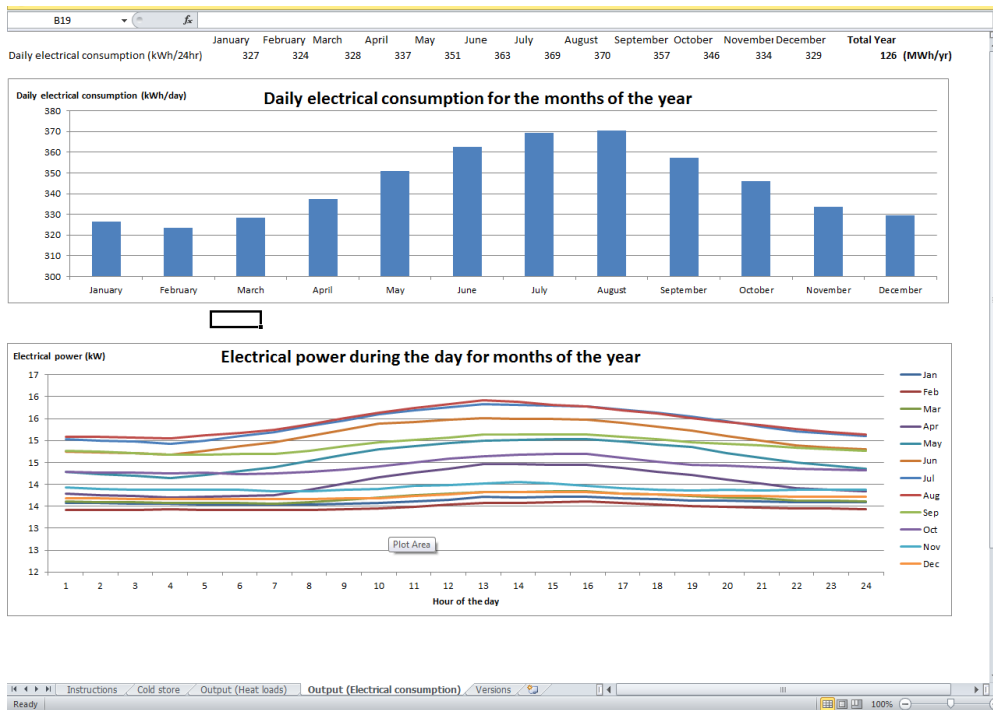


Figure 2. Electrical consumption and power output screen for the complex model

If the simplistic refrigeration model (eq. 1) is not adequate (due to complexity of the system) the hourly heat loads can be exported via another macro accessed by an 'Export' macro. These heat loads can be imported into Pack Calculation (IPU Technology Development, Denmark). Pack Calculation is an application for comparing the yearly energy consumption of refrigeration plants. Among other features, transcritical CO₂ systems can be compared with traditional systems. (<http://www.ipu.dk/English/IPU-Manufacturing/Refrigeration-and-energy-technology/Downloads/PackCalculation.aspx>)

4. VALIDATION METHOD

The simple model was validated against data measured at a cold store during an extensive energy audit.

The audited facility consisted of a single cold room having an internal volume of 60 m³. It operated at positive temperature (from 2 to 4 °C). It had a rectangular lay-out and the room height was 2.9 m. It had a single, hand operated door, with strip curtains. The cold room was installed inside a building. The space around the cold store was not temperature controlled. The cold store was built in 2011. Data obtained from site plans showed that the cold room walls and ceiling were:

- Walls and ceiling - 80 mm Polyurethane foam (density: 39 kg/m³, thermal conductivity (@23°C): 0.029 W/(mK);
- Floor - granolithic concrete.

Water consumption for a steam cleaning process was measured. It was assumed that the steam was fully condensed over the surfaces cleaned inside the cold room. This gave an average heat load of 100 W.

The cold store was monitored and audited during a 4 week period in February/ March 2012.

The refrigeration system was a dry expansion R404A unit with air cooled condenser. The main characteristics are listed in Table 1.

Table 1. Details of the refrigeration system.

Temperature	Refrigerant	Compressor type, manufacturer, model and quantity	Condenser type and number	Evaporator type, manufacturer, model, number and defrost	Expansion type and number
Positive	R404A	Semi-hermetic, Dorin, HI350CC, 1	Finned coil, 1	Ceiling unit cooler, ECO, DFE 33EH3, 1, Electric defrost	Mechanical TX, 1

Data used in the analysis were collected from;

- the existing monitoring and control system (Eliwell EWDR 985);
- selected positions on the refrigeration system using data loggers (temperature and energy loggers) placed there by the auditing team
- manufacturers
- direct observation of the cold room use
- direct measurement of specific temperatures in and around the cold room.

Door openings were monitored by means of a switch connected to a timer. Lighting was automatically switched off when the door was closed. Throughput of product was registered by the operators. No forklifts were used in the cold store (only a hand operated trolley).

Data were logged over a period of 28 days. During that period the logging interval was varied from 1 to 10 minutes.

The energy consumed by the plant was evaluated from the logged data. Energy meters were used for recording the energy consumption of the condensing unit (compressor and condenser fans), evaporator fans and of the electrical defrost. Lighting power consumption was evaluated from manufacturer's data.

5. VALIDATION RESULTS

All of the inputs to the simple model for the cold store are shown in Figure 3.

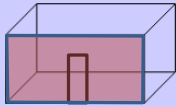
North wall Surface area: 20.0 m ² Shaded from the sun? Shaded Temperature on the outside: 17.2 °C		Weather still (no wind)
East wall Surface area of the wall: 8.0 m ² Shaded from the sun? Shaded Temperature on the outside: 17.2 °C Colour of external wall: Light		Insulation Type of wall insulation: Polyurethane foam Thickness of wall insulation: 80 mm Type of floor insulation: Concrete Thickness of floor insulation: 50 mm Type of roof insulation: Polyurethane foam Thickness of roof insulation: 80 mm
West wall Surface area: 8.0 m ² Shaded from the sun? Shaded Temperature on the outside: 17.2 °C Colour of external wall: Light		Heat loads Fork lifts Number: 0 Size: Power source: Operation time: h/day
South wall Surface area: 20.0 m ² Shaded from the sun? Shaded Temperature on the outside: 17.2 °C Colour of external wall: Light		Lights Operation time: 0.3 h/day Lux: 562 lm/m ² Efficacy: 49.1 lm/W
Roof/ceiling Ceiling surface area: 20.3 m ² Shaded from the sun? Shaded Temperature above roof insulation: 17.2 °C Colour of the roof: Light		Personnel Number: 1 Time: 0.4 h/day
Floor Surface area: 20.3 m ² Temperature under floor insulation: 15.7 °C Floor heating average power: 0 W		Product Mass loaded: 150 kg/day Temperature when loaded: 18 °C Total mass in store: 350 kg Type: Mixed Foods Weight loss: 6 kg/day
Door Width of the door: 1.4 m Height of the door: 2.2 m Temperature outside the door: 17 °C RH outside of the door: 60 % Number of door openings per day: 60 Duration of each door opening: 50 s Volume of traffic passing through the door whilst it is open: Low Door protection: strip curtain		Defrosts Type: Electric
Refrigeration Store temperature: 1.3 °C What is the refrigerant? R404A Temperature around condenser: 16 °C Number of compression, expansion stages: 1,1 Isentropic efficiency of compressor: medium (0.6)	Evaporator fans Number: 3 Shaft power of each fan: 110 W Motors inside refrigerated space? yes Motor efficiency: 55 % Condenser fans Number: 2 Shaft power of each fan: 175 W Motor efficiency: 55 % Other heat loads Average power: 100 W	
<small>Disclaimer The sole responsibility for the content of this model lies with the authors.</small>		

Figure 3. All of the inputs to the model for the cold store.

Figure 4 shows the heat loads predicted by the simple model. The total heat load was predicted as 3.32 kW. By far the largest heat load was the transmission load of 2.43 kW, the next largest load was the evaporator fans at 0.6 kW.

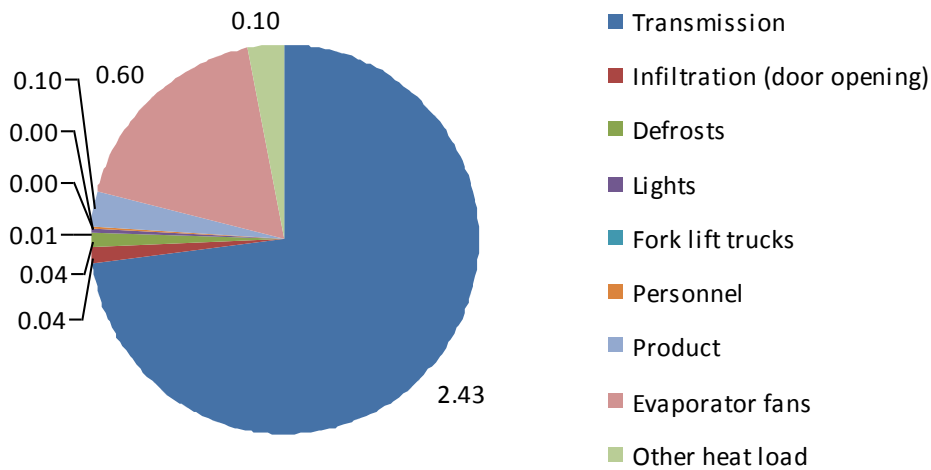


Figure 4. Calculated heat load values (kW).

The measured electrical consumptions of the different components were compared with those predicted by the simple model and shown in Figure 5.

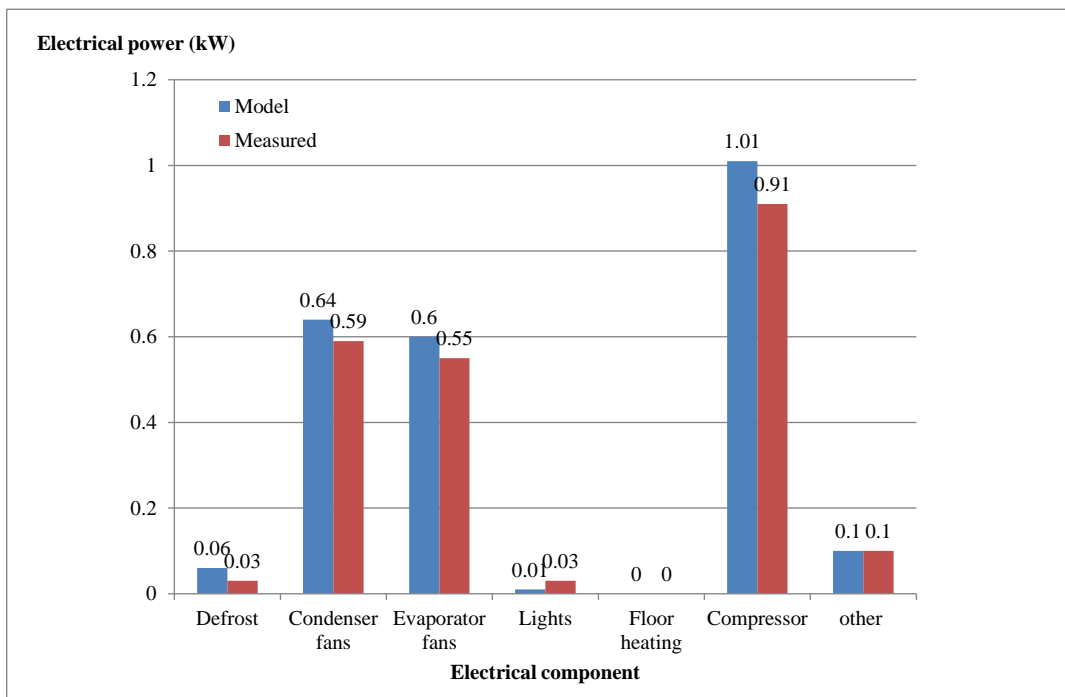


Figure 5. Measured vs. predicted (by simple model) power consumption.

The largest electrical power was from the compressor. The model over-predicted this power by 11%. Condenser and evaporator fans formed the majority of the rest of the electrical power. The model over-predicted these powers by 8%. Defrosts were heavily over-predicted (100%), however, they only accounted for about 1 or 2% of the total power. Light power was heavily under-predicted (33%), however, this was also a minor part of the total power. The total electrical power of the store was over-predicted by 10% (2.42 kW instead of 2.21 kW).

6. DISCUSSION

The simple model was shown to be accurate to approximately 10% of the total power consumption of the validation cold store. The major power-using components: compressor, condenser and evaporator fans, were also predicted to this level of accuracy (10%).

The level of accuracy of the modelled compressor power will be highly related to the accuracy of the heat loads. In this case the largest heat load was transmission. As the transmission load is dependent on temperature difference, thermal conductivity and thickness of insulation, it is important that these values are entered correctly. An estimate of thermal conductivity of the walls can be made using temperature sensors attached to the walls, however it is likely that cold store operators will use manufacturers data. It should be noted that the age and condition of the insulation can have a large effect on this value and a range of values should be considered.

The possible reasons for the errors in fan motor power were that manufacturer's data (output power and efficiency) are obtained in a standard wind tunnel. Such measurements are not fully representative of the actual installation of the fans in an evaporator or condenser. This may lead to an imprecise evaluation of the fan efficiency in actual application. Defrost power over-prediction would be due to the predicted infiltration of moisture into the room being over predicted. The under prediction of light power was likely because the luminous flux from the lights was divided by the area of the floor and walls to give a uniform luminance. In reality there will be more lumens near the lights and shadows from racking etc. Some of the lumens will illuminate the ceiling and some will be absorbed by product and reflectors.

7. CONCLUSIONS

The 'simple model' tool is a freely available simple-to-use tool which allows cold store operators to investigate energy saving measures on their cold stores. The tool has been shown to be accurate to within 10% (total energy consumption) of data collected during an audit.

The 'complex model' allows energy consumption during the whole year to be calculated taking into account local weather. It also allows heat loads to be exported, such that more sophisticated refrigeration tools can be used. Although this tool has not been validated, it is based on the simple model and therefore similar accuracies would be expected.

8. REFERENCES

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