How and to what extent can the use of solar and waste heat recovery technologies in industrial premises decarbonise the economy of an industrialised nation?

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Abstract

This paper investigates the potential of waste heat recovery and solar technologies in decarbonising UK industry. Currently, waste heat recovery is more commonly used in energy intensive processes. However, lower grade heat from less energy intensive industries can be utilised. These technologies include heat pumps, Organic Rankine Cycle and the Kalina cycle. For example, a Lime Plant in Thrislington uses the Organic Rankine Cycle to produce electricity from waste heat (Lhoist, 2015) reducing CO_2 emissions by 1,600 tonnes/yr (Heatcatcher, 2014). The challenge with waste heat recovery is matching the grade of heat with the most suitable heat recovery technology and appropriate heat sink. Industrial implementation of waste heat recovery is limited by economic and technological factors. Waste heat recovery can assist in the move towards a low carbon economy, but to encourage industrial uptake greater government support and legislation is required. Solar also has a key role to play. There has been a continued growth of solar technology in the UK, particularly solar photovoltaics (solar PV). The introduction of the feed-in tariff (FiT) has been a key driving force in the growth of solar PV. However, uptake of solar PV in industry is low; at present, only 5% of solar PV installations are installed on commercial and industrial roofs (STA, 2015). There is potentially sufficient industrial and commercial roof space in the UK to install 3.44 TW of solar PV, which could produce 8.8 times more electricity than required annually by the UK. Energy storage is required to maximise the benefits of waste heat recovery and solar technologies. Different solutions include phase change materials and cryogenic energy storage. However, the main issues with electrical and thermal energy stores are space, cost and life time. Wolseley UK's National Distribution Centre (NDC) has a 2MW solar PV array that is used as a case study in this report. Analysis of import, export and generation meter readings identify that solar PV generation is meeting 27% of Wolseley's annual electricity demand, saving 854466kg/yr of $CO_{2e.}$ A significant amount of electricity is also exported. Daily and seasonal battery storage is suggested as a method to reduce export, with the required size of the battery identified alongside a required price point. The inverters also vent waste heat which is ducted into Wolseley's air handling units, improving the efficiency of the solar PV system while reducing heating requirements. Solar and waste heat can work individually or be combined to reduce the energy demand of industry. Their versatility and scalability make them suitable for many different industries. However, to ensure maximum carbon and energy reduction, efficiency of the industrial processes must first be maximised. Furthermore, it is important that the most suitable waste heat recovery and / or solar technology is installed.

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Glossary

- CO_2: Carbon dioxide
- CO_{2e}: Carbon dioxide equivalent
- CoP: Co-efficient of Performance
- DNO: Distribution Network Operator
- EAF: Electric arc furnace
- FiT: Feed-in tariff
- GHG: Greenhouse gases
- GW: Gigawatt
- kW: Kilowatt
- MCS: Microgeneration Certification Scheme
- MW: Megawatt
- NDC: National Distribution centre
- Solar PV: Solar photovoltaics
- TW: Terawatt

Introduction

Industrial energy consumption is becoming a growing concern. Much of the energy used to power industries comes from fossil fuels which are not a finite resource. They also pollute our environment and contribute to global warming. Therefore, reducing industrial demand for electricity and heat can contribute to industry becoming more sustainable and reducing its environmental impact. This dissertation looks to identify the potential contribution solar and waste heat recovery technologies can make in decarbonising industrial premises and operations within an industrialised country.

Globally, improvements in industrial energy efficiency have been made; yet, as a result of escalating production, energy use by industry is increasing and is expected to continue increasing (UNIDO, 2010). Increased economic growth is driven, in part, by a growing population which supplies workers and consumers (Berry, 2014). The global population currently exceeds 7 billion and, if the current growth rate continues, will reach 8.1 billion during 2015 and 9.6 billion in 2050 (UN, 2014). Therefore, unless significant action is taken, industrial energy consumption will continue to increase, driven by the requirements of a growing population.

The current consumption of fossil fuels that power our economies is not sustainable. Fossil fuel reserves are not finite and will eventually run out. There is some debate over when global supplies will peak and start to decline. Shafiee and Topal (2009), for example, estimate that the depletion dates for oil, coal and gas are 2045, 2116, and 2047 respectively. However, as technology develops and the cost of fuel rises, it will become more economically and technologically viable to access reserves that could not be utilised previously (Mueller, 2013). While this will further prolong the lifetime of the supply, it merely delays the inevitable.

In 2013 there was a 2.3% increase in global primary energy consumption with coal (the fastest growing fossil fuel), oil and gas accounting for 86.7% of the primary energy consumption (BP, 2014). This reliance on fossil fuel to power the national and global economies has resulted in a 40% increase of atmospheric CO_2 compared with pre-industrial revolution levels (HM Government, 2011). The anthropogenic driven increase in atmospheric CO2 is causing global climate change. Even if emissions stopped, the atmospheric CO_2 concentration would potentially be irreversible for 1,000 years (Solomon et al., 2009). The longer energy consumption is allowed to increase, the more difficult it will become to manage.

It is in all organisations’ best interests to consider how the potential impacts of climate change can affect the future success of their operations. Every industry has its own unique set of environmental requirements and will therefore be affected by climate change in a different way. Agroindustries, for example, are vulnerable to changes in rainfall and extreme weather events (Moreno and Skea, 2011). In today's society there is a strong interrelation between industries across the globe; therefore, environmental impacts that affect one organisation can be expected to ripple through the global network causing a variety of indirect impacts. Organisations that rely on energy, water and agriculture are expected to be particularly vulnerable (Moreno and Skea, 2011). However, the global industrial network is large and complex, making it difficult to predict the scale and diversity of the potential consequences.

Price volatility and security of supply are serious concerns for industry. The volatility of oil prices is becoming increasingly more sensitive, affected by war, extreme weather, stock market and OPEC production quota decisions (Ji and Guo, 2015). In 2006 the total fossil fuel reserves were 934 gigatonnes of oil equivalent, of which 389 gigatonnes of oil equivalent were located in the Middle East and Russia (Shafiee and Topal, 2009). It is therefore understandable that the current tension between Russia and the developed West, periods of war in different regions of the Middle East, and the recent issues with the global economy have highlighted the need for industry to reduce reliance on imported fossil fuels.

Despite the economic and environmental benefits of energy reduction, organisations can be reluctant to adopt new technologies and processes. Barriers include lack of knowledge, lack of resources and an unwillingness to make significant changes to a process that is working and profitable. In these instances, government legislation can be a significant catalyst in motivating companies to start working towards more sustainable and energy-efficient business practices. For instance, the EU Emissions Trading System (EU ETS) applies to an excess of 11,000 power stations and industrial plants in 31 European countries with the aim of cost effectively reducing industrial greenhouse gas (GHG) emissions (EC, 2015). However, this policy only applies to energy intensive industries like metal production and power stations, which equates to only 45% of EU emissions (EC, 2015). While there are a range of policies and regulations in place at different levels of government, from the EU down to regional level, there remains significant scope for governments to further encourage an industrial shift towards energy efficiency and sustainability, through legislation and financial support.

Attitudes towards adopting sustainable, less energy intensive processes within organisations are improving. The economic and environmental benefits, alongside the need to stabilise and protect the long term viability of business, are powerful drivers, especially when supported by government policy. Furthermore, consumer attitudes also play a part. Consumers are becoming more environmentally conscious, questioning the sustainability of the processes that produce the goods they require / desire (Roberts and Bacon, 1997). Therefore, adopting sustainable working practices can be utilised in the marketing of a company and its products.

Once energy efficiency improvements have been made to a process, minimising energy losses and reducing consumption as far as is technically and economically feasible, additional steps need to be considered to identify further energy reduction measures. There are numerous approaches that organisations can take to further decrease their energy consumption and reliance on importing energy. Hydro-power, for example, is already widely used in applications with very high electricity demand, like aluminium manufacturing (Hydro, 2014). However, some technologies like hydro and wind power are limited by location. The reason waste heat recovery and solar technology have been chosen as the focus of this paper is that they are less limited by location and their versatility and scalability gives them the potential to significantly contribute to decarbonising UK industry.

Most processes generate waste heat; therefore, the idea of using waste heat applies to most industrial scenarios. Even if it is low grade, it is often better to capture and re-use waste heat than let it escape. The challenge is identifying how to economically and effectively transport waste heat from its source to a location where it can be utilised. Capturing waste heat in some scenarios simply will not be economical. In Finland, for example, 19 TWh/a of waste heat could, technically, be utilised; however, only 4.5 TWh/a could be recovered economically (Suomalainen and Hyytia, 2014). In comparison, 5 to 28 TWh/yr of waste heat could be recovered in the UK, depending on the financial rate of return and an industry willingness to develop (Element Energy, 2014). With 73% of UK industrial energy demand being for heating (Element Energy, 2014), reducing energy consumption through utilisation of waste heat has the potential to significantly reduce the UK's industrial carbon emissions.

It is recognised that renewable technology also has a key role to play in reducing fossil fuel consumption and GHG emissions in industry. Over the past decade there has been significant growth in the renewable energy sector. In 2013 renewables reached 2.7% of global energy consumption compared with 0.8% in 2003 (BP, 2014). Furthermore, during 2012 in Europe 22.3% of primary energy production came from renewable energy with Germany being the largest producer; wind and solar energy output in particular expanded rapidly (EC, 2015). There is a range of renewable energy generating technologies. Each technology has its advantages and disadvantages and it is important that, when considering commercial viability of a renewable technology, its technical suitability is carefully considered. Poor choice of technology and / or poor design can result in under-performance and inadequate payback.

Of the different renewable technologies available, solar (predominantly solar PV) has been selected for this project as it is particularly versatile and reliable when compared with other renewable generating technologies. Furthermore, the current UK government is looking to increase the number of large scale roof top mounted solar arrays. However, for this to occur, industries need the reassurance that solar is a genuinely viable option for their business operations. Solar PV also has the additional advantage of being relatively easy to install, and is scalable, allowing it to be designed and incorporated into a range of different operational processes.

Currently, much of the focus of industrial efficiency is on power generation and energy intensive manufacturing processes. This is logical, as this is where the largest and easiest savings can be made. However, the more technically and economically challenging industrial processes should receive due attention as the move towards industrial sustainability develops. For example, despite being instrumental to the industry, the warehousing and logistics sector is often overlooked (apart from transport). The UK Warehousing Association (2015) estimates that the logistics sector is worth more than £93 billion to the UK economy and employees constitute 8.3% of the UK workforce. Their current 700 members have a total of 2,000 depots equating to 10 million square metres (UK Warehousing Association, 2015).

The logistics and warehousing sectors are instrumental to the manufacturing process and are involved from the beginning through to the end of the chain. They store, organise and transport goods, all of which has a significant environmental impact. The logistics industry is in a good position to lead by example. Warehousing and logistics act as the "link" between each product stage; the sector is therefore well placed to work with different organisations at local, national and international level and share ideas on how to improve efficiency.

There is clearly a significant potential for industry globally and in the UK to reduce carbon based emissions and move towards more sustainable operational processes. A literature review has been carried out to identify the different grades of waste heat available and the technology that can be used to capture it. A review of solar technology (focusing on solar PV) is also carried out to identify the level of uptake of medium to large scale solar PV in the UK and its potential. Barriers and benefits of waste heat and solar are also identified. Furthermore, industrial examples are drawn on to identify their potential in reducing carbon emissions. Energy storage is also reviewed for both technologies as this is the next step in industry being able to maximise the benefits of adopting waste heat recovery and solar technologies.

Data gathered from a 2MW solar PV array installed on Wolseley's NDC is used to demonstrate the impact solar PV has had on a large scale, industrial operation. The data is used to draw comparisons between predicted and actual performance, demonstrate current and future carbon saving potential and outline the financial benefits. The potential of using batteries to store surplus energy is also calculated. Furthermore, the waste heat from the inverters is ducted into the buildings' air handling units and the benefit of this has been calculated.

Overall this paper will show that solar and waste heat recovery technologies have significant potential to assist in the move towards a low carbon industry. Both technologies work well independently, but, more importantly, can also work together to effectively reduce the carbon emissions of industrial processes.

Literature Review

Industrial energy

The increasing demand for industry comes, in part, from a growing population. Based on the current population growth rate there will be approximately 2.6 billion more people in 2050 than today (UN, 2014). However, even if the global population were to stabilise, industry would continue to expand as countries develop and people's incomes increase. This is because energy extracted from fossil fuels is the cornerstone to modern human survival, economic development and social progress (Xiong et al., 2015). This reliance on fossil fuel to power the national and global economies has resulted in a 40% increase of atmospheric CO_2 compared with pre-industrial revolution levels (HM Government, 2011).

Global consumption of fossil fuel has increased by a factor of 50 since 1900, with the world's industrial production increasing greater than 100 fold (Graedel and Allenby, 2010). The production of CO_2 linked to this anthropogenic economic activity has, therefore, grown significantly, predominantly due to a rapid growth in energy consumption (Graedel and Allenby, 2010). Furthermore, this energy consumption by industry is expected to continue increasing (UNIDO, 2010). There is a clear need for industries and the countries they operate in to identify and implement more energy efficient manufacturing processes.

Kazakhstan is an example of a country that is struggling to keep its carbon emissions down. Between 2000 and 2010 its carbon emissions increased rapidly, due to industrial growth increasing the demand for energy met by fossil fuels (Xiong et al., 2015). While economic growth is important to industrialised and developing nations, this growth needs to be sustainable or the industries and the countries they operate in could face economic and environmental turmoil in the future. In order to address climate change, sustainable development strategies need to be incorporated by industries, with the support of government, to decarbonise their operational processes.

There are self-serving benefits that provide incentives to industries that can reduce their energy consumption. Primarily, energy efficiency reduces expenses, and increases productivity and competitiveness (UNIDO, 2011). Developing countries have the opportunity to grow their industries, incorporating energy efficiency into their developments as they grow. However, for established industries, adapting energy efficient technologies into their existing infrastructure can be more challenging and can include significant capital cost. However, it has been estimated that between 10% and 30% of energy consumption could be decreased without additional net costs (UNIDO, 2011). Financial savings from energy reduction can then be reinvested into other energy reduction schemes.

Industrial symbiosis is one approach some industries have taken to reduce their energy consumption, waste and associated carbon emissions. Figure 1 shows how the Xinfa group has adopted industrial sustainability, reducing their emissions by 10.84%, equal to 1.98 Mt of CO_{2e} (Yu et al., 2015). The industrial symbiosis approach is multi-dimensional, re-using waste by-products, waste heat and water. Not only does this approach reduce carbon emissions, but it reduces waste to land fill and demand on water resources, which can be scarce in some countries.

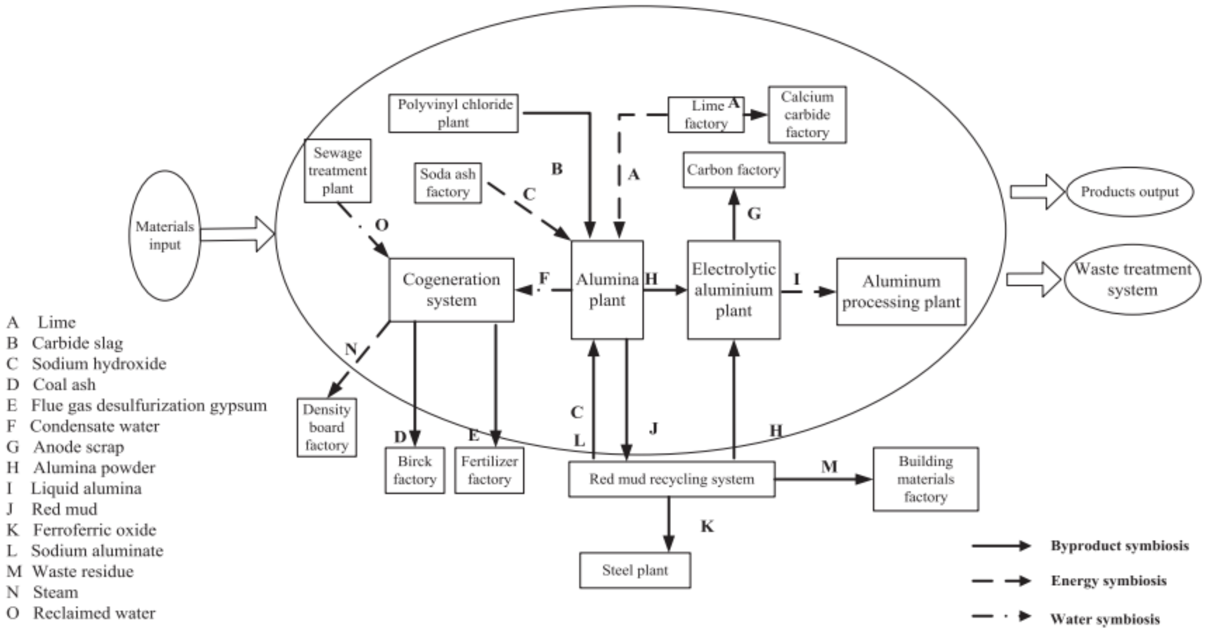

Figure 1: Industrial symbiosis network of the Xinfa Group (Yu et al., 2015)

Operating a zero carbon industry is the ultimate aim. This is difficult and potentially costly to achieve for existing industrial infrastructure. However, for new and developing industries it is achievable. SMA (a solar PV inverter manufacturer) are operating a zero carbon manufacturing facility in Germany. To achieve its zero carbon status SMA (2013) developed a purpose built manufacturing plant that incorporated the following features:

- Building envelope, compliant with the German Low Energy Building Standard
- Natural lighting design
- Smart ventilation system (to keep building cool)
- 1 GW solar PV array
- Combined heat and power plant (fuelled by bio-gas)
- Heating is piped from a renewable waste incineration plant

Any energy shortfall is imported, but it is supplied from renewable generation (SMA, 2013). What is clear from the technologies used by SMA is that a multi-lateral approach is required. In order to totally reduce carbon emissions a number of different technologies are required. The challenge is identifying which are the most suitable technologies and how they can be used together to provide the maximum benefit. For existing industries, the challenge is identifying those technologies that can be most effectively adapted into existing processes.

Waste heat recovery

Energy is required to complete work, whether used by an inanimate object or a living being. Energy will be lost if the system within which the task is being completed is not 100% efficient. This energy is commonly lost as heat. To reduce waste heat loss the system can be made more efficient and / or waste heat can be captured and re-used. By adopting these approaches industry can reduce energy costs and CO_2 emissions. The first, most cost-effective, step should always be to improve the efficiency of the heat generating process (Carbon Trust, 2015). This can be achieved by:

- identifying areas of inefficiency and heat loss
- reducing the amount of work that needs to be done
- improving the technology itself so that it requires less energy to operate
- improving insulation

Once a system has been made as efficient as technically and economically possible the next step, to capture and re-use waste heat, can be taken. The use of heat recovery technology provides an emission-free substitute for fossil fuels (US DoE, 2008). Heat recovery can be applied to any process where heat that would normally be lost to the system is collected and re-used (Carbon Trust, 2015). The order of the steps taken to implementing waste heat recovery is important. There is minimum benefit in investing in waste heat recovery if system improvements are made after the heat recovery technology is installed, which results in a reduction in the availability of waste heat. A considerably better approach is to reduce waste heat first and then identify possible solutions to re-using any waste heat that remains. US DoE (2008) highlights the essential components required for heat recovery:

1. an accessible source of waste heat
2. a recovery technology
3. a use for the recovered energy (heat sink)

In 2011, 32% of the UK's heat related emissions were from industry (Element Energy, 2014). The reduction of waste heat through efficiency improvements and re-use is an important strategy to decrease industrial carbon emissions and mitigate against climate change (Pastowski et al., 2014).

Recovered waste heat can, depending on the temperature of the source, have a range of applications. Carbon Trust (2015) has outlined the following common uses of recovered heat:

- pre-heating combustion air for boilers, ovens, furnaces
- pre-heating fresh air to ventilate the building
- hot water generation, including pre-heating boiler feed water
- space heating
- drying
- other industrial process heating / pre-heating
- power generation

The reuse of waste heat can reduce energy demand of these and other processes; the efficiency of the process is greater when the heat source and sink are coincident (Carbon Trust, 2015). Waste heat can be transferred from source to sink, although using waste heat directly will not always be feasible (Forni et al., 2014). The choice on the best use of waste heat is predominantly driven by economic and technical viability. Low grade heat is more likely to be transferred to a sink and used as a heat supply, whereas higher grades of waste heat can be used for electricity generation. A summary of different waste heat streams and their potential application is shown in Table 1.

Temperature Classification	Waste Heat Sources	Characteristics	Commercial Waste Heat to Power Technologies
High (>650°C)	• Furnaces ○ Steel electric arc ○ Steel heating ○ Basic oxygen ○ Aluminium reverberatory ○ Copper reverberatory ○ Nickel refining ○ Copper refining ○ Glass melting • Iron cupolas • Coke ovens • Fume incinerators • Hydrogen plants	• High quality heat • High heat transfer • High power-generation efficiencies • Chemical and mechanical contaminants	• Waste heat boilers and steam turbines
Medium (260°C - 650°C)	• Prime mover exhaust streams ○ Gas turbine ○ Reciprocating engine • Heat treating furnaces • Ovens ○ Drying ○ Baking ○ Curing • Cement kilns	• Medium power-generation efficiencies • Chemical and mechanical contaminants (some streams such as cement kilns)	• Waste heat boilers and steam turbines (>260°C) • Organic Rankine Cycle (<425°C) • Kalina cycle (<540°C)
Low (<260°C)	• Boilers	• Energy contained in	• Organic Rankine Cycle

	• Ethylene furnaces • Steam condensate • Cooling water o Furnace doors o Annealing furnaces o Air compressors o IC engines o Refrigeration condensers • Low-temperature ovens • Hot process liquids or solids	numerous small sources • Low power-generation efficiencies • Recovery of combustion streams limited to acid concentration if temperatures reduced below 120°C	(>150°C gaseous streams, >80°C liquid streams) • Kalina cycle (>95°C)

Table 1: Waste streams and their use classified by temperature (after EPA, 2012)

Waste heat to heat direct

In an ideal scenario the waste heat will be emitted next to, or close to, an area of demand. In reality the heat source is normally separated from the heat sink, requiring transport from source to sink; the temperature of the heat supplied from the source does not always match the temperature required by the heat sink (Element Energy, 2014). Furthermore, the heat output of the source and heat requirement of the sink are both likely to fluctuate, often not in unison, as in the example of an air compressor where the availability of waste heat depends on the use of compressed air and presence of leaks. Little use and / or low leakage means little waste heat.

A simple example of waste heat being used directly, with no additional investment, is in an office environment where lighting, computers and other electronic equipment like printers emit radiant heat. The cumulative effect of this waste heat will increase the temperature of the room, although the extent of this will depend on the physical aspects of the room i.e., size, insulation levels etc. In colder months this waste heat can reduce heating demands. However, in the summer months this waste heat can result in the space becoming too warm, driving the requirement for air-conditioning and thereby increasing energy usage.

A study being carried out at time of writing by the energy supplier Eneco is investigating heating homes with computer servers. The computer servers are placed inside custom-made radiators and the waste heat emitted is used to heat the home (Eneco, 2015). Some heat is still wasted, however, and is vented to the outside when there is no heating demand.

If Eneco's trial proves successful it could have commercial applications. Computer servers are often kept in one room away from the office space itself. However, offices could use their own servers and computers as radiators. Computers need replacing over time so the radiator would need to be designed in such a way that computers or servers could be switched out and upgraded easily. This could be scaled up further, particularly for large scale industry, through two approaches. If the industry has large servers on site, heat pumps could be used to cool the server room and the heat could be transferred to an area within the industrial process that has a heat demand. This enables one piece of technology to meet two requirements, replacing the need for separate cooling and heating. Alternately, the industry with the heating requirement could partner with a server company with the premises next to each other and then use the waste heat from the large servers to provide heat for the industrial process.

Large scale waste heat to electricity / heat

Large scale, power hungry industries produce a continuous and significant volume of waste heat at a high temperature (such as furnaces, iron cupolas, coke ovens, fume incinerators and hydrogen plants, as detailed in Table 1). As the waste heat produced is predictable, high grade and continuous they have the opportunity to use this waste heat to create electricity and / or heating.

In the United States, approximately 33% of industrial energy consumption is discharged as heat to the atmosphere or actively cooled (EPA, 2012). This figure can be reduced in the US, UK, and other countries. The primary restriction for converting waste heat to electricity is the temperature of the heat source, followed by the flow rate (Forni et al., 2014). A key issue in the US is that most of the waste heat is less than 149°C or is lost as radiant heat (EPA, 2012). Therefore, it is logical to first identify the "low hanging fruit" (Arens and Worrell, 2014), those industries that produce waste heat at above 250-300°C. If this approach is adopted in the UK, with support from both industry and government, it will allow UK industries to become familiar with heat recovery technology; the increase in uptake of technology will help fund the research and development of utilising lower grades of waste heat.

Siemens have identified and installed a solution that utilises waste heat from an electric arc furnace (EAF). Exhaust gases from the EAF process can reach 1,700°C (Siemens, 2015). Water is run through salt storage units that are heated by the exhaust gas, producing steam which drives a turbine to create electricity (Siemens, 2015). The advantage of using salt storage units is that the process can manage changes in source temperature. This process can recover approximately 20% of the electricity used by the EAF, saving approximately 40kg of CO_2 per tonne of steel (Siemens, 2015). A current EAF takes 90 minutes to produce a batch of approximately 150 tonnes of steel (UK Steel, 2015). Therefore, Siemens' technology has the potential to save 6,000kg of CO_2 per batch. In 2013, 1.9 million tonnes of steel was produced using EAFs (UK Steel, 2014). If Siemens' heat recovery technology is implemented by all EAF production plants in the UK the CO_2 reduction potential, based on 2013 figures, would be 76,000 tonnes. This is equivalent to 0.016% of the UK's total green house gas emissions of 464.3 million tonnes in 2013 (DECC, 2014).

Waste heat to electricity - Organic Rankine Cycle (ORC)

Most industrial waste heat, for example 60% in the US, is produced at temperatures <232°C that cannot economically be harnessed to drive steam powered turbines (US DoE, 2008). However, the Organic Rankine Cycle (ORC) uses an organic, high molecular mass fluid with a lower boiling point than water (Liu et al., 2004). This enables electricity generation to occur at lower temperatures. ORC technology is developing quickly as there are many applications for generating power from waste heat. Identifying the most suitable working fluid that suits the temperature of the heat source and power range is pivotal to enable the best exploitation of the heat source (Bombarda et al., 2010). The challenge stems from identifying the most suitable of many different options of working fluids.

The ORC process has the advantage of being flexible in terms of size. Its power output can go from tens of kWs to MWs (Forni et al., 2014). For the ORC process to be viable, source temperatures need to be available 6,000 plus hours a year and in excess of 100°C (Suomalainen and Hyytia, 2014). However, Minea (2014) successfully used a 50kW ORC generator that utilised waste heat at temperatures between 85 - 105°C. It is worth noting though that an increase in source temperature will increase system efficiency (Liu et al., 2004).

As with any technology upgrade, each industry needs to carefully identify which technology best suits their needs. Industries that could be compatible with the ORC process include cement, glass and steel industries. When identifying and modelling the suitability of an ORC system for industrial waste heat recovery it is important to consider the fluctuations and durations of the waste heat temperature; if the modelling assumes that the temperature is constant, the system design may prove unsuitable and the payback will likely be much longer (Liu et al., 2004).

There are currently 13 Lime manufacturing plants in the UK (MPA, 2013). Approximately 2 million tonnes of lime is manufactured a year by these plants (BLA, 2015). Lime is a versatile product. For example, it is used in iron manufacturing, water purification and emissions cleansing (BLA, 2015). Although lime is used in emissions cleansing, its manufacture also has a carbon footprint. In 2012 lime production in the UK produced 1,178 kilotonnes of Green House Gases (in CO_2 equivalent) (NAEI, 2015).

Lhoist (formerly Steetley Dolomite) have integrated ORC based technology into their Thrislington Lime Plant to produce electricity from waste heat and reduce their CO_2 output (Lhoist, 2015). The system installed should generate 3,000MWh/yr, reducing CO_2 emissions by 1,600 tonnes/yr (Heatcatcher, 2014). Furthermore, the electricity import savings should give Lhoist a 5 year payback on the investment (Heatcatcher, 2014). As the system has a 15 year life, it will pay for itself three times over. This money can then be further invested in upgrading to the latest heat to power technology which, by 2030, should be even more efficient.

Waste heat to electricity - Kalina cycle

The Kalina cycle is a thermodynamic process; it can be used to convert thermal energy to electrical energy. It uses two fluids, normally water and ammonia, as the working fluid (Nag and Gupta, 1998). Using two fluids with different boiling points improves efficiency (compared to the Organic Rankine Cycle which uses one fluid) of the waste heat to energy process as more energy can be extracted from the heat source (Elsayed et al., 2013). Furthermore, to better match the heat source the ratio of the two working fluids can also be altered to ensure the maximum amount of heat can be extracted (Elsayed et al., 2013). This process can be used to harness waste heat and can also have geothermal and solar applications. However, while the Kalina cycle has the potential to provide a net plant efficiency of 58.8%, reducing the process' carbon emissions, there is limited commercial experience (Pilavachi, 2000). As shown in Table 2, there are only a handful of plants in the world that have adopted the Kalina principle (Ogriseck, 2009).

Project name/location	Country	Heat source	Electrical output	Start up
Canoga park (Demo)	USA	515 °C exhaust gas of gas turbine, later solar centaur gas turbine	3 MW, later 6.5 MW	1992–1996
Fukuoka city	Japan	Waste heat from incineration plant	5 MW	1999
Kashima steel works	Japan	98 °C water, waste heat of production	3.1 MW	1999
Husavik	Iceland	Geothermal brine at 124 °C	2 MW	2000
Unterhaching	Germany	Geothermal	3.4 MW	2007

Table 2: Projects that have adopted the Kalina cycle to generate electricity from waste heat (Ogriseck, 2009)

The Kalina cycle could cost less to build than an equivalent sized Rankine cycle plant (Elsayed et al., 2013), and is more efficient (Nag and Gupta, 1998). Therefore, the Kalina cycle has the greater potential for reducing industrial carbon emissions than the ORC. More support needs to be provided to encourage uptake of the Kalina cycle by industry.

Waste heat - use of heat pumps

A heat pump absorbs heat from where there is ample and transports it to an area where it can be used, i.e., heating / hot water. There are different types of heat pump including air source, ground source and water source heat pumps, depending on the medium from which heat is being extracted. The temperature of these mediums varies, particularly of air, and the temperature is generally not warm enough to be used directly so a heat exchanger is used to increase the temperature to between 30 and 45°C (McCrea, 2008).

For heat pumps to work efficiently the heat source needs to be as warm as possible while the heat sink needs to be kept as low as possible (McCrea, 2008). This is to ensure the best Coefficient of Performance (CoP). For example, if a heat pump has a CoP of 3 it means it is using 1 unit of electrical energy to generate 3 units of heat energy. Heat pumps generally have a CoP of between 3 or 4, but it does depend on whether it is a ground, air or water heat pump and the time of year. For example, air source heat pumps are particularly affected by the seasons. Their CoP drops in colder weather as the temperature gradient between source and sink is greater, so more energy is needed to produce sufficient heat.

Industry uses approximately 43% of global thermal energy demand, much of which is lost as waste heat, of which most is lost as low temperature waste heat (Bor et al., 2015). This waste heat could, through the use of heat pumps, have the potential to be utilised. Industrial waste heat that is low grade could be captured though the use of heat pumps. However, at present most of the uptake of heat pumps in the UK is on a domestic level. There is little information available to assist decision makers, particularly in non-energy intensive industries, on deciding how to utilise low grade heat and the viability of heat pumps for their organisation (Suk et al., 2015).

Where possible, it is better to use waste heat as heat, instead of converting it to electricity. At equal waste heat input the economic value of heat delivered from heat pumps is between 2.5 and 11 times greater than the value of electricity delivered by power cycles (i.e., Organic Rankine Cycle) (Bor et al., 2015). However, the economic viability of heat pumps that use electricity is dependent on gas prices (Suk et al., 2015). Furthermore, the carbon savings from heat pumps will vary depending on the fuel type it is replacing and its operating CoP. For example, if one unit of gas costs 5p and one unit of electricity costs 15p then a minimum CoP of 3 is required for it to match the cost of gas.

Suk et al. (2015) found that the implementation of heat pumps for heat recovery in the food and drink sector in France could achieve a 12% energy reduction and 9% CO_2 emissions reduction. This is dependent on which fuel is being replaced. Heat pump benefits are least effective when replacing gas, which produces less carbon emissions per kW of heat than electricity and oil. However, when using heat pumps to re-use waste heat the efficiency of the whole system is being improved and the savings are therefore greater.

One key area that applies to all industry is sewage. Sewage from industry contains heat from human waste, water and effluent from various processes. It is estimated that more than 15% of thermal energy is lost though sewers (Culha et al., 2015). Harvesting this waste heat through the use of heat pumps could significantly assist in the reduction of carbon emissions in industry. In the UK, the temperature of waste water varies between 9 and 14°C in winter and 28 to 29°C in summer (Culha et al., 2015). Some industrial processes have temperatures greater than this. If the waste water has a temperature of 30 to 40°C the CoP of a heat pump can be as great as 8 (Culha et al., 2015). Any CoP greater than between 3 & 4 is likely to result in greater efficiency than any other non-renewable fuel alternative.

The Metropolitan Water Reclamation District successfully reduced its energy costs and carbon emissions for heating and cooling by 50% through the use of a $175,000 sewage heat recovery system (Kaufman, 2012). The system is on track to pay for itself inside three years (Kaufman, 2012). Sandvika, located in the Oslo region of Norway, uses waste heat from sewage to contribute to the local district heating and cooling scheme. The waste heat from sewage provides 52% of the heating / cooling demand of the area with a heating capacity of 13MW and a cooling capacity of 9MW (Friotherm, 2010). Heat pump technology is clearly effective and viable for a range of different uses and, if applied to UK industry, could have the potential to reduce waste heat, carbon emissions and energy costs.

Development of industrial waste heat recovery - barriers and drivers

Waste heat recovery often has an investment payback time of greater than four years (Forni et al., 2014). Organisations often look for a quick return of two to three years for non-core investment projects (Element Energy, 2014). In order to encourage the uptake of new technologies industries need a reason to incorporate the technology into their processes. Typical drivers include cost-saving, time-saving, labour-saving, competitive advantage and government legislation (Element Energy, 2014). There is legislation in place to promote the reduction of carbon emissions including:

- EEA Agreement
- Article 17 - Kyoto Protocol
- 5th Environmental Action Program
- ETS Directive 2003/87/EC

However, there are no common guidelines around waste heat (Brunner et al., 2014). Furthermore, there is a lack of specific legislation and long term regulatory framework, with targets, that covers waste heat recovery in industry (Forni et al., 2014). Uptake needs to increase to stimulate a price decrease of waste heat recovery technology to an affordable level. This is why government support at the early stages of development is so important. Therefore, the lack of current legislation and government support means industries are unlikely to invest in waste heat recovery, unless there are demonstrative financial benefits to introducing heat recovery technologies.

The wide range of industrial processes with different operating and demand characteristics means that there is not one technology available that will work in each situation from concept development to implementation (Brunner et al., 2014). Bespoke design can result in a system being perfectly matched to a process, but equally there is always an increased risk of inadequate design and / or installation and / or operation. Furthermore, data acquisition on the system performance and its effectiveness can be difficult to evaluate (Brunner et al., 2014). These risks can result in industry being more reluctant to invest in waste heat recovery.

Much of the waste heat available is low grade which, at present, is not economical to recover (Hills et al., 2014). However, very little work has been done on industrial space heating although it has a high energy saving potential (Biere et al., 2014). Low grade heat could potentially be used for space heating and there may be potential for innovative use of heat pumps to harness this large resource. Biere et al. (2014) identified that within the EU space heating could be reduced by 38% in the best case scenario and 6% in the base line scenario.

Waste heat recovery can contribute to meeting the EU's 2020 target for carbon reduction (Hummel et al., 2014). Heating and cooling place significant energy demand on industry. The waste heat from these processes has the potential to be reused in a variety of ways. In summary, waste heat can be used at the industrial plant, neighbouring companies / buildings and district heating systems (Hummel et al., 2014). The number of methods of capturing waste heat and the number of uses it has make it a highly versatile solution.

The expected decrease in the availability of fossil fuels and potential price spikes is driving the concern for greater industrial energy efficiency (Pastowski et al., 2014). While there is no specific legislation for waste heat, environmental legislation and carbon reduction targets for industries are driving industries towards the implementation of more energy efficient technologies (Suomalainen and Hyytia, 2014). Waste heat recovery has the potential to be part of the solution as the recovered heat replaces heat from other sources and their associated emissions (Forni et al., 2014).

Waste heat has value as a source of energy and harnessing waste heat can reduce operational costs which, in turn, increases competitiveness (Forni et al., 2014). Efficiency savings can also improve productivity (Arens and Worrell, 2014), which also contributes to competitiveness. Furthermore, reusing waste heat either for heat or power will reduce dependency on other organisations (Hills et al., 2014). The technological development of waste heat recovery technology will also help to encourage its uptake in industry over time (Suomalainen and Hyytia, 2014).

Solar technology

Solar energy

The sun provides an inexhaustible supply of energy to earth; in one hour the world receives more solar energy than the annual global energy demand (Thirugnanasambandam et al., 2010). The technology that harvests this solar energy has the potential to revolutionise the way in which energy is generated and used in homes and industry. Harvesting solar energy can be passive or active. Where the sun's energy is harvested without mechanical means it is passive; when mechanical devices are used it is active (McCrea, 2008).

Passive solar energy can be used in heating, cooling and to provide light (Winter, 1998). In order to maximise the benefits of a passive solar energy, it is best to incorporate it to the building design. For example, large south facing windows, walls with high thermal mass, and good insulation enable a building to harvest the sun's energy and reduces its requirement for heating (Winter, 1998). Also, the more natural light allowed into a building, the lower the requirement for artificial lighting. However, if too much light is allowed in then, particularly in summer, buildings can become too hot and require artificial cooling which is counterproductive. For industries, passive solar energy should be incorporated into new building designs, but it is more difficult and expensive to incorporate into existing buildings.

Active solar energy can be used to heat water and provide electricity. It is these applications that have the greatest potential for decarbonising industry. Solar thermal is scalable, having domestic and industrial applications, providing the necessary input for a range of uses (McCrea, 2008). Solar hot water and heating requires a thermal store as well as electricity to power the pump(s) to circulate the fluid. The installation of a 1MW solar hot water heating system on an egg powder making plant in India reduced the annual oil consumption by 78% and saved 1,247 tonnes $CO2_e$ (Nagaraju et al., 1999). While solar thermal can be used in conjunction with waste heat technology and solar photovoltaic technology, the main focus of this section is on solar photovoltaic technology.

Solar photovoltaics

Solar photovoltaic (solar PV) technology can be used to convert the sun’s energy into electricity. The electricity is generated within a semi-conductive silicon material, has no moving parts, and can be used as a building material (McCrea, 2008). Solar PV technology provides an intermittent source of energy. It only produces energy during daylight hours and its output fluctuates depending on weather conditions, time of year and time of day (McCrea, 2008). However, particularly when compared with other renewable technologies, it is versatile. Wind turbines, for example, need extensive studies carrying out before install both to ensure that there is sufficient wind over the course of a year in that specific location, and to check for problematic environmental impacts, i.e., shadow flicker, noise and aesthetics. Planning permission is also needed in the UK (Planning Portal, 2015). Solar panels can be installed in a range of different environments (rural / urban / costal / mounted on roof tops / facades / fields), do not cause any environmental impacts during operation and, in the UK, most installations fall under permitted development (Planning Portal, 2015).

Due to solar PV's modular nature, it can be manufactured, transported and installed on a small to very large scale (IEA, 2015). Solar PV can be used to power pocket calculators and charge mobile phones. Equally it can be used to help provide electricity to industry or military bases. An example is the Nellis Air Force Base in North America which installed a 14.2 MW array that has an annual energy output of 30,100,100kWh, saving the base $1million and reducing their carbon footprint by 24,000 tonnes/yr (US Air Force, 2007). Furthermore, the manufacturing of the key components, module, inverters and mounting kit can be done in large plants which enables economies of scale, reducing overall material costs (IEA, 2015).

Since the introduction of the Feed-in Tariff on 1 April 2010, solar PV has become one of the fastest growing renewable technologies in the UK (EST, 2014). Figure 2 demonstrates this growth, showing the cumulative installed solar PV capacity between January 2010 and May 2015. Initially uptake was slow as the infrastructure required to support a robust solar PV install market (for example relatively low numbers of suppliers and installers) was in its infancy. Furthermore, for domestic home owners and businesses, the idea of installing solar PV was relatively new and the capital cost was high at approximately £4,000 to £6,000 per installed kW. Even allowing for the economy of scale, with the install price decreasing for larger array sizes, the capital outlay was often still prohibitively large.

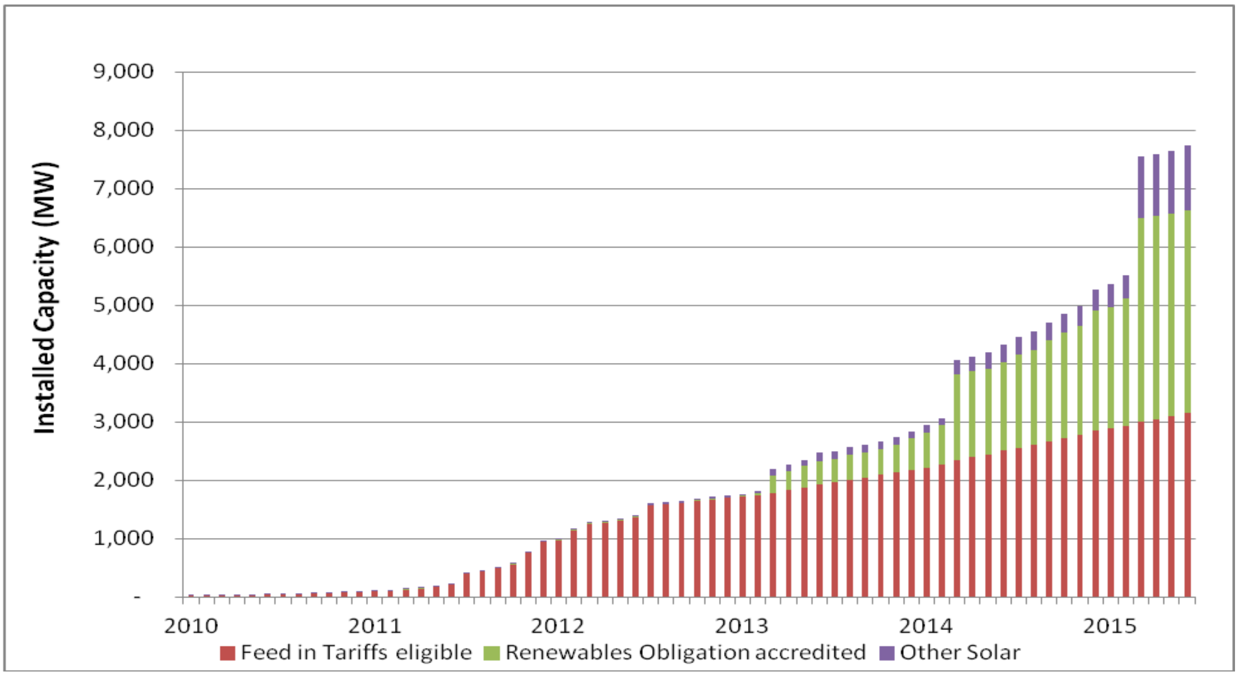

Figure 2: Graph of cumulative (monthly) installed solar PV capacity since 2010 (after DECC, 2014)

Despite the capital cost, the introduction of the FiT kick-started the solar PV installation market, as Figure 3 shows, with slow but overall gradual increase in the uptake of PV during 2010 and then gaining momentum in the first half 2011 with a significant increase in July. However, in March 2011, when the FiT scheme was still less than a year old, the Government announced that due to a rapid uptake in solar PV and falling prices, the FiT would be cut from August 2011 for installations over 50kW; this was followed by a further review in October 2011 that suggested the FiT would also be significantly reduced for installations below 50kW in December 2011 (Vaughn et al., 2011). This announcement caused the spike in installations shown in Figure 3 for November and December 2011 and the following drop off in January 2012. A legal challenge resulted in system sizes below 50kW being able to access the higher rate FiT up until the end of March 2012.

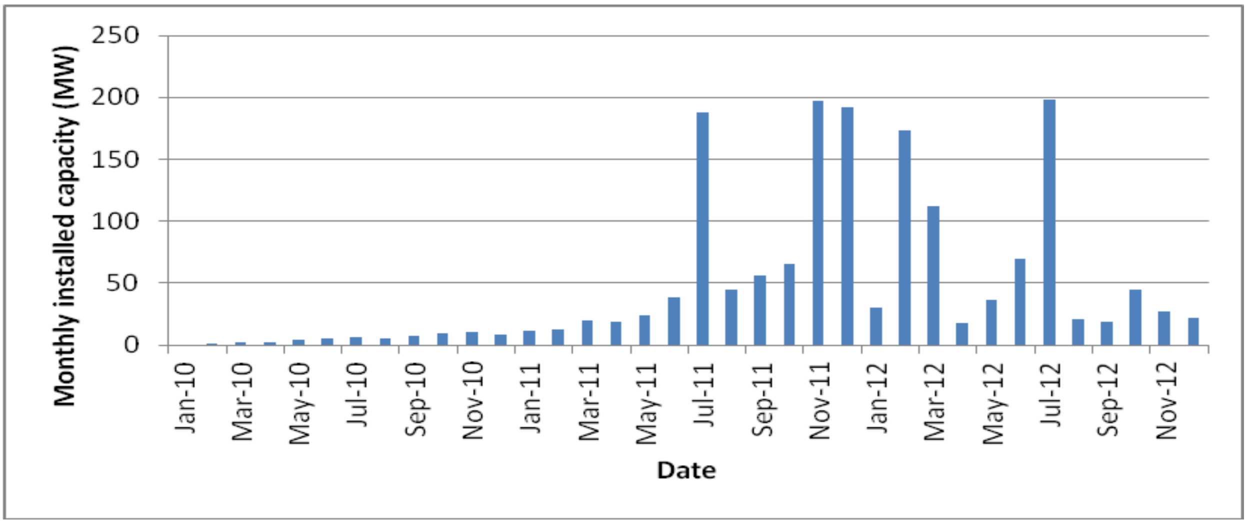

Figure 3: Graph of monthly installed capacity of solar PV (DECC, 2014)

The issue of the action by the UK Government, reducing the FiT so significantly in such a short time from the introduction of the scheme, is the impact on consumer and investor confidence (Stuart, 2010). The FiT was a very positive incentive and had resulted in rapid growth, but there was a need to ensure that this growth was sustainable (ESP KTN, 2013). Despite the cut in the FiT, the UK's solar PV capacity increased by 60% in 2013; by the end of 2013 the total installed solar PV capacity was 2.7GW (DECC, 2014) and by May 2015, this had increased to 7.265GW.

While the domestic market struggled to regain momentum, the commercial and industrial market, which had undergone a smaller FiT reduction, was less affected. Very quickly some of the benefits of the FiT reduction and increasing competition between both manufacturers and installers drove the price of the materials and installations down (ESP KTN, 2013). With lower capital costs, the payback became equal to or even less than it was before the FiT drop. The reduced costs and a continued return on investment over a 20 year period, that was index linked, proved to be a strong enough incentive to keep the commercial uptake of solar PV moving forward.

While this section of the report is primarily focused on solar in industry, the figures used so far in this section and some of the discussion incorporates smaller domestic systems. While a product is in its infancy, there is a link between the commercial and domestic uptake and implementation of the product (ESP KTN, 2013). During the early uptake of the solar PV installations, driven by the introduction of the FiT, the overall investment in the technology by domestic and commercial customers combined to finance the growth of the industry. Furthermore, the combined demand from the commercial and domestic uptake helps to reduce material and install costs. Also, key decision makers in industry live in domestic dwellings and if they buy into solar PV at a domestic level, and find it to be a worthwhile investment on a small scale, then they may be more willing to drive the uptake of the technology in their respective organisations on a much larger scale.

Potential of solar photovoltaics in industry

In 2013 UK business consumed 199,738GWh of electricity costing an approximate total of £20.4billion (Kingspan, 2014). If none of the electricity was provided by renewables the total CO_2 emissions would be 104,462,974 tonnes. Industrial rooftops are often large uninhibited areas that have no use other than keeping out rain. By covering these roofs in solar panels, organisations can reduce their electricity bills and their carbon footprint. However, compared with other European countries, the uptake of solar PV in commercial and industrial buildings in the UK is low (DECC, 2014). At present, only 5% of solar PV installations are installed on commercial roofs (STA, 2015). Figure 4 shows the number of different sized systems installed in the UK that are claiming the feed-in tariff. The Solar Trade Association (2015) has also identified that there is a requirement for more support to industries to increase solar uptake as the DECC data shows that there are only 1200 installations between 50 to 250 kW and 70 > 250kW installations on commercial roofs. Given the amount of potential commercial roof space there is clearly room for significant growth in installing 50 to 5000kW Solar PV systems on industrial and commercial properties.

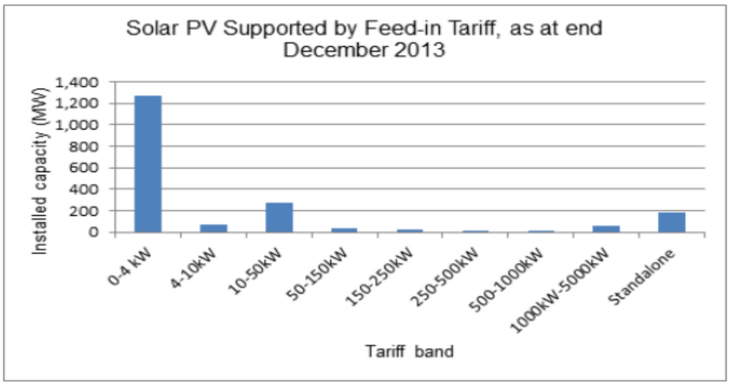

Figure 4: Graph of the number of FiT registered Solar PV installations by tariff band up to December 2013 (DECC, 2014)

Figure 5 shows the cumulative solar PV, by installation type, that has been installed in the UK as of April 2014. In installed capacity, ground-mount solar PV is moving towards the 50% mark (Colville, 2014). However, the UK Government, through the Department of Energy & Climate Change's (DECC) Solar PV Strategy 2, would like a drive towards an increased uptake of large scale roof top mounted solar PV on commercial and industrial buildings (DECC, 2014). One of the key advantages of roof top solar over field arrays is that the electricity is generated at the point of demand. This minimises transmission power losses and the requirement for expensive grid infrastructure. Furthermore, roof top solar is better aesthetically than solar fields and reserves arable farm land for agricultural use.

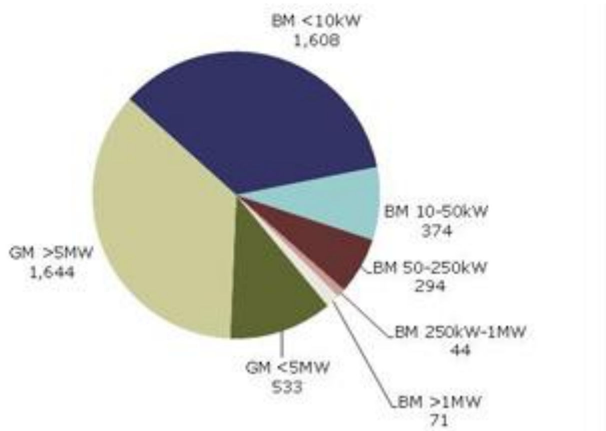

Figure 5: Pie chart showing the cumulative solar PV installed in the UK by install type and size [BM - Building mounted & GM - Ground mounted] (Colville, 2014)

The UK has approximately 250,000 hectares of south facing commercial roof tops (DECC, 2015); these roofs provide an excellent opportunity for solar PV generation. 250,000 hectares = 2,500,000,000m^2 therefore, assuming 250W panels are used which have an area of 1.63m^2 then 1kW of PV requires an area of 6.54m^2. Dividing the total available roof area by the area required for 1kW of solar panels and multiplying by 0.9 (providing a 10% allowance for a boundary between array and the edge of the roof) gives an answer that suggests there is potentially enough south facing roof space for 3,444,037MW (3.44TW) of solar PV.

Using the method outlined in the Guide to the installation of solar PV systems (MCS, 2012) for calculating PV yield and allowing the following assumptions: all the roof space is in the midlands area, the roofs are due south, not shaded and pitched at ten degrees, then 3,444,037MW (3.44TW) of solar PV could generate 2,793,113 MWh/yr (2793.11TWh/yr). In 2013 the total UK energy consumption was 317 TWh with 15% (47.55TWh) coming from renewables (DECC, 2014). Therefore the calculation suggests that if all the available roof space is used then solar PV alone could produce 8.8 times more electricity than required annually by the UK.

This is an optimistic conclusion. There will be issues including roof obstructions, shading and structural integrity that will reduce the available roof space. Furthermore, there is an issue with matching supply with demand as solar PV only works intermittently, with fluctuating outputs throughout the day. The grid would also require significant reinforcement in some areas and the development of grid balancing strategies to deal with fluctuations in supply.

This section demonstrates that organisations are investing in medium to large scale building mounted solar PV arrays and that the solar PV market is maturing and growing. However, it is also clear that the potential for solar PV uptake, particularly on an industrial scale, is considerable. Therefore, with the right support solar PV could genuinely make a considerable difference to decarbonising UK industry. It is therefore imperative that the drivers and barriers of solar PV integration into industry are understood both on a macro and micro level. One of the challenges of this research product has been identifying within the literature what the full extent of the technical and economic drivers and barriers are. They are often only referred to in general terms.

Drivers and barriers of solar PV uptake

A number of factors have successfully driven the growing uptake of solar PV in domestic and commercial markets. Understanding what the successful drivers are and the why and how of their effectiveness are important to ensure that the appropriate support can be given to the continued development and integration of solar PV in industry.

Government led incentives and legislation are a proven, effective way to instigate change (COBIT, 2011). For example, the UK's Carbon Reduction Commitment is a mandatory requirement for medium to large businesses / industries to reduce their CO_2 emissions (EA, 2013). A considerable factor in the growth of renewables in the UK and other countries like Germany and Spain is the various forms of a feed-in tariff (FiT) (Solangi et al., 2011). In the UK, it was the key driver to stimulating the uptake of Solar PV (DECC, 2011). As Figures 2 and 3 show, there has been a rapid growth in the uptake of solar PV in the UK since the FiT introduction.

In this author's experience of dealing with commercial and industrial clients, the FiT has been crucial in driving the uptake of renewables from a financial perspective. However, the term feed-in tariff can confuse potential investors in renewable energy. The term feed-in tariff can lead people to the conclusion that the primary incentive comes from exporting energy to the grid. However, the ideal scenario for industry financially and environmentally is maximising the use internally of the electricity that is produced by the renewable generating technology. As explained by the Energy Saving Trust (2014) the FiT for solar PV covers systems up to 5MW and provides the following threefold benefits:

1. The system owner gets paid for each kWh of electricity generated, regardless of whether it is consumed or exported.
2. For each kWh of electricity exported to the grid the owner gets paid, however, the cost per kWh received for export is and always will be lower than the cost paid to import electricity (in systems below 30kW the FiT is deemed at 50% of the generation, systems above 30kW needs export metering. This does leave a grey zone as half hourly metering can cost more than one may get from the export).
3. For each kWh generated and used in the property a saving is made on not paying for the equivalent in imported energy.

Investors need to consider that every three months the FiT is reviewed and, depending on the volume of solar PV systems installed in the previous quarter, the FiT will decrease by approximately 3% (DECC, 2014). However, once a system is installed and commissioned the FiT rate will be set for that system and is index linked, so will not devalue over time (EST, 2014). This approach provides a regular financial deadline that causes installations to peak as each quarterly deadline before a price regression looms. It also provides an incentive to encourage investors to act sooner rather than later.

The previously discussed reduction in the FiT demonstrated that it stimulated competition within the market, significantly reducing material costs, making solar PV more economically viable (UK ERC, 2012). This was because the lower FiT rate was balanced out by the fall in material price giving similar paybacks but with a lower capital cost. This resulted in the technology being more affordable for individuals and organisations who were previously financially unable or unwilling to invest in the technology before the FiT drop.

One of solar PV's main advantages over other renewable technologies is its versatility. As long as there is an unshaded roof that is within 90 degrees of south that can support the weight of the array, panels can be installed. Furthermore, solar PV falls under permitted development so planning permission, in most cases, is not required in England and Wales (Planning Portal, 2015). The rules in Scotland are different as building warrants from the Local Authority are required.

To help encourage the uptake of solar PV by businesses, the UK Government is working on a proposal, to come into force in 2019, that allows solar PV systems to be moved between buildings without losing the FiT payments (DECC, 2015). This will allow organisations to take their solar PV arrays with them if they move premises. While this may sound like a good idea it may not have the impact that the Government hopes. The paper "Government response to the consultation on the transferability of building-mounted solar PV installations" (DECC, 2015) highlighted the following considerations when re-locating a solar PV system (this list is not exhaustive):

- Scaffolding
    - Scaffolding would need to be erected on both the old and new premises. The cost can run into tens of thousands of pounds depending on the size of the building and the array.
- Labour
    - Labour forms a significant cost of a solar PV install.
    - It could take longer to un-install the solar PV array than to install it as extreme care would need to be taken to prevent breakages and safely package the equipment for transport.
    - Care would need to be taken to minimise loss of equipment, particularly the smaller parts of the kit.
    - Remedial works to the roof will need to be carried out, particularly if penetrative fixings have been used.
- Design
    - The solar PV system will have been specifically designed for the original building.
    - The new building may have a different roof construction, requiring a different fixing type.
    - The roof may have a different orientation or be a different size requiring the array to be reconfigured - this may result in the inverters no longer being suitable if the string configurations, number of panels and orientation of the array has changed.
    - The array may not be able to be connected up in the same way.
    - The electrical infrastructure of the new building may not work with the PV system, i.e., new building has a generator which requires the PV array to have a cutout relay installed.
    - The cabling routes and run lengths will change and will need to be re-specified.

- Warranties on equipment may become void
- DNO
    - The DNO may not permit solar PV in the new location if the local grid is saturated already or if it simply cannot support a medium to large scale system.

However, the "Government response to the consultation on the transferability of building-mounted solar PV installations" (DECC, 2015) indicated that the proposal would be going ahead. It would be more beneficial if the Government allowed the organisation to install a similar system onto the new premises. The original FiT rate for the old installation would remain valid up until the point it expires on the old building. The FiT rate would then convert to the one that was in place when the new system was installed until the time period expires. However, this will be trickier to manage from an administrative perspective. Leaving the old system in place for the new occupier also ensures that the new occupier starts off positively as no effort is required on their part and their business starts saving energy and carbon straight away.

Existing electrical infra-structure can limit the size of the array, particularly if connecting the system in at low voltage. Internally the size of the array is limited to the capacity of the main consumer unit and the fuse size on the main incoming cable. The Distribution Network Operator (DNO) may also cap the maximum system size permitted (without network upgrades), due to restrictions on the local grid network. The cost to upgrade the local network to enable a solar PV install is often cost prohibitive.

Rising energy demand, that exerts pressure on existing grid infrastructure, can impact on the availability of energy (Hoffmann, 2006). This is critical if industries wish to expand and develop: they will need to ensure that they have sufficient energy to meet their evolving requirements. Furthermore, the current investment in upgrading the grid infrastructure is not able to keep up with the increasing demand (Samad and Kilicote, 2012). This could potentially lead to black outs in some areas. Solar PV can help to de-centralise and decrease energy requirements from the grid. However, unless sufficient battery and generator back up is available, grid support will still be required.

In order to maintain and upgrade the ageing grid to meet evolving industrial and domestic demands, utilities will charge increasingly higher rates for electricity which in turn will make the generation from solar PV increasingly more affordable (Hoffman, 2006). Therefore, rising electricity costs will continue to drive the demand for solar PV. Eventually a point will be reached where the cost of solar PV electricity is less than grid electricity. At this point, government financial incentives will no longer be required.

For new industrial buildings, solar PV can be integrated into the building facade, glazing and roofing. This does increase the cost per Watt peak of the solar PV (Hoffmann, 2006). However, some of this cost can be offset if the solar PV materials are used in place of regular building materials. Furthermore, once installed it has an operational value attached as it is producing energy and reducing the operational costs of the building.

There are a number of additional barriers to the uptake of renewable technologies, including solar PV, with industrial uptake and integration predicted to be low (Taibi et al., 2011). Industries can be wary of adapting new technology, even if it has the potential to benefit the company. Reluctance can stem from concerns of how it may affect the operation of the existing infrastructure and how day to day production could be impacted during the install. Furthermore, the ownership of assets of both building infrastructure and the machinery within can be complex, making it challenging to get all the approval required to make a significant infrastructure modification, like the installation of solar PV (Schleich and Gruber, 2006). Even when a building is rented, the owners may be reluctant to have solar PV installed which can be frustrating for the business or industry who is trying to reduce their carbon emissions.

The installation of solar PV falls under permitted development but, until recently, this only applied to system sizes of less than 50kWp. However, in March 2015 the UK Government amended the Permitted Development regulations to allow up to 1MWp of solar PV to be installed without requiring planning permission (UK Gov, 2015). This move has now removed a barrier for many businesses, although for larger scale industrial premises that have roof spaces greater than 7,200m^2 and wish to capitalise on them, the barrier remains firmly in place. Fortunately, many councils are supportive of solar PV initiatives which helps to facilitate the planning process. (Please note in Scotland the rules are different and building warrants are needed before works proceed on all commercial sized systems).

Solar PV is an intermittent source of electricity (McCrea, 2008). This intermittency makes it difficult to match supply to demand. In order to balance out the intermittency and ensure industry gains the maximum benefit from the electricity produced the energy could be stored. This is investigated further in the next section, Energy storage.

The barriers identified in the literature focus on general economic social factors and technical factors. However, when installing a solar PV array a range of practical issues can arise with varying levels of impact. It is important that these potential issues are identified and understood by the industry as they can have significant impact on the viability of a project and on the potential size of the solar PV array. These fall outside the scope of this work and include asbestos, insurances and roof warranties (STA, 2015). However, the Solar Trade Association has recently produced a checklist as a guide for organisations considering large scale rooftop mounted solar PV which has been provided in the appendix (Appendix 1).

A range of considerations that can reduce the solar PV array size have been discussed. These potential barriers can have both technical, economical and environmental impacts on the proposed solution. It is therefore important that organisations understand these so they can be factored in when estimating the environmental and economical benefits of the proposed solar PV system.

Energy storage

Waste heat can be produced when there is no demand for it; for example, heat demand reduces in the summer months. Solar has a similar issue: at peak production generation can exceed demand. Therefore, waste heat recovery could be redundant for parts of the year, reducing its energy and carbon saving effectiveness and increasing payback times. For solar PV the surplus energy can be exported to the grid, which acts like a battery. However, due to electricity import costs being higher than the price paid for electricity export, the industrial operator does not gain the maximum benefit from the system. Furthermore, for waste heat, the level of heat from the source can fluctuate. It may also not be technically or economically feasible to turn the heat into electricity, or to transport it for use elsewhere i.e., district heating system.

Storing thermal and electrical energy can decrease an industry's imported energy demand and carbon emissions. A heat store can be used to reduce or remove a mismatch between energy demand and supply, reducing final energy consumption (Pfleger et al., 2015). This approach can be applied to waste heat recovery technologies and renewable technologies. Where the power produced is electrical energy, its state can be changed to heat for storage.

A domestic example of heat storage is storage heaters used in some homes. Storage heaters store up heat during the night using cheap electricity and slowly release the heat over the course of the day to keep the property warm. This process uses electricity and is generally used only on a domestic scale. However, heat can be stored on a more industrial scale.

Techniques that could be used to store energy on an industrial scale include:

- Using molten salt
- Phase change material
- Storing heat in rocks / concrete / aggregate
- Cryogenic energy storage
- Diverting surplus energy electrical energy to a thermal store
- Battery storage

The properties of molten salt (nitrate salt is predominantly used) make it a good material for sensible energy storage at temperatures above 100°C (Pfleger et al., 2015). Molten salts have a high heat capacity, density and thermal stability and the material costs are low (Pfleger et al., 2015). The material cost is critical for this solution to be economically viable. Material costs of sensible energy materials can be further reduced by using filler materials like ceramic to partially replace the molten salts (Calvet et al., 2013). As with different waste heat technologies, the source temperature can affect which thermal energy storage method will be most suitable.

Molten salts can be classed as a phase change material. A phase change material can absorb thermal energy by melting and release thermal energy when freezing. The disadvantage of molten salts is their low thermal conductivity (Zhang et al., 2014). Where molten salts are not a suitable option a range of other phase change materials could be considered. One phase change material that has potential is metal materials as they have an ultrahigh thermal conductivity (Zhang et al., 2014). Zhang et al (2014) found that copper capsules encased in refractory metallic shells could store heat up to 1000°C. The challenge with phase change materials, particularly when they reach high temperatures, is finding a vessel that can contain the heat and minimise further heat loss.

In areas where the local geology is suitable, heat can be stored underground. Anderson et al. (2009) identified that 2,800MWh of heat could be stored per year from a foundry operation in

Emmaboda, Sweden. When using a natural store, like bedrock, energy is lost to the surroundings. The rate of thermal loss is dependent on the permeability of the bedrock; the greater the permeability of the bedrock the larger the heat loss. The bedrock under the foundry in Emmaboda has a low permeability and so heat loss is estimated to be relatively low at approximately 1200MWh/yr (Anderson et al., 2009). Heat can be delivered to the bedrock and transferred from the bedrock using heat pump technology. In these scenarios heat pumps can be used for both heating and cooling. Where local geology is not suitable, concrete or aggregate can be used as a storage medium.

Cryogenic storage uses liquid air or nitrogen to store energy. Slough power station is the first in the UK to implement cryogenic storage. The cryogenic system used at the Slough power station returns 50% of the energy put in but this increases to 70% when waste heat is used (KTR, 2011). Not all the energy is recovered. However, as the energy being used to store the power is surplus it has a lower cost attached to it. Cryogenic storage also has the advantages of being modular, scalable and portable (KTR, 2011). These benefits make the technology more able to be incorporated into a greater range of industrial processes. Furthermore, it can be used to store surplus energy from renewable generation.

One way of storing surplus electrical energy would be to divert it to an area that does not have an immediate demand, but where the use of the energy would be beneficial. For example, converting electrical energy to thermal energy for heating hot water. The Immersun is an example of a control device that is currently used on some domestic scale renewable installations - predominantly solar PV. The device directs excess energy to a designated load, normally a hot water tank (Immersun, 2015). This decreases energy export and, in this instance, reduces the need for gas or oil to power the boiler to heat the hot water. This technology, if further developed, could have industrial applications. It could be used to replace or boost heat processes that normally use gas or oil during times of excess electricity production.

Electrical battery storage can store surplus energy. However, costs are prohibitively high for mass deployment (AECOM, 2015). It is therefore important to identify where the price point of energy storage needs to be to make it commercially viable. There will also be a demand for trial projects to be run before large scale industry implementation. Trial projects provide important lessons that can be used to assist the key stakeholders including regulators, policy makers, manufacturers, installers and end users to make informed decisions (AECOM, 2015).

Tesla is currently an industry leader in developing battery storage. In 2016 Tesla will be trialling a 1MW pilot project in Ireland (Allen, 2015). One of the challenges of integrating large batteries into existing infrastructure is finding sufficient room to locate the technology. However, the utility-scale storage groups battery blocks together making it easily scalable (Allen, 2015). It would also be possible to have the batteries split up over more than one location although this would potentially increase installation costs.

Key issues with battery storage are battery life time (degradation), safety and cost (Chandler, 2015). However, research is being carried out to counter these. A solid state battery is being developed that lasts for hundreds of thousands of cycles with minimal degradation and no risk of combustion (Chandler, 2015). The current and future developments of battery storage could significantly impact on the decarbonisation of industry as safe, large scale, affordable batteries are developed.

For large scale industry that is suitably located, hydro pump-storage can act as a battery. This form of storage could reduce the cost of UK decarbonisation by £3.5 billion (Allen, 2015). The technology is not a new idea. Dinorwig power station in North Wales pumps water uphill at night when electricity is cheaper and releases it when there is peak demand during the day. The main barrier to this is the initial capital cost, although for existing systems like Dinorwig, they could invest in renewable technology to power the pumps.

The challenge to identifying the most suitable energy store for different industries is identifying which technology best suits the user's needs and budget. There is also an understandable reluctance to invest in niche technologies that are not widely proven. Government legislation and incentives can help to drive change.

Methodology

Research question

- How and to what extent can the use of solar and waste heat recovery technologies in industrial premises decarbonise the economy of an industrialised nation?

Project aim

- To demonstrate that solar and waste heat recovery technologies can make a positive contribution to the decarbonisation of industry.

Objectives

- Identify, through a review of academic, government and industry literature, the different options for heat recovery, how they can be and / or have been applied, and their effectiveness in terms of energy and carbon reduction.
- Identify, through a review of academic, government and industry literature, the different options for solar, how they can be and / or have been applied, and their effectiveness in terms of energy and carbon reduction.
- Identify the potential extent waste heat recovery and solar could decarbonise UK industry.
- Identify if waste heat and excess electrical energy generated from solar is worth capturing.
- Analyse the impact an installed solar PV system has had on a large distribution centre.
- Identify if the waste heat from the inverters is worth recovering.

Method

A review of academic journals and government papers, alongside other relevant sources, has been carried out, as shown above. Different heat recovery technologies alongside their applications and impacts are identified and examples of industries that have incorporated these technologies into their operational processes are used to demonstrate their effectiveness. The review has also been used to identify the current uptake and future potential of solar technology with the focus on solar PV. The drivers and barriers of solar and waste heat recovery have been identified as these can affect the implementation of these technologies by industry. Energy storage has also been investigated to identify whether it is a viable option for maximising the benefits of solar and waste heat recovery by storing surplus energy at times of peak production.

To demonstrate the effectiveness of an installed solar PV system, a case study on a 2MWp solar PV system that was installed on Wolseley UK's National Distribution Centre in Leamington Spa has been used. Wolseley makes a good case study. 7% of employed people work in the logistics and warehousing sector, which is very competitive (DfT, 2011). Reducing energy consumption of this sector could therefore significantly contribute to the overall decarbonisation of UK industry as well as improving competitiveness. Furthermore, the waste heat from the inverters, which converts direct current to alternating current, has been captured, demonstrating how solar PV and waste heat recovery can be combined to reduce carbon emissions. Wolseley has also maintained clear records of electricity consumption prior to and after the solar PV install.

The following data has been provided by Wolseley UK:

- Two year’s worth of half hourly electricity consumption data prior to the solar PV being installed
- Over one year's worth of half hourly electricity consumption data after solar PV was installed
- The available data on the measured solar PV export to the grid
- The available data on the total generation of the solar PV system

Having at least 12 months worth of data prior to the solar PV install and 12 months after the solar PV install was important. If a smaller data set had been used, any conclusions would be less valid as solar PV generation is affected by seasonal trends. Furthermore having half hourly data enabled the data set to be analysed at a high level, reviewing monthly and annual averages as well as in detail, identifying daily trends.

To identify the extent solar PV installation has helped Wolseley UK's National Distribution Centre (NDC) to reduce their carbon emissions, the data (provided in Appendix 2) was first separated as the solar PV was split over Buildings A and B. For each building the following data was collated from the different meter readings provided by Wolseley:

- Half hourly imported electricity readings (Appendix 2, tabs 1 & 2)
- Daily exported electricity readings (Appendix 2, tabs 3, 4 & 5)
- Half hourly solar PV generation readings (Appendix 2, tabs 8 & 9)

The following data sets were then extracted:

- Annual average daily load profile (Appendix 2, tab 6)
- Detailed half hourly import profiles for specific months and days (Appendix 2, tab 7)
- Daily average import versus export profiles for each month (Appendix 2, tabs 10 & 11)

These data sets were then converted to graphs to identify the amount of electricity generated by the solar PV array, the impact it was having on Wolseley's imported electricity and to demonstrate how much electricity was being exported. The impact of weather and the seasons will also be identifiable.

The data is also used to identify how much energy could be saved if battery storage is implemented. Furthermore, different payback times were selected and this was used to put a price point on what the energy storage would cost. This was done by calculating the value of the exported electricity. The minimum value of the surplus electricity was calculated by subtracting the export value from import value of the generated electricity and the maximum value was set at that of the import value. Payback was set at 3 years and 5 years and set at 100%, 75%, and 50% and 25% surplus electricity storage. The calculations are in Appendix 2 tab 12.

Waste heat is recovered from the inverters and diverted to the buildings' air handling units. Given that most waste heat is likely to be produced in the summer, it is important to identify if the waste heat is really worth capturing. To identify the benefit of this the potential of the waste heat recovered was calculated based on the efficiency of the inverters and their output over the year. It was assumed that all energy lost was heat and that it was all captured. The value of the waste heat and the carbon savings are based on the captured waste heat reducing heat demand that was previously fuelled by electricity. The calculations are in Appendix 2 tab 13. These figures would alter with different fuel types.

Case study - Wolseley

The 2MW install of solar PV at Wolseley UK's NDC and its impact on decarbonising business operations forms the main case study of this paper. Wolseley is an international distributor of plumbing and heating products and a supplier of building materials (Wolseley, 2014). Wolseley is committed to developing sustainable business practices and its UK National Distribution Centre

(NDC) is a prime example of what steps can be taken to reduce the environmental impact of a large organisation. As well as having a zero waste to landfill policy in operation, Wolseley UK has had a 2MW solar PV system installed and achieved a BREEAM rating of Excellent (Wolseley, 2014).

The aim of this case study is to demonstrate the extent an operational solar PV system has had on decarbonising an industrial scale operation in the UK. Wolseley has been selected for use as a case study for the following reasons:

- Its building portfolio matches the category of which the UK Government wishes to target for the installation of commercial on-roof solar PV.
- It has kept and provided access to its half hourly imported electricity meter readings for 2 years prior to the installation of solar PV.
- It has had a medium to large scale solar PV system installed.
- The solar PV system has been operational for over 12 months.

The data for this study was provided by Wolseley UK. The data spanned from 2012 to 2015 and was collated from:

- Half hourly imported electricity readings.
- Half hourly solar PV generation readings.
- Daily exported electricity readings.

The solar chapter discussed drivers. Some of the key drivers for Wolseley in investing in solar PV were:

- The company was investing in new, energy intensive equipment.
- The continued increases in the cost of energy.
- Corporate image: some of Wolseley's product lines included renewable technology. Installing solar PV would demonstrate confidence and belief in their product lines and provide the opportunity to showcase the renewable technology that the organisation promoted and sold.

The author of this paper was one of two lead designers on this project and was involved in completing detailed survey work of the premises, estimating project costs, generation yield and payback and final design.

Wolseley NDC system design

It is important for the organisation to have a clear objective and design brief so that the solar PV designer understands clearly what the client is trying to achieve. This affects the design approach and ensures production of a suitable and efficient design that meets the client's needs. Wolseley outlined the following parameters:

- The solar PV system was to supply sufficient electricity to negate the load of new infrastructure with a load of 500kW.
- The solar PV system would need to reduce their carbon emissions.
- Preferred payback of approximately 5 years.
- The export of electricity to the grid was to be minimised to maximise system effectiveness and financial return.

The challenge for the design team was designing a solar PV system that would ensure as much of the energy produced would be available for consumption on site with little or no export. The array was to be split over two units, each with its own electricity supply. As shown in Figure 6 the two buildings are joined by a bridge and Building B (with the smaller roof area) had the higher electricity load of the two. In order to maximise the usage of the energy produced by the solar PV array 1,906 (out of 4026) of the panels on Building A were connected into Building B by running cables over the bridge. This meant that:

- o Building A utilised 0.53MW from the solar PV array
- o Building B utilised 1.49MW from the solar PV array

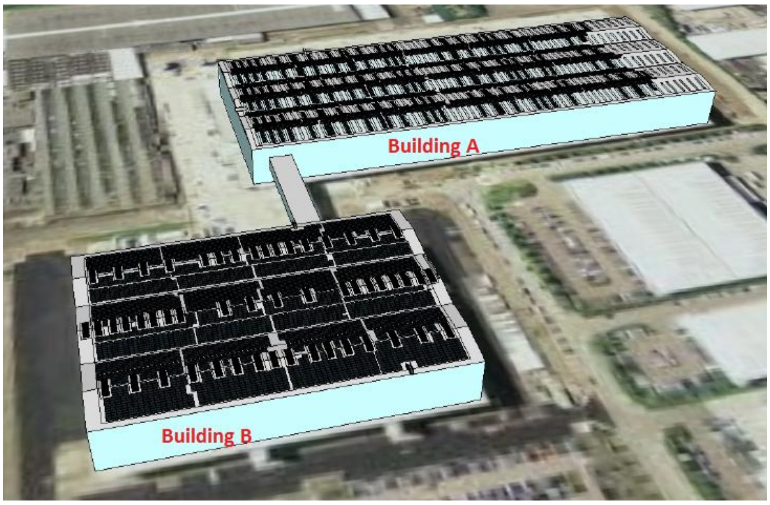

Figure 6: Sketch of Building A and B with an solar PV array on Wolseley's NDC

Maximising the use of the electricity generated by the solar PV was important to Wolseley from an economic standpoint. Based on an export tariff of £0.0485, and an approximate import rate of £0.12, the price to import electricity is much higher than what is received for exporting electricity. Therefore, the more renewable generated electricity used on site the quicker the system will pay for itself.

It was also identified that the inverters used to convert DC electricity to AC electricity emitted heat. The inverters in both buildings were located in close proximity to the buildings' respective air handling units. Therefore, after consultation with the inverter manufacturer and heating and ducting engineers, it was decided to duct the waste heat emitted from the inverters into the air handling units as shown in Figures 7 and 8. This would reduce heating requirements. To the author's best knowledge this was an industry first.

Figure 7: Showing the inverters and duct work in Building B

Figure 8: Showing duct work and the air handling unit

Results and analysis

For Wolseley, as with most companies, the forecasted financial payback and carbon reduction are critical to senior management when deciding on whether the proposed project meets their requirements. There is different software available on the market for simulating these figures, for example, PVSol. PVSol is an excellent tool. It uses historical climatic data and modelled data from the MeteoSyn climate database. It can also factor in different makes and manufacturers of module and inverter performance as well as cable losses and various other specific system losses for a particular solar PV system. This is a useful tool for system designers; however, for direct comparison the method used for predicting yield will be the one outlined in Guide to the installation of solar PV systems (MCS, 2012).

The MCS 2012 calculation takes location into account and is relatively straight forward, meaning that non-experts of PV can understand the methodology and even carry out the calculations themselves. When a company is considering in investing in a decarbonisation through renewables, understanding how the forecasted figures were calculated is important as it gives the decision makers confidence that no exaggeration of results has occurred. It gives transparency.

This first section of data analysis demonstrates what the simulated yield of the 2MW system at Wolseley is and compares it to what the actual annual yield is. This is important as it demonstrates how accurate the simulation can be in assessing the extent to which solar PV can decarbonise an industry. It is also important that future investors have confidence that the simulation calculations are reliable.

	System Size	Cost (inc. VAT)	*kWh/yr	CO2e saving kg/yr	**Year 1 FIT (Generation)	**Year 1 FiT (Export)	**Year 1 Saving (Electricity)	20 Year FiT & Export Payments	20 Year Electricity Saving	**Year 1 Total Financial Benefit	***Complex Payback (yrs)	***IRR (%)
Estimated	2MWp	£2,000,000.00	1586207	767042	£117,537.94	£15,386.21	£152,275.87	£2,950,051.15	£1,161,005.15	£285,200.02	7.01	16.26%
Actual	2MWp	£2,000,000.00	1766996	854466	£130,934.42	£25,709.80	£148,427.69	£3,299,314.44	£1,939,997.50	£305,071.90	6.56	17.33%

*"The performance of solar PV systems is impossible to predict with certainty due to the variability in the amount of solar radiation (sunlight) from location to location and from year to year. This estimate is based upon the standard MCS 2012 procedure and is given as guidance only. It should not be considered as a guarantee of performance."

** figure for first year only as degradation of the module will occur

***Assumptions	
Annual Performance degradation	0.80%
% of electricity exported (estimated)	20 %
% of electricity exported (actual)	30 %
General inflation per annum	3%
Electricity inflation per annum	5%
Export inflation per annum	3%
FiT rate >250kW	£0.0741
Cost of electricity (present)	£0.1200
Export price (present)	£0.0485
Location - Leamington Spa	
Roof Pitch	6
Azimuth	85 / -95

Table 3: Summary of estimated financial and carbon saving performance against actual

(*Please note the cost of the solar PV system used is not the price Wolseley paid. This information is commercially sensitive. Instead a guide price is used based on current industry rates of £1.00/Wp for larger systems*)

The data in Table 3 and below was calculated using the calculation described in MCS 2012. The following yields are predicted:

- Building A - 530kWp solar PV system will have an estimated yield of 419,230kWh/yr
- Building B - 1484.95kWp solar PV system will have an estimated yield of 1,166,797kWh/yr
- Total estimated yield = 1,586,026kWh/yr

Reviewing the generation meter data provided by Wolseley, the actual annual yields are as follows:

- Building A - 530kWp solar PV system (01/05/14 - 30/04/15) generated 436,172.5kWh
- Building B - 1484.95kWp solar PV system (01/05/14 - 30/04/15) generated 1,330,823.5kWh
- Total generation (2014/2015) = 1,766,996 kWh

Comparing Wolseley's actual annual yield from the solar PV to the estimated yield shows that the installed solar PV array performed approximately 11% better than the MCS calculated yield. Given the variety of factors that can affect the output of a system including weather, selected equipment and the different possible system configurations, this difference is tolerable. This demonstrates that the MCS calculation does provide a reasonably reliable, albeit conservative, indicative figure of potential yield. As long term future weather cannot be predicted, it is never possible to be certain and over the next year, if the weather is particularly bad, the yield may drop below the MCS calculated yield. However, over the longer period of time it is expected that the system will perform relatively consistently.

An important figure in Table 3 is the actual 20 year electricity saving of £1,939,997 (inflation of 5% per year has been factored in to the calculation). This figure is very close to the cost of the system and suggests that the system is potentially capable of paying for itself within its lifetime. This is particularly true if electricity price inflation is greater than 5% per annum. Degradation of the modules has also been factored in to prevent the figures being overestimated. Furthermore, as Figures 9 and 10 demonstrate, based on the current FiT incentive, export tariff and electricity savings, the system will pay for itself four times over in a twenty year time span. While the payback is more than 5 years, the financial return alone is a significant incentive.

It is prudent to allow a percentage of the revenue from the solar PV generation to be ring-fenced to cover the cost of any replacement parts. Traditionally, the most likely and costly failure to occur is the inverters. However, inverters' reliability has improved over time and some manufacturers provide twenty year warranties. Furthermore, the inverters used at Wolseley are serviceable on site with components that, if damaged, can be replaced. Therefore, it is unlikely that a whole inverter would ever need replacing, reducing potential costs.

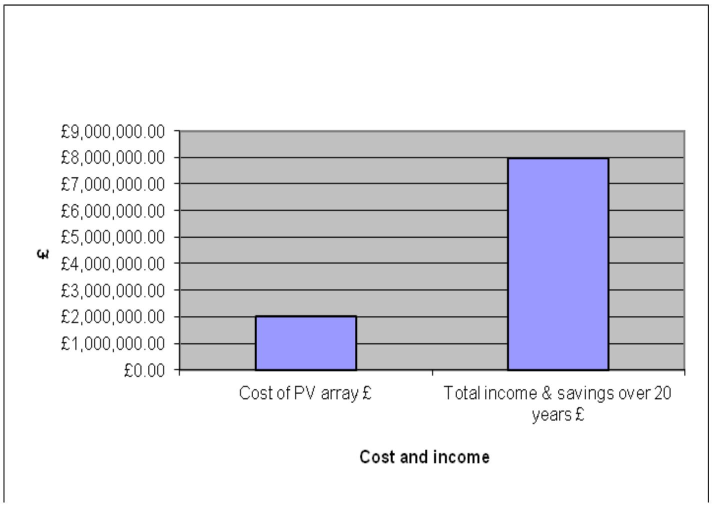

Figure 9: Cost of PV array against total income and savings over 20 years estimated

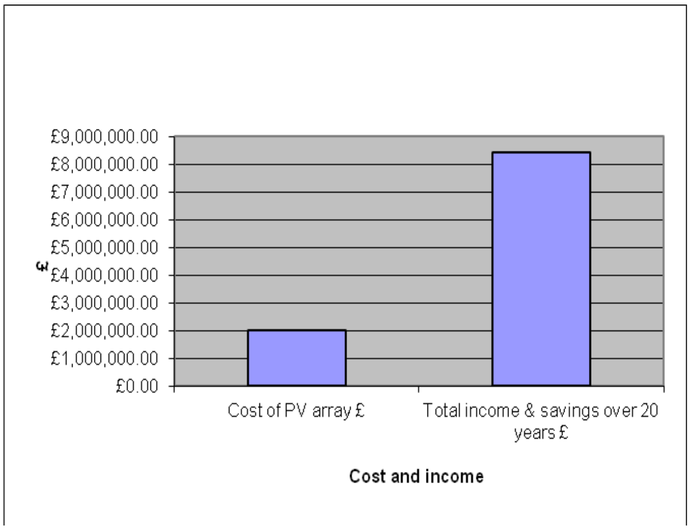

Figure 10: Cost of PV array against total income and savings over 20 years actual

Wolseley's first year's results demonstrate that investing in large scale roof top solar PV can prove to be a sound investment. This is significant because many companies would like to become more energy efficient, but, for investment purposes, a guarantee of a reliable rate of return is required.

For industries looking to become more sustainable, reducing carbon emissions is important. Grid electricity emits 0.48357kgCO_2e/kWh (DEFRA, 2013). Solar PV can, therefore, contribute to reducing carbon emissions. Even where electricity is exported it is supplying zero carbon electricity to the national grid and offsetting the carbon from imported electricity produced from non-renewable sources. Table 3 used the figure 0.48357kgCO_2e/kWh to calculate the carbon savings for 1 year's solar PV generation at Wolseley with a total saving equalling 854,466 kgCO_2e. As Figure 11 shows, this figure will decline each year, due to degradation of the panels; the cumulative total reduction over twenty years extrapolated from Wolseley's first year data is 15,952,887kgCO_2e. Even after twenty years, the solar PV array will still have a significant impact on reducing the carbon emissions of Wolseley UK's NDC.

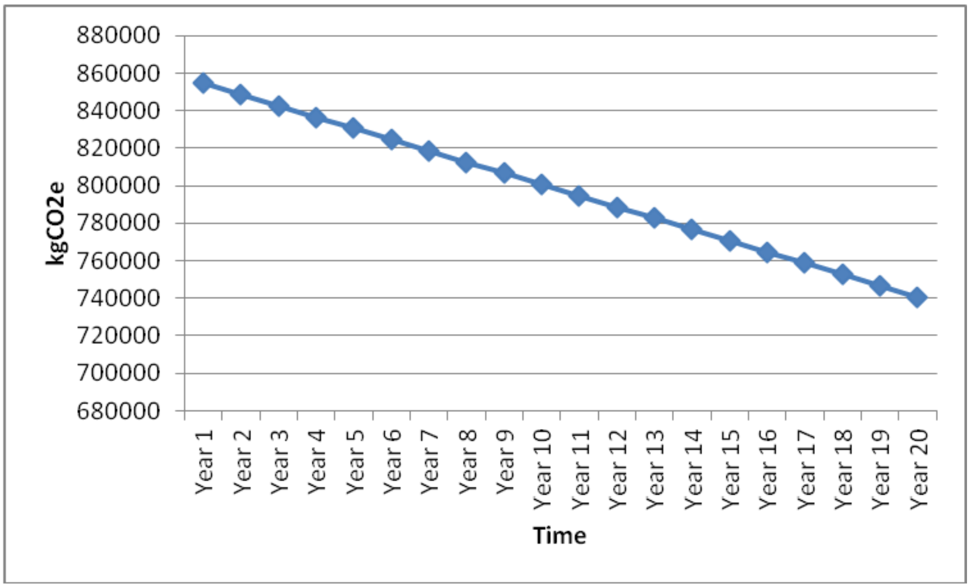

Figure 11: Predicted carbon savings of 2MW system at Wolseley over twenty years, allowing 0.8% degradation factor per year, based on Wolseley's first year's yield

The headline figures from the Wolseley case study, discussed above, demonstrates definitively that significant financial and carbon savings can be made by industrial premises that install solar PV. However, the next part of this section investigates the potential to further increase the carbon and financial savings. Identifying ways solar PV system performance can be optimised through proper design and install, as well as how an organisation makes use of the electricity generated by the solar PV array, could further improve the positive environmental impact of the solar PV install.

The 2MW array is split over two buildings, with each building having its own main supply and import / export and generation meter. The data from the two buildings will be analysed side by side. This will show the scalability of solar PV as a technology and allows for an element of comparison between two different systems in the same location. The solar PV system was commissioned and became operational in April 2014.

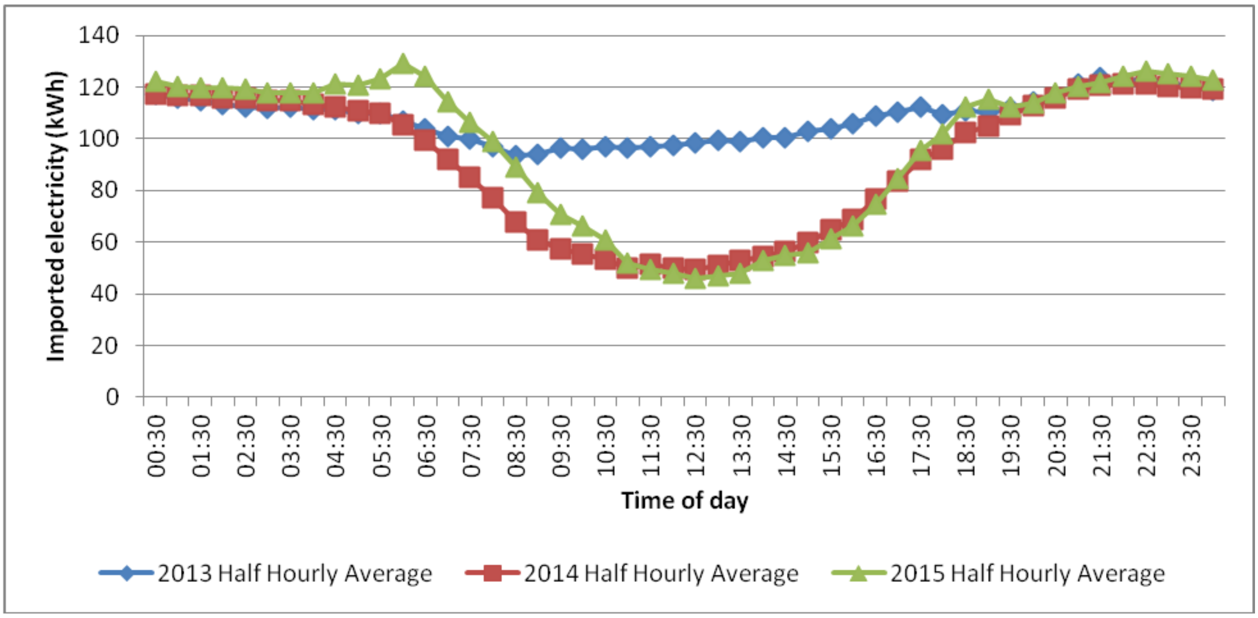

Figure 12: Graph of average annual half hourly imported electricity for Building A

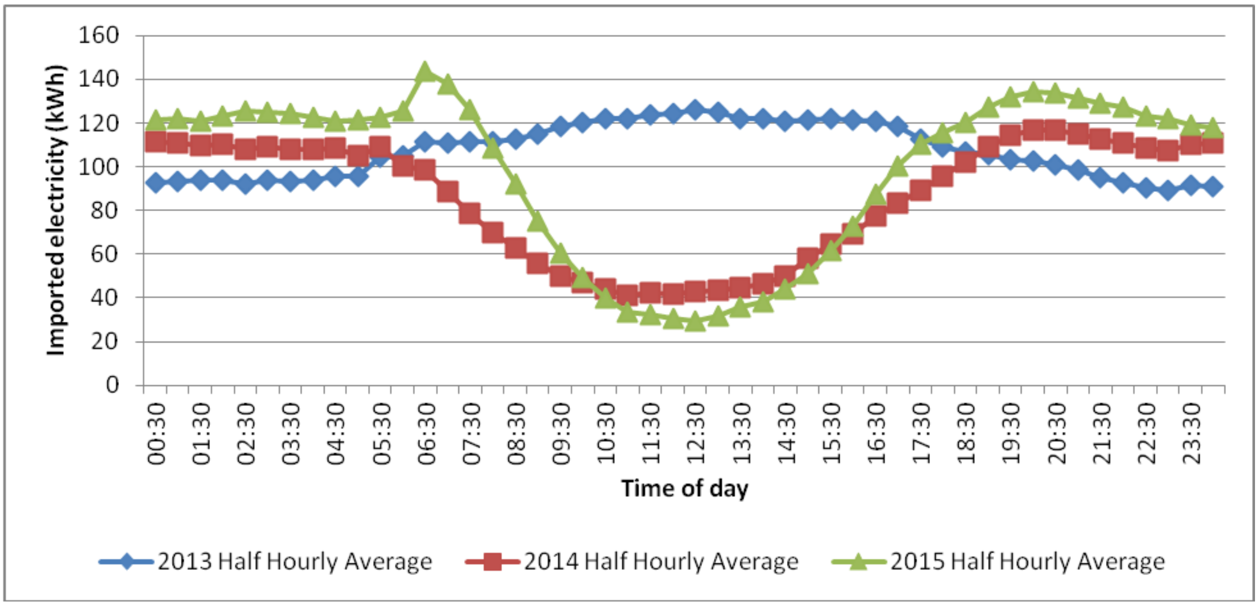

Figure 13: Graph of average annual half hourly imported electricity for Building B

Figures 12 and 13 show that the half hourly loads for 2013, prior to the solar PV install, were relatively flat. Building A's 2013 load profile mostly falls between 100 & 120kWh and does gradually dip towards noon before gradually increasing again. This could be attributed to less lighting being used during daylight hours. Building B's load profile falls between a slightly larger range of 90 & 125kWh and gradually increases towards midday before gradually declining. This suggests that this is where more machine based activity happens that is used during the normal working day.

Figures 12 and 13 show the impact of the solar PV install on each building's 2014 load profile. The solar PV increasingly reduces imported electricity requirements from morning to noon before its impact gradually decreases towards evening. The solar PV array powering Building B is approximately 3 times larger than that powering Building A. However, the imported electricity of Building B only appears to decrease slightly more than that of A. This is partly because the load is higher during the day in Building B than that of A (based on 2013 load prior to the solar PV install).

Comparing the midday load between 2013 and 2014 for Buildings A and B shows that the difference is approximately double for Building B. However, as the solar PV array feeding Building B is three times larger than the array feeding Building A, a greater difference would be expected. Reviewing the night time data for Building B, when the solar PV array is not operational, the load has increased for both 2014 and 2015. Building A on the other hand has a very similar night time load for all three years. This demonstrates an increase in Building B's load. This is due to new equipment in Building B with a full capacity load of 500kW that became operational at approximately the same time as the solar PV.

Figures 12 and 13 have demonstrated the impact the solar PV is having on reducing imported electricity and the associated carbon emissions. The sizing of the solar PV array for each building appears to have been correctly judged as the 2014 load profiles are close matches. If Building A had been the one with the greater amount of solar PV installed, then it may not have used the energy generated as effectively as Building B. Matching energy generation to building load and vice versa is important for the consumer to maximise the benefits of zero-carbon electricity.

Matching the seasonal performance of the solar PV array to the operational processes is difficult. Solar PV generation peaks in summer and dips in winter due to:

- more sunshine hours in summer than winter
- less daily cloud cover in summer than winter
- the sun is higher in the sky in summer than winter

Figures 14 and 15 show the seasonal effect. To represent seasonal change June is selected as it is the month with the longest daylight hours. December is selected as it is the month with the shortest daylight hours. A clear indicator of seasonal change should be visible.

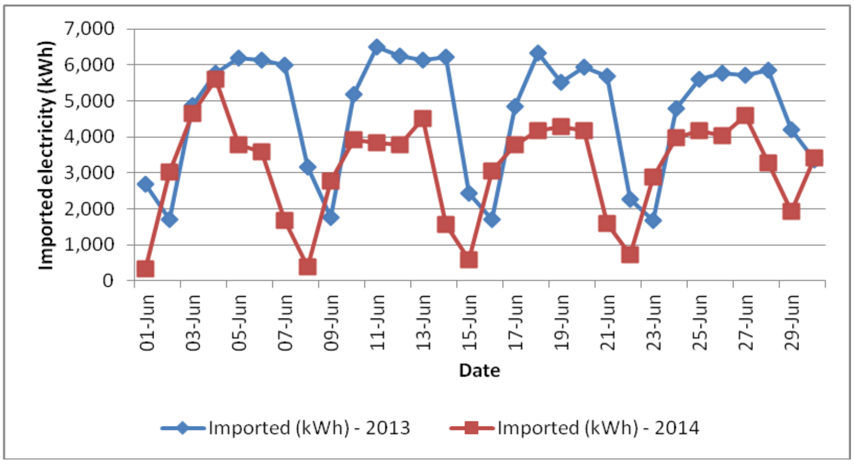

Figure 14: Graph of Building A daily imported electricity for June

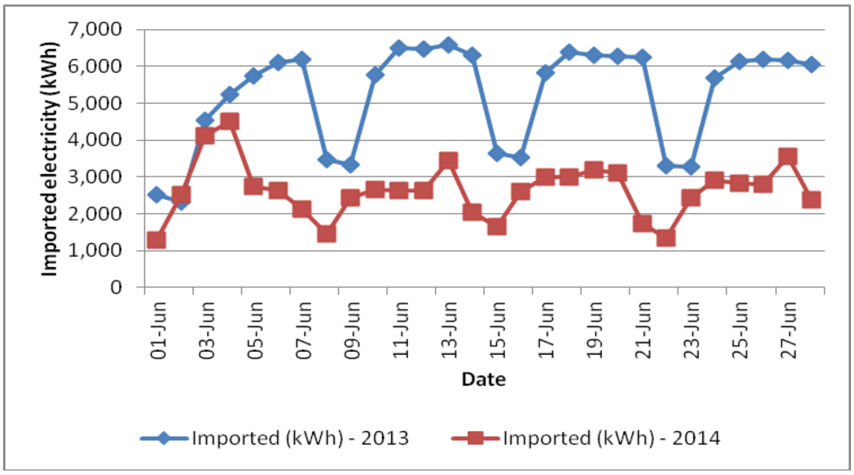

Figure 15: Graph of Building B daily imported electricity for June

Figures 14 and 15 demonstrate the significant impact the solar PV array has on reducing the imported grid electricity during June, for Buildings A and B. The second and third days of June on both graphs show that the array has less impact on these days compared with the rest of the month. This could be due to cloudier weather on these days. Furthermore, during the weekends very little electricity import is required. There may be an opportunity to identify processes that could operate during the weekend, instead of during the week, to take advantage of the decreased energy costs.

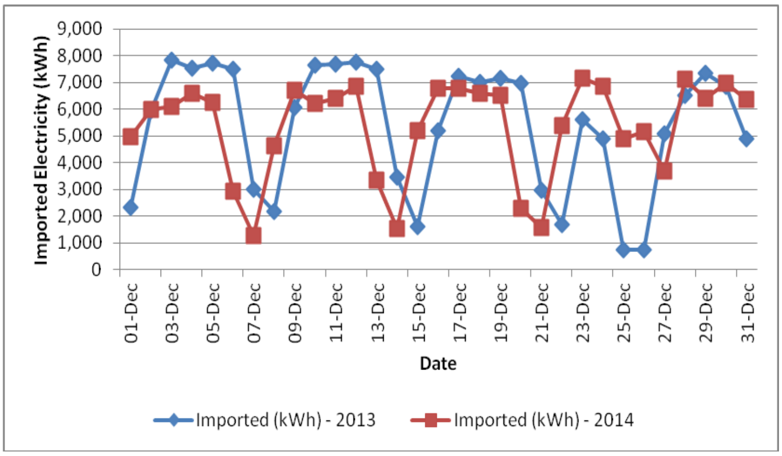

Figure 16: Graph of Building A daily imported electricity for December

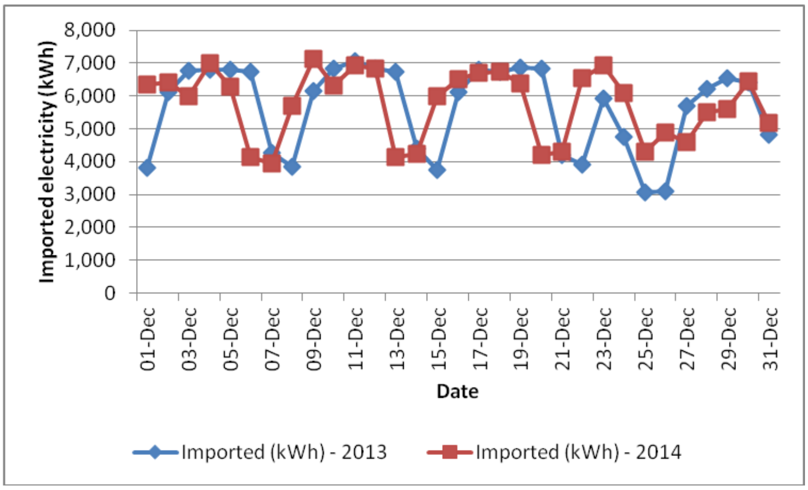

Figure 17: Graph of Building B daily imported electricity for December

Figures 16 and 17 for December show that the solar PV array is having little to no impact on daily consumption. This demonstrates the seasonal effect when compared with Figures 14 and 15 for June. Some industries will have a seasonal variation to their loads. If an industry has increased cooling demands in summer, for example air conditioning or refrigeration, then using solar PV as a source of energy would be more effective at reducing their grid import consumption than an industry whose loads were higher in the winter, i.e., they use electric heating.

Each data point on Figures 14 to 17 shows the total electricity imported over a 24 hour period. Solar PV only operates during daylight hours. Due to there being fewer daylight hours in December the solar PV is operational for fewer hours of the day compared with June, which is why Figures 16 and 17 suggest the solar PV is having little impact. It will, however, be having an impact during daylight hours. Furthermore, the demand profile of a building may change significantly during the day, and it may be possible to alter the timing of high energy processes throughout the day to make the best use of the energy generated.

Half hourly graphs of one day's imported electricity can provide more granularity into the impact the solar PV array is having. The following graphs show half hourly import readings for three days in June 2014 and December 2014. The three days selected were during the second week of each month and are the highest import day, lowest import day and the median import day of that week.

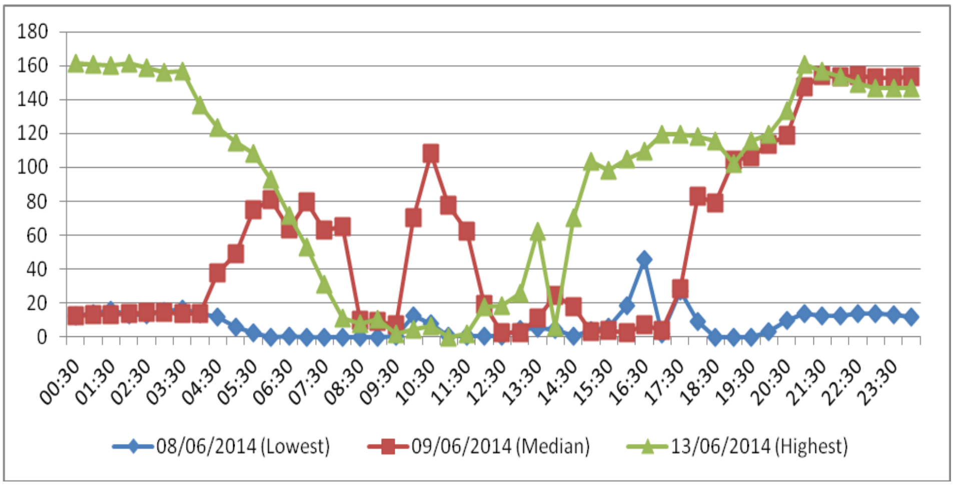

Figure 18: Graph of Building A Imported half hourly import readings for 3 days of June

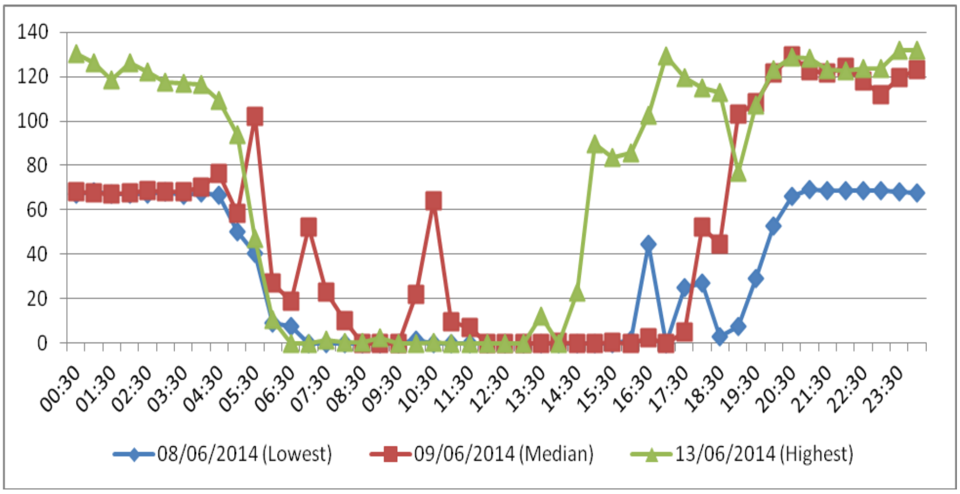

Figure 19: Graph of Building B Imported half hourly import readings for 3 days of June

Figure 18 demonstrates that the lowest import day has little or no electricity imported into Building A between 06:00 and 20:00. Figure 19 has a similar profile but Building B's import starts increasing earlier. This is because the solar PV system generates less electricity at the end of the day and the large load of Building B means grid electricity is required sooner. The matching spike around 16:30 on both graphs indicates that the cause is most likely to be a cloudy spell.

The median lines for Figures 18 and 19 follow a similar trend. The peaks on Building A are larger, likely because the array is smaller and so a reduction in output is more likely to result in an increase in demand for grid electricity sooner. Where the peaks between the graphs don't match it is more likely that the cause is due to an electricity demand fluctuation within the building.

For Figures 18 and 19 the lowest and median profiles are relatively low between 00:00 and 04:30 but the highest is considerably higher during this time. The solar PV array is not generating during this time, so to reduce the loading on the highest import days, the processes that are increasing energy use can, if possible, be moved to daylight hours. If unavoidable peak loads occur outside of daylight hours then energy storage could be beneficial.

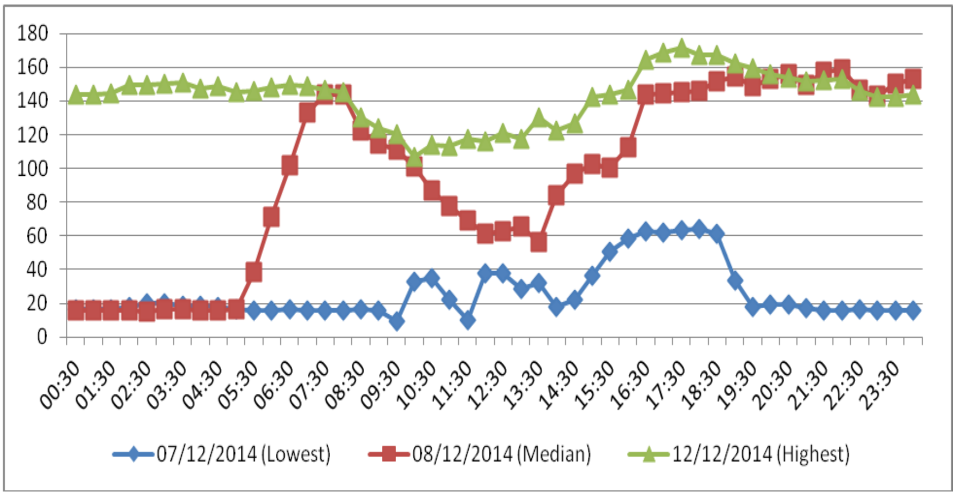

Figure 20: Graph of Building A Imported half hourly import readings for 3 days of December

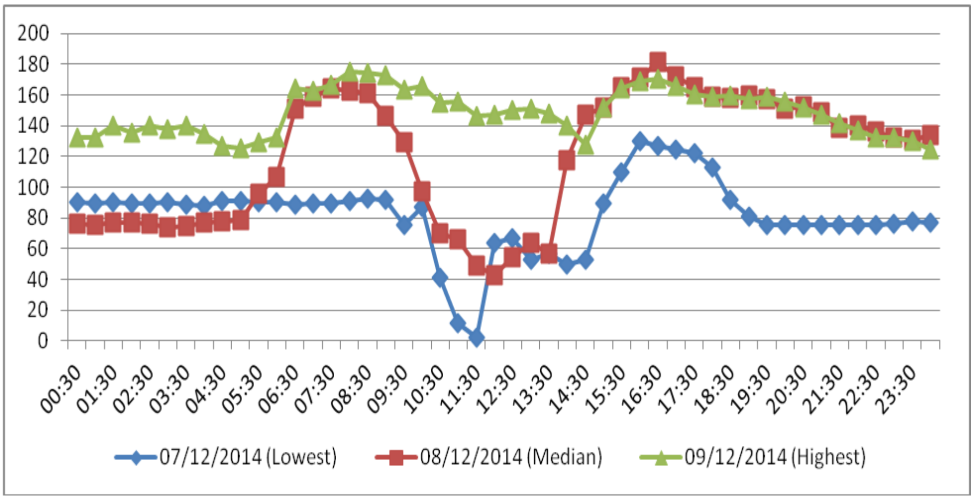

Figure 21: Graph of Building B Imported half hourly import readings for 3 days of December

As identified earlier, solar PV is least effective in December. However, unlike Figures 16 and 17, Figures 20 and 21 show that the solar PV is having an effect on the amount of electricity being imported. The effect is more pronounced in Building B due to it being the larger system. The lowest profile for Building A does not have any clear dip in import though the import is lower during the middle of the day than late afternoon. Therefore, for Building A, the energy intensive processes could be timed to be spread more evenly over the day.

The solar PV has positively impacted on the load profiles of Buildings A and B and, therefore, has effectively decreased the imported carbon emissions associated with grid electricity. However, the import load profile can fluctuate significantly during the day due to weather conditions. Seasonal variation results in the solar PV having a greater impact on the load profile during the summer months. If the intermittent generation could be smoothed out then it would enable Wolseley to better match their processes to take advantage of the solar PV generated electricity.

The import data does not show how much electricity is being generated by the solar PV array or how much electricity is being exported. This data can identify how much carbon free electricity is being produced, contributing to the total decarbonisation figure for the installed solar PV array. It can also demonstrate how much electricity is not being used on site. When export is occurring at regular times, internal processes could be altered to utilise the surplus. Furthermore, the data can be used to determine if electricity storage could be a cost effective solution. Therefore, the next section of the data analysis will review generation and export data to determine the current and potential extent to which the solar PV array could help to further Wolseley's decarbonisation.

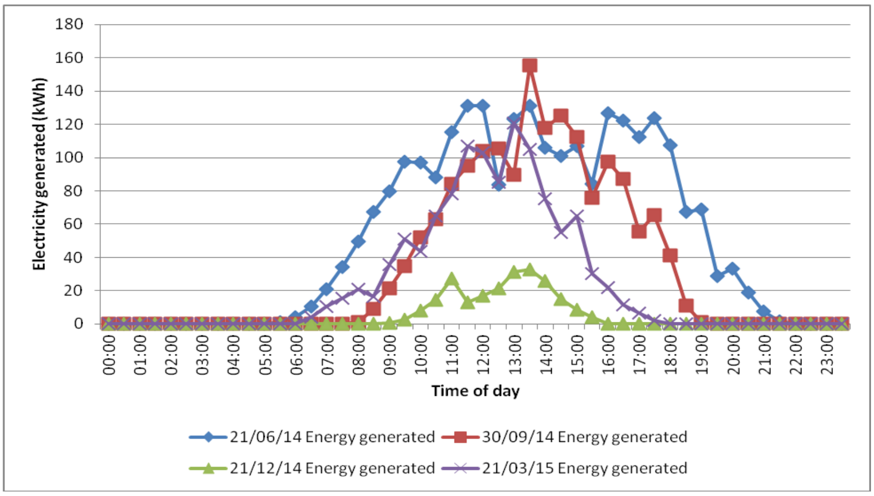

Figure 22: Graph of Building A Shows half hourly solar PV generation readings from 4 different days during the year

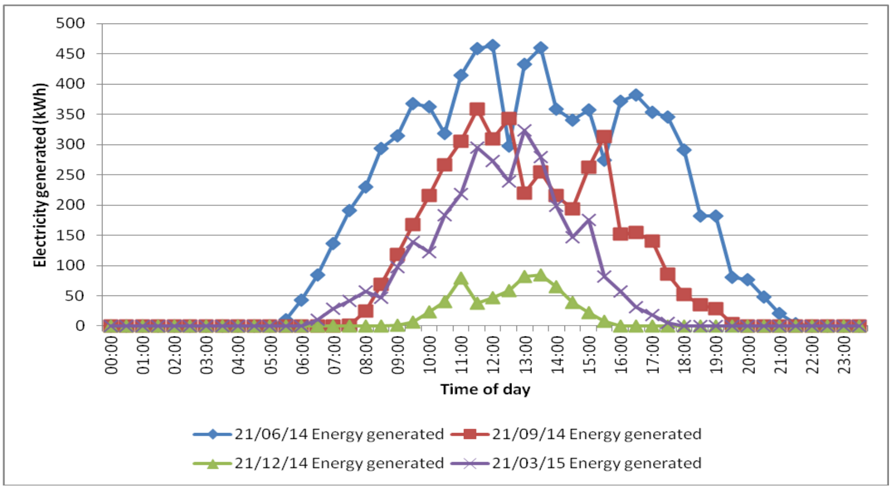

Figure 23: Graph of Building B shows half hourly solar PV generation readings from 4 different days during the year

Figures 22 and 23 demonstrate a clear trend: generation rapidly increases from dawn to between 10am and 11am where it then fluctuates, depending on weather, peaks at noon and then declines again towards evening. The seasonal effect is demonstrated by the time of generation start up and end being greater in the summer, less in the winter and falling in the middle during the equinox months. These graphs correlate with the import load profiles. The import load profiles show a u shape, with import decreasing towards midday before rising, which is clearly a result of the solar PV generation shown above following an n shape with generation peaking at noon and then declining towards evening. For Wolseley to make the most of the solar PV array its most energy intense operations should occur between the hours of 10am and 4pm. These hours could be extended in the summer.

An advantage of Wolseley's solar PV system is that it is split, relatively equally over east and west facing roofs. While less electricity may be generated around mid-day compared to an equivalent south facing system, the east and west orientations mean that the array will start generating earlier in the day and stop generating later in the day. Matching internal processes to solar PV generation is key to maximising payback of the system and reducing reliance on imported grid electricity with its associated carbon emissions. However, as the graphs show energy generated by the solar PV array only occurs during daylight hours and can fluctuate, making this challenging. Unless the solar PV array is undersized, so that generation never exceeds demand, there will always be electricity exported. However, it is difficult to calculate exactly how much electricity will be exported until an array is installed.

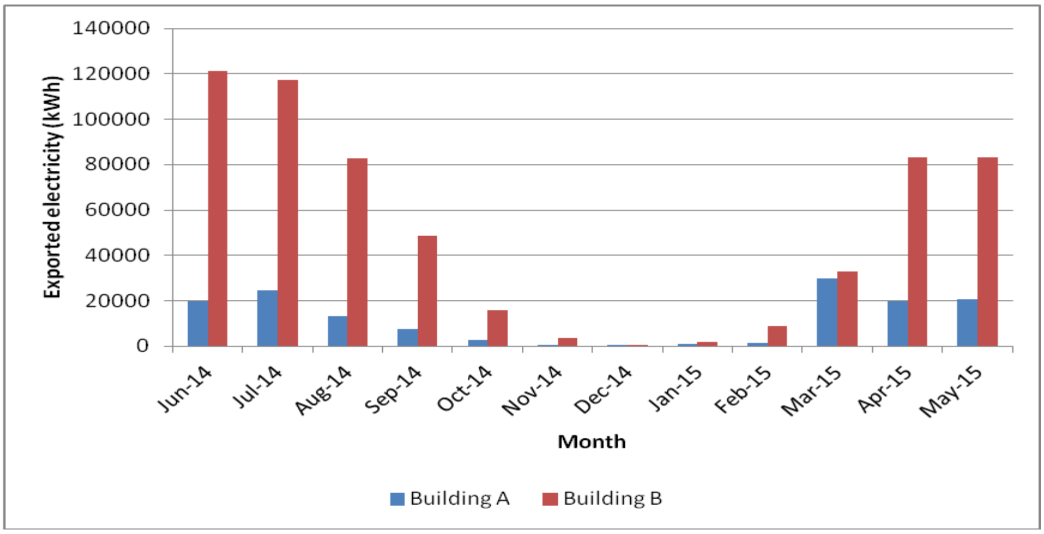

Figure 24: Graph of monthly total export figures for Building A and B

Figure 24 shows that a significant amount of electricity generated by the solar PV array is exported, particularly on Building B. Most of the electricy export occurs between March and September with April to July being particularly high. The system is effectively “over-sized” in summer, however, its minimal export in the winter months suggests that actually the system has been appropriately sized. In its lower production months there is little loss to the grid. Just enough is being lost to suggest it is effectively contributing to a reduction in the baseload demand. As production of electricity occurs only during daylight hours and the summer months in particular have such high export levels, electricity storage could significantly reduce the buildings' reliance on imported electricity. The stored electricity could be used to meet electricity demand at night and during poor weather conditions.

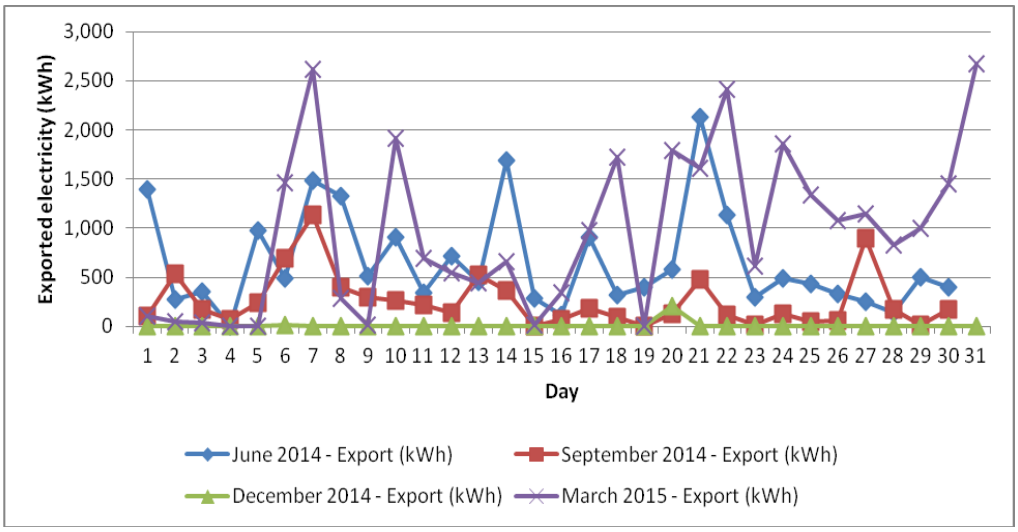

Figure 25: Graph of Export readings for Building A for 4 days of the year

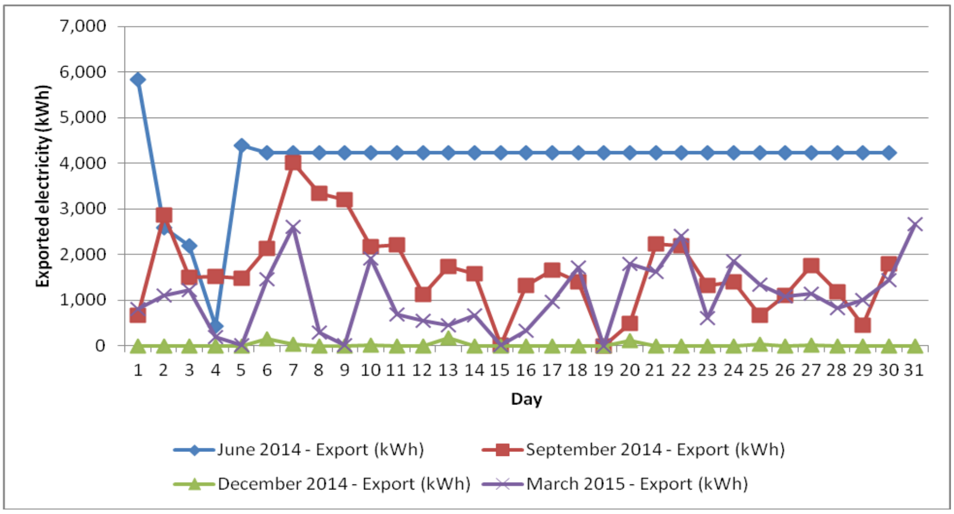

Figure 26: Graph of Export readings for Building B for 4 days of the year

If Wolseley is to consider using energy storage, the next step is to identify the size of the battery needed and whether it is economically feasible. Figures 25 and 26 show that the amount of electricity exported to the grid can vary significantly on a day by day basis. However, on Building B the amount exported is the same for every day from 5th to 30th June. While it may have been a good weather month, the likelihood of the export figure being identical every day, is, while not impossible, very unlikely, suggesting there may have been a temporary technical glitch with the data recording. Understanding the fluctuations in export on a daily basis is important when energy storage is being considered.

Figure 24 shows that the months where the greatest export occurs are April to August. It is logical to size the storage capacity to these months. Ideally the battery will be charged during daylight hours and discharged during night time, to reduce wear on the battery.

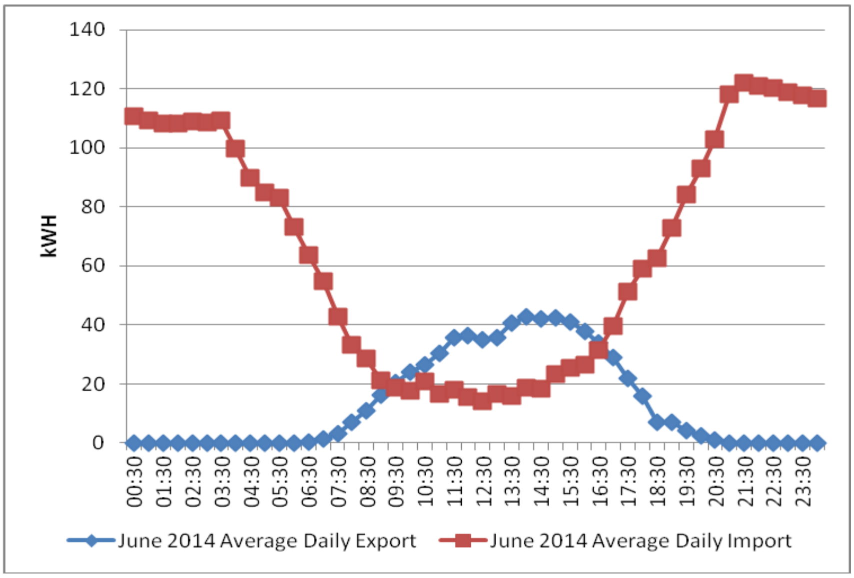

Figure 27: Graph of Building A electricity export v import

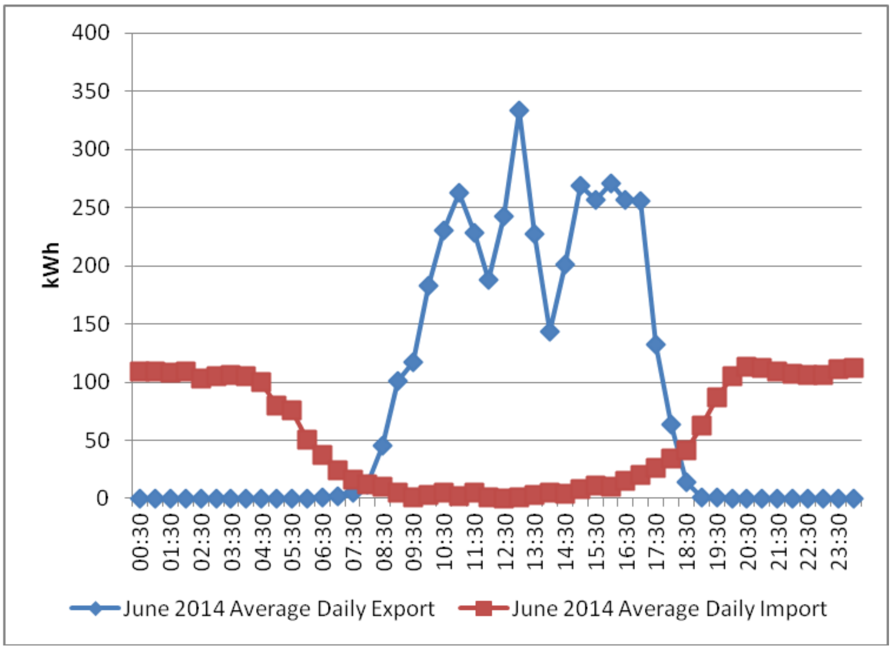

Figure 28: Graph of Building B electricity export v import

For Building A, Figure 27 clearly shows that more energy is imported than exported on average each day with 3136kWh being imported versus 788kWh being exported. Therefore, a maximum storage size of 800kW for Building A in June would be sufficient to store the majority of the surplus energy, and it would be used within 24 hours. However, Building B has the larger system and Figure 28 shows considerably more energy is exported. The average daily import of electricity is only 2596kWh compared to 4044kWh being exported. If the average monthly import is 2596kWh X 30 = 77,880kWh and the average monthly export is 4044kWh X 30 = 121,320 and all the surplus energy was stored to negate the need for imported electricity there would still be a surplus of 121320kWh - 77880kWh = 43,440kWh of electricity.

Based on the results discussed above (acknowledging that June and July are the highest export months), the following approach for Building A is proposed. For Building A battery storage is designed for daily charge and discharge as all the stored electricity can be used over a 24 hour period. To account for: 1. a gradual decrease in performance of the solar PV array; 2. the fluctuating generation of the solar PV array during the day; and 3. to ensure that the battery can receive more than a 50% charge during the primary producing months, it would be logical to size the battery based on the average export between March and August which is approximately 700kWh.

For Building B a seasonal approach could be considered with large scale battery storage which is designed for seasonal charge and discharge. This will mean minimal, if any, energy will be exported to the grid even in June and July. Figure 29 shows that in June and July more energy is exported than imported on average each day and in August there is only a small difference between import and export. Therefore the surplus energy stored over the summer months could considerably reduce import requirements in the autumn to winter months. The battery size would need to be large enough to accomadate the June and July surplus of approximately 238,810kWh. This would be sufficient to meet more than one month's energy requirement.

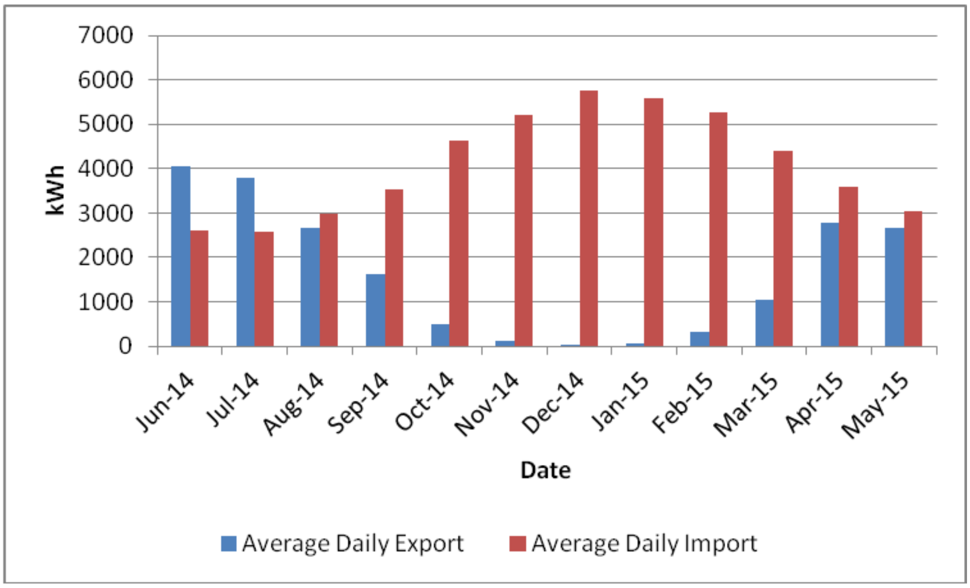

Figure 29: Graph of average daily export v import for each month

Alternatively, a more affordable option, using the same principles as Building A but using months April to September (September had a higher export than March for Building B) it would be logical to size the battery based on these months' daily export average which is approximately 3,000kWh. Furthermore, any additional surplus energy could be used for a secondary purpose, for example heating hot water or another industrial process that requires heating but uses a different fuel type.

The main challenges of storing energy are cost, space and durability of the battery. A range of energy storage options are discussed in this document but before investigating suitable storage options it is logical to identify what the budget is. This can be calculated by looking at the value of the energy saved by implementing storage and proposing different payback times.

	12 month export total (kWh)	Cost of import electricity	Price for exporting electricity	Annual value of solar PV generated electricity if used	Annual value of solar PV generated electricity if exported	Minimum annual value of solar PV generated electricity if stored	Maximum annual value of solar PV generated electricity if stored
Building A	141554	£0.12	£0.0485	£16,986.48	£6,865.37	£10,121.11	£16,986.48
Building B	599978	£0.12	£0.0485	£71,997.36	£29,098.93	£42,898.43	£71,997.36

Table 4: The annual value of the solar PV generated electricity that was exported between June 2014 and May 2015

Table 4 shows the total annual energy export from Buildings A and B between June 2014 and May 2015. The maximum value of solar PV generated electricity offsets the cost of importing electricity. The minimum annual value of solar PV generated electricity deducts the export value from the import value as the export value is claimed at a relatively minimal cost to the large scale solar PV operator.

		3 year payback		5 year payback	
		Minimum budget	Maximum budget	Minimum budget	Maximum budget
Storing 100% of surplus electricity	Building A	£30,363	£50,959	£50,606	£84,932
	Building B	£128,695	£215,992	£214,492	£359,987
Storing 75% of surplus electricity	Building A	£22,772	£38,220	£37,954	£63,699
	Building B	£96,521	£161,994	£160,869	£269,990
Storing 50% of surplus electricity	Building A	£15,182	£25,480	£25,303	£42,466
	Building B	£64,348	£107,996	£107,246	£179,993
Storing 25% of surplus electricity	Building A	£7,591	£12,740	£12,651	£21,233
	Building B	£32,174	£53,998	£53,623	£89,997

Table 5: Based on the figures shown in Table 4, this table shows the potential finance available to invest in energy storage at Wolseley UK's NDC

As demonstrated in Table 5, the price of a prefered energy storage solution cost can be calculated. The capital investment an organisation is willing to pay will depend on the potential payback time. The nature of energy storage is that it can be carried out as separate works to the solar PV installation. It is logical to identify the storage requirement after the system has been operational for at least one year to ensure that the storage solution is adequately sized.

Using energy storage will not reduce the carbon emissions of an industry further in that the exported electricty is providing renewable energy to the grid. However, it does reduce the requirement for import so that the industry gains more benefit from the carbon free energy.

EFFICIENCY	FRONIUS AGILO 75.0-3
Max. efficiency	97.1 %
European efficiency (η_{EU})	96.4 %
η at 5% $P_{ac,r}$ [1)]	89.8 % / 83.4 %
η at 10% $P_{ac,r}$ [1)]	93.4 % / 89.0 %
η at 20% $P_{ac,r}$ [1)]	96.0 % / 93.4 %
η at 25% $P_{ac,r}$ [1)]	96.5 % / 94.9 %
η at 30% $P_{ac,r}$ [1)]	96.9 % / 95.2 %
η at 50% $P_{ac,r}$ [1)]	97.1 % / 95.9 %
η at 75% $P_{ac,r}$ [1)]	96.9 % / 95.9 %
η at 100% $P_{ac,r}$ [1)]	96.6 % / 95.8 %

Table 6: Efficiency ratings of the Fronius Agilo 75.0-3 inverters that have been installed at Wolseley NDC (Fronius, 2012)

Table 6 shows the efficiency of the inverters used at Wolseley. The efficiency of the inverters impacts on their working capacity. The efficiency does not reach 100% as some of the energy is lost as heat. This heat has been ducted into Wolseley UK's air handling unit.

	Annual Generation June-14 to May 15 (kWH)	Maximum waste heat produced Inverters operating at 100% output (kWh)	Maximum waste heat produced Inverters operating at 75% output (kWh)	Maximum waste heat produced Inverters operating at 50% output (kWh)
Building A	444757	18680	18235	18235
Value of waste heat		£2,242	£2,188	£2,188
Carbon savings (kg)		9,033	8,818	8,818
Building B	1349304	56671	55321	55321
Value of waste heat		£6,800	£6,639	£6,639
Carbon savings (kg)		27,404	26,752	26,752

Table 7: Approximate heat loss from the inverters and the value and carbon savings of the waste heat

Table 7 shows how much waste heat is theoretically being saved through ducting the heat from the inverters into the airhandling unit at different operating outputs. This is very much a best case guide and assumes in each instance that the inverters are permanentley operating at a set output capacity. In reality, the output of the inverters will fluctuate depending on time of day, season and weather.

Using a guide price for the ducting in each building of around £12,000, assuming the inverter is predominantley operating at 75% output capacity and only 25% of the recovered heat is used (because it may only be useful in winter months) then the ducting used to recover waste heat for use in Building A will pay for itself within 22 years and Building B within 7 years.

The actual payback and carbon savings will vary depending on the fuel type it is replacing and the usefulness of the heat recovered. For precise figures, the heat recovery would need to be measured and recorded (these figures have not been provided). It is likely that during the summer, when the solar PV is performing at its maximum, the waste heat is surplus to requirement and that at these times it is being vented outside. This would significantly reduce the benefits of recovering the waste heat.

Discussion and conclusions

There is a clear requirement for industrialised nations, like the UK, to identify ways to reduce its industries' carbon emissions. The current reliance on fossil fuels to power industrialised economies is significantly increasing atmospheric CO_2 (HM Government, 2011). The literature review identified that by improving energy efficiency, industries become more competitive with lower costs and increased productivity (UNIDO, 2011). Ultimately a zero carbon industrial process can be achieved as demonstrated by SMA's inverter manufacturing plant. However, for most established industries this is not technically or economically feasible. Therefore, the focus needs to be on how energy reduction can be implemented into existing processes. Industrial symbiosis also has a role to play, but is dependent on inter-industry co-operation and longevity.

It is technically possible to recover 5 to 28 TWh/yr of waste heat from UK industry (Element Energy, 2014). However, there has been little uptake of heat recovery technologies by UK industry. Increasing energy costs and concerns over stability of supply are strong drivers of improving energy efficiency. However, these are often not enough to encourage industry to take the risk of installing new technology into their existing, working processes. Therefore, to stimulate industrial uptake of heat recovery, specific legislative and government support is required. Once uptake of waste heat recovery technology increases it will improve and become more affordable.

The range of waste heat recovery technologies identified in the literature review demonstrates how waste heat recovery is a viable solution in reducing industrial carbon emissions. The challenge to industry is identifying the most suitable technology for each of the many different processes and identifying the most effective use for the recovered waste heat. The literature review provides an outline in Table 1 of different waste heat grades and the most suitable waste heat recovery technologies. However, it is quite generalised, and a more extended study could interrogate further the specifics of matching different processes with suitable heat recovery technologies.

The literature review reveals that waste heat recovery can be adapted in a number of intuitive ways including harvesting waste heat from computer servers and effluent. Furthermore, when waste heat recovery is implemented it is effective in reducing carbon emissions as Lhoist has proven at Thrislington Lime Plant. ORC technology reduced their CO_2 emissions by 1,600 tonnes/yr (Heatcatcher, 2014). However, industrialised processes are highly diverse, and to ensure the best results a bespoke approach to waste heat recovery will often need to be taken. This makes it difficult to calculate the actual extent waste heat recovery can contribute to the decarbonisation of an industrialised nation. It is also why the values of potential heat recovery in the UK are so broad. Once a suitable technology has been trialled for an industrial process, for example Siemens' solution that utilises waste heat from an electric arc furnace, the extent to which waste heat recovery can contribute to the decarbonisation of that particular industry can be calculated.

Solar thermal and solar PV both have the potential to reduce industrial carbon emissions. The uptake of solar PV in the UK has been greater than that of solar thermal, due to quicker payback and its ease of install. However, only 5% of solar PV installations are installed on commercial and industrial roofs (STA, 2015). That said, the UK Government is now encouraging greater uptake of large scale rooftop solar PV. There is scope for further study to identify the role solar thermal could play in decarbonising UK industry as well as scope to examine further the effects of solar PV in light of future legislative change that may come about as a result of the recent news regarding the proposed significant decrease to the FiT rates (McGrath, 2015).

The literature review identified that there is potentially enough south facing commercial and industrial roof space in the UK for 3.44TW of solar PV, which could produce 8.8 times more electricity than required annually by the UK. Solar PV could, in theory, fully decarbonise UK industry. However, this is very optimistic as the calculation assumes all available roof space is suitable, i.e., structurally sound, unshaded, no roof furniture and with a suitable electrical infrastructure. Furthermore, significant energy storage would also be needed. To accurately identify true potential a survey of all these buildings would need to occur. While this would be a significant undertaking, Google is trialling "project sunroof" in America which calculates a building's suitability for solar PV, factoring in local weather, irradiance and shading (O'Brien, 2015). This software could be used in the future to build a more accurate picture of the suitability of industrial buildings in the UK for solar PV.

Government support for renewables and the introduction of the FiT has been the main driving force behind the uptake of solar PV. Solar PV's scalability and ease of install have also been contributing factors. However, large organisations have long term energy contracts and buy energy in bulk. Solar PV installations that reduce demand may cause contractual obligation issues. Industries can also be reluctant to install solar PV due to the initial capital costs, even though they have reduced considerably over the past five years.

For solar PV to meet its potential the National Grid needs significant investment to manage the growth of decentralised large scale solar generation. There is a risk that the UK's ageing electrical grid could become a major limiting factor to the uptake of solar technology. Furthermore, the intermittency of solar PV generation makes it difficult both for the National Grid to manage, and for industry to match their processes to key production times to make the most of the renewable generation.

Energy storage is a possible solution for maximising the benefits of both heat recovery technology and solar PV. There are a range of energy storage solutions identified in the literature review but the key issues are price, size and life-time. Industries are unlikely to invest in these technologies until storage solutions become more affordable. Promising development work is being carried out by TESLA, who are starting to manufacture large scale batteries (Allen, 2015).

The solar PV array installed on Wolseley UK's NDC met 27% of their electricity requirements in the first year, offsetting their carbon emissions by 854,466kg, demonstrating that solar PV can significantly reduce an industry's carbon emissions. Solar PV generation was shown to vary due to season and weather. However, the impact on imported energy demand is clear, with reduced import requirements during the day. It was also identified that a significant amount of energy is exported during peak generation. One solution is to adapt the operational processes to better match the energy generation, but it is likely energy would still be exported.

If the excess energy generated by Wolseley UK's solar PV system during June and July was stored, it could provide over an additional month's worth of energy. TESLA are manufacturing a battery that can store 1MW worth of power, which could be useful for Building A, depending on the cost, as the maximum stored power requirement is 3MW. However, considerably more would be needed for Building B if all the excess energy was to be stored as there would not be sufficient room for all the batteries needed. Therefore, it may be best to size the batteries for both systems so that they store sufficient energy to cover sudden drops in production due to a change in weather and reduce some of the night time import demand. As battery technology develops seasonal storage may become a more viable option.

Ducting the waste heat from the inverters at Wolseley was carried out to improve the efficiency of the solar PV system. Actual measurements need to be taken to verify the full benefit. However, based on the energy production of one year, and the estimated waste heat emitted from the inverters, the system is having financial and carbon reduction benefits. Waste heat recovery on Building B's inverters is more economically viable. Recovering waste heat is not going to be worthwhile for smaller systems, but is worthwhile considering for systems of 1MW and above in some scenarios. Ideally, there needs to be a demand for the recovered waste heat during the summer months.

The literature review and case study demonstrate that waste heat and solar are two technologies that can make a positive impact on decarbonising UK industry. They work well independently, but also have great potential for being combined. For example, solar PV can be used to produce electricity that is then used to power heat pumps that utilise waste heat. This utilisation of renewable energy effectively improves the carbon saving potential of the heat pumps. Furthermore, the same storage method for waste heat can be used for solar PV, improving the effectiveness and benefits of both technologies. Capturing surplus energy can be beneficial, although this is limited by technical and economic factors. By calculating the value of surplus energy, this research has shown what price battery storage needs to be for it to be economically viable for Wolseley. This value will vary between different organisations.

Innovation is important when reviewing options on how best to utilise surplus waste heat and solar PV generated electricity. When there is no obvious use for it, a different approach is need. As surplus energy is a potentially valuable resource the following questions need to be asked:

- How could it be used to benefit the industry?
- Could it be used to create another product?
- Could it be exported to a neighbour?

Industries should be encouraged to look at how the different technologies available can be incorporated into their industrial processes to reduce their carbon emissions. It is, however, important that the right technology is selected and bespoke solutions are likely to be the norm. Although the same basic technological principles of waste heat recovery can be used for a range of different industrial processes, their method of implementation often needs to be innovative. Whether it involves ducting heat from inverters, like Wolseley has done, or using heat pumps to cool server rooms and heat offices or to power industrial processes by taking waste heat from sewage, bespoke design and installation methods are necessary.

It is recommended that more research and government support, backed up by legislation, is used to encourage more industries to reduce waste heat, starting with energy intensive industries, but eventually targeting low energy users. Furthermore, Wolseley UK has shown how solar PV and waste heat recovery can effectively be applied to reduce carbon emissions in the UK's logistics and warehousing sector. However, more work needs to be carried out to identify low cost thermal and electrical storage solutions to maximise the benefits of available surplus energy.

Recommendations for future work

While it is clear that industrial solar PV and waste heat has a bright future, it is important that the implications of the existing installations and continued growth are considered. While there has been some work done on the life cycle of a solar PV module (Tao and Yu, 2015), now is the time for government and industry to start working together and driving forward solutions for what to do when solar panels, and the associated kit, reach the end of their useful life. Other future initiatives and research avenues might include the following:

- Jevon's Paradox suggests that improved efficiency actually increases demand. It would therefore be interesting to investigate whether industries that invest in waste heat recovery and solar technologies end up increasing their energy consumption.
- Wolseley's solar PV annual generation was approximately 11% higher than that calculated using the MCS 2012 method. It would be useful to identify the exact cause, whether it is better than average weather or if it is system performance. If there is local irradiance data available it would be possible to compare the historic irradiance data with the irradiance data recorded during the time the solar PV system was operating.

- Large scale batteries are expensive and take up space which may not be available in some industries. There may be industrial processes that could use interchangeable small scale batteries that can be charged during peak renewable generation, for example forklift truck batteries. This could lead on to investigating the potential for staff car charging points that use surplus energy during peak production times to charge vehicles.
- There is significant scope for further investigation of utilising low grade heat in UK industry, as most industrial waste heat is lost as low temperature waste heat (Bor et al., 2015). Research has shown that France could achieve a 12% energy reduction and 9% CO_2 emissions reduction by using heat pump technology in industry (Suk et al. 2015). Similar research could identify comparable savings in UK industry.

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Appendices (Electronic - please see attached CD)

- Appendix 1: STA Rooftop Solar Confidence Checklist
- Appendix 2: Data Analysis Wolseley NDC
    - Tab 1: Import Building A (Electricity import readings for Building A)
    - Tab 2: Import Building B (Electricity import readings for Building B)
    - Tab 3: Export Building A (Electricity export readings for Building A)
    - Tab 4: Export Building B (Electricity import readings for Building B)
    - Tab 5: Export Building A & B (Electricity import readings for Buildings A & B)
    - Tab 6: Annual average daily load profiles (Annual average electricity imported for Buildings A & B)
    - Tab 7: Detailed HH import graphs (Graphs of half hourly imported electricity for Buildings A & B)
    - Tab 8: Generation A (Solar PV generation meter readings & graphs for Building A)
    - Tab 9: Generation B (Solar PV generation meter readings & graphs for Building B)
    - Tab 10: A Export v Import (Graphs of Building A export v import meter readings)
    - Tab 11: B Export v Import (Graphs of Building B export v import meter readings)
    - Tab 12: Battery storage cost (Table of the potential value of stored electricity)
    - Tab 13: Waste heat (Tables of the calculated emitted waste heat from the inverters and its value)

Declaration

I certify this is my own work and I understand that plagiarism is an academic offence. All the material in this assignment which is not my own work has been referenced and no material is included which is substantially the same as material I have already submitted for assessment purposes in any other module. I have read and understood the current University leaflets on 'Bad Academic Practice' and 'Academic Offences'.
MICHAEL GALLAGHER