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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: AC0405

2. Project title: Potential for Solar Energy in Food Manufacturing, Distribution and Retrail

3. Contractor organisation(s): Brunel University
Uxbridge, Middlesex
UB8 3PH

4. Total Defra project costs: £ 55,000

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

end date .... 31 December 2007

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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 overall aim of the study was to assess the potential for increasing the use of solar energy in the food sector. For comparative purposes the study also included an assessment of the benefits that could arise from the use of other renewable energy sources, and the potential for more effective use of energy in food retail and distribution. Specific objectives were to*: i) establish the current state of the art in relevant available solar technology; ii) identify the barriers for the adoption of solar technology; iii) assess the potential for solar energy capture; iv) appraise the potential of alternative relevant technologies for providing renewable energy; v) assess the benefits from energy saving technologies; vi) compare the alternative strategies for the next 5-10 years and vii) Consider the merits of specific research programmes on solar energy and energy conservation in the food sector.*

To obtain the views of the main stakeholders in the relevant food and energy sectors on the opportunities and barriers to the adoption of solar energy and other renewable energy technologies by the food industry, personal interviews and structured questionnaires tailored to the main stakeholders (supermarkets, consultants for supermarket design; energy and equipment suppliers) were used. The main findings from the questionnaires and interviews are:

- Key personnel in supermarkets and engineers involved in the design of supermarkets are aware of the potential contribution of renewable energy technologies and other energy conservation measures to energy conservation and environmental impact reduction in the food industry. A number of supermarket chains have implemented such technologies at pilot scale to gain operating experience, and more importantly, for marketing reasons, to gain competitive advantage through a green image.
- From installations to date in the UK the most notable are a 600 kW wind turbine at a Sainsbury's distribution centre in East Kilbride and a 60 kWp photovoltaic array at a Tesco store in Swansea.
- The main barrier to the application of renewable energy technologies in the food sector is the capital cost. Even though significant progress has been made towards the improvement of the energy conversion efficiencies of photovoltaic technologies (PVs) and reduction in their cost, payback periods are still far too long, for them to become attractive to the food industry.
- Wind energy can be more attractive than PVs in areas of high wind speed. Apart from relatively high cost, the main barrier to the wide application of wind turbines for local power generation is planning restrictions. This technology is more attractive for application in food distribution centres that are normally located outside build-up areas where planning restrictions can be less severe than in urban areas. In these applications it is likely that preference will be for large wind turbines of more than 1.0 MW power generation capacity as the cost of generation per unit power reduces with the size of the turbine.

Analysis using a case study in a retail store employing design features for the utilisation of solar energy in the form of daylighting has shown that there is significant potential to reduce energy consumption in retail food stores through the use of daylighting. Main barriers to the wider application of daylighting is the requirement to satisfy the new building regulations in terms of the overall thermal performance of the building fabric, the high cost of the first store design to incorporate daylighting and the requirement to have consistent levels of illumination on certain types of food and non food products. Integration of daylighting with artificial lighting should be able to satisfy both energy and merchandising requirements at acceptable additional capital cost.

In the UK, with over 6000 large supermarkets of average sales area of 15000 ft^2 (1400 m^2), 9000 petrol station forecourts and around 140 large distribution centres there is the potential for annual generation of over 500 GWh or 0.5 TWh of electrical power using PV. The total UK annual electrical energy consumption in supermarkets and forecourts is estimated to be around 12 TWh indicating that PVs have the potential to generate around 5% of the electrical energy requirements of the food retail and distribution industry. At current PV installed prices, however, and PV array efficiencies of around 15% the payback period of PVs are far too long to make them economically attractive to the industry. For a 3% annual electricity price increase, the payback period of a 20 kWp PV array will be around 65 years, reducing to 30 years for an annual increase of 10%. If a 50% government grant is provided towards the capital cost of the installation, for a 3% annual grid electricity price increase, the payback period for the array will be around 40 years, reducing to around 20 years for a 10% annual electricity price increase. In 5 to 10 years time, assuming capital costs remain constant, an array with an efficiency of 30% will have a payback period of 40 years if the annual electricity price increase is 3% and 20 years if the electricity price increase is 10%.

The payback period of a 80 kWp wind turbine was found to be around 13 years for a 3% annual grid electricity price increase and 10 years for a 10% increase. The cost of wind turbines per kWh electricity generation capacity reduces as the size of the turbine increases. This makes them attractive in applications with high electrical loads such as distribution centres in rural or semi-rural areas where planning restrictions are also less severe.

Comparison of renewable energy technologies with energy conservation measures in retail food stores has shown that with current energy prices and the absence of government legislation that makes the installation of renewable technologies mandatory, reduction of the energy consumption of refrigeration equipment and artificial lighting are much more economically attractive. However, as the potential to increase further refrigeration and lighting efficiency at reasonable cost is exhausted, further reduction of the carbon footprint of supermarkets and other food facilities could be achieved through:

i) better integration and control of current technologies;
ii) technological developments and radical approaches to merchandising;
iii) improvement of the performance of renewable technologies and their optimum integration within the building structure, for example, application of transparent PV modules into appropriately oriented supermarket façades to replace conventional glazing. Consideration should be given to potential reduction of structural costs over conventional roof mounted PVs; impact on daylighting; integration of daylighting and artificial lighting to achieve required lighting levels at minimum running costs.
iv) evaluation and integration of renewables such as solar, wind, biomass and other low carbon technologies such as CHP, tri-generation, ground source heat pumps within the context of overall thermal energy management and environmental control of the food facility.

To achieve these objectives, a concerted research and development effort, funded by the food industry and the government, is required in all of the above areas.

A study to investigate the potential for solar capture and use in the food distribution sector has shown that:

- It is feasible to use photovoltaics to power the refrigeration systems of food distribution vehicles. The use of PV systems will be more suitable for vehicles with relatively low refrigeration requirements, for example, vehicles used for the distribution of chilled foods and for short journeys. For the transport of frozen foods that require higher refrigeration power requirements, hybrid systems (diesel/solar) could be considered. The use of solar energy becomes more effective as the refrigeration power requirements are reduced. Within the requirements of the ATP agreement this can be achieved through the use of vacuum insulation.
- A number of alternative approaches that have potential to reduce energy consumption in refrigerated food distribution have been identified, such as the use of the heat from the engine and the exhaust gases to power thermally driven refrigeration systems and integration of conventional and thermally driven refrigeration technologies with solar energy and thermal storage. More work is required to assess the potential, life cycle cost and environmental impacts and research and development needs to bring the most promising of these technologies to the market.

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:
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   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
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Aims
The overall aim of the study was to assess the potential for increasing the use of solar energy in the food distribution and retail sectors. For comparative purposes the study also includes an assessment of the benefits that could arise from the use of other renewable energy sources, and the potential for more effective use of energy. Opportunities are also identified for research into improving or providing new energy saving technologies.

Objective 01: To establish current state of the art in relevant available solar technology

1.1 Abstract
A detailed literature search of photovoltaic electricity generation has been carried out and its application to food retail, storage and distribution has been reviewed. Details of this review are given below.

1.2 Photovoltaics

1.2.1 Introduction
Photovoltaics (PVs), is the term used for all technologies which convert incident light directly into electricity by a semiconductor junction device. Photovoltaic cells are the smallest unit in a PV power producing system, typically available in different square sizes between 12.5 and 20 cm [1]. A single solar cell has an output voltage of about 0.6 V, i.e. for a common pn junction, and a maximum power output of 2-3 W under standard conditions. (Standard Test Conditions, STC, are widely used to measure the nominal output power of photovoltaic cells or modules. The irradiance level is 1000 W/m², and cell or module junction temperature of 25°C.)

The electrical capacity of PV cells and modules is given in Watt peak (Wp) and represents the maximum output power of the considered device under STC . The maximum output current is directly linked to the area, but depends, also, on several parameters such as the junction's temperature, the intensity of the incident radiation and the spectral composition of the incident radiation. The output power of a silicon-based PV device usually decreases by 0.4%-0.5% when the temperature increases by 1°C. To provide useful power, PV cells are connected together and encapsulated between a transparent front and backing material, usually polymer or glass, so that they can be protected against mechanical strains, impacts and humidity. The ensemble so obtained is called a PV module, or PV panel, and usually has a guaranteed lifetime of between 20 and 30 years. A complete PV system normally comprises a number of modules making a PV array. A PV system also requires several additional components such as support structures, wiring, conversion and control devices. Inverters are needed for grid connected systems and most off-grid systems to convert the energy from DC to AC. Off-grid systems also require storage batteries and charge controllers. The majority of PV devices are currently made of silicon in different internal structures, but alternative thin-film technologies, such as gallium arsenide or cadmium telluride, have also been commercialized over the past few years [2]. Table 1 gives details of current state of the art PV technologies including current and projected efficiencies.

1.2.2 Market Trends
The cumulative installed PV capacity in the IEA (International Energy Agency) PVPS countries is reported every year. The total PV power installed has shown annual growth rates of between 35% and 42 % since 2000 [1]. At the end of 2004, the cumulative PV capacity in the IEA PVPS countries was around 2.6 GWp. It is reported that the worldwide cumulative installed solar PV electricity generating capacity expanded by 39% in 2005 and now the total capacity exceeds 5 GWp [3]. In the European Union, 645 MWp of solar modules were installed in 2005 giving a cumulative capacity of 1.8 GWp. Grid-connected applications (solar roofs, facades and power plants) represent nearly 99% of the EU PV power. More than 85% of the 2005 installed capacity was in Germany. This

was driven by incentives within the renewable energies legislation programme which guarantees a purchase price for PV generated electricity between 0.457 and 0.624 €/kWh and an annual increase of 5% for a period of 20 years. Similar incentives to Germany have also been introduced in Spain and Italy [3].

In the UK there has been a significant increase in the annual installed PV generation capacity over the past few years helped primarily by the introduction of a Major Demonstration Programme in 2002. This programme, which ended in March 2006, provided more than £26 million of funding for 1200 domestic and 180 commercial installations and helped increase the cumulative installed capacity from 4.1 MWp in 2002 to 10.7 MWp in 2005. The funding covered between 40% and 50% of the installed cost of the PV systems [4]. The demonstration programme has, since 1st April 2006, been replaced by the DTI's low carbon buildings programme that is providing grants for micro-generation technologies for householders, community organisations, schools, the public sector and businesses.

1.2.3 Price Trends

It is quite difficult to give a generic price for PV solar modules and systems, since this depends on several factors such as system size, location, grid connection and technical specifications. The price of PV modules and systems decreased strongly until 2004 but has begun increasing slightly over the last two years due to the present shortage of silicon. In 2003, module prices in the UK were typically in the range £2.5-3.7 per watt peak for reasonable volume orders [1]. For small orders (just a few modules), the average price was £3.8 per watt peak. Module prices today are similar to the 2003 prices. Turnkey prices of typical PV applications in 2003 were in the range £5.2-£10/Wp for off-grid systems. For grid connected systems prices were £4.3-£12.8/Wp for domestic systems of 1.0 to 3.0 kWp capacity, £4.4-£6.6/Wp for commercial systems up to 10 kWp capacity and £7-£13.1/Wp for building integrated PV applications [1].

A reasonable estimate is £5/Wp for a 2.5 kWp domestic installation and £4/Wp for a 40 kWp commercial installation.

Table 1: State of the art PV details [2,5,6,7,8]

	Technology (basis)	Maximum Cell Efficiency (%)	Maximum Module Efficiency (%)	Efficiency of available modules (%)	Efficiencies expected by 2010 (2020)
Multicrystalline Silicon	mc-Si	20.3	15.3	10-14.5	18 (20)%
Silicon Ribbon	Ribbon Si	-	-	10-12.5	17 (19)%
Monocrystalline Silicon	sc-Si	24.7	22.7	10-16	20 (22)%
	HIT	21	18.4	15-17	-
Amorphous Silicon	a-Si	10.1 single junction	10.4 triple junction	4-9	10-12 (15)%
Microcrystalline Silicon	a-Si/µc-Si	11.7 (submodule)		-	
Admium Telluride	CdTe	16.5	10.7	6-9	
	CIS	18.4	13.4	9-10.5	
Gallium Arsenide	GaAs multijunction	37.9	-	-	45%

According to EPIA (European Photovoltaic Industry Association), small off-grid PV systems in the kW range are more cost-effective than systems using pure diesel generators [6]. Larger PV hybrid systems (5-30kW) using diesel generator are also less expensive than pure diesel powered systems because of the high life cost of a diesel generator set making costs reach 0.4-0.6€/kWh. Regarding grid-connected systems, EPIA expects prices to decrease from about 6 €/Wp to 3-4 €/Wp by 2010 for small integrated rooftop systems. Grid connected systems are expected to eventually become price competitive with conventional power generation by 2020. The capital costs of small grid connected PV installations (a few kWp) in the UK is expected to decrease from £5/Wp in 2005 to about £1/Wp in 2025 [10].The geographical location of a PV installation, on which the annual irradiation depends, directly influences the generating costs. EPIA estimates that, in 2000, the cost of solar energy was 0.6 €/kWp in Germany but only 0.3 €/kWp in Spain for a similar installation. PV is expected to become cost-competitive with conventional power sources by 2010 in Southern Europe, and by 2020-2025 in Germany. In the UK, it should happen circa 2030-2040 for domestic applications.

1.3 Solar Thermal Energy

There are several types of solar collector that can be used to heat liquids. Selection of a solar collector type will depend on the local climate and the temperature of the application being considered. The most common types of collector for smaller scale applications are the non-concentrating flat plate and evacuated tube collectors. The market development of flat plate and evacuated tube collectors has shown an annual increase over the years 1999 – 2004 of 25% in China and Taiwan, 19% in Australia and New Zealand and 13% in Europe. The annual collector yield of all solar thermal systems in the 41 countries participating in the IEA SHC (Solar Heating and Cooling) programme was 58,117 GWh at the end of 2004, equivalent to the avoidance of 25.4 million tonnes of CO_2 [10].

In 2005, the total number of solar thermal installations in the UK was 78,470 at an estimated cost of £358 million. This is the largest microgeneration industry in the UK by far, but considering most of the solar hot water systems were installed pre 2000, the growth of installations in the last five years was minimal compared to other micro generation technologies. Solar thermal systems are most cost effective at replacing electric water heating systems [10].Investment costs of solar thermal systems consist of the cost of hardware (collector, tank, piping and where appropriate the control unit and pump) and the cost of installation. Solar thermal systems are sold in a wide range of sizes and applications, and the cost of the hardware therefore varies substantially. This also depends on quality criteria. The cost of installation also varies depending on the timing of installation: it is much cheaper to install a solar thermal system during the construction or refurbishment of a building than at a later time. For small systems, installation typically accounts for 20%-30% of the total investment costs.The total cost of a typical solar domestic hot water system for a one-family dwelling is in the range of £500-£3500. The system price for large collector fields (thousands of square meters), as used for industrial process heat or district heating, is approximately £175/m^2.The initial investment constitutes by far the largest part of heat production costs [12]. Modern, good-quality solar thermal systems have a lifetime of 20-25 years with very low maintenance requirements. As with investment costs the final heat production costs vary greatly depending on the type and size of the system, the location, the timing of the installation and several other factors [12]. Annual operation and maintenance costs are usually below 1% of the investment. The simplest systems hardly require any maintenance, but, more complex systems need regular monitoring and some maintenance to maintain peak performance throughout their lifetime.

1.4 Wind Energy

Wind turbines can produce electricity by using the natural power of the wind to drive a generator. The technology is developing fast and turbines are becoming cheaper and more powerful. Currently, Europe is at the hub of this high tech industry. At the end of 2005 the total power generated by wind turbines in the EU (25 countries) totalled 40,504 MW of electricity an increase of 15.14 % over 2004 [13]. The top 5 European countries produce 85.5 % of total power output of the EU25. The UK has excellent wind power potential as the wind speeds available are some of the highest in Europe. Installed capacity in the UK in 2004 was 1353 MW which represented only 3.3% of the total installed capacity in the EU.

Research and development of wind turbine design has been ongoing for many years, increasing the efficiency of the turbine though research into new construction materials, increased generator efficiency, blade design, grid integration and minimising the impact of the turbine on the surrounding environment. The total installation cost of wind turbines can be expressed as a function of the wind system's rated electrical capacity. A grid-connected residential-scale system (1-10 kW) generally costs between £2,400 and £5000 per installed kilowatt. A medium-scale, commercial system (10-100 kW) is more cost-effective, costing between £900 and £2000 per kilowatt. Large-scale systems of greater than l00 kW capacity, cost in the range of £600 to £1500 per kilowatt, with the lowest costs achieved when multiple units are installed at one location. In general, costs per kW capacity decrease as machine capacity increases [13].

1.5 Biomass

Biomass is a collective term for all plant and animal material. A number of different forms of biomass can be burned or digested to produce energy. Examples include wood, straw, poultry litter and energy crops such as willow and poplar grown on short rotation coppice and miscanthus. Biomass is a very versatile material and can be used to produce heat (for space and water heating), electricity and a combination of heat and power (electricity). Biomass utilised by well-developed technologies can result in very low emissions compared to fossil fuels, and if grown sustainably can have a zero contribution to net carbon dioxide release. The ash content of biomass is much lower than that of coal, and is generally free from heavy metals, allowing environmentally friendly uses for the ash, such as soil conditioner, instead of landfill. Over the last few years considerable progress has been made in the use of biomass for thermal energy production. Biomass can also be used for electricity production and is expected to play an important role in meeting the EU's goal as set out in a White Paper and Directive to have 22% of electricity consumption from renewable energy sources by 2010 [14]. This is equivalent to 20,000 MWe biomass fired CHP capacity [15].

CHP (Combined Heat and Power) is the simultaneous generation of electrical power and heat in a single process. CHP can be substantially more energy efficient, more than 2 times, compared to separate generation of electricity and thermal energy because the heat that is normally wasted in conventional generation is recovered and can be used for heating or cooling or for both heating and cooling (tri-generation). The higher efficiency of CHP systems can lead to significant reductions in CO_2 emissions. The potential advantages of CHP systems over conventional separate generation of electrical power and heat, is leading to increasing applications of the technology to industrial processes and commercial buildings. CHP plants are currently available in a variety of capacities and can make use of a variety of fuels such as coal, light fuel oils, natural gas, waste fuels and solid or gaseous biomass. The prime mover can be of a variety of forms such as steam turbine, gas turbine of the open or closed loop type, combined cycle gas/steam turbines, reciprocating internal combustion engines, Stirling engines and fuel cells [18]. In recent years, development of micro-turbines with low emissions and fuel cells that have practically zero emissions, have started to present attractive solutions in the range 1.0 kWe to 1.0 MWe CHP plant. Table 2 gives current and future costs and efficiencies of biomass power generation technologies.

Table 2: Costs of biomass power generation technologies

Power generation technology	Capital cost £/kWe (2002)	Capital cost £/kWe (2020)	Electrical efficiency (%)
Grate/fluid bed boiler +steam turbine	1000 - 1750	1000 - 1750	20% - 40% ≥ 10 MWe
Gasification+diesel engine or gas turbine	1000 - 1750	750 - 1250	20% -30% 50 kWe – 300 MWe
Gasification + combined cycle	3500 - 4500	750 - 1500	40%-50% (30 MWe –100 MWe)
Wet biomass digestion + engine or turbine	1250 - 3500	1250 - 3500	25% - 35%

Objective 02: Identify the barriers for the adoption of solar technology

2.1 Abstract

The real and perceived barriers to the uptake of solar energy technology options were investigated. This was done by obtaining the views of stakeholders by structured interviews and questionnaires. The stakeholders were categorised as follows:

- Supermarkets and other smaller food retailers and consultants used for supermarket design
- Energy Suppliers

The results for each stakeholder group are summarised below:

2.2 Food Retailers and Store Designers

2.2.1 PVs

A small percentage of the supermarket chains interviewed currently use solar PV at a small pilot scale for the following purposes:

- To illuminate external store advertising signs.
- One supermarket chain recently installed a 60 kW solar array on the roof
- A small number of supermarket chains installed PV arrays on a petrol station canopies.

Most large supermarket chains have considered the use of solar PV. However, under current conditions of cost and financial incentives, any plans to use solar PV in the future were on a small scale limited to using solar PV to power car park signage or ticket machines.

Attractions

Retailers and store designers saw the following attractions to PV.

Public Relations

- The use of solar PV was considered to be a major attraction for public relations in applications where the PV panels could be seen by the public as it helped give supermarkets a 'Green image'. However, as many panels are located on the roof they cannot be in direct view of the public, which creates difficulties in justifying the PR value of investing in solar PV. This problem can be overcome to a certain extent by integrating PV in the façade of the supermarket provided it has the appropriate orientation.

Energy Savings Potential

- The energy saving potential of PV was identified as a major attraction when compared to the rising energy costs in the UK.

Barriers

The following were identified as the main barriers to PV Installation

- Cost was identified as a major barrier with all interviewed supermarket chains. The capital cost of purchasing the solar PV panels was considered to be very high, with long pay back periods.
- One energy provider commented that the cost of purchase of PV should be integrated with the costs of public relations (PR) to help reduce the cost of investing in PV.
- One of the building services designers commented that as the price of external building cladding material increased, using photovoltaics as a direct replacement may become a more viable option in the future.

Space Requirement

- The space required for PV was a problem for most urban stores. These stores are located on the ground level usually with offices above. Access to the roof was limited either because the roof already had many mechanical equipment or no access was allowed. This was less of a problem with out of town stores which have a large roof area as well as large car parks.

Maintenance

- One supermarket chain commented that it was necessary to clean the PV panels to remove dust and bird droppings. This reduces the efficiency of the panel leading to a reduced power output.
- The reliability of the inverters was also identified as a problem, leading to a decrease in the output power delivered to the supermarket.

2.2.2 Solar Thermal Energy

From the supermarkets interviewed none were currently using solar collectors as a source of hot water.

Attractions

Retailers and store designers saw the following attractions to solar-thermal energy.

Energy Saving Potential

- The energy saving potential of the solar collector for hot water production was seen as attractive provided there was sufficient need for the hot water for staff areas or a café. Supermarkets also have opportunities for heat recovery that may reduce the attractiveness of solar water heating.
- High temperature evacuated tube solar collectors may have the potential to generate water at sufficiently high temperatures for use by in-house food production facilities.

Public Image

- The use of solar collectors for water heating provides opportunities for 'public green image'. The problem, however, is the location of the collectors in areas where the public would be able to view them.

Barriers

The barriers identified to the application of solar water heating were:

Cost

- The capital cost of the installation was a barrier but was viewed as a more attractive option compared to the cost of PV panels.

Space

- As for solar PV, space was considered a problem for urban stores because of roof access and orientation.

2.2.3 Daylighting

The use of day-lighting for parts of the store was seen, overall, as an attractive option by all the supermarket chains interviewed. To date, supermarkets have used the following methods to increase daylighting.

- Light pipes mainly in the office areas.
- Maximise daylighting through the store's façade at design stage.
- Daylighting through glazed parts of the roof introduced at the design stage.

Attractions

- Improved visual environment in the store
- Savings in lighting energy requirements.

Barriers

- The cost of glazed façades and the cost of introducing glazing in the roof for the purposes of daylighting is high. This cost can be reduced through the standardisation of new store designs.
- The glazing will increase thermal losses in winter and will increase heat gains in the summer. This will increase energy requirements for heating in winter and may also increase cooling requirements and refrigeration system power consumption in the summer.
- A detailed analysis should be carried out on the benefits and impacts of day lighting on store environment and energy use.

2.2.4 Wind Energy

From the interviews completed all supermarket chains responded very positively towards the use of wind turbines for on site power generation. Two of the supermarkets interviewed had plans for installing more turbines but with larger power output. The larger the power output of the turbine the better the payback period.

Attractions to more wind power development

- Wind power is more economically attractive than PV because of the lower capital cost for the same power output.
- Greater electrical energy generation potential than PV due to the relative high wind speeds in many parts of the UK.
- Planning restrictions on many supermarket sites for public relations and 'green image' as they are more visible than solar technologies.

Barriers to the adoption of Wind Energy

- Relatively high capital cost
- Not a real option for urban sites due to:
  - Space limitations
  - Low wind speeds in built-up areas
  - Planning restrictions.

2.2.5 Biomass

Biomass was a well known renewable source of energy for most retailers. A small number of retailers interviewed currently have a small number of pilot biomass installations for water heating. Others are considering the use of biomass as a means of reducing landfill costs from food waste.

Attractions

- Reduction of landfill costs
- Opportunities for heat and power generation
- Public relations value in 'green image'

Barriers

- Space requirements for the storage of biomass fuel and cost of fuel transport
- Large area needed to grow fuel crops
- Relatively high capital cost
- Planning restrictions for large plants
- Reliability of systems not yet proven
- High maintenance costs.

2.3 Views of Renewable Energy Providers and Equipment Suppliers

The renewable energy providers see the use of PV for power generation as currently having too many barriers compared to other energy generation technologies. Capital cost was identified as the most important barrier and the feeling was that effective government subsidies of up to 50% of capital cost would be required to make PV a more attractive option to the energy user. Another barrier to the development of PV generation sites is the amount of large land space required compared to energy generation from wind turbines. Even though wind turbines have more planning restrictions than PV, they offer much shorter payback periods which makes them more economically attractive.

Objective 03: Assess the potential for solar energy capture

3.1 Abstract

In this work package the potential of solar energy capture for use in supermarkets and distribution centres was evaluated. This was achieved through modelling using available software packages and spreadsheet models developed specifically for the task.

3.2 Modelling of solar capture for electricity generation

The RETscreen® International Clean Energy Analysis Software, was used to model the electrical energy that can be generated from PV. The model requires a number of specific user defined inputs to estimate the annual or monthly electricity generated by a specific PV array as follows: i) monthly average daily Irradiation on a horizontal surface for location (kWh/m^2/day); ii) monthly average temperature for location (°C); iii) latitude of Project location (°N); iv) technical specification of PV array; v) positioning of PV array; v) Nominal PV array power; vi) technical specification of power conditioning equipment. Outputs from the model are: i) specific Yield of photovoltaic array (kWh/m^2); ii) overall PV system efficiency (%); iii) PV system capacity factor (%); iii) Renewable energy collected (MWh); iv) renewable energy delivered (MWh).

Different locations in the UK have varying values of solar irradiance and average temperatures which will have an impact on the annual electricity generation from an installed photovoltaic array. Four different locations were considered for the array installation and to cater for different sizes of food facility from a petrol station to a distribution centre, 7 different sizes of photovoltaic array were modelled for each location as shown in Table 3. It can be seen that electricity generation will be maximum in the South coast of England and minimum in Scotland but the difference will be small, only 14%. Table 4 shows the percentage of total electricity consumption that the 7 sizes of PV array can meet for different food facilities in different locations in the UK. It can be seen that the percentage PV contribution will be small, around 5%, and in general will be constrained by the space availability for the installation of PVs.

Table 3: Electrical generation capacity of different size PV arrays in different locations

Capacity of PV array (kWp)	London (MWh)	South coast of England (MWh)	North of England (MWh)	Scotland (MWh)	UK Average (MWh)
5	4.19	4.72	4.06	4.04	4.25
10	8.37	9.45	8.13	8.66	8.65
20	16.74	18.89	16.25	16.17	17.01
40	33.48	37.78	32.51	32.34	34.03
60	49.93	56.33	48.47	48.23	50.74
100	83.11	93.78	80.68	80.28	84.46
200	166.22	187.58	161.30	160.56	168.91

Table 4 shows the percentage contribution to the total electricity consumption for different food facilities.

Table 4: Percentage of total electricity demand that photovoltaic arrays can meet

	% of total electricity consumption that PVs may generate						
	5 kWp	10 kWp	20 kWp	40 kWp	60 kWp	100 kWp	200 kWp
Small supermarket with petrol station (Forecourt) ~ 240 m^2	**0.82**	**1.64**	**3.27**	**6.54**	**9.76**	**16.24**	**32.49**
Large Supermarket ~1700 m^2	**0.22**	**0.45**	**0.89**	**1.79**	**2.66**	**4.44**	**8.87**
Superstore ~ 5700 m^2	**0.08**	**0.16**	**0.31**	**0.62**	**0.93**	**1.54**	**3.17**
Distribution centre 18200 m^2	**0.06**	**0.14**	**0.25**	**0.51**	**0.76**	**1.27**	**2.53**

3.3 Use of Daylighting to Displace Electric Lighting

To investigate the energy saving potential of daylighting, a superstore in Swansea, Wales, of 7432 m^2 floor sales area, designed to allow natural daylight into the building through a series of angled skylight windows directly above the sales floor area, was used as a case study. The front of the building also has a floor to roof glass façade to allow daylight into the front area of the store. Artificial lighting in the sales area is provided by 418 high bay luminairs, of 250 W power rating each. 110 of the luminairs are controlled by suspended lighting sensors which switch rows of lights off during daylight hours to maintain a minimum lighting level in the store. A spreadsheet model was developed and used to evaluate the energy savings that would arise from the daylighting design features of the store. The annual energy consumption of the lights in the sales area of the store with and without daylighting controls is shown in Table 5. It can be seen that the daylighting design features of the store should achieve annual energy savings of the order of 104 MWh which represent 22 % of the annual lighting energy consumption.

Table 5: Daylighting spreadsheet model results

	Average daylight hrs/day	Coefficient for light quality	Average daylight hrs/month	Monthly energy use during daylight hours with day lighting luminaries always on (kWh)	Monthly energy savings from daylighting (kWh)
Jan	8	0.65	161.2	25916	4433
Feb	10	0.75	210	29260	5775
Mar	12	0.85	316.2	38874	8696
Apr	14	0.9	378	43890	10395
May	15.5	0.9	432.45	50212	11892
Jun	16.3	0.95	464.55	51101	12775
Jul	16.8	0.95	494.76	54424	13606
Aug	14.5	0.9	404.55	46973	11125
Sep	12.8	0.85	326.4	40128	8976
Oct	10.5	0.8	260.4	34015	7161
Nov	9	0.65	175.5	28215	4826
Dec	8	0.65	161.2	25916	4433
Annual (kWh)				468923	104093

3.4 Energy Savings Potential of PVs and Daylighting in Supermarkets

UK supermarkets come in a range of sizes and offer different services and product ranges depending on the size. The three main classifications of supermarket are local stores, medium size urban high street supermarkets and large out of town superstores. Each supermarket category will have different barriers to the uptake of PVs and daylighting. Local stores may not have the roof space to install PV arrays as they may be in urban locations where the roof space is used for another function or there is no access to the roof. This will also limit the opportunities for daylighting.

For the calculation of the energy saving potential of PVs a figure of 5508 was assumed for the total number of supermarkets in 2004 as shown in Table 6 [16]. This enabled the total electricity that could be generated in the UK if every supermarket installed photovoltaic arrays to cover 60% of roof space to be estimated. The grid electricity for lighting that could be saved by designing a store for daylighting was also determined assuming a savings potential of 14 KWh/m² of sales area determined from Table 5. The results of the analysis are shown in Table 6. It can be seen that if PVs covering 60% of the roof space of the sales area of 5508 supermarkets are installed, their annual energy savings potential will be in excess of 374,000 MWh of electrical energy and their emissions reduction potential will be in excess of 160,000 tonnes of CO_2. If daylighting is designed in all the stores, its electrical energy savings potential will be 114,000 MWh and its emissions reduction potential 49,000 tonnes of CO_2.

Table 6: Energy Savings from PVs and daylighting in supermarkets

Retailer	A	B	C	D	E	F	G	I	TOTAL
No. Stores	125	1600	780	125	481	143	501	1275	5508
Average Size (m²)	3344	350	4459	3344	2138	1618	2684	?	
60% of roof space (m²)	2007	210	2675	2007	1282	970	1610		
Array size that can be acommodated (kWp)	200	20	200	200	100	100	200	10	
Electricity generation capacity by single array (MWh)	170.11	17.01	170.11	170.11	84.46	84.46	170.11	8.65	
Supermarket chain annual PV electricity generated (MWh)	21,264	27,216	132,686	21,264	40,625	12,078	85,225	11,029	373,605
PV Emissions reduction (tonnes CO_2)	9122	11676	56922	9122	17428	5181	36561	4730	160,277
Electrical lighting energy saved from daylighting design	**5852**	**7840**	**48692**	**5852**	**14397**	**3239**	**18825**	**3570**	**114,160**
Daylighting Emissions reduction (tonnes CO_2)	**2510**	**3363**	**20889**	**2510**	**6176**	**1389**	**8076**	**1531**	**48,975**

3.5 Energy Saving Potential of PVs in Petrol Stations

Petrol stations may provide a good opportunity for PV installations. The canopy used to protect the customer from the weather when refuelling provides a flat raised surface for the photovoltaic array. Not all petrol stations have canopies but the total number of petrol stations in the UK enables an estimate of the electricity that could be generated using the canopy for installations of a photovoltaic arrays. Assuming that an average canopy will have an area of 100 – 150 m², the array sizes that are small enough to be accommodated are shown in Table 7. The Table also shows the total electricity generation capacity of these arrays for a total of 9764 sites in the UK [17].

Table 7: Electricity generation potential of PVs in petrol stations

Nominal PV array power (kWp)	5.0	10.0	20.0
Total UK petrol station electricity generation potential (MWh)	41,524	84,471	166,122
Annual UK greenhouse gas emissions reduction (tonnes CO_2)	17,814	36,238	71,267

If 10 kWp PV arrays are installed in all the petrol stations in the UK their annual energy savings potential will be 84471 MWh which will lead to a reduction of 36238 tonnes in CO_2 emissions.

3.6 Energy Saving Potential of PVs in distribution centres

Distribution centres in the UK provide excellent opportunities for photovoltaic array installations because of the large flat roof areas and out-of-town locations. The number of distribution centres in the UK is estimated to be 146 consisting of national, regional and temperature controlled centres (Cold Store and Distribution Federation – CSDF) [18].

Table 8: Electricity generation potential of PVs in distribution centres

Nominal Photvoltaic array power (kWp)	100.0	200.0
Total UK Supermarket Electricity Generation (MWh)	12,331	24,836
Total UK Green House Gas Savings (tonnes CO_2)	5,290	10,654

If 200 kWp PV arrays are installed in all the distribution centres in the UK, their annual energy savings potential will be 24,836 MWh which will lead to a reduction of 10,654 tonnes in CO_2 emissions.

Objective 04: Assess the potential of relevant alternative technologies for providing renewable energy

4.1 Abstract

Ways of using indirect solar energy such as wind power were investigated and compared with photovoltaic generation.

4.2 Introduction

Other renewable energy technologies, such as wind power, could also be used to replace non-renewable energy sources for food retail and distribution. This section of the report considers the contribution that these technologies can make in the reduction of grid electricity consumption and emissions.

4.3 Wind Power

To estimate the electricity that could be generated by the installation of wind turbines in supermarket or distribution sites, the RETScreen [19] spreadsheet model was employed using specific details for each of the different sites in the South Cost, London, North of England and Scotland. Each site has different wind resources which is the variable that will ultimately decide whether or not the installation of a wind turbine will generate enough electricity to be economically viable.

The average wind speed for each site was determined from the NASA Surface meteorology and Solar Energy Data Set website [19] which is based on meteorological and solar data recorded for each site by satellite. To accommodate for the different ground morphological data, a wind shear exponent was employed. The wind shear exponent is a dimensionless number that expresses the rate at which the wind speed varies with height above the ground. This value is used to calculate the average wind speed at the wind turbine hub height and at 10 m. The wind shear exponent typically ranges from 0.10 to 0.40. The low end of the range corresponds to a smooth terrain (e.g. sea, sand and snow from 0.10 to 0.13). A wind shear of 0.25 corresponds to a rough terrain (i.e. with sizeable obstacles). The high end of the range (0.40) corresponds to a wind turbine in an urban area.

Table 9 shows the annual average wind speed, shear exponent and the size of each food facility considered for each location.

Table 9: Table of location properties for wind turbine modelling

Food Facility Type	Location	Gross Sales area ft^2 (m^2)	Wind Shear	Av Wind Speed at 50m (m/s)
Petrol station in urban location	London	2585 (240)	0.4	5.4
Supermarket in Urban Location	South Coast of England	18935(1700)	0.35	5.72
Large Supermarket in a Semi-rural Location	North of England	61382(5700)	0.25	7.2
Distribution Centre in Rural Location.	Scotland	196000(18200)	0.2	7.12

The annual electricity that could be generated by locating a specific size wind turbine on each site was determined and is shown in Table 10.

Table 10: Electricity generation from selected wind turbines and different UK locations (MWh)

Wind Turbine Rated Power	2.5 kW	25 kW	80 kW	250 kW
Petrol station in urban location – London (MWh)	3	36	110	304
Large Supermarket in Urban Location – South Coast of England (MWh)	4	41	123	342
Superstore in a Semi-rural Location – North of England (MWh)	6	51	146	413
Distribution Centre in Rural Location – Scotland (MWh)	7	58	160	457
Average Annual Electrical Energy Output (MWh)	**5**	**46.5**	**134.75**	**379**

Objective 05: The Potential for reducing energy demand by improving efficiency

5.1 Abstract

This work package assessed the potential for reducing energy demand by using more efficient plant and improved controls in refrigeration and lighting.

5.2 Introduaction

Reducing the demand for energy in food retail outlets and distribution centres could increase the potential contribution of solar energy. The stakeholders during interviews, meetings and questionnaires completed for work package 2 provided information on programmes currently underway or planned, to improve energy efficiency. Energy consumption in supermarkets can vary widely depending on the store size, the type of refrigeration and lighting equipment used, services offered (dry cleaning, bakery) and the balance between the refrigerated and 'dry' goods areas. Typical figures for electrical and gas energy use and the apportionment of the electrical energy to the main energy consuming processes and equipment is given in Table 11. It can be seen that the major energy consuming processes are refrigeration, lighting, and HVAC (Heating Ventilation and Air Conditioning).

Refrigeration systems have been steadily improved in recent years and efficiencies for both components and systems have increased. Some of the measures introduced by some supermarket chains in recent years to improve energy efficiency are:

- Detailed energy consumption monitoring of systems
- Use of night blinds - (night blinds, however, cannot be used in 24 hour opening stores).
- Use of anti sweat heaters.
- ECM (electronic commutated motors) for evaporator fans (some supermarket chains)
- Installation of wier plates on cabinet shelves
- Redesign of refrigeration cases
- Variable speed compressors
- Floating condensing pressure and trials with floating evaporating pressure
- Heat reclaim from the refrigeration system to supply hot water.
- Reclaim of refrigerated display case cooling air overspill from the front of the case and use it to cool store (Tesco).
- Use of scroll compressors
- Application of CHP systems.

Table 11: Typical electricity and gas energy use in supermarkets

Electrical Energy	800-1200 kWh/m^2
Gas Energy	200 kWh/m^2
Energy Consumption in Supermarkets	
Refrigeration Energy	40% to 50%
HVAC Energy	20% to 30%
Lighting	15% to 25%
Hot water	1% to 3%
Other (Bakery, dry cleaners, rotisserie	10% to 15%
Energy Consumption for Refrigeration in Supermarkets	
Compressors	55% to 60%
Cabinets (fans and lights)	25%
Condensers	10%
Defrost and anti-sweat heaters	10%

Lighting systems have also seen steady development in recent years and lighting fixture efficiencies have increased. Different control strategies are also being used to switch off unnecessary lighting when not needed. From work package 2, the main energy efficient measures that have been introduced into supermarket lighting systems are as follows:

- Installation of energy efficient bulbs where ever possible; replacement of old fluorescent tubes with T5 bulbs with new electrical ballasts. One supermarket chain has introduced T2 bulbs.
- Automatic control of lighting system in back room areas using PIR.
- Daylight linked controls which control lighting fixtures using dimmable electrical ballasts.
- Reduction of display lighting levels
- One supermarket chain has reduced lighting levels at night in a 24 hour opening store by 60% at night.
- Reduction of design lighting levels in the sales area.
- Piloting LED lighting systems for refrigerated display cabinets.

To assess and compare the energy that a supermarket could save by adopting refrigeration and lighting energy conservation measures, the energy that could be saved in a 1700 m^2 urban supermarket in the South of England by reducing energy consumption by a certain percentage was determined and shown in Table 12.

It can be seen that by reducing energy consumption of refrigeration and lighting by 10% the supermarket will be able to save more than 100 kWh and around 38 kg of CO_2 per m^2 sales area. A comparison of energy conservation measures with renewable energy is considered in Work Package 6.

Table 12: Effect of reducing refrigeration system energy consumption on energy and CO_2 emissions savings

% Reduction in refrigeration and lighting system energy consumption	Annual supermarket energy savings from refrigeration (MWh)	Annual supermarket energy savings from lighting (MWh)	Total savings (MWh)	Annual supermarket energy savings (KWh/m^2)	CO_2 Savings (tonnes CO_2)	CO_2 Savings (kg CO_2/m^2)
0.5	6.7	3.2	9.9	5.8	4.3	2.6
1	13.1	6.4	19.5	11.5	8.4	4.9
2	26.2	12.8	39.0	22.9	16.8	9.9
5	65.5	32.1	97.6	57.4	42.0	24.7
10	131.0	64.2	195.2	114.8	63.9	37.6
15	196.5	96.3	292.8	172.2	125.9	74.1
20	262.1	128.4	390.5	229.7	167.9	98.8

Objective 06: Comparison of alternative strategies for the next 5-10 years

6.1 Abstract

In this work package the results of the previous work packages are reviewed and the economic viability of alternative renewable technologies is evaluated and compared with energy conservation measures.

6.2 System Costs

The cost of the various renewable energy technologies considered in Work Packages 3 and 4 were calculated per unit of energy generated or saved. This was done by dividing the installed cost of each technology by the annual energy generated or saved over one year. The results are shown in Figure 1.

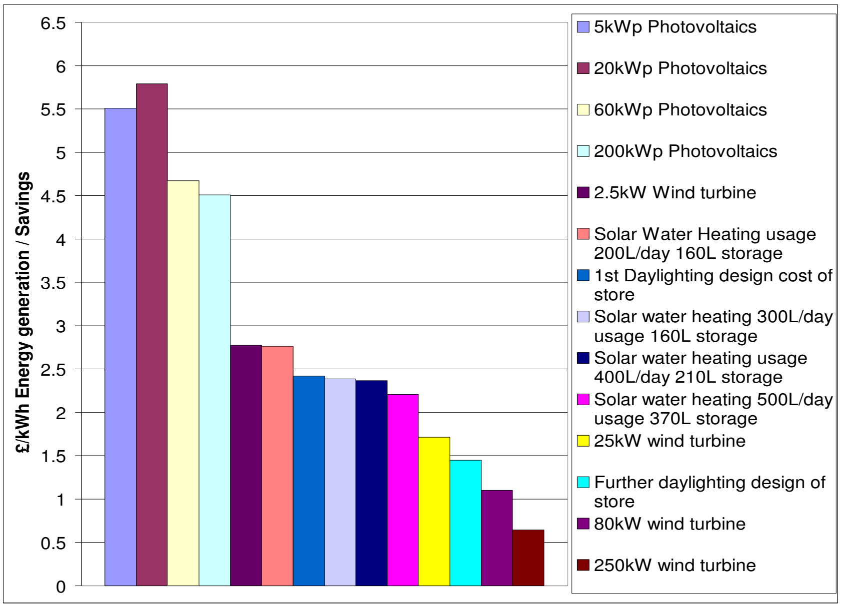

Figure 1: Cost comparison of each technology per kWh of annual energy output or savings

It can be seen that from the technologies considered, large wind turbines offer the lowest cost per kWh delivered whereas PVs offer the highest cost. Designing a store to incorporate daylighting is shown to be the most cost effective method for direct solar capture and use. The cost of the design of the first store will be high but the cost will reduce significantly with replication of the design.

6.3 Payback period of renewable technologies

Based on the costs in Figure 1, the payback period of some of the technologies has been determined and plotted in Figure 2 for a range of annual fuel price increases. It can be seen that for a 3% annual electricity price increase, the payback period of a 20 kWp PV array will be around 65 years, reducing to 30 years for an annual increase of 10%. The payback period for a 80 kWp wind turbine will be around 13 years for a 3% annual electricity price increase and 10 years for a 10% increase. The payback period for a daylighting system will reduce from around 18 years down to 10 years if the annual electricity price increase rises from 3% to 10%.

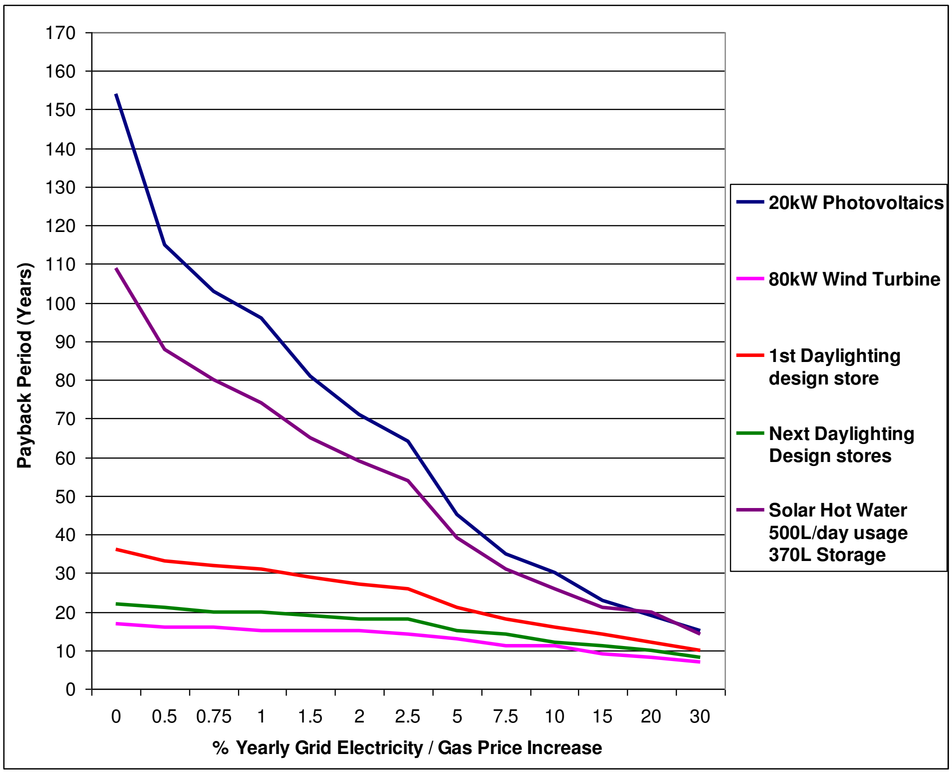

Figure 2: Payback period of renewable energy technologies in a supermarket for varying fuel energy price increases

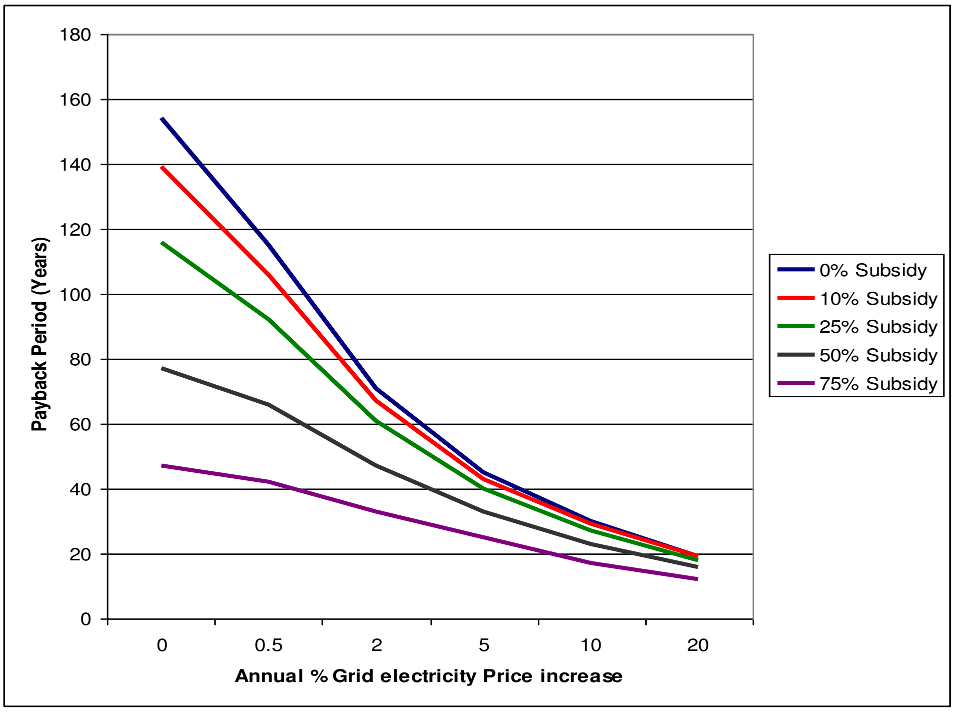

Figure 3: Payback period of a 20 kWp PV array for varying fuel energy price increases and levels of subsidy

Figure 3 shows the payback period for a 20 kWp PV array for different rates of annual electricity price increase and different levels of subsidy (government grant). It can be seen that for a 50% subsidy and a 3% annual price increase, the payback period for the array will be around 40 years, reducing to around 20 years for a 10% annual electricity price increase. Figure 4 shows the impact of future increases in PV efficiency on the payback period of the 20 kWp PV array. An array with an efficiency of 30% will have a payback period of 40 years if the annual electricity price increase is 3% and 20 years if the electricity price increase is 10%. Any government grants will reduce the payback periods further.

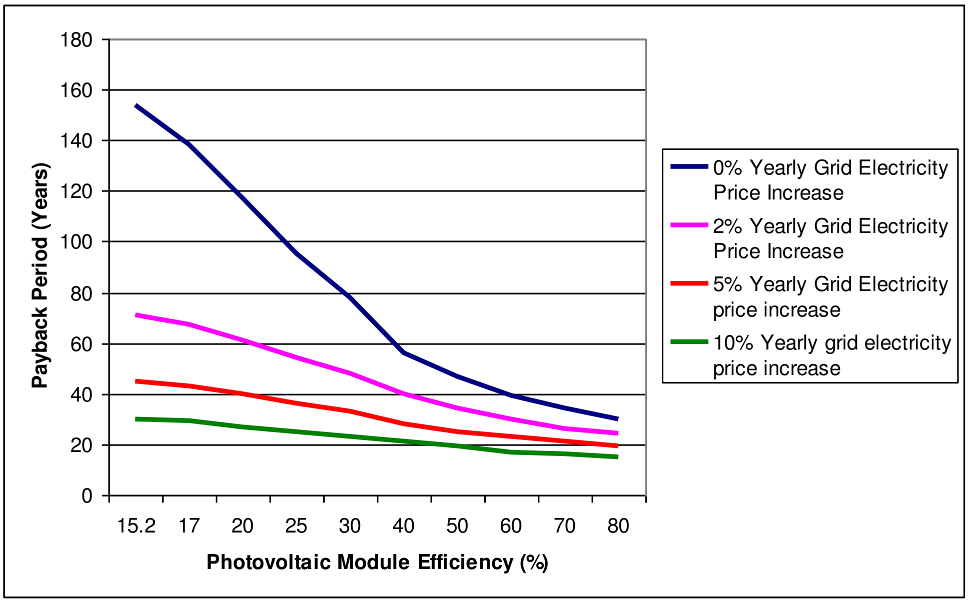

Figure 4: Payback period of a 20 kWp PV array for varying efficiencies and grid electricity price increases

6.4 Comparison of renewable and energy conservation technologies for different ranges of energy savings

To summarise the results of comparisons of the different renewable and energy conservation technologies all technologies were applied to one supermarket. Because of the large range of annual energy savings that the different technologies could provide, the results are presented in three bar charts each for a different range of annual energy savings, 0-10 MWh, 10-100 MWh, and 100-500 MWh. The three bar charts are presented in Figures A1 to A3 in Appendix A.

Figure A1 shows that a 5 kWp photovoltaic array will produce similar energy savings as a 2 m^2 solar thermal collector and a 0.5% increase in lighting efficiency. The increase in lighting efficiency will be by far the easiest to achieve by installing energy efficient bulbs or simply switching lights off when not needed. Figure A2 indicates that a 20 kWp photovoltaic array will produce similar energy savings as those produced by increasing lighting efficiency by 2% or increasing refrigeration efficiency by 1%. Again, the efficiency measures will be much cheaper and easier to achieve than the installation of a photovoltaic array. A 25 kWp wind turbine will generate similar annual electricity savings as a 60 kWp photovoltaic array, at roughly 1/6th of the cost. From Figure A3, a 80 kWp wind turbine will produce similar energy savings as a 10% improvement in refrigeration efficiency or a 20% increase in lighting efficiency.

6.4 Comparison of solar PV and wind for application at a regional distribution centre

To compare the potential energy savings from the application of PV and wind energy to regional distribution centres (RDCs), a distribution centre in the South of England was considered. It was assumed that the PVs and the wind turbine will have a capacity of 600 kWp and would be used to reduce maximum demand. The monthly electrical energy consumption of the distribution centre is shown in Figure 5. It can be seen the electrical energy demand of the RDC is fairly constant throughout the year, rising slightly in the summer months due to the higher ambient temperatures. The maximum variation between summer and winter is around 16%. The monthly energy generation of the PV array and wind turbine and their potential percentage contribution to the total electrical energy demand of the RDC are shown in Figure 6. It can be seen that the output of the PV peaks in the summer months and the output of the wind turbine peaks in the winter months. If the PV technology is used on its own it will be able to contribute 2% of the electrical energy demand of the RDC in the winter months, rising to 8% between April and September. The wind turbine will contribute 4% in the summer months rising to 10% in the winter. If the two technologies are used together they will be able to satisfy between 12% and 16% of the electrical energy requirements of the RDC throughout the year.

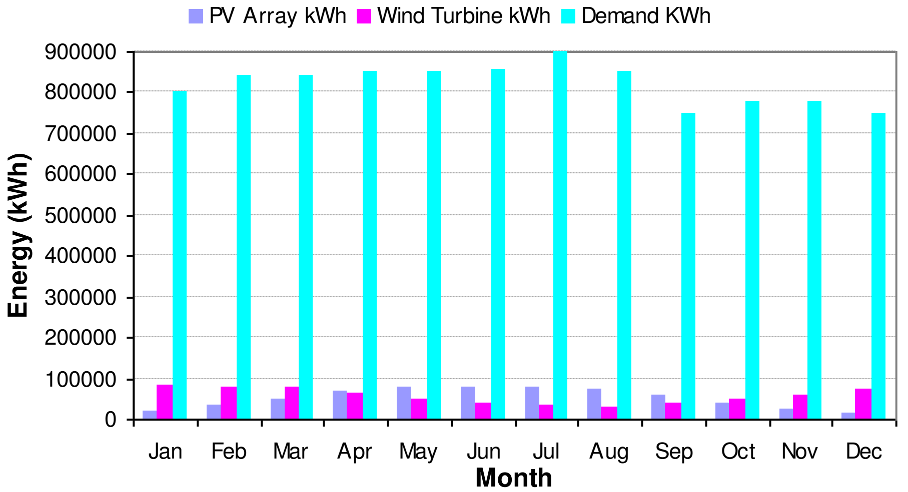

Figure 5: Monthly RDC energy demand and energy output from PV and wind turbine

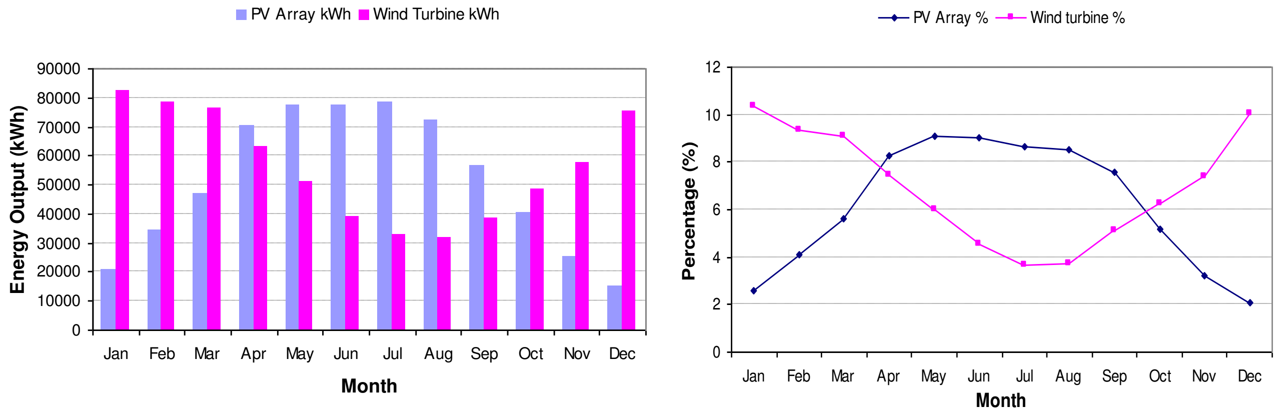

Figure 5: Monthly energy output from PV array and wind turbine and percentage contribution to monthly energy demand

Table 13 compares the life cycle cost and cost of the electrical energy that will be generated by the two technologies, assuming a lifetime of 30 years for each case. It can be seen that the annual owning and operating cost of the PV will be 3 times higher than the cost of the wind turbine. The cost of electricity generated was calculated to be £0.22/KWh for the PV and £0.036/KWh for the wind turbine. The literature review indicated that the cost of PV will reduce and their efficiency increase much faster than those of wind turbines. This will lead to a narrowing of the life cycle cost difference and the unit cost of electricity generated by the two technologies in the future.

Table 13: Cost analysis of PV and Wind Turbine for application to a RDC

Item cost	Solar	Wind
Life Cycle Cost	1,766,952	483,948
Annualised Life Cycle Cost	134,389	43,009
Annual Energy Output (AEO) kWh	603,943	1,193,328
Cost (£) / kWh	0.223	0.036

Objective 07: Opportunities for using solar energy in refrigerated food distribution

7.1 Abstract

In this work package a review of food transport refrigeration was carried out and the possibilities of using solar energy to reduce refrigeration energy consumption and emissions were considered.

7.2 Introduction

The contribution of food transport to the UK's greenhouse gas emissions is estimated to be 1.8% [19]. European and British regulations set general requirements as regards the storage and transport of perishable foodstuffs. Chilled products are usually transported at temperatures in the range 0°C to 7°C whereas frozen products require temperatures between -10 °C and -25°C. To protect perishable products during land transportation, mobile vapour compression refrigeration units are usually installed on transport vehicles. Most of these units are driven by a diesel engine, resulting in greenhouse gas emissions and noise. To study the potential of using PV to drive on-board refrigeration systems, a spreadsheet model was developed and a number of scenarios and design approaches were investigated: long haul operations (the vehicle is used continuously and spends most of the time on the road); long hours and deliveries (the vehicle is intensively used for long delivery rounds - long distances between delivery points); delivery rounds (the vehicle is used for relatively short delivery rounds) and short deliveries (the vehicle is only used for short delivery rounds). For each of these cases, two types of load (chilled and frozen) and two types of vehicle (articulated and rigid) were considered. The results of the analysis are detailed in Table 14.

Table 14: Application of PVs to refrigerated transport

Type of vehicle	Articulated vehicle								18-tonnes rigid vehicle							
Type of cargo	Chilled				Frozen				Chilled				Frozen			
Scenario	Long haul operations	Long hours and deliveries	Delivery rounds	Short deliveries	Long haul operations	Long hours and deliveries	Delivery rounds	Short deliveries	Long haul operations	Long hours and deliveries	Delivery rounds	Short deliveries	Long haul operations	Long hours and deliveries	Delivery rounds	Short deliveries
Total daily thermal load (kWh) Typical day with a 10°C ambient temperature	39	29	22	9	42	68	60	19	18	17	14	5	23	51	49	13
Total annual electrical load (kWh)	13500	10100	6800	3700	27200	42300	36000	12800	7200	6700	4700	2400	15400	32700	29800	9000
Yearly number of days with a positive balance (solar power in excess in respect to energy requirements)	0	0	49	163	0	0	0	0	0	0	13	115	0	0	0	0
Yearly solar fraction (%)	**31**	**41**	**61**	**100**	**15**	**10**	**11**	**32**	**28**	**30**	**43**	**86**	**13**	**6**	**7**	**23**

Under the considered assumptions, the only case for which the output from a PV array on the roof of the vehicle will be sufficient to power the refrigeration unit successfully throughout the year to satisfy 100% of the load is the "short deliveries" of chilled products using a semi-trailer. For all other chilled food transport scenarios the PV will be able to cove between 30% and 86% of the refrigerated vehicle's cooling load. For frozen food transport the PV will be able to cover between 6% and 35% of the cooling load. IN both cases hybrid systems will be required to satisfy annual cooling load demand.

7. Conclusions

This project considered the application of solar and other renewable energy technologies to the food distribution and retail industry. The main results of the study are summarised below.

- The food industry is well informed of the potential contribution of solar and other renewable energy technologies such as wind to energy conservation and reduction of greenhouse gas emissions.
- The main barriers to the application of renewable energy technologies in the food industry is the high capital cost of these technologies and their very long payback periods. PVs have much longer payback periods than wind turbines and also suffer from larger space requirements for their installation.
- Out of town supermarkets, petrol station forecourts and distribution centres have sufficient roof surface area for the installation of PVs to satisfy, on average, 5% of their electrical energy requirements.
- Analysis using a case study in a retail store employing design features for the utilisation of direct solar energy in the form of daylighting has shown that there is significant potential to reduce energy consumption. Main barriers to the wider application of daylighting is that it can only be applied to new stores or stores undergoing extensive refurbishment, the requirement to satisfy the new building regulations in terms of the overall thermal performance of the building fabric, the high cost of design and implementation in the first store, and the requirement to have consistent levels of illumination on certain types of food and non food products. Integration of daylighting with artificial lighting should be able to satisfy both energy and merchandising requirements at acceptable additional capital cost.
- Comparison of renewable energy technologies with energy conservation measures in retail food stores has shown that for current energy prices and government legislation, reduction of the energy consumption of refrigeration equipment and of artificial lighting are much more economically attractive than the application of renewable energy technologies. However, as the potential to increase further refrigeration and lighting efficiency at acceptable cost reduces, further reduction of the carbon footprint of supermarkets and other food facilities would only be achieved through: better integration and control of current technologies; technological developments and radical approaches in merchandising, and, the improvement of the performance of renewable technologies and their optimum integration within the building structure and with other conventional technologies.
- Comparison of the feasibility of application of PVs and a wind turbine, both of a 600 kWp electrical generation capacity, to a regional distribution centre has shown that over the lifetime of the investment the wind turbine will offer much lower electrical energy unit costs than PV. The generation capacity of the two technologies will vary out of face during the season and their use in combination will enable steady electrical energy generation throughout the year.
- Analysis has shown that it is feasible to use PVs to power the refrigeration systems of food distribution vehicles. The main drawback is the additional weight (1000-1500 kg) that will be added to the vehicle by the solar array and the storage device (batteries or phase change materials). The use of PV systems will be more suitable for vehicles with relatively low refrigeration requirements, for example, vehicles used for the distribution of chilled foods and for short journeys. For the transport of frozen foods that require higher refrigeration power requirements, hybrid systems (diesel/solar) could be considered. The use of solar energy becomes more effective as the refrigeration power requirements are reduced. Within the requirements of the ATP agreement this can be achieved through the use of vacuum insulation.
- A number of alternative approaches that have potential to reduce energy consumption in refrigerated food distribution have been identified, such as the use of the heat from the engine and the exhaust gases to power thermally driven refrigeration systems and integration of conventional and thermally driven refrigeration technologies with solar energy and thermal storage. More work is required to assess the potential, life cycle cost and environmental impacts and research and development needs to bring the most promising of these technologies to the market.

The project has identified a number of areas where further research and development is required to enable the wider adoption of renewable energy technologies in the food retail and distribution sectors.

- *Daylighting*: Design of supermarkets to maximise the use of daylighting at minimum capital cost. Issues to be considered include minimum acceptable lighting levels at different times of the day and optimum integration and control of natural and artificial lighting to continuously minimise energy consumption.
- Research into the application of transparent PV modules to appropriately oriented supermarket facades to replace conventional glazing. Research should include impact on reduction of structural costs over conventional roof mounted PVs and impact on daylighting.
- Investigation of approaches for integrated thermal management and real time intelligent control and diagnostics in supermarkets to optimise system operation and minimise emissions in real time.
- Evaluation and integration of renewables such as solar, wind, biomass and other low carbon technologies such as CHP, tri-generation, ground source heat pumps, within the context of overall thermal energy and environmental control of food facilities.
- Research into the reduction of thermal loads in refrigerated vehicles and alternative approaches to provide on-board refrigeration (sorption systems, PVs with thermal storage and all electric systems charged overnight using renewable energy at the regional distribution centre).

APPENDIX A.

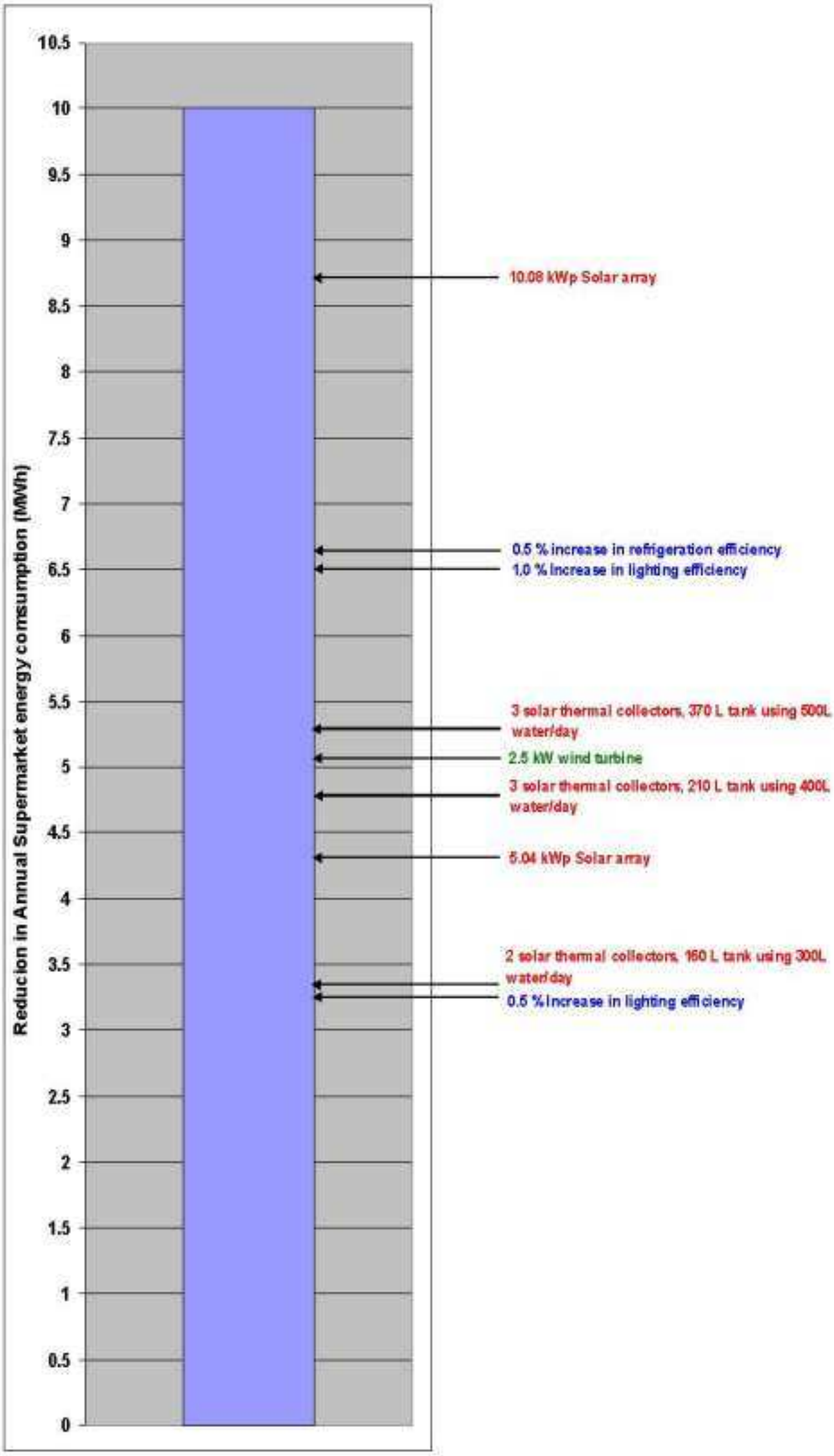

Figure A1: Comparison of supermarket energy saving contributions from solar capture technologies, alternative renewable energy technologies and energy efficiency measures for a range 0 - 10 MWh annual energy savings

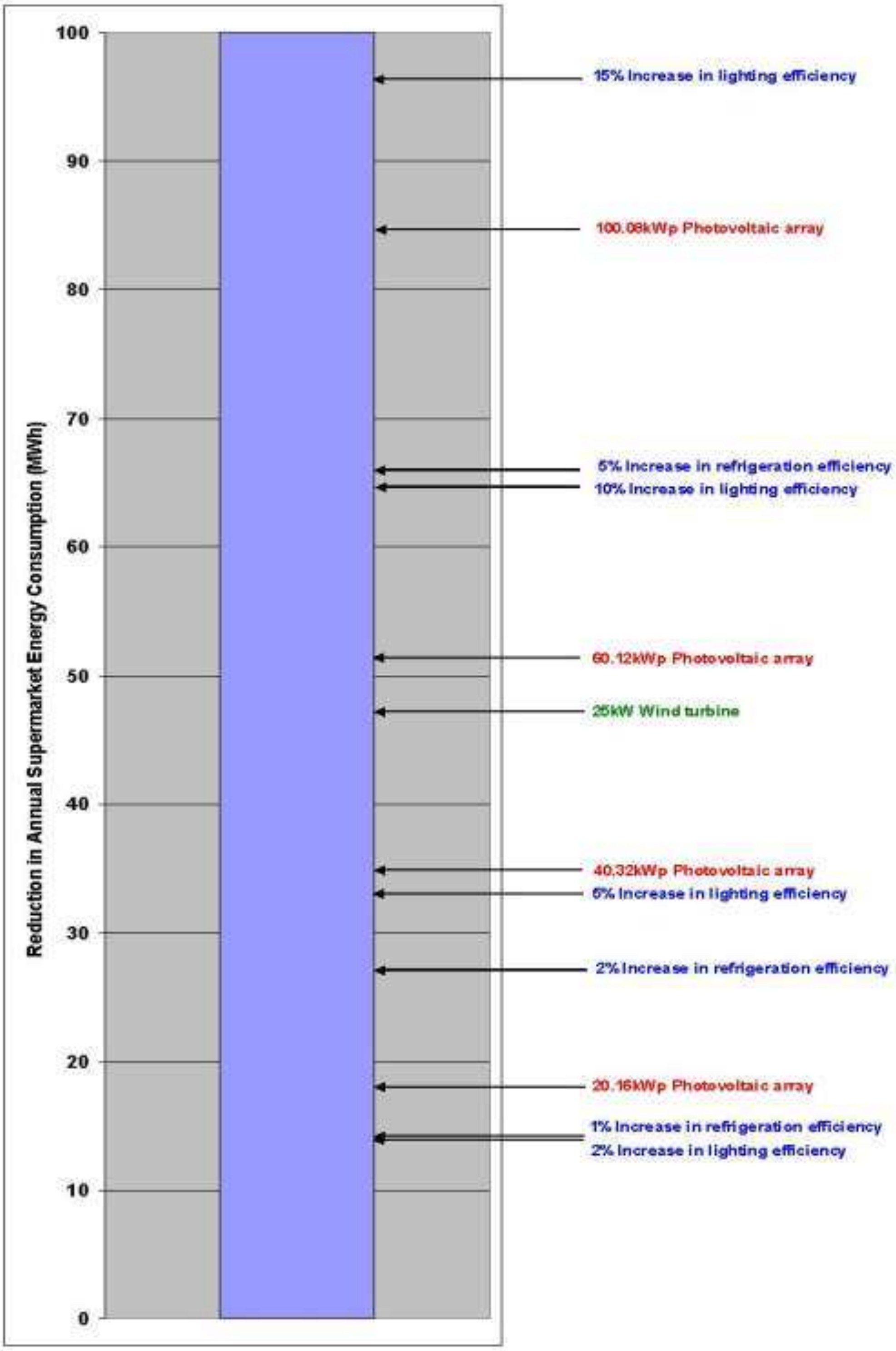

Figure A2: Comparison of supermarket energy saving contributions from solar capture technologies, alternative renewable energy technologies and energy efficiency measures for a range 10 - 100 MWh annual energy savings

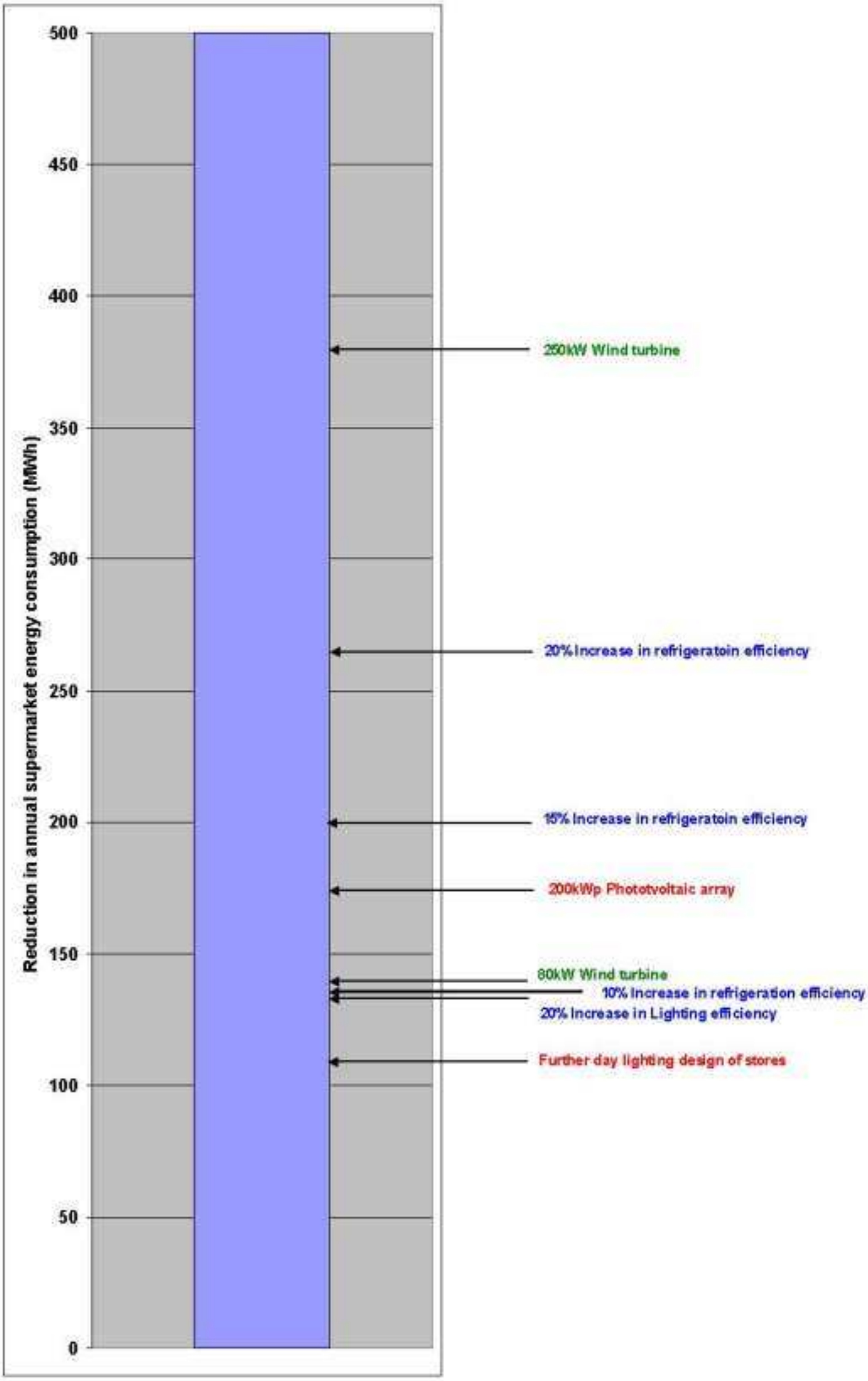

Figure A3: Comparison of supermarket energy saving contributions from solar capture technologies, alternative renewable energy technologies and energy efficiency measures for a range 100 - 500 MWh annual energy savings

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.

A number of publications are being prepared based on the work carried out in this project.

[1] S. A. Tassou, G. Delille, J. Shilliday. Feasibility of the Use of Solar Energy for Food Transport Refrigeration, Paper to be presented at the 22ND IIR International Congres of Refrigeration, August 21-26 2007, Beijing, China.
[2] S. A. Tassou, G. Delille, J. Shilliday. Renewable energy technologies and their potential for application to UK Regional Food Distribution Centres. To be submitted for publication, Journal of Applied Thermal Engineering (April 2007).
[3] S. A. Tassou, J. Shilliday, R. Watkins. Application of renewable energy technologies and energy conservation in the UK food retail industry. To be submitted for publication, Proceedings of the IMechE, Part E, Journal of process Mechanical Engineering (May 2007)

References used in report

[1] International Energy Agency (IEA). *TRENDS IN PHOTOVOLTAIC APPLICATIONS – Survey report of selected IEA countries between 1992 and 2004*, 2005 (available online, http://www.iea-pvps.org/products/rep1_14.htm).
[2] RW Miles, KM Hynes, I Forbes. *Photovoltaic solar cells : An overview of state-of-the-art cell development and environmental issues*, Progress in Crystal Growth and Characterization of Materials, Volume 51, Issue 1-3, 1 January 2005, Pages 1-42
[3] EurObserv'ER. *Photovoltaic energy barometer – 1793.5MW installed in European Union*, Systèmes solaires n°172 (April 2006) (available online, http://www.energies-renouvelables.org/observ-er/stat_baro/observ/baro172.pdf).
[4] http://portal.est.org.uk/
[2] RW Miles, KM Hynes, I Forbes. Photovoltaic solar cells : An overview of state-of-the-art cell development and environmental issues, Progress in Crystal Growth and Characterization of Materials, Volume 51, Issue 1-3, 1 January 2005, Pages 1-42 (available online, http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6TJB-4HNS67R-1-6&_cdi=5306&_user=545641&_orig=search&_coverDate=12%2F31%2F2005&_qd=1&_sk=999489998&view=c&_alid=440757024&_rdoc=1&wchp=dGLzVlz-zSkWz&md5=6bcc413335d87050b812bbe442673772&ie=/sdarticle.pdf).
[5] Olivia Mah, Fundamentals of Photovoltaic Materials, December 1998 (available online, http://www.solar-works.com/sos/fundamentalsofphotovoltaicmaterials.pdf#search=%22Olivia%20Mah%2C%20Fundamentals%20of%20Photovoltaic%20Materials%22).
[6] EPIA ROADMAP (European Photovoltaic Industry Association), 2004 (available online http://www.epia.org/documents/Roadmap_EPIA.pdf#search=%22EPIA%20ROADMAP%22).
[7] Green, K Emery, DL King, S Igari, W Warta. Solar Cell Efficiency Tables (Version 25), Progress in Photovoltaics: Research and Applications, Volume 13, Issue 1, Pages 49 – 54, 2005
[8] http://www.spectrolab.com
[9] Potential for Microgeneration Study and Analysis – Final report, November 2005.
[10] Solar Heat Worldwide, IEA Solar heating & cooling programme, http://www.iea-shc.org/welcome/IEASHCSolarHeating
[11] European Renewable Energy Council (EREC), Renewable Energy in Europe; Building Markets and Capacity, James & James, London 2004, 244 pgs.
[12] http://www.bwea.com/energy/europe.html
[13] European Commission. Energy for the future: Renewable sources of energy, white paper for a community strategy and action plan, COM(97)599 final 26/11/1997, http:/europa.eu.int/comm./energy/library/599fi_en.pdf.
[14] Directive 2001/77/EC of the European Parliament and of the Council of the 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market, Official Journal L 283. 27/10/2001 P. 0033-0040, http:europa.eu.int/eur-lex/pri/en/oj/dat/2001/1_28320011027en00330040.pdf.
[15] Gallagher, D. G. Development of a small-scale biomass CP system. Final report, DTI publication, URN 02/681, UK,
[16] How Green is your Supermarket? A guide for best practice, Norman Baker MP, March 2004
[17] http://www.ukpia.com/faqs/petrol_retailing.aspx
[18] http://www.csdf.org.uk/
[19] UKCERK. *Catering Policy* (available online, http://www.ukerc.ac.uk/component/option,com_docman/task,doc_download/gid,235).