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SID 5 Research Project Final Report

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Project identification

1. Defra Project code AC0403

2. Project title

Fostering the Development of Technologies and Practices to Reduce the Energy Inputs into the Refrigeration of Food

3. Contractor organisation(s)

FRPERC, University of Bristol
Brunel University (EBERC)
LSBU
Sunderland University
Grimsby Institute

4. Total Defra project costs (agreed fixed price) £ xxxxxxx

5. Project: start date .... 01 July 2006

end date .... 30 June 2010

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so. ....**YES** ☒ **NO** ☐

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N/A

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The project has used the data that is currently available to map energy use in the refrigerated cold chain from primary chilling through to catering and retailing together with estimates of potential for improvement. This has provided a ranked order of the top 10 application areas where the largest gains can be made. The top 10 and the data used to calculate the top ten has been widely disseminated and discussed. It has stood up to intense scrutiny and is accepted by the industry as a true reflection of the current cold chain.

It is notable that retail and catering are top of the list, followed by transport with food processing and storage applications coming much lower down. The energy saving potential of the top three sectors being almost 10 times that of the next 7 combined. However, in the case of transport the CO_2 equivalent is lower since it has already been counted in primary energy terms. The global warming effect of refrigeration leakage was not considered in the energy mapping. This has been reported to vary with application being as little as 2%, of the total warming potential, in domestic refrigeration and 37% in mobile air conditioning. There are however substantial uncertainties in the estimates of current energy use and thus savings potential. This is mainly due to a lack of detailed metering in the industry and mechanisms for collating such information. The lack of detailed data also means that it has not been possible to benchmark actual versus theoretically needed energy in the various application areas. This is especially true in refrigeration operations such as primary and secondary chilling and freezing where there is little data relating the energy consumed to the throughput of the food being processed. Utilization is a key factor in batch chilling and freezing systems. For example, previous measurements carried out at 5 pork abattoirs showed that the mean base demand (i.e. an empty chiller running at design conditions) was 1655 MJ and the product demand when the chiller was fully loaded was 1245 MJ. The base demand is therefore 57% of the total energy consumed during the chilling operation for a full chill room. The energy consumption per kilogram of pork chilled was therefore dependent on the utilisation of the chill room. Similar results were obtained in a survey of 14 beef carcass chillers. Recent work in factories processing fish and fish products has again measured large base loads and a very poor relationship between energy per tonne of product and throughput.

The savings that have been identified have been backed up by a set of individual actions that could be taken in each application area, and the expected savings from each. These actions do not factor in new technology and thus represent what could be done now. This is especially true in retailing and catering where there are large differences in energy consumption between appliances that perform similar functions and also large differences due to use.

What comes out very clearly is that maintenance is an area of weakness across the board. There is also a lack of optimisation of the operation of existing plant and a lack of installation of relatively simple augmentations such as curtains and other devices to reduce infiltration through doors. This all points to lack of understanding and skills.

Another recurring theme is the lack of good design of systems, including controls. This is again a reflection of a lack of understanding and skills. In many cases this lack of understanding starts with the original process specification for the total refrigeration system, which may only contain details of the peak load conditions in a system that may operate under part, or no load for much of the time.

A number of specific approaches to energy reduction have been discussed and the expected saving quantified through examples. This includes Ambient cooling, Liquid Pressure Amplification; Vacuum panel insulation in transport; and Head pressure control.

The potential for new or emerging technologies to make major contributions to energy reduction has been examined. It has been concluded that such technologies are likely to be for niche applications only and are not likely to contribute to any step change in energy use. Vapour compression systems seem set to continue to be used, although in some applications CO_2 is likely to replace F-gases due to the environmental benefits of the former.

In view of the importance of good system design the project has developed new and more advanced tools for modelling individual components and system performance under dynamic conditions of use. Model outputs have been tested against a small number of real data and very good agreement found. This modelling tool is very advanced compared with what has existed before and this is a major output from the project. It has been placed on the web and a training seminar given on how to use it to help with component and system design, including control. Feedback on the model from the final dissemination meeting was that in its current state few people would realise its full potential. It was very complicated with many input variables. A simplified version with default values for most of the variables and a number of worked examples of its use would be of great aid to many users.

The unexpectedly large challenges with developing the modelling tool has meant that it has taken far longer for this to be developed than anticipated. The model has clearly shown that reducing the height of solid/liquid hot foods in a batch cooling operation can increase the throughput of product and substantially reduce the energy per kg of food cooled. The late availability of the model has meant that a range of ideas on how to save energy have not been able to be explored through modelling. However, the ideas are still a valuable output that can be pursued beyond the end of the project.

A notable success of this project has been its ability to disseminate results and activities rapidly to all elements of the food and refrigeration industries. A large stakeholders group was set up at the start of the project and new members joined as the project progressed. A web site was established in the first few months and stakeholders were regularly informed of new additions and progress reports. During the project there has been three very successful dissemination events 1) Excel London, 19th February 2008; 2) National Motorcycle Museum, Solihull, 3rd April 2009; and 3) HSI Building Grimsby, 8th June 2010. Over 50 different food and refrigeration companies and organisations were present at the final event in Grimsby and the feedback from attendees has been very positive. The FDF would like further events organised at other sites. As more and more information is placed on the website its use and importance is growing and it is becoming the key repository for food refrigeration energy saving thoughts and opinions.

The work of the project has been disseminated in over 90 separate activities including 6 peer reviewed publications, 3 book chapters, 20 conference papers, 5 journal articles, 37 presentations and 22 project reports. All the publications can either be found directly from the web site http://www.grimsby.ac.uk/What-We-Offer/DEFRA-Energy/ or via links/information on the web site.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

All the publications referenced [ ] in this report are detailed in section 9 and can either be found directly from the web site http://www.grimsby.ac.uk/What-We-Offer/DEFRA-Energy/ or via links/information on the web site.

Objectives

Objective 1 – Identify and rank 10 ‘operations’ (process/food combinations) in order of the potential by the use of improved technology and enhanced business practice to reduce energy usage in food refrigeration.

Objective 2.1 – Develop generic technologies and business practices that have the potential to reduce refrigeration energy consumption.

Objective 2.2 - Identify the features of the most efficient current systems and make them and their energy saving potential widely known to the industry.

Objective 2.3 - Identify and overcome any barriers to the uptake of current technologies that have the potential to substantially improve the energy efficiency of the 10 operations identified in 1.

Objective 2.4 – Quantify work being carried out to fill gaps in knowledge/technology identified to improve energy efficiency of the 10 operations identified in 1.
Objective 2.5 – Develop programmes to obtain the funding required to provide the missing information if no current work identified in objective 2.4.
Objective 3 – Carry out feasibility studies on current technologies that have the potential to achieve substantial energy saving in food refrigeration that are developed to a stage where they can immediately obtain funding from other sources.

Objective 1 – Identify and rank 10 'operations' (process/food combinations) in order of the potential by the use of improved technology and enhanced business practice to reduce energy usage in food refrigeration.

Table 1. 'Top Ten' food refrigeration sectors in terms of energy saving potential.

	Sector	Energy		Saving	
		'000 t CO_2/y	GWh/y	%	GWh/y
1	Retail display	3098-6819	5768-12698	30-50	6349
2	Catering – kitchen refrigeration	2147	3998	30-50	1999
3	Transport	1206	4822	20-25	1206
4	Cold storage – generic	483	900	20-40	360
5	Blast chilling – (hot) ready meals, pies	160-330	310-614	20-30	184
6	Blast freezing – (hot) products	117-223	218-415	20-30	125
7	Milk cooling – raw milk on farm	53-169	99-315	20-30	95
8	Dairy processing – milk/cheese	134	250	20-30	75
9	Potato storage – bulk raw potatoes	77-100	144-187	~30	56
10	Primary chilling – meat carcasses	59-77	109-144	20-30	43

The aim of objective 1, carried out by FRPERC, was to identify and rank the top 10 food refrigeration processes with the most potential to reduce the UK's energy consumption. Initially the data available concerning UK production and consumption of food was analysed to identify 1) the major food commodities in the UK and 2) those which were most likely to consume substantial amounts of energy for refrigeration. In parallel to this, data on the different sectors throughout the food chain was analysed to determine the scale of refrigeration processes in use and the energy being consumed.
The final mapping exercise identified and ranked the 'Top Ten' food sectors/operations that have the greatest potential for energy savings and are shown in Table 1.

The data and calculations used to produce Table 1 are presented in Energy use in reference 77.

Objective 2.1 – Develop generic technologies and business practices that have the potential to reduce refrigeration energy consumption.
Within objective 2.1 all the academic partners have worked to:

- Review new and emerging technologies (objective 2.1.1).
- Assess energy savings potential from efficiency improvements of current technologies (objective 2.1.2).
- Development of system models (objective 2.1.3).
- Assessment of business practices upon equipment requirements & performance (objective 2.1.4).
- Development of dynamic food models (objective 2.1.5).

Objective 2.1.1. Review new and emerging technologies.
The review covered:
a) Technologies that could be applied to all types of refrigeration equipment in the food sector [86*;* *5*].
b) Technologies for constant temperature refrigeration that are or could be applied to the food distribution and food retail sectors [8; 1].

a) Technologies that could be applied to all types of refrigeration equipment in the food sector [86; 5]
The general refrigeration technology review considered the following technologies: Sorption refrigeration systems (adsorption), ejector refrigeration systems, trigeneration, air cycle refrigeration, magnetic refrigeration, Stirling cycle refrigeration, thermoelectric refrigeration, thermoacoustic refrigeration, ground cooling and heating. The review established the current state of development of these technologies, their potential and barriers to their wide application and research and development needs.

A summary of the characteristics and potential applications of emerging refrigeration technologies is given in Table 2.

Table 2. Characteristics and applications of emerging refrigeration technologies.

Technology	State of development	Cooling/refrig Capacity of presently available or R&D systems	Efficiency/COP of presently available or R&D systems	Current/Potential application area(s)
Trigeneration	Large capacity bespoke systems available. Smaller capacity integrated systems at R&D stage	12 kW to MW	Overall system efficiency 65-90%. Refrig. system COP: 0.3 at -50°C 0.5 at -12°C	Food processing; cold storage; food retail.
Air Cycle	Bespoke systems available	11 kW to 700 kW	0.4-0.7	Food processing; refrigerated transport
Sorption-Adsorption	Available for cooling applications > 0°C. Systems for refrigeration applications at R&D stage.	35 kW to MW	0.4-0.7	Food processing; cold storage; retail; refrigerated transport
Ejector	Bespoke steam ejector systems available	Few kW to 60 MW	Up to 0.3	Food processing; refrigerated transport
Stirling	Small capacity `Free' piston systems available. Larger systems at R&D stage	15 W – 300 W	1.0 – 3.0	Domestic refrigerators, vending machines, refrigerated cabinets
Thermoelectric	Low cost low efficiency systems available.	Few Watts to 20 kW	0.6 at 0°C	Hotel room mini bar refrigerators, refrigerators for trucks, recreational vehicles; portable coolers; beverage can coolers
Thermoacoustic	R&D stage. Predicted commercialisation: 5-10 years.	Few watts to KW capacity	Up to 1.0	Domestic and commercial refrigerators, freezers and cabinets
Magnetic	R&D stage. Predicted commercialisation 10 plus years from now	Up to 540 W	1.8 at room temperature	Low capacity stationary and mobile refrigeration systems

Alternative technologies:
Reports have also been compiled by FRPERC on alternative chilling and freezing technologies (85) and equipment operation and optimisation (84). The report on alternative technologies included a review of the operation of refrigeration systems, process optimisation and new/alternative refrigeration methods and systems. The review of equipment covers equipment optimisation and available energy efficient technologies.

b) Technologies for constant temperature refrigeration that are or could be applied to the food distribution and food retail sectors

Transport refrigeration: In transport refrigeration the size and energy use of the refrigeration system can be reduced through the use of thermal energy storage based on phase change materials (PCMs), which can be charged at base. Ice slurries are also under consideration for thermal storage in chilled distribution. Total loss systems (cryo-coolers) are also being re-evaluated as a replacement for vapour compression systems. Other possible systems include air cycle, hybrid and solar powered systems. Magnetic refrigeration also offers potential for the future. Where greatest potential exists, though, is in the recovery of thermal energy from the engine exhaust and its use to drive sorption systems, ejector systems, thermoacoustic refrigerators and or/for power generation using thermoelectrics or turbogenerators.

Integral refrigeration equipment (cabinets): Hydrocarbons are already being used as a replacement refrigerant for HFCs in many integral refrigerated cabinets. CO_2 systems have also been developed and a small number of integral CO_2 cabinets are now in service. Stirling cycle coolers are already commercially available and reduction in cost accompanied by efficiency improvements can make them serious contenders for cabinet refrigeration systems. Other candidate technologies approaching commercialisation are thermoelectric and thermoacoustic refrigeration. Magnetic refrigeration is also a candidate technology but its commercialisation is further downstream and placed approximately 10 years from now.

Supermarket refrigeration systems: The environmental impacts of supermarket refrigeration systems can be reduced through the improvement of equipment efficiencies, reduction in the refrigerant charge and reduction or elimination of refrigerant leakage. There are also opportunities for thermal integration of refrigeration and HVAC systems and the application of CHP and trigeneration technologies. CO_2 based systems are also making inroads into the UK commercial refrigeration market and a number of different system configurations are currently being trialled. CO_2 systems on their own or in a cascade arrangement with hydrocarbon (HC) or ammonia (R717) are likely to become the dominant supermarket refrigeration technology in the future.

Food processing: Vapour compression systems are dominant in food processing. Plant energy savings can be achieved through improvements in component design and control and heat recovery. Possible system alternatives include CO_2 systems and CO_2 /R717 cascade systems. Air cycle technology offers potential for low temperatures, below -50°C and for combined heating and cooling. Other possible approaches include the recovery and use of waste heat for refrigeration through sorption and ejector systems and for power generation (thermoelectric, Stirling, thermoacoustic, turbo-generators). There may also be possibilities for the use of biomass, which may be a bioproduct of food processing for CHP and trigeneration.

Food storage (cold stores): Large food storage facilities normally employ ammonia vapour compression plant and it is likely that this will continue in the future. Another possibility that offers heat recovery potential is the use of CO_2 as a refrigerant on its own or in combination with ammonia in a CO_2/R717 cascade arrangement. Because of their location, normally in sparsely populated areas, food storage facilities offer potential for the use of biomass for combined heat and power or for trigeneration. A small number of such plants are already in operation. Large food storage facilities also offer potential for the use of wind power and solar energy to generate electricity to drive vapour compression equipment and/or heat for sorption systems.

Objective 2.1.2. Assess energy savings potential from efficiency improvements of current technologies

Due to the unavailability of junior research staff at EBERC this work was carried out as a desk-based study rather than through equipment tests and field system monitoring. The study showed that there is significant potential for energy savings from the improvement of the performance of vapour compression systems through the use of more efficient components and controls. Vapour compression systems also offer the potential for heat recovery from the condenser but care must be taken to ensure that the quantity of energy recovered outweighs the higher compressor power consumption that will arise from higher condensing pressures.

Transport refrigeration

Food transport refrigeration systems are predominantly based on the vapour compression refrigeration cycle. These systems, in order to meet the requirements of the ATP agreement and satisfy the refrigeration demands over a wide range of operating conditions are oversized by up to 1.75 times the calculated load. The COP of transport refrigeration systems is quite low, ranging from around 0.5 at –20°C space temperature to 1.5~1.75 at + 3°C space temperature and 30°C ambient temperature.

Articulate vehicles over 33 tonnes are responsible for over 80% of refrigerated food transportation in the UK. Refrigeration systems in these vehicles are invariably driven by auxiliary diesel engines.

The environmental impacts of diesel engine driven systems can be significant and up to 40% of the impacts of the vehicle engine. The capacity, size and environmental impacts of these systems can be reduced through the reduction of thermal loads by using better insulation materials such as vacuum insulation and thermal energy storage (eutectics). For small journeys the vapour compression system can be eliminated completely.

Sufficient reject heat is available from the engine of articulated vehicles to drive sorption refrigeration systems at normal out of town driving conditions but insufficient heat will be available in town driving. This shortcoming can be overcome through the use of an auxiliary heat source or eutectic energy storage. Other issues to be addressed are the size and mounting of the sorption refrigeration system. The air cycle technology is also quite promising for food transport applications. Main disadvantages at present are the low COP compared to that of the vapour compression system, particularly for chilled food distribution applications, and the unavailability of off the shelf systems. The potential savings of using sorption/air cycle has not been calculated.

Direct power generation from the heat in the exhaust of the engine to power refrigeration systems may be a promising technology for the future. Other technologies that need further investigation and consideration are Stirling cycle powered systems, magnetic refrigeration and solar energy driven systems and hybrid system arrangements.

Retail Food Refrigeration Systems

The energy consumption and emissions from supermarkets varies widely and can depend on many factors such as the type and size of the store, business and merchandising practices and refrigeration and environmental control systems used. The refrigeration systems account for between 30% and 60% of the electricity used and are responsible for significant environmental impacts from both the electrical energy consumption and refrigerant leakage.

To reduce the environmental impacts of retail food refrigeration systems considerable effort has been devoted to the development of refrigeration technologies using CO_2. The application of the first such systems in large retail food stores has been based on the cascade technology with CO_2 in the medium and low temperature refrigeration circuits and another refrigerant such as propane, ammonia or R404A for heat rejection. A small number of trascritical systems have also been installed using CO_2 for both refrigeration and heat rejection.

There is little published data on the practical performance on the application of subcritical and transcritical CO_2 systems to food refrigeration. Results to date indicate that subcritical CO_2 systems for low temperature applications may be more efficient than conventional R404A systems. For high temperature applications where the system will operate in the trascritical region the efficiency of CO_2 systems has been found to be inferior to that of R404A. Overall, across the whole operating range in a retail food store, CO_2 systems are though to be efficiency neutral compared to R404A systems.

Estimates of capital cost of CO_2 systems compared to R404A vary but are quoted to be between 10% and 30% more expensive than comparable R404A systems. The higher cost is due to the low volume of production and the specially designed components and fabrication needed particularly for transcritical systems. These costs are expected to reduce significantly with the wider adoption of CO_2 refrigeration systems.

Other technologies, i.e. secondary loop refrigeration systems have also been employed to avoid the use of HCFC and HFC refrigerants. Results to date are mixed but efficiency and cost comparisons between secondary loop and R404A systems are thought to be similar to those between CO_2 and R404A systems.

Irrespective of the type of refrigerant employed, improving the efficiency of the compressors, reducing the pressure ratio in the system, and continuously matching the refrigeration capacity to the load can achieve significant energy savings. Employing floating and suction pressure control or heat rejection to the ground can reduce the pressure ratio. Considerable opportunities also exist from refrigeration and HVAC system integration, heat recovery and amplification using heat pumps and demand side management and system diagnostics.

Another area that provides significant opportunities for energy savings is the design of more efficient display cabinets. Research and development areas to be addressed are the reduction of the infiltration rate, reduction of fan and lighting energy consumption, the design of more efficient evaporator coils to increase the evaporating temperature, reduce frosting rates and the implementation of defrost on demand.

Objective 2.1.3 Development of system models.

The general objective was to develop scientifically based models of refrigeration systems common across the food chain, so as to allow study of performance and component choice. It was specifically aimed to investigate the industrial cooling systems commonly used across the food chain in order to determine optima for design, performance and energy use.

The initial role of LSBU was developing steady state system models using custom software. A review of proprietary software packages concluded that none would meet the project aims and a specification for the model required for the project was developed [87]. A literature investigation into modelling refrigeration systems including work on component and system modelling and IoR System Efficiency Index was carried out [88]. The specification for the dynamic model and a target completion date of July 2007 was agreed [89]. A working cold store model was produced and a way to integrate the VCR model with FRPERC software agreed [90]. Further progress on linking and structuring of the model was reported [91]. A VCR transient model was completed and debugging undertaken and FRPERC tasked to produce a case study for validation of the model [92]. A successful validation of the Pieminister pie cooling case and the model used to demonstrate methods of saving energy [93] for the IoR presentation on the project [4]. The fully working model can now be access through the project website [70] and a workshop was carried out on 21st June 2010.

Objective 2.1.4 Assessment of business practices upon equipment requirements & performance.

The work carried out by the University of Sunderland has shown that a large number of companies do not collect and analyse maintenance data and therefore are unable to develop a new maintenance strategy based on historical trends [55,71]. In addition, companies rarely collected data regarding the cause and effect of a failure and what corrective action had been implemented. The research has also shown that the cost to maintain (including energy consumption) and utilisation costs (running cold rooms on maximum when less that 20% full) were rarely recorded.

The data collection exercise and the data collected by the University of Sunderland and Diagnostic Solutions Ltd has shown that a new approach to maintenance is required [13, 14]. This new approach will need to embrace new and relatively inexpensive technologies, including thermal cameras, vibration sensors and oil analysis. The use of Condition Bases Maintenance (CBM) techniques can be used to determine objectively the condition of machines and can predict failures. Their application is dependent upon cost to purchase, the ease of use (intrusive or non-intrusive) and the ability of the company to collect, analyse and determine maintenance.

However, the diagnostic capabilities of predictive maintenance technologies have increased in recent years with advances made in sensor technologies. These advances in component sensitivities, size reductions, and most importantly reduced cost, have opened up an entirely new area of diagnostics to the maintenance engineer and equipment operator [71].

Better maintenance can reap substantial benefits:

- Improved Energy efficiency
- Better reliability
- Less leakage of greenhouse gasses

Examples of situations where maintenance improvement have led to reduced energy consumption are summarised in Table 3. It can be seen that substantial savings are possible.

Item	Saving	Source
Computer Monitoring System to inform maintenance policies	£400,000	Westbury Dairies Case Study (Carbon Trust 2007)
Energy and maintenance strategy based on improved control procedures	20% reduction in maintenance costs	Nestle Ice Cream Plant in Mulgrave, Australia, ((State Government of Victoria 2002)
Use of an automatic controller to regulate set points	$2000 annually	Stonyfield Farms Yogurt (D'Antonio et al 2006).
Monitoring system for refrigerant pressure and operation of relief valves	$7439	Skating Arena, Madison, Wisconsin (Brownwell et al 2006)
Fuzzy control for compressor speed	13%	Aprea et al (2004)

Table 3 – Examples of Energy savings through maintenance and condition monitoring.

In order to improve maintenance procedures monitoring of energy consumption and plant condition is crucial. In determining the optimal maintenance and set-up of a refrigerant plant design, simulation and modelling all have a major part to play. The maintenance and monitoring issues related to each part of a conventional refrigeration system are shown in figure 1.

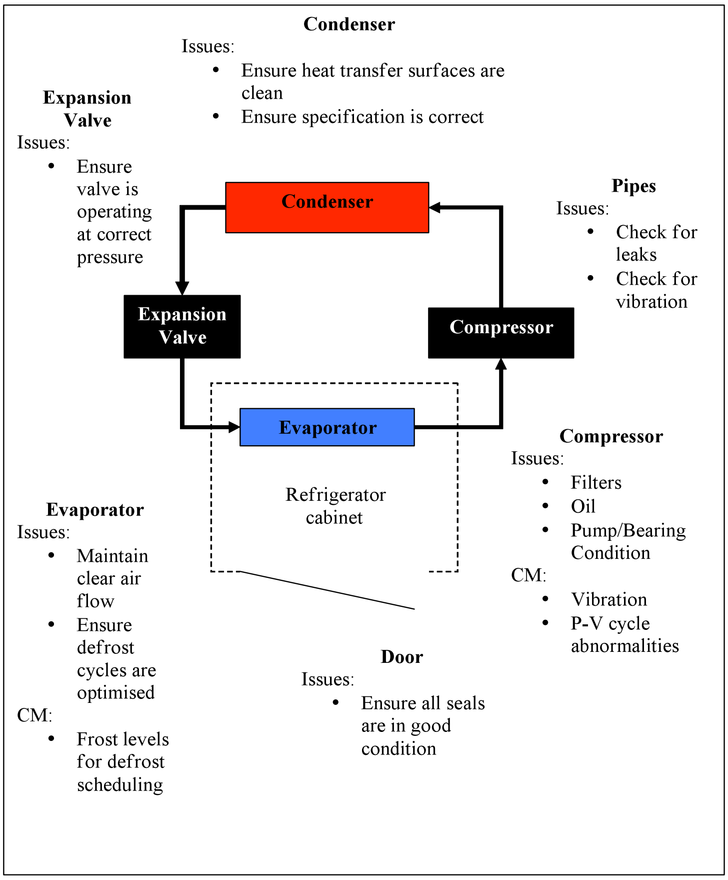

Figure 1 – Maintenance and Monitoring in a Conventional Refrigeration System

Objective 2.1.5 Development of dynamic food models.

As already described in 2.1.3 the general objectives of the modelling study were to develop scientifically based models of refrigeration systems common across the food chain, so as to allow study of performance and component choice. The sequence of activities leading to the development of the final model is detailed in 2.1.3 and the following describes the final model.

A scientifically based transient to steady state computer based simulation model of a cold space cooled by a vapour compression refrigerator has been written and validated. A schematic view of the system model is shown in Figure 2.

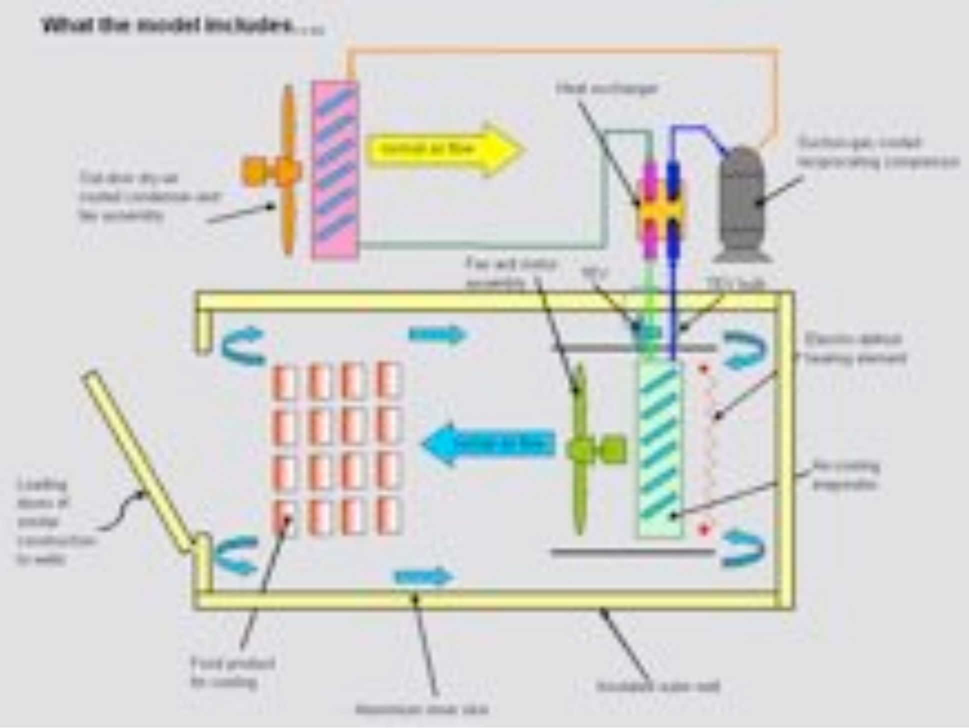

Figure 2: Schematic of refrigerated model cold space

The code has been debugged and guidance notes for users on how use the software has been provided through *HELP* pages and a *WIZARD* function, to assist new users to get started. This completely original piece of work proves industry with a tool for estimating the energy consumption and carbon generation resulting from refrigerated storage and refrigerated processing equipment in the food chain, ranging from small chill-cabinets to large cold stores.

The software provides the following functions:

- A Run-time screen, shown below in Figure 3, is provided through which all design screens and other functions are accessed. If necessary a user can navigate through the data input function using the *WIZARD* function, accessed by the click of a button in the toolbar in the Run-time screen. The Run-time screen also provides a facility, which displays the current ‘model-time’, and to set both model start and end-times and the loading time for the food-product: That is the period of time the model is to simulate. The start-up environmental conditions (temperature and humidity) of the cold-space (for example a cold-store or chill-cabinet) are also set within the Run-time screen. Once all the input data have been set and model is set to RUN, the Run-time screen acts as a control and instrument panel for the system being simulated. It displays in ‘model’ time instantaneous values of input and output data, such as evaporator cooling effect, ambient temperature, energy consumption and power values as well as performance data such as instantaneous COP and COSP values. Continuously updated graphical output of selected operating parameters is also provided through the Run-time screen. Depending upon the configuration of the compressor and evaporator fan controls (discussed below), the Run-time screen provides a facility to manually vary compressor and fan speeds in order to allow a user to investigate the effects of varying these important part-load parameters.

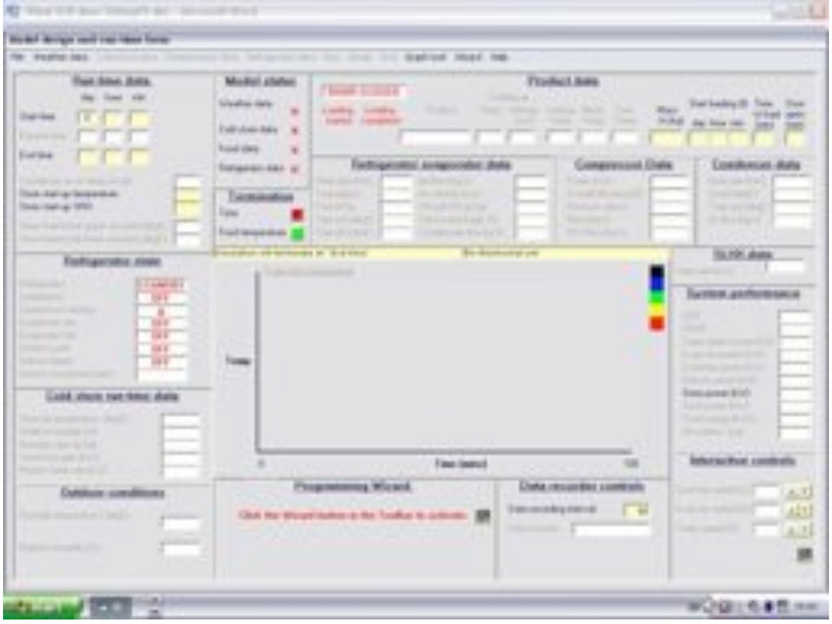

Figure 3: Run-time screen

- Easy to navigate design data input screens, exampled by that shown for the Cold-store in Figure 4, are accessed through the Run-time screen for both the cold-store unit and refrigerator system. Both are provided with default data settings and guidance on the setting of design values through the *HELP* function. Data text boxes are also provided with 'hover' functions. When the cursor is placed over a data text box the range in which entry data should lie is automatically displayed for the users information. Also, in many cases, if inappropriate or out of range data are entered in text boxes then the software automatically inserts default values before the simulation can be run.

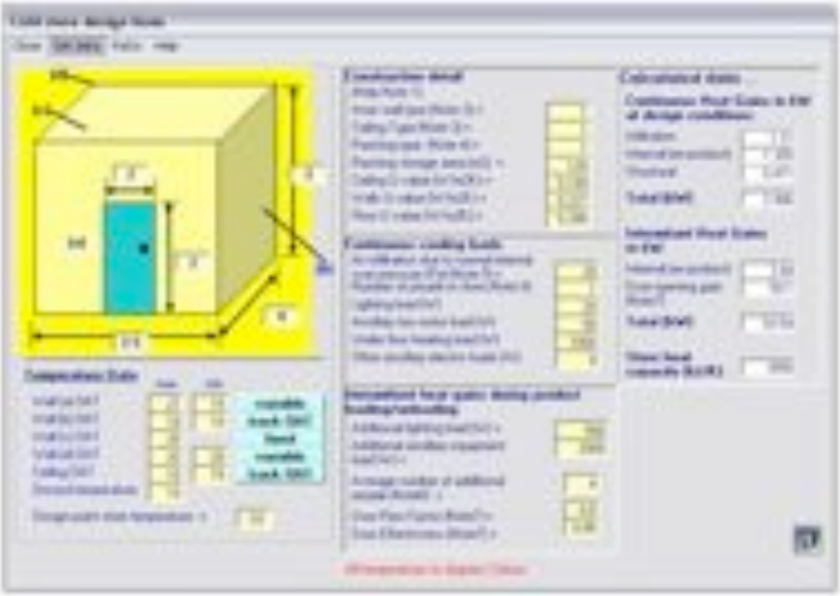

Figure 4: Cold store design screen

- The refrigerator design screen, shown in Figure 5, allows users to specify design-point data either by default or individually or in any combinations, for the evaporator, condenser, compressor, fans and motors, thermostatic expansion valve and refrigerant pipelines. If catalogue data are available for the compressor or evaporator or condenser (or for any combination of these) special easy to follow data input screens are provided for each.

Figure 5: Refrigerator design input screen

- The refrigerator design screen also allows users to choose between from a range of system control options, including six system thermostat control options, three evaporator fan speed control options (manual, automatic variable and automatic fractional), three compressor control selections, (manual speed control, automatic speed control based on temperature and staged, with up to six compressor stages available), two automatic electric defrost control options, (set either on by time and on by ATD), High and Low Temperature cut-out controls and compressor and fan motor start-up delay controls. In addition user can alter the time-constant and cooling capacity of the thermostatic expansion value to simulate the effects of both a badly positioned sensing bulb and an over or undersized valve, resulting in valve hunting and evaporator flooding.
- VCR software allows users to select between fixed or simulated variable outdoor temperature and relative humidity. For the variable option a user must select both the location of the plant they wish to simulate (from a list of seven major UK mainland cities) and the month of the year for which they wish to simulate the operation of the plant. The variable weather screen is shown in Figure 6. With the variable outdoor weather option set, the model simulates the diurnal variation in ambient temperature and humidity ratio. This simulation is based on published whether data for average monthly peak temperatures in seven UK cities taken over 30 years.

Figure 6: Variable ambient weather data screen

- In the Run-time screen there is a facility, which allows all the necessary system design data, which has been entered during a session, to be saved for future use in a user named file. There is a library function provided for saved input data files so that, conversely, if project data has been previously saved it can easily found and reload into the VCR model and RUN without further inputs being required.
- The Run-time screen allows model output data to be saved to a user named Excel file for later analysis and assistance in preparing project reports using a 'report generation function' which saves necessary information to a WORD.DOC

At this time the software appears to be robust. As already mentioned the fully working model can now be access through the project website [70], a workshop was carried out on 21st June 2010 and publications/presentations made [27, 47, 56, 67].

Validation case study:
The LSBU team provided the FRPERC team with a list of Input data required to run the model. The LSBU team used this data to set-up the model. The LSBU team also acquired manufacturer's performance data for the compressor. This was used to further develop the mathematical model of the compressor and its control. FRPERC recruited Pieminister Ltd for a Case Study. FRPERC recorded the electrical power consumption and temperatures around the subject refrigeration system over a period of weeks. One day's worth of data – the validation case – was supplied to the LSBU team for comparison against the models predictions. Close correlation between the validation data and model predictions has been shown [93].

Objective 2.2 - Identify the features of the most efficient current systems and make them and their energy saving potential widely known to the industry.
Experience had shown that the factors leading to energy inefficiency can be broadly combined under three areas a) Inefficient extraction of heat or poor protection from heat ingress into the food; b) inefficient refrigeration plant; or, c) poor operational practices. Progress in this area was limited because the initial mapping exercise found few if any food refrigeration processes with sufficient data on energy consumption and throughput to accurately determine their efficiency let alone the reason(s) for inefficiency.

A lack of available researchers also limited the number of case studies that could be carried out however the following desk based studies was carried out by EBERC and desk/practical studies by FRPERC.

Dairy plant – Energy Savings Potential of Liquid Pressure Amplification.
A case study was performed on the evaluation of the performance of liquid pressure amplification systems (LPA) and the energy savings potential from their wide application to the food processing and retail sectors of the industry [25].

The LPA technology utilises a refrigerant pump in the liquid line after the receiver to maintain a high enough pressure differential across the expansion valve to compensate for the pressure drop in long liquid lines. This allows the condenser pressure to be varied in line with variations in the ambient temperature leading to lower discharge pressures during periods of low ambient temperatures and lower compressor power consumption. Operation at lower pressures also increases the refrigeration capacity of the system enabling it to cope with increased load demands. LPA can be applied to new refrigeration plant and as a retrofit to existing plant. LPA also enables the use of liquid injection into the discharge line of the compressor, which desuperheats the refrigerant vapour before entering the condenser. This increases the capacity of the condenser, which in turn enables operation of the plant at lower condensing temperatures.

The case study considered the application of a LPA and liquid injection to a cold store at the Dale Farm dairy plant in Ballymena Northern Ireland. Before the application of the technology the cold store had difficulty maintaining temperature during periods of high ambient temperatures, with a drift of 5°C from design. The plant incorporates a 100 kW coldroom refrigeration system consisting of an air cooled condenser and 3 semi-hermetic reciprocating compressors arranged in parallel and serving 4 plate fin evaporator coils in the cold room. The refrigeration system was comprehensively instrumented with pressure and temperature sensors to measure temperatures and pressures at different points in the cycle. Other parameters monitored included the ambient temperature and the power consumption of the compressor.

Data obtained for a short period before and after commissioning of the LPA technology on 17 May 2008, through a web based monitoring system were used to investigate the performance of the system and energy savings achievable. The data were extrapolated over a whole year and through system simulation were used to evaluate the seasonal performance and energy savings potential of the system.

It has been shown that the use of LPA in conjunction with liquid injection can lead to up to 10% energy savings over and above those achievable with floating head pressure alone. The level of energy savings that can be achieved with LPA, however, is system specific and each application will require careful consideration of the savings against the capital cost of the technology.

Transport Refrigeration - Carbon Dioxide Transport Refrigeration Systems
This case study considered the use of CO_2 based cryogenic refrigeration systems for food transport refrigeration applications to investigate its environmental impact and energy savings potential [1]. The case study also provided a comparison between cryogenic systems and vapour compression systems driven by an auxiliary diesel engine. Cryogenic systems offer an alternative to vapour compression systems where a cryogenic fluid is expanded directly into the vehicle or in a heat exchanger to provide fairly rapid cooling. Cryogenic systems offer a number of advantages over conventional diesel driven vapour compression refrigeration technologies.

In the absence of field data the analysis was based on a spreadsheet model which was developed to analyse the thermal loads of refrigerated transport. The model takes into account the construction of the insulated container, the properties of the food cargo, the weather conditions and the operating schedule and determines the thermal loads from: i) the food product, ii) transmission and infiltration through the container walls, iii) precooling of the space, iv) infiltration due to door openings for loading and unloading.

For a cryogenic system the amount of cryogen required is determined from the thermal load and the latent heat of the cryogenic liquid. The analysis considered two different food types, chilled and frozen, and three operating schedules for each: - Long distance deliveries, Delivery rounds (10 hours operation per day) and short delivery rounds (5 hour operation per day).

The economics of vapour compression and cryogenic systems are to a very large extent dependent on the relative cost of diesel fuel and the cost of liquid CO_2. The cost of liquid CO_2 will in turn depend on the bulk quantity purchased as well as the infrastructure cost. These costs reduce significantly as the number of vehicles supplied from the same storage facility increase. The analysis in this case study has assumed a cost of £1.0/litre for diesel and £0.1/kg for liquid CO_2.

The results have shown that with the assumptions made there is no clear-cut economic advantage between the two systems. The CO_2 system though offers significant advantages in terms of Greenhouse Gas Emissions as these will be low if the CO_2 is a biroduct of other processes such as the manufacture of fertilisers. However, energy is required to compress it. Other advantages include very low noise and vibration compared to conventional systems, and much lower maintenance costs.

Transport Refrigeration - Energy Savings Through the Use of vacuum Insulation Panels

One approach to reduce the energy consumption of refrigerated food transportation is to reduce the thermal load of the insulated body. The main part of the thermal load of refrigerated vehicles, particularly for long haul operations, is thermal conduction through its insulation and any attempt to reduce this load offers the potential for significant energy savings. One way of achieving this, without affecting the external dimensions of the vehicle body or its load carrying capacity is through vacuum insulation [16].

Although it has been known for a long time that a vacuum can bring a significant improvement in insulation (the first vacuum panels were available in the 1950s), constructing a low-cost flat panel to take advantage of it was not an easy task. Silica panels were first investigated in the 1960s and found their way to the market in the 1990s. Vacuum Insulation Panels (VIPs) are now slowly becoming more popular as a novel insulation material showing conductivity values in the range 3-10mW/(m K), approximately 7 times better than those of conventional insulation materials.

To evaluate the thermal and economic performance of vacuum insulation panels in refrigerated transport the spreadsheet model developed for transport refrigeration systems was used to analyse the thermal loads for conventional and vacuum insulated vehicle bodies for 2 refrigerated products, chilled and frozen, and 4 operating schedules for each: long haulage operations; long operating hours and deliveries; delivery rounds (10h daily operating cycle); short deliveries (5h daily operating cycle).

The results of the analysis reported in detail [74] have shown that VIPs are a very promising technology for considerably reducing the thermal load of refrigerated transport vehicles. Significant reduction in the thermal load, up to 60% can be achieved. The level of load reduction will depend on the thickness of the VIP, the operating schedule of the vehicle, the ambient conditions and the refrigerated compartment temperature. VIPs can therefore be used to either reduce the fuel consumption and emissions of a diesel refrigeration unit or to improve the feasibility of alternative cooling solutions (e.g. solar cooling).

VIPs are now available in a wide range of shapes and specifications and their prices are expected to decrease in the next few years as their application increases. The case study has shown that a 20 mm-thick vacuum insulation can reduce the fuel consumption and emissions of the refrigeration unit by about one third, even when conservative assumptions for the thermal conductivity of VIPs are used. The use of VIPs is more effective in long haul operations and long operating hours where thermal transmission through the vehicle body is the dominant load. In these conditions vary favourable payback periods can be achieved of between 1.0 and 4.0 years.

Supermarket energy conservation measures

For this case study, in order to enable the investigation and assessment of energy conservation measures and the impact of alternative refrigeration technologies on the energy and environmental impacts of retail food stores, an in-house supermarket model ‘SuperSIM’ was developed further as part of the project to enable the analysis of R404A and CO_2 as refrigerants.

SuperSIM was developed within the TRNSYS (transient system simulation) environment and consists of a number of major submodels: the building model, the Heating Ventilation and Air Conditioning (HVAC) model and the refrigeration system model. SuperSIM enables integration of these models and using hourly weather data for a particular location enables the investigation of the interactions between the various subsystems in the retail food store as well as the resulting thermal environment of the store and the energy consumption of the major energy consuming systems. The model was validated using hourly data from a 4300 m^2 supermarket in Glasgow. A description of SuperSIM and its validation is given in reference 76.

Comparison between the use of R404A instead of R22 as a refrigerant has shown that the annual energy consumption of the compressors of the refrigeration system (2 high temperature packs and 1 low temperature pack) will increase by 7.5% and that of the condenser fans by 2.8%. The R404A system however, offers greater potential for heat recovery, 20% higher than that of R22 [75].

An approach that is becoming common place in centralized retail food refrigeration systems is ‘head pressure control’ where the condenser pressure is either 1) kept fixed throughout the year at a much lower value that was commonly used, by varying the air flow rate across the condenser or 2) allowed to vary with the variation of ambient temperature. These two similar control strategies are based in 1 on pressure and in 2 on temperature. A limitation of the variation of the head pressure is the pressure differential required across the expansion valve to ensure proper operation, and the availability of sufficient heat in the compressor discharge gas when heat recovery is applied. The results show that reduction of operation from a fixed pressure of 17.8 bar to 11.0 bar will lead to a net energy savings of the order of 40% even though to maintain the pressure at 11.0 bar for the majority of the year the fan power will increase by more than 50%. Operation at 11.0 bar will also reduce the heat available for heat recovery by 300%. Floating head pressure control using a fixed temperature differential between the condensing temperature and ambient temperature of 10k for the LT packs and 15 K for the HT packs. This produces similar results to operation with a fixed heat pressure control of 12 bar. Using a temperature differential of 10K for the HT back for the HT pack instead of the 15 K when a high efficiency condenser coil is used, will produce energy savings for the whole system of the order of 3.5%.

The refrigeration system models were also used to investigate optimised control strategies for CO_2 cycles in retail food refrigeration systems. A transcritical CO_2 system design was assumed that could operate either subcritically or transcritically depending on the ambient temperature. For transcritical operation, an optimum refrigerant discharge pressure is determined from thermodynamic cycle calculations. When the system operates in the subcritical cycle, a floating discharge pressure control strategy is employed and the effect of different transitional ambient temperatures between subcritical and transcritical cycle operation was investigated. The control strategy assumes variable compressor speed and adjustable air flow control for the gas cooler/condenser to achieve fairly constant refrigeration load requirements at different ambient conditions [76].

Cold stores

Chilled and frozen cold storage and distribution operations have been identified as major users of energy. Work at three UK cold stores has shown that significant opportunities for energy savings exist, even with current technologies such as air curtains and other devices to reduce air infiltration, optimisation of existing plant operation and effective maintenance practice [9, 15, 18, 32, 41].

Meat

The electrical energy consumption of refrigeration processes throughout a red meat abattoir and cutting plant has been measured in detail over a three-month period. The primary chilling of meat immediately post slaughter was the process that used the majority of the electrical energy in the plant and used more energy than the sum of all the other monitored refrigeration systems. Energy saving measures most appropriate to primary chilling included significantly reducing infiltration through open doors, general optimisation of existing refrigeration plant and repair of faulty components and introduction of appropriate maintenance procedures [37, 85]. Vascular chilling for carcasses also shows potential [21, 42].

Utilization is a key factor in batch chilling and freezing systems. Previous comprehensive studies in out at 5 pork abattoirs showed that the mean base demand (i.e. an empty chiller running at design conditions) was 1655 MJ and the product demand when the chiller was fully loaded were 1245 MJ. The base demand is therefore 57% of the total energy consumed during the chilling operation for a full chill room. The energy consumption per kilogram of pork chilled was therefore dependent on the utilisation of the chill room. Similar studies in14 beef slaughterhouses have shown that average energy required to maintain a beef chiller at the desired temperature when empty was 34.3 kJ/kg of chill room capacity. During the first 24 hours of chilling beef sides the extra energy consumed was 48.4 kJ/kg and in the next 24 hours 14.1 kJ/kg. The base load therefore makes up a significant proportion of the total energy consumed.

Recent work in factories processing fish and fish products has again measured large base loads and a very poor relationship between energy per tonne of product and throughput [69]. Developing processing systems that maximise the throughput of produce through batch refrigeration systems and reducing the base demand by improved insulation, fan speed control more efficient lighting, etc could substantially reduce energy consumption per tonne. Switching refrigeration systems off when not in use are a clear message from these studies.

Potato cooling and storage

The analysis of UK raw materials immediately post harvest or post slaughter identified that after milk, potatoes had the next highest production volume. Although in the past potatoes were not always cooled and stored under refrigeration there is an increasing trend towards total refrigeration. The British Potato Council has estimated that approximately 50% of the UK potato production (6.5 million tonnes) is refrigerated, but refrigeration contractors and design consultants contacted have commented that in their opinion this is an underestimate. Estimates of the total energy used for refrigerated potato cooling and storage have been made based on a previous study over a two year period recording energy used in a UK store. More recent data are required on the increasing number of refrigerated UK stores and their operating efficiencies to determine the potential savings that are greater than most vegetables due to the volume of production and the length of storage of the crop.

An attempt to set up the systems required to obtain the required data failed because of the cost and difficulty of obtaining meaningful data before the end of the project. However we were informed at the Grimsby dissemination event that the company concerned had been convinced of the need and funded the system. When the resulting data is analysed it will be reported on the web site.

Products chilled/frozen after cooking

Within the manufacturing sector of the food chain it is estimated that the products requiring the most refrigeration are those having the highest production volume/throughput and require to be rapidly cooled over the greatest temperature range. Work has been carried out to examine the cooling of cooked foods in a pie factory and the freezing of fried potato products. In both cases there were considerable process and energy advantages in using an initial ambient cooling stage [20, 34, 47, 60, 80]. However, since the process was introduced in the new pie factory one of the companies new clients, a large retailer, is restricting its use. They consider that the reduction in cooling rate and air borne bacterial contamination could reduce pie quality. Further studies are required to determine if there is increase in measurable bacterial contamination. If there is the most cost effective way of filtering the air needs to be investigated.

Catering sector

Due to the diversity of the catering sector and the vast numbers of catering outlets in the UK, estimates of energy use and the potential for savings are the most variable. However, it is known that there are large variations between the energy efficiency of the best and worst of existing equipment and upgrading the current stock to the best of current technologies would have a significant impact on total energy use in the sector.

Overall it has been identified and confirmed by a number of experimental studies in specific food sectors that major potential savings in energy used for food refrigeration are often still available using a combination of existing technologies, improved process control, optimisation of existing refrigeration systems and components and the introduction and adherence to improved refrigeration maintenance procedures. However, as has been highlighted by recent surveys (FDF/Carbon Trust) there is a serious shortfall of suitably trained staff in the food (and refrigeration) industry that can implement these changes. There are existing opportunities for significant energy savings, which have been demonstrated, in comparative studies of catering refrigerated cabinets and small changes to their use [6, 63, 81, 82].

Objective 2.3 - Identify and overcome any barriers to the uptake of current technologies that have the potential to substantially improve the energy efficiency of the 10 operations identified in 1.

Some elements of this have been included in Objective 2.1.4 (Assessment of business practices upon equipment requirements & performance.) However, the work carried out in the previous objectives did not clearly identify the barriers to uptake of current technologies that have the potential to substantially improve the energy efficiency of the 10 operations. In many cases the energy improvements were small and incremental in nature and were being introduced as refrigeration systems were replaced.

There was a lack of optimisation of the operation of existing plant and a lack of installation of relatively simple augmentations such as curtains and other devices to reduce infiltration through doors. This all points to lack of understanding and skills. Another recurring theme was the lack of good design of systems, including controls. This is again a reflection of a lack of understanding and skills. In many cases this lack of understanding starts with the original process specification for the total refrigeration system which may only contain details of the peak load conditions in a system that may operate under part or no load for much of the time.

Objective 2.4 – Quantify work being carried out to fill gaps in knowledge/technology identified to improve energy efficiency of the 10 operations identified in 1.

Some elements of this have been included in Objective 2.2 (Identify the features of the most efficient current systems and make them and their energy saving potential widely known to the industry.) However, by the end of month 12 when this work was due to start it was clear that it was impossible to identify the gaps in knowledge/technology required to improve energy efficiency of the 10 operations identified in 1. This was due to the almost complete lack of any reliable published information on the energy efficiency of the current processes. This was especially in terms of data relating the energy used to the throughput of product, changes in thermal energy of the product or in temperature maintenance operations the amount stored or transported.

Recent work has identified considerable fundamental gaps in the design process for producing a whole factory for the production of chilled or frozen foods [69]. The base refrigeration energy load of factories in times when no product is being processed can be ay least 30% of that under peak production. Lighting, evaporator fans and defrosting resulting in heat loads of many hundreds of kWs.

Objective 2.5 – Develop programmes to obtain the funding required to provide the missing information if no current work identified in objective 2.4.

In June 2007 a workshop was run at FRPERC, Bristol to specifically target the potential for energy saving and reducing carbon emissions from retail display. The main outcome was a proposal to produce a prototype cabinet that would incorporate significant energy saving measures and meet the carbon emission savings demanded by modern supermarket chains. This was submitted to LINK but was not funded since it was not fully thought to acknowledge and build on the very extensive research already undertaken on cabinet design.

Objective 3 – Carry out feasibility studies on current technologies that have the potential to achieve substantial energy saving in food refrigeration that are developed to a stage where they can immediately obtain funding from other sources.

Some elements of this have been included in objective 2.2. However no formal feasibility studies have been carried out as part of the project. This has been due primarily to the mapping exercise being far more complicated and time consuming due to the lack of real measured data relating energy consumption to use throughout the cold chain from primary chilling to retail/catering operations. In view of the importance of good system design the project has developed new and more advanced tools for modelling individual components and system performance under dynamic conditions of use. This has consumed a considerable resource that has considerably reduced that available for any feasibility studies.

The project has clearly shown that the most attractive technologies are:

Food transport refrigeration:

There are a number of energy conservation measures which when applied individually or in combination can lead to substantial energy savings [1]. Further work is required to determine their technical and economic viability as well as their environmental performance in comparison to current practice. Further work is also required to develop cost effective technologies to recover the energy rejected in the exhaust gas for refrigeration and/or on-board power generation.

Supermarket refrigeration system and thermal environment modelling:

Validation of CO_2 refrigeration system models and their use in the design and optimization of CO_2 cascade and transcritical systems [22, 23].

Retail display:

Work is required to optimise air flows within retail cabinets would provide substantial energy savings [24]. Reduction in radiant heat gains to frozen cabinets could potentially increase evaporating temperatures by 5°C.

Food cooling:

The use of ambient cooling hot product has been shown to reduce heat loads by up to 50% [20, 34, 47, 60, 80]. Further work is required to optimise processes. Considerable potential exists for energy saving in meat chilling by use of perfusion cooling [21, 42].

Energy monitoring and management

A topic that repeatedly came up during the course of the project was the lack of reliable data concerning energy consumption in food refrigeration. This was mainly due to the absence of electrical sub-metering, or if sub-metering was present it was not at sufficient level to determine the energy consumed by single refrigeration systems. Where more detailed sub-metering had been installed, it was not uncommon to find that the data was not being analysed on a regular basis and rarely linked to product throughput data (i.e. to enable specific energy consumption figures in kWh/tonne to be determined). This highlights that there needs to be a real and ongoing commitment from the organisation to energy management if any savings are to be identified and maintained. Where companies had made progress with energy management, it was often due to the efforts of an individual who had ‘championed’ the use of sub-metering and had taken on the additional role of analysing the data etc. However, in one case, once the individual had left, the expertise was lost and nobody was left to continue the good progress made. Therefore, it is essential that a decision and commitment is made at management level to ongoing support for energy saving initiatives throughout the company – with refrigeration energy use highlighted where it appears to be significant.

However, a concerted attempt, in the final stages of the project, to carry out a number of practical and theoretical feasibility studies on a range of current technologies to demonstrate clearly there energy saving potential were a marked disappointment. This was due to three main factors:

1. A failure to design, construct and commission bespoke pilot plant with accurate energy monitoring facilities in time to carry out the required experimentation prior to the end of the project.
2. A failure to produce a model in time for it to be fully validated and used to investigate energy saving scenarios prior to the end of the project.
3. The lack of resource in terms of researcher man-hours within the consortium to carry out practical studies quickly.

Dissemination of results

A notable success of this project has been its ability to disseminate results and activities rapidly to all elements of the food and refrigeration industries.

A large stakeholders group was set up at the start of the project and new members joined as the project progressed. A web site was established in the first few months and stakeholders were regularly informed of new additions and progress reports. Since the web site was re-established [70] more and more project reports, sector reports, case studies and dissemination presentations have been added and as it nears completion all the documents contained in the ‘References to published material’ section of this report will all be mounted or links provided. The site is now open access and has generated considerable attention. FRPERC at the Grimsby Institute are committed to maintaining and further developing the web site in the future.

During the project there has been three very successful dissemination events 1) Excel London, 19th February 2008; 2) National Motorcycle Museum, Solihull, 3rd April 2009; and 3) HSI Building Grimsby, 8th June 2010. The final dissemination event replacing one planned at Campden in June 2009. The event being cancelled due to lack of response which was probably due to the proximity in terms of time and location to the previous event. Over 50 different food and refrigeration companies and organisations were present at the final event in Grimsby and the feedback from attendees has been very positive. The FDF would like further events organised at other sites.

In addition in June 2007 a workshop was run at FRPERC, Bristol to specifically target the potential for energy saving and reducing carbon emissions from retail display. A final workshop on the model held on April 21st at LSBU was well received but only attracted 5 outside participants.

Currently the work of the project has been disseminated in 6 peer reviewed publications, 3 book chapters, 20 conference papers, 5 journal articles, 37 presentations and 22 project reports.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

All the following publications can either be found directly from the web site http://www.grimsby.ac.uk/What-We-Offer/DEFRA-Energy/ or via links/information on the web site.

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