# **R&D REPORT**NO. 268

**Utilisation of waste heat from food factories** 

2008

## Campden BRI

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R&D Report No. 268

## **Utilisation of waste heat from food factories**

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2008

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#### **EXECUTIVE SUMMARY**

This report describes work on the project AFM248Br, which involved CCFRA and Bristol University as a research consortium and the collaboration of Shipton Mill, Kerry Aptunion, Kraft Europe, Kellogg's UK, Warburtons, Unilever, RHM Culinary Brands, Greencore, Weetabix and GlaxoSmithKline Nutritionals.

AFM248Br was a one year Bridge-LINK project that finished in October 2007. The project identified sources of waste thermal energy from food processes that could be recovered to produce mechanical power using Stirling engine technology. In the context of the project 'waste thermal energy' implied any source of heat released from a process that was rejected to the environment. Flue gases from combustion processes, hot air from baking ovens, and steam or steam condensate from cooking operations were a few examples found in the food industry.

Stirling engines are external combustion heat engines, with several advantages that make them suitable for waste heat streams (no contact between heat source and moving parts, scalable to application, low maintenance). They have high theoretical efficiencies and have been developed for several applications (micro CHP systems, biomass and solar powered), although they have not yet reached full commercial development except for very specific niche applications.

Ten different food factories were visited to gather information on waste energy streams released from processing operations. The nature of manufacturing operations studied was varied because the companies chosen for collaboration in the study belonged to different food sub-sectors. These included bread and cereal manufacturing, wheat processing, fruit processing, production of coffee, elaborated and prepared foods and soft drinks.

The survey was concerned with collecting information on energy usage, identifying the key processes contributing to energy consumption and waste energy, and obtaining quantitative data. The key parameters studied for the identified waste energy streams were: temperature, mass flow rate, media of rejection, presence of contaminants and accessibility. The first three parameters allowed the heat load (exergy) in the stream to be calculated. The exergy content and the temperature at which energy was released from a system were the key parameters for evaluation of its quality and usability for power generation. More than 30 energy streams were identified across the 10 factories visited, and from these, a total of 16 were accurately quantified (specific figures for temperatures and flow rates were known). The calculations gave a total value of 9.7MW of energy lost from these factories. The following Table presents these data.

Table 1: Summary of calculated energy available from the waste energy streams

Туре	Process of origin	Stream Temp (°C)	Mass Flow (kg/s)	Energy (kW)
Air	Coffee roaster	370	0.08	29
Air	Continuous oven	186	0.17	29
Air	Rack oven	129	0.38	42
Air	Hot water boiler	171	0.37	57
Air	CHP steam boiler	177	0.43	70
Air	Oven stage 4	116	2.36	229
Air	Oven stage 3	120	2.34	237
Air	Oven stage 2	140	2.23	271
Air	Oven stage 1	160	2.13	303
Air	Hot air drier	60	31.84	1,282
Air	Post coating drier	120	26.97	2,731
Steam	Continuous steamer	100	0.17	56
Steam	Blow-down steam	175	0.20	136
Water	Finished product cooler	30	7.00	293
Water	Continuous vacuum condenser cooling loop	40	12.50	1,045
Water	Batch vacuum condenser cooling loop	45	28.00	2,927

Bristol University carried out a review of Stirling engine technology, from its thermodynamic working principles to the current state of the art and commercial development. This assessed the technical feasibility of producing electricity from waste thermal energy streams. Thermodynamics showed that thermal to mechanical energy conversion efficiency increased with the temperature of the heat source, and this proved to be a limiting factor given the range of operating temperatures in food processes. The research identified that at the moment there are no commercial Stirling engines (or any other type of engine) which would be economically viable considering the energy stream temperatures originated in food processes.

The project showed that although a significant amount of energy was lost during food manufacturing, the range of temperatures at which it was released (typically in the range between 30°C and 200°C maximum) did not allow for an efficient and cost effective conversion into mechanical power. It concluded that further exploitation was constrained by the lack of suitable technology. Attractive alternatives to the Stirling engine are now emerging, for example rotary scroll compressors for refrigeration and automotive airconditioning. When coupled with new methods of manufacturing compact heat exchangers and reactors (direct laser deposition, DLD), these could form the basis of a new rotary heat engine using a recuperated rotary Ericsson cycle. This "scroll" engine will have the same

theoretical efficiency as the Stirling engine, but will deliver a higher proportion of it in practice, at commercially acceptable costs.

However, another potential application for heat engines within food processing facilities was identified. This comprised the concept of utilising high grade primary energy (from gas burning) to run a Stirling engine and produce electricity, and then use the remaining thermal energy to run the food process (e.g. baking oven).

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#### 1. INTRODUCTION

The food and drink industry is the third largest energy consumer in the UK industrial sector. In 2006 it consumed 3725 thousand tonnes of oil equivalent, which accounted for 11.5% of total industry energy consumption (Dukes, 2007).

Data on energy consumption within the sector in the last ten years indicate that the Food and Drink industry has progressively improved its performance, having increased its energy efficiency per tonne of production by 9.5% since the late 1990s. This is in response to a need to minimise energy consumption to reduce costs and improve environmental performance (FISS 2006).

Recent Government measures to tackle climate change following European Union policies, and especially the implementation of the Climate Change Levy in April 2002 under the Climate Change Programme, have further increased the pressure on energy use and its associated costs for industrial businesses. The Food and Drink Federation or other sub-sector industry associations, most businesses have negotiated Climate Change Levy Agreements (CCLAs) with the Government. These agreements, granted a discount from the CCL of typically 80%, provided that the company meets energy efficiency or carbon saving targets by agreed deadlines.

Solutions to address the energy problem include energy management policies, good energy practices, and more efficient processes and technologies. However, even if all efforts are put into these measures, there will still be a certain amount of energy inevitably released as an output from most food processing operations. Therefore, research on energy recovery systems is also important.

Redirecting energy that normally escapes from food processing operations to perform other functions within a process, or utilising this energy to generate power, can have an overall effect of reducing the energy input required. This has clear implications both on the costs associated with energy provision and on the carbon emissions attributed to a food manufacturing operation.

#### 1.1 Food processing - energy use

The Food and Drink industry is a diverse and complex sector. It comprises many different sub-sectors each utilising different raw materials, processes, manufacturing installations and utilities to produce a wide range of products.

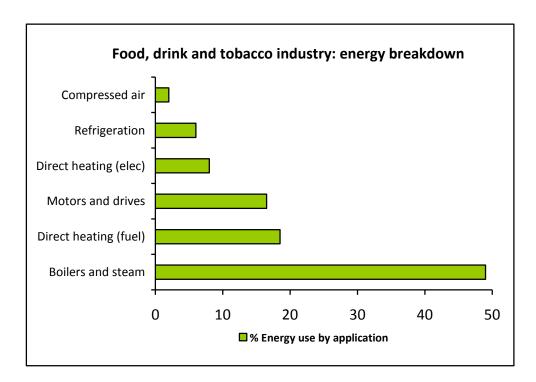
The sector is highly energy intensive as food and drink production requires electrical and thermal energy for virtually every step in the process. Electricity is used for lighting, refrigeration, heating, and process instrumentation, and as driving power for machinery such as motors and drives. Heat is required for heat processing through different unit operations. Thermal energy is normally produced by the combustion of fossil fuels and then transferred to the product by heat transfer media, generally steam, hot water, thermal oil or hot air. Natural gas is the main fuel consumed by the industry (64%), followed by electricity (28%) and petroleum (7.5%); a small amount of coal is still used in some cases (DUKES, 07). The consumption of petroleum has significantly decreased in the last fifteen years; for example, in 2005 the consumption was 68.9% less than in 1990.

Food and drink processing involves a large variety of energy demanding operations:

- Utility processes: thermal energy generation, refrigeration, compressed air generation, motors, pumps, and drives.
- Heat processing: baking, roasting, frying, cooking, boiling, blanching, pasteurisation, sterilisation, UHT, melting and tempering.
- Processing by removal of heat: cooling, freezing, freeze-drying.
- Concentration by heat: evaporation, drying, dehydration.
- Specific processing technologies: distillation, extraction

From these, production of steam accounts for almost 50% of total energy consumed by the sector. Direct heating operations involving the use of fuel or electricity such as baking, roasting or drying account for approximately 27% of the total energy consumed. The rest of the energy is used for running motors and drives (16%), cooling and refrigeration operations (6%), production of compressed air and other production technologies (Carbon Trust).

Figure 1. Energy use breakdown



Traditionally, the food sector has been product focused, with processes designed to obtain a certain product of determined specifications, and subsequent effort put into achieving production rates and improving product quality and safety. Attention has been placed on process design and efficient energy use. In this way, the sector is very different from other industries, such as the chemical sector, where techniques like process integration have been widely applied to minimise energy consumption and maximise process heat recovery.

In terms of thermal energy, all processes involved in the production of food and beverages are classified as medium or low temperature processes (those operating at temperatures below 500°C). Processes in the medium-low temperature regime consume the largest amount of energy in the whole industry, with around 80% of all process heating, cooling and interprocess heat transfer applications taking place in the temperature range from ambient to 200°C. Other industries operating within this temperature range are the chemicals, paper and textiles industries.

#### 1.2 Process heat recovery

All industrial processes consume energy and usually reject surplus heat. Heat recovery techniques make the most effective use of this thermal energy by applying different technologies to give an alternative use to the waste heat, instead of releasing it to the environment. Process heat recovery has a direct effect on the efficiency of the process, which is reflected in fuel consumption and total processing costs. Additionally, there are indirect

benefits associated, the most important being the reduction in pollutants and greenhouse gas emissions (products of combustion) as primary fuel consumption decreases.

Depending upon the type of process, waste heat can be rejected at virtually any temperature, from low temperature cooling water to high temperature waste gases from an industrial furnace. Temperature is a critical parameter for process heat recovery, as it is the driving force for thermal energy transfer between the heat source and the sink. Therefore, the higher the temperature of a process heat source the higher its quality and more cost effective will be the heat recovery system. Depending on their temperature, process heat streams are classified as high grade (>500°C), medium grade (200 – 500°C) or low grade (<200°C) streams. The quality of a process heat stream also depends on its physical properties (presence of contaminants, potential fouling), the media of rejection (gas, liquid), the moisture content (specific heat capacity, potential for latent heat recovery, condensation problems), and its location within the process (relative position to a heat sink, practicability of installation). Additionally, the mass flow rate must be known to calculate the heat load available for recovery.

Sources of high temperature waste heat are generally found in the metal, cement, glass and ceramic industries. Thermal energy released from furnaces in these industries has temperatures ranging from 650 to 1,600°C. Medium temperature range (100 to 500°C) sources of waste thermal energy include exhaust gases from prime movers such as gas turbines, exhaust gases from steam rising boilers and also from ovens and dryers in specific applications. The amount of operations that generate waste heat in the low temperature range (<100°C) is considerable, and includes convective and radiant heat released from machinery, heat streams from process cooling and heat released from different effluent sources (hot air from heating or drying, condensates, hot cleaning water).

The food industry operates at the medium-low temperature regime, and therefore waste heat streams from food processing fall into the low temperature range. Being a large and diverse industry with many different sub-sectors, the list of unit operations contributing to waste heat streams is extensive. Common to most food factories are steam raising operations, compressed air generation, process cooling, refrigeration plants and prime movers. Other common processes are evaporation, pasteurisation, sterilisation, drying, baking, roasting, extraction and distillation.

There are several applications or end uses for waste process energy. The most common and generally most cost effective is within the process where it originates. Normally a heat exchanger is used as a recovery system but in some cases it is possible to re-circulate the energy directly without a heat exchange surface. A second option is to use the waste heat in another process, where the 'heat sink' is most appropriate (generally depending on temperatures). Other applications are space heating or domestic water heating.

In all cases, in-depth knowledge of the process operation and of the characteristics of the energy streams is necessary in order to apply the most cost effective solution.

Process heat recovery can be applied following a 'unit' approach, that is, considering unit operations individually and assessing waste streams one by one, or alternatively it can be done considering a process as a whole. The last is known as process integration technology and it maximises process heat recovery by optimising heat exchange networks in a plant. The technology examines process systems rather than individual items of equipment, often identifying additional energy savings and guidance for longer-term efficiency improvements.

When the requirements of the plant are appropriate, waste heat can be used as a driving force to drive an absorption chiller. This technology has been available for a number of years and is quite well known in the food industry. New adsorption chillers have been developed in recent years, using a solid medium instead of liquid, but the technology is still under development.

A better opportunity for the use of waste thermal energy is to produce electricity. This option has been applied to high grade waste heat streams and constitutes one type of cogeneration technology (combined heat and power). Known as bottoming-cycle CHP technology, the cycle uses prime thermal energy (fuel) to run a process and uses the waste heat to drive a turbine to produce electricity. The technology, though, can only be applied to industrial processes that release very high temperature waste heat (such as glass kilns and metal furnaces).

For lower temperature waste heat, a technological barrier exists for its efficient conversion into power. While low-grade heat sources may be found to contain high amounts of energy, their low temperature provides a temperature gradient that is often insufficient for many exclusive energy conversion technologies to work effectively.

#### 1.3 Stirling engines

Conversion of thermal to mechanical energy has fascinated and challenged some of the best scientific and engineering minds for hundreds of years. When Newcomen, in 1712, demonstrated his 'heat engine' a device that was actually capable of pumping water out of mines, heat engines became real wealth generators. Following the Newcomen engine, which was really a steam vacuum engine, engineers quickly moved to steam piston engines in which high pressure steam did the work. These engines became more powerful but were quite dangerous, with exploding boilers being a common occurrence. They were also wasteful in their use (waste) of energy, with the latent thermal energy in the steam being discarded. In 1816 Robert Stirling patented his hot air engine, with the title 'Improvements for diminishing the consumption of fuel, and in particular an engine capable of being applied to the moving of machinery on a principle entirely new' UK Patent 4081 (1816). His 'entirely new' engine

became known as the Stirling engine; indeed, the term 'Stirling engine' is now used to describe a wide range of heat engines which have an enclosed working fluid, are externally heated and cooled and use regeneration in order to increase thermal efficiency. A full description and technical explanation is given in section 3.

Stirling engines can in principle approach Carnot cycle efficiency, although no heat engine can be more efficient than an ideal Carnot engine. In practice, although the efficiencies of real Stirling engines are good, they tend to have relatively low power density (compared with modern internal combustion engines) and can have absolute efficiencies that may be lower than internal combustion engines. These disadvantages do not detract from Robert Stirling's original claim, that his engine diminishes fuel consumption, for given available temperature differences.

Stirling engines were built and operated in the eighteenth and nineteenth centuries, they prove safe and reliable, but never really challenged the high power density available from high pressure steam engines. Over the past fifty or so years, individuals, private companies and government organisations have studied these engines and in some cases have had reasonably successful ventures using them. Despite these efforts, Stirling engines have never really challenged the internal combustion engine. More recently (over the past 10 to 15 years) there has been renewed interest in the possible use of Stirling engines to convert heat into electricity (via an alternator). This looks particularly attractive if the load is steady or slowly varying with time. Over the past five or so years the following two events have resulted in commercial companies developing energy saving offerings

- Climate change and carbon footprints being taken seriously by governments.
- Escalation of fossil fuel costs.

The most commercially successful is including combined heat and power (CHP) packages at domestic consumer size. Governments who are keen to meet their carbon dioxide reduction targets are encouraging their use. Several of these CHP offerings use Stirling engines as the prime movers. The reason for the choice of Stirling engine is that this engine is thermodynamically more efficient than any other operating between the same temperature limits.

Given the efficiency claim, the renewed interest and the commercial developments taking place in Stirling applications, it seems sensible to study the potential for these devices in harvesting waste heat in food manufacturing and processing plants.

#### 2. AIMS AND OBJECTIVES

The aim of this research project was to quantify sources of usable waste process energy released from food processes and to assess the feasibility of its recovery and conversion into power through the application of Stirling engine technology. The recovery system proposed would use highly efficient Stirling engines to take waste process heat and convert it into rotary movement into the engine. This energy could then be directly used to power devices or be converted to electricity.

The project pursued two main objectives. The first objective was to perform a quantitative and qualitative analysis of energy released from food manufacturing processes. This involved obtaining information on different waste energy streams originating in food operations and evaluating them in terms of energy available and suitability for conversion into mechanical power. The key parameters to evaluate were:

- process of origin of the waste energy stream
- media of rejection (air, water, steam, other)
- stream flow-rate
- temperature of rejection
- presence of contaminants
- localisation and physical accessibility

By gathering the above information from a specific waste energy stream, its capacity for thermal energy transfer and the presence of physical barriers (corrosion, fouling, and practicability of installation) could be determined.

As a second objective, the project assessed the potential of Stirling engine technology for the conversion of waste energy into mechanical power. This included a review of the state of the art of this technology and its current commercial availability. At the same time, the project studied what technology developments were required to integrate a Stirling engine into a food manufacturing facility. It was thought that the current state of the art with Stirling engines would require some level of technology development before this could be achieved. Finally, conclusions were drawn about the suitability of the technology to recover energy from waste energy streams previously studied.

#### 3. METHODS

## 3.1 Quantitative and qualitative analysis of waste heat from food manufacturing processes.

#### 3.1.1. Industrial collaboration

Food and drink companies with interest in waste heat recovery were invited to collaborate in order to supply the basis for an energy survey. The survey was intended to identify sources of waste energy arising from processes at the factories of the collaborative companies. These energy sources would then be evaluated and quantitative data obtained to calculate the energy available from each waste energy stream.

A total of 10 companies from different Food and Drink industry sub-sectors collaborated in the project. As a preliminary input, each company provided a list of potential sources of thermal energy they had identified in their manufacturing facilities, as given in Table 1.

Table 1. List of industrial collaborative companies and potential waste energy streams.

<b>Company Name</b>	Waste Energy Stream				
	Steam heating of noodle fryers.				
Unilever UK Foods	Steam-heated tunnels and retorts.				
	Evaporation processes in yeast extraction.				
	Flue gases from steam boilers.				
DIIM Culinami Duanda	Heat from reduced pressure evaporative processes.				
RHM Culinary Brands	Hot water from product cooling and factory washing.				
Division	Heat from the evaporators of chillers, freezers, and				
	compressors.				
Kerry Aptunion – Fruit	Boiler flue gases from steam generation.				
Preparations	Hot cleaning fluids from CIP operations.				
Warburtons	Gaseous emissions from bread baking ovens.				
w arountons	Boiler flue gases from steam generation.				
Construction Construction	Gaseous emissions from travelling and static ovens.				
Greencore Group	Flue gases from steam and hot water boilers.				
	Boiler flue gases from steam generation.				
GlaxoSmithKline	(Combustibles such as cardboard packaging and wood.)				
	Boiler flue gases from steam generation.				
Vroft Europa	Combustibles such as cardboard packaging, wood and				
Kraft Europe	coffee shells.				
	Gaseous emissions from coffee bean roasting ovens.				
Weetabix	Hot air from biscuit ovens and dryers.				
Weetably	Blow-down steam and flue gases from energy centre.				
	Boiler flue gases from steam generation.				
Vallaga's	Combustibles such as cardboard packaging and wood.				
Kellogg's	Cooling water.				
	Hot air from toasting ovens.				
Chinton Mill	Hot air from milling operations.				
Shipton Mill	Combustible organic and packaging waste.				

#### 3.1.2. Energy surveys

Energy surveys were carried out at manufacturing sites, as this permitted the research team to gain a better understanding of the manufacturing processes and specific characteristics of the site. In order to gather all relevant information and obtain detailed data from each company, a pro-forma was developed for use as a reference document through the energy survey. The pro-forma comprised the following sections:

- a. Company background: products manufactured.
- b. Overall energy usage: energy type, quantity consumed, specific energy consumption, usage profile, potential applications for recovered thermal energy (heat sinks), heat recovery systems in place.
- c. Specific energy usage:
  - i. Energy intensive processes.
  - ii. Waste heat streams associated: temperature, media and mass flow rate of rejection.
- d. Waste and waste management policy.
- e. Company policy on energy and Climate Change Levy.
- f. Equipment information.
- g. Further details.

Each factory visit involved a brief meeting with factory staff responsible for utilities and/or energy management, followed by a site tour through the production floor to identify waste energy streams. Once the waste sources had been identified, the survey proforma was completed with information provided by company representatives.

#### 3.1.3. Energy available and quality

In heat transfer, the temperature difference between the heat source and heat sink is the driving force. Therefore, the amount of energy recoverable from a waste heat stream is a direct function of its temperature. The information required from a waste stream to determine its energy load or the energy available for recovery is the temperature range  $\Delta T$  (difference between stream temperature and environment temperature) and the heat capacity Cp (kW/kgK). The latter can be calculated from measured stream mass flows (kg/s) and the specific heat capacity for the stream fluid at the working temperature. When the stream flow rate is measured in volume (m3/s), the density of the fluid at the corresponding temperature is used to calculate the equivalent mass flow.

Additionally, physical properties of the stream such as media of rejection, presence of contaminants, or stream accessibility are required in order to identify potential problems (fouling, corrosion) or requirements for the heat recovery device.

Hence, the following parameters were assessed through the energy survey:

- Stream temperature
- Stream media of rejection (gas, liquid)
- Stream mass flow rate
- Presence of contaminants

#### Physical accessibility

For each energy stream, heat load was calculated using the following equations:

$$dQ = m \cdot Cp \cdot dT \tag{1}$$

$$Q = \int_{T_e}^{T_w} m \cdot CP \cdot dT = CP \cdot (Tw - Te) = m \cdot Cp \cdot (Tw - Te) = \Delta H$$
 (2)

Where:

m = mass flow rate (kg/s)

Cp = specific heat capacity (kJ/kg K)

Tw = temperature waste stream (K)

Te = temperature environment (K)

 $Q = \Delta H = \text{heat load (kW)}$ 

The heat load Q from a heat source is also known as exergy, the thermal energy available for conversion into mechanical energy.

#### 3.2. Review on Stirling engine technology

#### 3.2.1. Underlying physics

The Stirling engine is an external combustion engine with a sophisticated heat exchange process allowing for near-ideal efficiency in conversion of heat into mechanical movement. A perfect Stirling engine will yield Carnot cycle efficiency, which is as efficient as thermodynamic laws will allow. Although Robert Stirling is generally credited for the engine, and it is clear that he did more than anyone else to identify the need for regeneration, hot air engines were around before Stirling filed his patent in 1816. The pre-Stirling hot air engines did not attempt to recover and re-use thermal energy within the cycle.

A typical hot air engine works by the repeated heating and cooling of a sealed amount of working gas, using the resultant pressure swings to drive a piston flywheel arrangement. When the gas in a sealed container is heated, its temperature and pressure rise. If the container has a cylinder-piston arrangement, it is possible to use the rise in pressure to act on the piston to produce a power stroke. When the gas is cooled, the temperature and pressure drop, and it becomes possible to recompress the gas on the return stroke using less force than was absorbed on the power stroke. This gives a net gain in power available on the shaft. The

brilliant contribution made by Stirling was to introduce a heat exchanger between the compression and rearification strokes, so that the exchanger became an effective heat bank. The exchanger acting as the heat sink in absorbing unwanted heat on one part of the cycle, and then becoming the heat source in donating heat to the working fluid during another part of the cycle. The working gas was sealed within the piston cylinder arrangement with all heating/cooling imposed at the engine external boundaries. The engine did not require valves, and hence looked very attractive.

Over the past years, various designs of Stirling engines have appeared. The major variants are described in section 3.2.2. The important physics that need to be understood about Stirling engines is that they are closed devices in which the working fluid is alternatively heated and cooled. The pressure swings that occur as a result of the imposed temperature changes are converted into mechanical motion and work. The uniqueness of Stirling engines arises from the fact that the recouperator/regenerator ensures that the minimum possible amount of heat is wasted between the heating and cooling operations. This, above anything else, gives Stirling engines their 'green' credential.

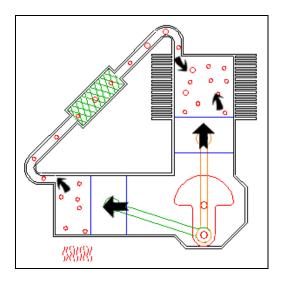
#### 3.2.2. Engine variants

Stirling engines have a regenerator, typically a high thermal inertia mass with high surface area to volume ratio, located between the reservoirs. As the gas cycles between the hot and cold sides, its heat is transferred to and from the regenerator. It is this regenerator that enables the ideal Stirling engine cycle to have the same theoretical efficiency as a Carnot heat engine for the same input and output temperatures. The specific layout and ways in which power is taken from the engine depends on the design. There are three major variants, known as alpha, beta and gamma. The differences result from the manner and layout of power and displacer pistons.

#### 3.2.2.1. Alpha Stirling engine

An alpha Stirling engine contains two separate power pistons in separate cylinders, one "hot" piston and one "cold" piston (see Figure 2). The two separate cylinders are hydraulically linked via the regenerator. The pistons are attached to a crank in a manner which ensures that they are always 90 degrees out of phase with each other. Rotating the crank results in changing the effective volume within the pressure envelope. The elegance of this design is that the working fluid is made to move from the hot to cold region, through the regenerator, whilst net mechanical power is harvested from it. Note that both the hot and cold cylinders are effectively at the same pressure. The movement of the piston delivers mechanical power to the crank as well as displacing the working gas to the regions required.

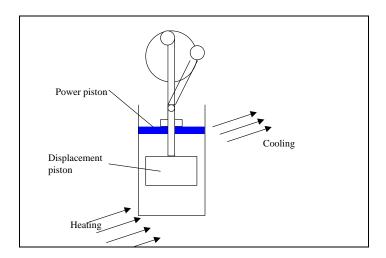
Figure 2. Alpha Stirling engine



#### 3.2.2.2. Beta Stirling Engine

A beta Stirling engine compresses everything within a single cylinder; it has a single power piston and a displacer piston housed within the cylinder which provides the pressure envelope (see Figure 3). The displacer piston is a loose fit and does not extract any power from the gas but only serves to shuttle the working gas from the hot to the cold end of the engine. For the unit to be a viable engine, the displacer and power pistons have to be 90 degrees out of phase, which is achieved by the manner in which they are connected to the crank.

Figure 3. Beta Stirling engine

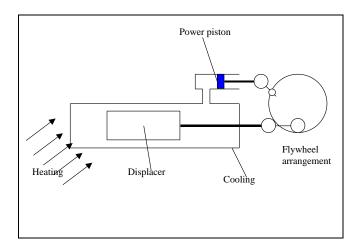


#### 3.2.2.3. Gamma Stirling Engine

A gamma Stirling engine is simply a beta Stirling engine in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but is still connected to the same flywheel, again with the 90 degree phase shift between the power and displacer

pistons (see Figure 4). The gas in the two cylinders can flow freely between them and remains a single body.

Figure 4. Gamma Stirling engine



The alpha, beta and gamma variants are the classical ones. Newer and more innovative devices have appeared over the past fifty or so years. These include rotary, free piston and acoustic Stirling engines. In the rotary engine, reciprocating movement is replaced with a pure rotary motion. This has some similarity to the move from reciprocating internal combustion engines to the rotary (e.g. Wankel) engine. In the case of the free piston engine, the displacer device is free to move in the cylinder; its actual movement being controlled by transient pressure loading on its specific topology and its mechanical inertia. These engines have the significant advantage of not being subjected to lateral forces from the crank mechanism. The acoustic engines appear to offer even more advantages, in that they totally remove moving components from the work portion of the engine. To date most commercial power Stirling engines are either alpha, beta or gamma engines.

#### 3.2.3. Potential for development

The Stirling engine concept has intrigued individuals, companies and organisations for many hundreds of years. The engine does have great promise. Commercial companies such as Philips and Ford have invested heavily in developing the technology. More recently there have been government backed programmes to investigate the use of Stirling engines for CHP and for electricity generation from solar farms. The perceived potential for these devices arises from a number of advantageous factors including:

- 1. External combustion; which means that burning of a fuel-air mixture can be more accurately controlled. A continuous combustion process can be used to supply heat, so emission of unburned fuel can be reduced. Further, the quality of the fuel is less important, as it never gets into the engine
- 2. Simplicity of design; for example, no valves are needed, minimal lubrication, no electrics (i. e. no spark plugs), fewer moving parts.
- 3. Quiet operation; smooth power production, no internal explosions, no r.f. emissions or electrical interference.
- 4. Highest possible thermodynamic efficiency

However, there are problems and challenges associated with these engines. These include:

- 1. Need for new and non-standard regenerators to achieve high thermal efficiency.
- 2. Tend to be large for a given power rating. This translates into expensive and heavy for given ratings when compared with conventional internal combustion engines.
- 3. Work best when operated under constant load, they are difficult to efficiently operate at part load (need to alter the operating volumes)
- 4. Load following can be difficult, as the heat has to be conducted into the engine. The engine has to be warmed up before it can be started.

It is generally accepted that there is a well-defined and profitable niche market for well engineered and targeted Stirling engine devices. It is believed that there may well be much larger markets in the micro (or domestic) CHP area. Significant investment is currently being made in this area by commercially driven organisations.

#### 3.2.4. Model for the project

To demonstrate generic Stirling devices and how these might be used to harvest heat and convert it to mechanical power, a small (toy size) engine was constructed (see Figure 5). The model clearly showed that it was possible to scavenge even low grade heat and convert it to motion. However, the model was not designed to investigate the efficiency of this scavenging process. The physical model demonstrated the possibilities, but was never intended as a commercial viabilities.

Figure 5. Stirling engine model



#### 4. RESULTS AND DISSCUSSIONS

### 4.1. Quantitative and qualitative analysis of waste heat from food manufacturing processes.

#### 4.1.1. Energy survey findings

The energy survey involved the assessment of ten food and drink manufacturing operations. A wide range of processes comprising different unit operations were studied and sources of waste energy were identified.

The first part studied the overall energy consumption, types of fuel used, their usage profile and specific demands (continuous, discontinuous, season variability). These data were compared against production figures so that specific energy consumption quantities were calculated for each production factory. Results are presented in Figures 6 and 7.

Figure 6. Breakdown of energy usage by type (Note that company names are omitted for confidentiality reasons)

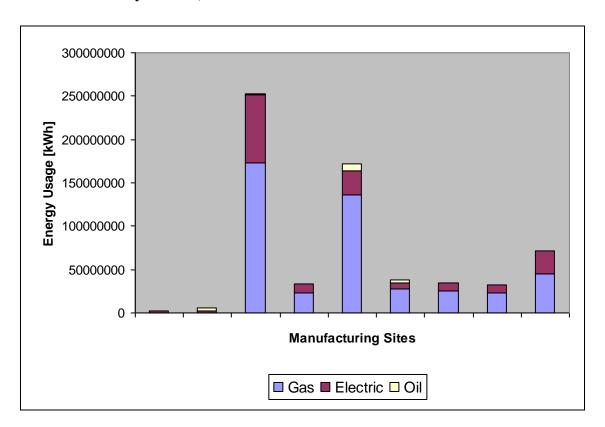


Figure 6 shows the energy distribution by type of fuel and the typical energy consumed on a year basis for nine of the visited companies. The main fuel was gas, followed by electricity and only a very small proportion of oil. The main application of gas was boilers for steam generation, CHP plants and direct heating applications (e.g. ovens). Electricity was consumed

mainly for motors and drives, compressors and refrigeration systems. This performance was in accordance with the overall profile of energy consumption through the food and drink sector. It was found that some companies had recently changed from oil to gas use in order to minimise impact on air pollution following actions to meet CCLAs targets.

Figure 7. Energy usage per tonne of product (Note that company names are omitted for confidentiality reasons)

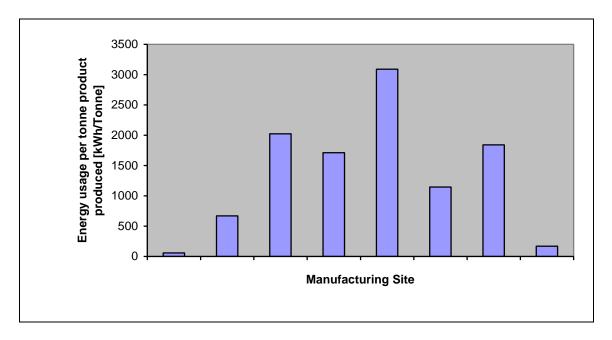


Figure 7 shows the specific energy consumption (kWh/tonne product) for eight of the sites visited. Large differences can be seen between the different sites. This variability in specific energy consumption was due to (a) the factories in the survey belonging to a range of subsectors, which have different energy requirements due to the inherent characteristics of the processes themselves and (b) in some factories individual processes were fundamentally inefficient in their design, implying that waste energy generation was significant in these processes, and therefore overall and specific energy consumption was higher than in other similar production processes.

The main body of the survey studied individual processes and associated energy waste streams. Table 2 shows information collected from each company, giving the most energy intensive processes at each site and the associated sources of waste energy. A number of processes releasing waste energy were common to most food factories.

Boiler plants were a source of exhaust gases. These could be recovered to pre-heat the combustion air (using pre-heaters) or to pre-heat boiler feed-water (using economisers). A more efficient use of exhaust waste heat is achieved by recovering the latent heat of the water vapour contained in the exhaust gas, and for this, condensing economisers are used. In the survey, however, it was found that most exhaust gases were lost to the atmosphere with no

recovery system in place. It was also found that condensate from steam systems was not always recovered.

Exhaust gases from ovens, roasters or driers was another common source of waste energy. As in boiler plants, heat could be redirected to pre-heat combustion air; however, this measure was not in place at any company visited.

Air compressors consumed a considerable amount of electricity, with most of it released as heat from the compressor motor, oil and the cooling system. In some companies heat recovery units had been installed to redirect this heat to pre-heat other working areas but in most cases heat was released to the atmosphere.

Other energy related factors evaluated through the survey were:

- Presence of applications in the factory for recovered waste energy (heat sinks). It was not in the scope of this project to find technologies or applications for the re-use of waste energy as thermal energy, but the factor was considered as a potential alternative that could be recommended to companies depending on the results obtained from the survey.
- Information on energy recovery systems, process integration networks or efficient energy production technologies (cogeneration, tri-generation) already in place. This provided indication of the level of awareness and progress already achieved by factories on energy improvement.
- Company energy policy, Information on company energy management policy, initiatives, studies or projects taken or planned to improve energy performance. Specific questions were put on the impact of the Climate Change Levy and what measures companies had taken in respect of it.
- Waste and waste management policy. The survey looked at volumes and types of waste generated through the manufacturing process, as these could be a potential source of energy. The possibility of using waste materials to generate thermal energy which could then be used to run a Stirling engine was considered. Waste to energy technologies such as biomass incineration or pyrolysis could be applied to solid waste materials, such as cardboard, pallets and food shells to generate high quality thermal energy. This could then be used to run a Stirling engine and produce mechanical or electrical power. In this field, company policy on waste management and likelihood of getting involved in waste to energy projects was evaluated.

It was found that some companies had already investigated the waste to energy option. One company had already signed a contract with an independent waste processor to treat the waste generated in all their UK factories in a centralised plant. Given the

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characteristics of the food industry and the volumes typically generated in one production plant, it was concluded that the most attractive and economically feasible route for most food companies would be this last one, where an independent company provided the waste treatment service in a centralised plant. The option of installing a waste to energy facility on a food factory was possible in some cases if enough volume of waste of suitable characteristics was produced, but given the capital investment required for these infrastructures, it was difficult to find a positive case. However, government initiatives such as the Renewable Obligation Certificates and the Enhanced Capital Allowance could have a positive impact in the economic case for investment.

- Factory utilities and equipment status. Information on the condition of facilities, maintenance programs and budget for investment in process improvement or new equipment was obtained.
- Specific comments and concerns. This final section of the survey included any further information that the company representative considered relevant to the survey.

Table 2. Summary of energy survey (Note that specific production volumes and energy consumption data is not published for confidentially reasons)

Company	Products	Key processes	Type of energy	Major energy users	Waste energy sources	Additional information
Shipton Mill	types of flour	<ul><li> Milling</li><li> Refining</li><li> Packing</li></ul>	• Electricity	<ul><li>Rollers</li><li>Pumps and motors</li></ul>	• Convective air from milling operations	<ul> <li>Feasibility study on biomass CHP</li> <li>Installed heat pumps as heat recovery system</li> </ul>
Kraft Foods	Ground and instant coffee	<ul><li>Blending</li><li>Roasting</li><li>Grinding</li><li>Extraction</li><li>Spray-drying</li><li>Packing</li></ul>	<ul><li>Electricity</li><li>Gas</li></ul>		<ul><li>Boilers</li><li>Roasting ovens</li><li>Compressors</li></ul>	
Kerry Aptunion	Fruit preparations, compote	<ul><li>Pasteurisation/ Ohmnic heating</li><li>Cooling</li></ul>	Electricity     Oil	<ul><li>Ohmnic heater</li><li>Steam boilers</li><li>Refrigeration</li><li>Pumps</li></ul>	<ul> <li>Steam from sterilisation and CIP</li> <li>Cooling water</li> </ul>	Interested in biomass generator.

Kellogg's	Corn, rice and biscuit breakfast cereals	<ul><li>Cooking</li><li>Drying</li><li>Tempering</li><li>Flaking</li><li>Baking</li><li>Packing</li></ul>	<ul><li> Electricity</li><li> Gas</li><li> Oil</li></ul>	<ul><li>Boilers</li><li>Process gas</li><li>Chillers</li><li>Compressors</li><li>Wet scrubbers</li></ul>	<ul><li> Dryer exhaust</li><li> Oven exhaust</li><li> Cooker steam</li></ul>	<ul> <li>CHP plant to substitute steam boilers, estimated energy saving 12%.</li> <li>Implementing energy monitoring and management system.</li> <li>Heat recovery: compressors cooling water to pre-heat boiler feed-water</li> </ul>
Warburtons	Various types of bread	<ul><li> Mixing</li><li> Proofing</li><li> Baking</li><li> Cooling</li><li> Packing</li></ul>	<ul><li>Electricity</li><li>Gas</li></ul>	<ul> <li>Gas fired travelling and rack ovens</li> <li>Proofers</li> <li>Boiler</li> </ul>	<ul> <li>Condensate from proofing ovens</li> <li>Oven exhaust</li> <li>Boiler exhaust</li> <li>Cooling air</li> </ul>	<ul> <li>Heat recovery measures: proving oven installed above baking oven</li> <li>Energy monitoring system in place.</li> </ul>
Weetabix	Biscuit and flaked breakfast cereals	<ul><li>Cooking</li><li>Shaping</li><li>Baking</li><li>Cooling</li><li>Packing</li></ul>	<ul><li>Electricity</li><li>Gas</li><li>Oil</li></ul>	<ul> <li>CHP centre</li> <li>Process gas – ovens</li> <li>Compressors</li> </ul>	<ul> <li>Blow-down steam</li> <li>CHP exhaust</li> <li>Oven exhausts</li> <li>Dryer hot air</li> <li>Cooling air</li> <li>Cooling water</li> </ul>	<ul> <li>CHP in place</li> <li>Great awareness of energy streams and recovery options</li> <li>Presence of fines in waste streams make recovery difficult.</li> </ul>
Unilever	Pot noodles	<ul><li>Mixing</li><li>Rolling</li><li>Cooking/frying</li><li>Cooling</li><li>Packing</li></ul>	<ul><li> Electricity</li><li> Gas</li><li> Oil</li></ul>	<ul><li>Steam boiler</li><li>Compressors</li></ul>	Steam from cooking	<ul> <li>Plan to install steam condensate recovery</li> <li>Planning energy improvement: variable speed drives, leak reduction, compressed air management system</li> </ul>

RHM	Fruits • Cooking evaporate fruit chutney and sauces • Packing	• Electricity	manufacture • Process steam	<ul> <li>Boiler exhaust</li> <li>Water from steam condensing</li> <li>Product cooling water</li> </ul>	Factory closing down in the near future
Greencore	Cakes and desserts  • Mixing • Baking • Cooling • Packing	<ul><li>Electricity</li><li>Gas</li></ul>	<ul> <li>Hot water</li> </ul>	<ul><li>CHP exhaust</li><li>Boiler exhaust</li><li>Ovens exhaust</li><li>Compressor convective heat</li></ul>	<ul> <li>Plan to produce energy from solid waste streams</li> <li>Carbon footprint labelling may be driving force for energy efficiency improvement</li> </ul>
GSK	<ul> <li>Mixing</li> <li>Water</li> <li>Carbonated</li> <li>and still soft</li> <li>Carbonate</li> <li>Pasteuris</li> <li>Cooling</li> <li>Packing</li> </ul>	ion • Gas	<ul><li>Steam boilers</li><li>Compressors</li><li>Chilling plant</li></ul>	<ul> <li>Boiler exhaust</li> <li>Cooling air from chilling plant</li> </ul>	<ul> <li>Heat recovery from compressors, re-generation plate packs.</li> <li>Concern about security of electricity supply. Planning to install CHP system.</li> </ul>

#### 4.1.2. Energy available and quality

At each factory, the main energy consuming unit operations on site were individually assessed in order to study energy efficiency and potential sources of waste energy by order of importance. Individual sources of waste energy were identified and their characteristics evaluated: temperature, media of rejection, mass flow rate, flow pattern (continuous, discontinuous), presence of contaminants and physical accessibility. Table 3 summarises the characteristics of the waste energy streams identified in the factories object of study.

Table 3. Summary of waste energy streams by type, origin and quality.

Stream type	Origin	Quality	Accessibility
Gas/air	<ul> <li>Boiler exhaust</li> <li>Oven exhaust</li> <li>Drier exhaust</li> <li>Hot air from drying or cooling</li> <li>Convective heat</li> </ul>	<ul> <li>Temperatures around 150 °C</li> <li>Flow rates acceptable</li> <li>Contaminants in some cases</li> <li>Moist in some cases</li> <li>Low heat capacity</li> </ul>	• Good
Water	<ul><li>Machine cooling</li><li>Cooling operations</li><li>CIP operations</li><li>Steam condensing</li></ul>	<ul> <li>Very low temperatures</li> <li>High flow rates</li> <li>Mostly discontinuous</li> <li>Contaminants if from CIP</li> </ul>	• Good
Steam	<ul><li>Boiler blow–down</li><li>Cooking processes</li><li>Cleaning operations</li></ul>	<ul> <li>High heat load – latent heat</li> <li>Temperatures 100 °C or above</li> <li>From cooking high flow rates and continuous</li> <li>From cleaning and blow-down discontinuous and contaminants</li> </ul>	• Good

As shown in Table 3, energy waste streams were classified depending on the media of rejection. The most common streams found were hot gases or hot air, generally released to the atmosphere from exhausts of ovens, CHP systems, boilers or dryers. The temperature in these streams was variable, with values from around 50°C in the case of convective hot air released from machinery, to higher temperatures found in baking and roasting ovens, the maximum being 370°C. The level of energy available was generally good, due to acceptable flow rates and the fact that most processes of origin operated on a continuous basis. On the other hand, the presence of contaminants and moisture in some of these streams (generally when the stream was in direct contact with the product) might cause corrosion or fouling problems in any heat recovery device. It is possible to decontaminate these streams using

separation techniques (e.g. scrubbersand cyclone) but this will decrease the energy content of the stream itself.

Waste energy available from water was high in most cases, as sources of origin were normally were cooling and cleaning operations where mass flow rates were high. However, these streams were always of very low temperature, specially in cooling systems, and values found varied from as low as 15°C to a maximum of 80°C. Hot water from cooling operations did not contain contaminants; on the other hand, hot water from cleaning-in-place operations was generally highly contaminated. Additionally, the discontinuous nature of most processes complicated the recovery of thermal energy for a power generation application.

The last and most valuable media of rejection was steam. Sources of waste steam found were: process steam (e.g. from cooking and, evaporation), steam blow-down from steam distribution systems and waste steam from cleaning in place operations. As its very nature, steam has a high heat capacity due to its latent heat content that can be recovered when condensing. In the case of process steam, the waste streams were continuous although the mass flow rates were not high. In some cases, steam was condensed using large amounts of cooling water. A considerable saving could be achieved if the thermal energy content of the steam was reused directly. Steam released in blow-down operations was intermittent so it had limited application. When released from cleaning operations, it was also intermittent and continues a high level of contaminants, therefore its application was limited.

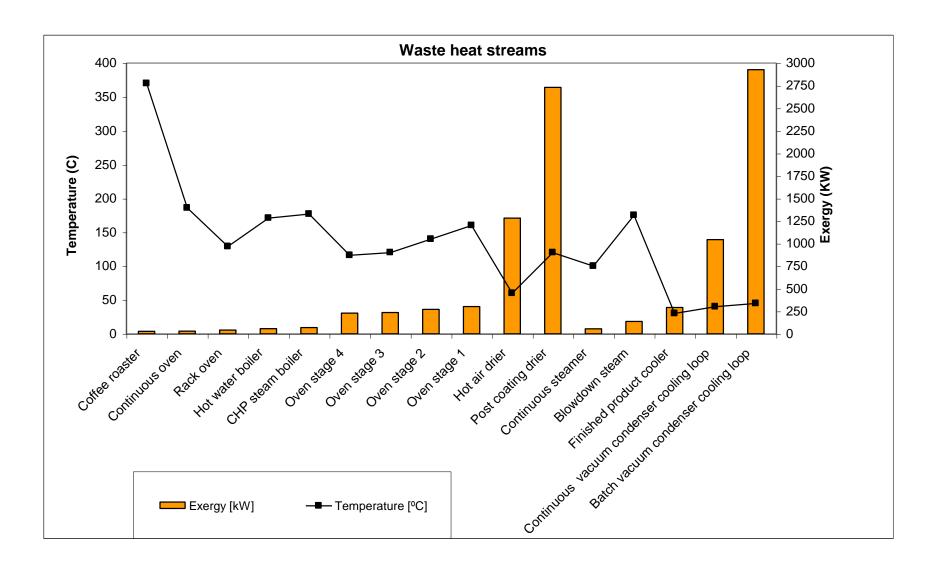
Results from calculations are presented in Table 4 and Figure 8.

Table 4. Temperatures, flow rates and exergy of waste energy streams.

Туре	Process of origin	Stream Temperature [°C]	Mass Flow [kg/s]	Exergy [kW]
Air	Coffee roaster	370	0.08	28.61
Air	Continuous oven	186	0.17	28.67
Air	Rack oven	129	0.38	42.47
Air	Hot water boiler	171	0.37	57.23
Air	CHP steam boiler	177	0.43	69.60
Air	Oven stage 4	116	2.36	229.49
Air	Oven stage 3	120	2.34	236.68
Air	Oven stage 2	140	2.23	271.46
Air	Oven stage 1	160	2.13	303.06
Air	Hot air drier	60	31.84	1282.43
Air	Post coating drier	120	26.97	2730.89
Steam	Continuous steamer	100	0.17	56.25
Steam	Blow-down steam	175	0.20	136.40
Water	Finished product cooler	30	7.00	292.53
Water	Continuous vacuum condenser cooling loop	40	12.50	1044.75
Water	Batch vacuum condenser cooling loop	45	28.00	2926.70

As shown in Table 4, the average temperature of waste energy streams was around 135°C, with a maximum of 370°C and a minimum as low as 30°C. It must be said that the quantity of streams on the very low range temperature found was big, although they were not all quantified in the table above. In terms of exergy, or energy available for conversion to mechanical power, the variation in the values obtained was considerable. Where the highest exergy value was found, the temperature given was extremely low and therefore insufficient to run a power generation engine. Additionally, as was the case of this stream, the flow was discontinuous. On the other hand, where temperatures were considerably higher, the exergy calculated was insufficient to power any Stirling engine of an economically viable size and power output.

Figure 8. Graph showing temperature of rejection and calculated exergy values for waste energy streams.



#### 4.2. Review of Stirling engine technology and potential for waste heat recovery

#### 4.2.1. Underlying thermodynamics

The important fact (law) is that although it is possible and easy to convert mechanical energy into heat (with 100% efficiency) the opposite is not true. That is, it is impossible to take thermal energy and convert all of it to mechanical energy. It can be shown that a hypothetical perfect heat engine, known as a Carnot engine, gives the very best conversion that can be achieved. If this engine operates between a hot source temperature of  $T_h$  and a cold sink temperature of  $T_c$  then its efficiency,  $\eta$ , defined as the ratio of mechanical work out, W, to thermal heat input,  $Q_h$  is given by

$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h}$$

Where,  $W = Q_h$  -  $Q_c$ , and  $Q_c$  is the heat which has to be rejected to the heat sink. It has to be stressed that this is the maximum possible efficiency, it says nothing about power density or how much absolute power is actually converted. Indeed as the efficiency approaches Carnot efficiency, the actual power output tends to zero! To maximise the power input, we have to be prepared to forgo some efficiency. It can be shown that the efficiency for maximum power product is:

$$\eta_{\mathrm{max}power} = 1 - \sqrt{\frac{T_c}{T_h}}$$

This has significant implications for what can be achieved in terms of waste heat utilisation. The sink temperature is fixed at environmental background temperature, and the source temperature is at best the temperature of the waste heat. The environment temperature can not be changed, and the food process will determine T<sub>h</sub>. The situation is probably made worse when one considers the fact that the heat engine is likely to be physically large to be able to recover and make use of relatively low grade heat. The size of the engine not only has an impact on cost (the larger, the more expensive), it also has an impact on dissipative frictional losses; again, the larger the device the higher the frictional losses. Most (perhaps all) commercial applications of Stirling engine devices attempt to increase efficiency and power density by harvesting at high temperatures. This is true for the proposed micro CHP units as it is for the novel solar harvesting engines.

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#### 4.2.1. Available commercial units

Table 5 provides a summary of some of the available commercial machines. The figures quoted come from the vendors' literature. Some appear to be rather optimistic. For example the quoted 13% for the ReGen unit when only 100°C hot source temperature is available looks challenging, and perhaps unachievable for any length of time and at any reasonable power level. Indeed, with the exception of the ReGen system all the others are designed to operate at reasonably high source temperatures much higher than might be found in the waste heat stream in a food manufacturing environment.

#### 4.2.2. Realistic potential for low grade heat harvesting

Thermodynamics suggests that the simplest way of increasing the efficiency of thermal to mechanical conversion is to run the heat engine at the highest possible temperature. Analysis also shows that operating at high temperatures will increase the power density (allow high output from a small engine), and the absolute power output. Hence and consistent with intuition, we are keenest on the highest temperature waste heat available.

Superimposed on the thermodynamic constraints are practical considerations of the availability of commercial heat engines. The work to date indicates that there are no commercial off the shelf Stirling engines (or any other type of engine) which will even begin to look economically viable for hot stream temperatures at the 100°C level.

The work suggests that there will most definitely be merit and value in using process integration techniques to make use of thermal energy as thermal energy. There may also be value in using low grade heat to power ab- and ad-sorption refrigeration, if cooling and refrigeration is required on the food processing site. These conclusions may change with energy prices and with legislative requirements.

Table 5. List of Stirling engine manufacturers. Description of engine types, applications and operational parameters.

Manufacturer	Interest	Engine Type	Required temperature at hot side (°C)	Electrical Efficiency (%)	Power output [kWe]	Size	Weight (kg)	Cost [£]
Whispertech (Powergen)	Micro CHP	4 Cylinder double acting Stirling cycle	1000	15%	1	500 x 600 x 850	138	Unspecified
Sunpower (Microgen)	Micro CHP	Free piston Stirling engine	550	28%	1.1	270 x 270 x 440	50	45,000 (500)
SOLO Stirling	CHP Solar power	Single acting 90° V two cylinder design	650	24.5%	2-9	1280 x 700 x 980	460	20,000
Stirling Denmark	Biomass Fired CHP	4 Cylinder double acting Stirling cycle	1000 – 1300	10 – 20%	35	Unspecified	Unspecified	70,000
ReGen Power Systems	Waste Heat Recovery	Fluidic Piston Stirling Engine	250 100	20% 13%	1000 500	Large Requires cooling towers	Unspecified	400,000 (for 500 kW)

#### 4. FURTHER RESEARCH

#### 5.1. Optimised energy use in food manufacturing and processing

#### **5.1.1.** Thermodynamic realities

In section 4 it was found that the simplest way of increasing efficiency was to run the heat engine at the hottest temperature possible. In most food manufacturing/processing factories, gas is the fuel of choice. This burns in air at a temperature higher than the upper operating temperatures of most engineering steels. Hence, it seems that it is relatively easy to get high temperature heat sources if we are prepared to use the high temperature end of the thermal source to drive the heat engine. All heat engines must reject heat, and this rejected heat can still be at a reasonably high temperature. Provided this temperature is sufficient to drive the food processing part of the operation, it will not be waste heat, it can be the required thermal energy matched to the needs of the factory. Indeed all commercial CHP initiatives use the highest grade heat (the highest temperature energy) to drive the heat engine. The rejected heat from the engine is used to provide the required process heat.

Although the original project focused on using waste heat from food factories to generate power, the quality and quantity of the energy rejected suggests that this may not be ecomomically viable. However, it has been noted that in almost all processes considered, the initial quality of the energy used to process food is higher than required. This situation lends itself naturally to a CHP like scenario. The situation is somewhat more demanding, in that the heat rejected by the heat engine must be available within tight specification constraints (temperature, quantity, no pollutants, no lubricant carry over, correct humidity and correct ratio of radiant to convective heating). Nonetheless, given the current pressures of increasing energy cost, the need to reduce carbon footprints and the desire to operate in an environmentally sound and sustainable manner, the adoption of some form of heat engine using the high temperatures achieved by burning gas looks very attractive.

#### 5.1.2. Availability of commercial equipment

From Table 5, there appears to be no off-the-shelf Stirling heat engines capable of delivering even marginal returns from typical waste heat streams from the food processing industry. However, there are proven devices available capable of yielding very reasonable efficiencies, provided higher temperature heat sources are available. Table 5 indicates that Stirling engines will do a reasonable job if temperatures of 500 to 1,000°C are available. The literature suggests that higher efficiencies can be achieved if internal combustion engines (either reciprocating or rotating devices) are adopted. These devices are currently being used in a domestic/industrial framework, for straight forward CHP provision.

#### 5.1.3. Required research to adapt/adopt energy saving and energy efficient cultures

Based on the findings, it is recommended that a proposal is initiated to implement and demonstrate the use of high temperature heat engines as the 'burners' providing heat for food processing and manufacturing activities. The thermodynamic case for this suggestion is compelling. Before this can be implemented a number of technical issues have to be resolved. These are:

- 1 Choice of heat engine (Stirling external combustion, reciprocating internal combustion, gas turbine).
- 2 Conditioning of rejected heat from the heat engine to the required form for downstream food process.
- If possible, use of waste heat from food process to condition the fuel feed to the heat engine.

The first task is about choosing the highest efficiency engine that is commercially available and which provides heat for the downstream process as close to the desired quality as possible. This will be relatively easy to achieve if a Stirling engine is chosen, where the reject heat will be transported by the flue gases which have never been inside the engine. However, it is more demanding if they are the exhaust gases of a working engine with the potential for lubrication and other hydrocarbon carry-over.

The second task may be relatively simple if the reject heat is simply used to raise steam, but considerably more complex if it is to provide direct heating to a baking oven. In this latter case there may be a need to control humidity, ensure that there is no undesirable carry-over, and perhaps a need to ensure an appropriate balance in the split between radiative and convective heating from the heat source.

The third task may enable this proposal achieve what seems uneconomical with a heat engine at the lower temperatures. The low grade heat rejected from the food manufacturing process could be used to preheat the air used to fire the high temperature engine.

#### 5.2. Scroll engines potential for low grade heat recovery

As discussed in the previous sections, the research work showed that the quality and quantity of energy available from food industry waste streams was not enough to efficiently run a Stirling engine. However, the work also showed that a considerable amount of energy was available from these streams. This demonstrates that the food industry has a high process heat recovery potential, as has also been reported in other recent research studies, but exploitation of this potential is constrained by the lack of suitable technology.

An attractive alternative to the Stirling engine is now emerging via unrelated developments from outside the Stirling industry: commercialisation of rotary scroll compressors for refrigeration and automotive air-conditioning; and new methods of manufacturing compact heat exchangers and reactors. Together these can form the basis of a new rotary heat engine using a recuperated rotary Ericsson cycle. This "scroll" engine will have the same theoretical efficiency as the Stirling, but will achieve a higher proportion of it in practice, at commercially acceptable costs. The Stirling engine's reciprocating compressor and expander cause reversing, unsteady flow of the charge gas, with gas conditions varying cyclically at any point in the closed gas circuit. Optimum specification of the heat exchangers at the heart of the cycle is therefore impossible, which makes achievement of its very high potential efficiency extremely difficult. In contrast, a similar engine based on rotary scrolls would have uni-directional, near-steady state charge gas flow and allow optimum specification of heat exchangers.

The scroll engine has the potential to reverse the sequence of high and low temperature engine developments. Low temperature scroll engines can use existing scroll technology, whereas high temperature systems will require considerable development. Also, the use of scrolls and the new manufacturing methods simplifies the heat exchanger components and greatly reduces their size, while increasing the proportion of theoretical efficiency that can be achieved. Both will improve financial viability significantly. So the development of low temperature waste heat to power systems using scroll engine technology is a promising opportunity and further research in this field is advisable.

#### 5. CONCLUSIONS

The research work within this project compiled findings from food industry processing operations and associated energy use practices and evidence on Stirling engine technology working principles and realistic applications.

When measuring waste energy streams from food factories, some technical barriers existed that made difficult the accurate quantification of the energy content on the streams identified. Food processing companies were well aware of the characteristics of their processes and the main sources of waste energy in their facilities. Most of them had in place energy management policies and had developed energy efficiency programs involving relatively straight forward and low cost initiatives. Some had made significant capital investments in energy efficient technologies such as cogeneration. In some cases, companies had used external consultant advice to obtain a detailed study of the company current use of energy and needs for improvement. It was found that a lack of accurate metering in place made it difficult to identify the main inefficient points in the process in order to establish priorities. For that reason, at the end of the project only sixteen streams were accurately quantified.

However, given the information collected through the survey, it was concluded that the streams quantified are representative of the facts found in the food factories visited.

Research on the fundamentals of Stirling engine technology and the viability of its application to the food industry drew various conclusions. Analysis of thermodynamics showed that the best was to increase the efficiency of thermal to mechanical conversion is to run the Stirling engine at the highest possible temperature. The analysis also showed that operating at high temperatures will increase the power density and absolute power output of the engine. This led to the conclusion that it was best to use thermal energy at the highest temperature possible. On the other hand, evaluation of the commercial status of Stirling technology showed hat there is no commercial Stirling engine capable of operating at the temperatures identified in food manufacturing operations.

The work suggested that, at the moment, the food industry would better benefit from process integration techniques to make use of thermal energy as thermal energy. Application of energy management policies that enable energy efficiency and waste minimisation at the source are the most economic and straight forward solution for energy improvement and cost reduction. Additionally, there may also be value in using low grade heat to power ab- and adsorption refrigeration, if cooling and refrigeration is required on the food processing site. These conclusions may change with energy prices and with legislative requirements.

#### 6. ACKNOWLEGMENTS

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Warburtons Trevor Oakley, Damian Magill

Weetabix Graham Byars,

Unilever James Peden, Sermet Baykaner, David Stephens, Tina Seward

RHM Culinary Brands John Mulvaney

Greencore James Cherry, Graham Thomas

GSK Nutritionals Andrew McDonald

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