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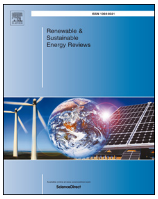

Reducing industrial energy demand in the UK: A review of energy efficiency technologies and energy saving potential in selected sectors

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ABSTRACT

Currently UK industrial and manufacturing sectors are facing dual challenges of contributing to national 80% reduction targets in CO_2 emissions by 2050 (compared to 1990 levels) and improving economic competitiveness in the face of low cost imports. Since energy consumption is the main source of CO_2 emissions and directly related to products being manufactured, improving energy efficiency in energy intensive sectors is key to achieve CO_2 targets. Energy consumption is unlikely to meet the targets unless energy efficiency opportunities and technologies are fully explored and timely changes are made to business models and policies This study explores potential energy efficiency improvements from three perspectives: system efficiency of steam networks, waste heat recovery technologies and bioenergy/waste utilisation. Two UK energy-intensive sectors, iron and steel, and food and drink, are selected for analysis and discussion. Potential business models for energy efficiency are also reviewed as there are now a variety of energy service companies who can support adoption of appropriate technologies. Furthermore, drivers and barriers to the adoption of energy efficiency technologies are considered in this paper revealing the factors affecting the diffusion of energy efficient and waste heat recovery technologies and their interactions and interdependencies to energy consumptions. Findings show that it is possible to achieve energy consumption reduction in excess of 15% from a technical point of view, however improving energy efficiency in UK industry has been hindered due to some inter-related technical, economic, regulatory and social barriers. The findings help to demonstrate the significant potential for energy efficiency improvement in two industrial sectors, as well as showing the specific types of technologies relevant for different sectoral processes. The range of business models show opportunities for implementation and for developing innovative business models, addressing barriers, and using enablers to accelerate the diffusion of energy efficiency technologies in UK industry.

1. Introduction

Under the Kyoto protocol, many countries and international communities in general have ambitious targets for the reduction of greenhouse gas emissions and global warming. For the UK, the government committed to reducing the levels of CO_2 and five other greenhouse gases by 12.5% below 1990 levels by 2008–2012. In fact these commitments have been surpassed so far and a new long term target was set to reduce by at least 80% by 2050 (against the 1990 baseline) [1]. Currently, primary energy consumption that fossil fuel represents still dominates in the world's energy consumption and this situation is expected to continue over the next decades. The long-term target is unlikely to be met if there are no substantial changes to policy and technological approaches in the usage of primary energy.

Facing the challenges of carbon reduction, a number of global organisations are working towards an energy revolution that is taking place to tackle greenhouse gas emissions by deploying low-carbon technologies and adopting renewable energy to increase energy sustainability and economic development. The International Energy Agency (IEA), is one of such groups that came up with a tool called the Energy Technology Perspective (ETP) model that presents options for a low-carbon future [2]. It has shown the effect of utilisation of available technologies on the reduction of CO_2 emissions and predicted that the end use fuel and electricity efficiency have potential to contribute 38% in CO_2 reduction, while Carbon Capture and Storage (CCS) and renewable energy technologies could reduce 19% and 17% of the

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Nomenclature

Abbreviations

AD	Anaerobic Digestion
BOOT	Build-Own-Operate-Transfer
BOO	Build-Own-Operate
BTO	Build-Transfer-Operate
BLT	Build-Lease-Transfer
BOT	Build-Operate-Transfer
BF-BOF	Blast Furnace-Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
EAF	Electric Arc Furnace
ESCO	Energy Service Company
EPC	Engineering Procurement Construction/Energy Performance Contracting
ESC	Energy Service Contracting
ETP	Energy Technology Perspective
FiT	Feed in Tariff
HE	Heat Exchangers
HP	Heat Pumps
ORC	Organic Rankine Cycle
PCM	Phase Change Material
PRV	Pressure Reduction Valve
RHI	Renewable Heat Incentive
RO	Renewables Obligation
TRC	Traditional Rankine Cycle
USCO	Utility Service Company

emissions, respectively. The contributions from other technologies options such as end use fuel switching, power generation efficiency and fuel switching and nuclear are collectively 26% towards the carbon reduction. Most of these values indicate the need for adoption of “energy efficiency” which is broadly defined and covered as the thermal energy recovery and its conversion into usable form of energy, use of low-carbon state-of-the-art technologies and improved energy integration and management. The ETP model also indicates that the reduction of energy use and emissions has already started from the “bottom up” approach, meaning concerns of the effect of emissions and challenges to tackle this in local contexts, which may encourage full utilisation of key technologies to improve energy efficiency of energies’ end use, renewable energy and CCS.

Globally, industrial primary energy use and transformation for electricity and heat are responsible for 46% of greenhouse gas emissions [3]. While UK industry consumes about 20% of the final energy consumption of the UK economy (291 TW h in 2011) [4] and generates 32% of the UK’s heat-related CO_2 emissions, mostly from fossil fuels [5]. Although UK industrial emissions have reduced in recent years [6], indirect impacts (e.g. the economic crisis in 2008) on carbon-intensive industrial sectors was the largest contributor to falling direct emissions besides some improvement in energy intensity and changes in fuel mix. Even so, UK industrial energy use still directly accounts for around a quarter of greenhouse gas emissions [7]. The majority (73%) of the UK industrial energy demand is for heat [8,9]. Steam systems are responsible for approximately 35% of industrial energy demand [10]. Superheated high pressure steam is usually produced by boilers and is reduced in pressure in the distribution network for use by different processes. Often this pressure reduction is accomplished through a pressure reduction valve (PRV) and energy embodied in the pressure drop is lost. Therefore, there is still a significant space to further improve the system efficiency of steam networks. Furthermore, all heating processes result in significant quantities of waste heat, up to 50% in some cases such as steel and glass making [11], and it is widely acknowledged that there is significant potential for emission reductions through waste heat recovery, estimated at between 10 and 40 TW h/yr which values up to £90/MW h at today’s energy prices [12]. Likewise, there is no denying the fact that bioenergy/waste utilisation offers a signification potential for reduction of carbon emissions and grid dependency in industry. In 2016, electricity generation from UK bioenergy was estimated to be 30 TW h [13]. It was predicted that the effective deployment of bioenergy and waste utilisation could contribute to 8–11% of the UK’s primary energy demand by 2020 and 8–21% by 2050 [14]. The UK government has embraced biomass strategies to define low-risk pathways that will help to achieve long-term decarbonisation objectives. These pathways include optimum utilisation of end-of-life wastes, use of biomass heating for buildings and industrial processes, use of biofuel in the transport sector and use of biomass for electricity generation [14]. The use of bioenergy and waste for heating and combined heat & power (CHP) generation can not only make a significant contribution to decarbonisation of the industrial sector [15], but also increase sustainability and energy security of the country. Although it is clear from previous studies that steam system efficiency, waste heat recovery and bioenergy/waste utilisation offer greater potential for energy consumption and emission reduction, yet most of this potential has remained unexploited due to technical, economic and organisational factors [15]. Moreover, lack of available business models to address those factors and to diffuse energy efficiency is also posing a barrier to achieve the UK’s long-term target. This study will therefore review energy efficiency technologies and energy saving potential in selected sectors.

The aim of this paper is to provide an overview of the energy consumption and emission reduction potential offered by UK industry, especially by the Iron and Steel and Food and Drink sectors, through three different perspectives: improving energy efficiency in steam systems, waste heat recovery and bioenergy/waste utilisation. Besides, the energy efficiency market is reviewed and presented, in terms of business models and drivers and barriers for energy efficiency. Investigation of drivers and barriers (e.g. legislative, technical, socioeconomic, local acceptance) to adopt the associated technologies can deliver additional insights to energy consumption reduction. It is expected that this study will provide information and direction to future research in the development of innovative business models for energy efficiency and will help government, industry and society to engage more in achieving the national targets.

In order to achieve the aim of this paper, recent literature on the subject including journal publications, conference proceedings, Ph.D. theses, subject specific professional web sources, UK Government organisations’ reports, industrial federations’ and research organisations’ reports, international energy agencies’ reports, are reviewed and the findings are adapted for UK industry cases. As a first step, the state-of-the-art technologies for improving steam system efficiency, waste heat recovery and bioenergy/waste utilisation in industry, are reviewed. Then, the current state of energy consumption within the selected sectors in the UK is studied from the UK Government sites such as former Department of Energy and Climate Change (DECC) and current Department for Business, Energy & Industrial Strategy (DBEIS) (https://www.gov.uk/government/organisations/DBEIS). The energy saving potential using the various technologies reviewed in this paper is assessed considering the current energy consumption and reported accordingly. At the end, a detailed literature review on energy efficiency markets, different business models and drivers and barriers to energy efficiency is conducted from a global perspective.

2. Common energy efficiency opportunities in industry

As mentioned before, steam systems and heating processes are the energy consumers in industry that contribute most to significant carbon emission to the environment. Since steam and heating systems are the greater losers of energy; recovering, reusing and conversion of this waste energy not only offers huge potential to carbon emission reduction but also increased economic competitiveness by reducing energy costs in the industry. To demonstrate different pathways, this section therefore reviews common energy efficiency measures and technologies that can be used to tackle heat losses from steam systems and processes in industry. Also, a review of potential bioenergy and waste utilisation technologies is provided in the context of the UK.

2.1. Improving energy efficiency in steam systems

Energy efficiency in a steam system is a combined result of efficiencies of different components in the system. A steam system has many components whose efficiency affects the overall system efficiency. Following the path of steam as it leaves the boiler and returns, a steam system can be divided into four components: generation, distribution, end use, and recovery. Fig. 1 shows some of the main potential losses that may deteriorate energy efficiency in a whole steam system. Although every operation has a few acceptable losses, a high percentage of losses can be prevented and eliminated. Table 1 summarises typical energy losses from a steam system. These figures imply that only 52.7% of the fuel energy was used successfully, and reveal that corresponding effective measures will definitely improve energy efficiency of the steam system, while reducing energy demand.

2.1.1. Generation

Boiler efficiency is the key index to evaluate the energy efficiency of a whole steam system, which depends on many more parameters apart from combustion and thermal efficiencies. In actual practice, two methods are commonly used to find out boiler efficiency, namely direct method and indirect method of efficiency calculation [18]. Both the methods of calculating boiler efficiency have their own advantages and disadvantages. In reality, indirect efficiency is measured at a particular time whereas direct efficiency is measured over a period of time and hence, losses on account of fluctuating loads, boiler on-off etc. are also taken into consideration.

Table 1

Typical energy losses from a steam system (adapted from [17]).

Steam system	Energy losses (% of total input)
Steam generation	
Boiler flue gases	16.4%
Boiler outer surface (radiation)	0.5%
Continuous blowdown	1.5%
Bottom blowdown	0.2%
Steam distribution	
Insulation (already added in our totals)	6.4%
Steam leaks (already added in the totals)	7.5%
End users	
Steam trap station failures	3.6%
Condensate recovery	
Condensate	3.8%
Steam loss to atmosphere	7.4%
Total losses	47.3%

Combustion efficiency relates to the optimum air-to-fuel ratio in the boiler combustion process. Oxygen lean combustion environment can cause smoking and incomplete combustion in reality whilst large excess oxygen would increase the heat losses through the stack. In order to achieve high efficiency operating, the air-to-fuel ratio needs to be controlled in a region throughout the firing range of the burner under variable load conditions. Fig. 2 shows the representative effect of excess air on combustion efficiency for boilers equipped with economisers and air heaters, adapted from the reference [19]. If excess oxygen reduces from 6% to 2%, the combustion efficiency increases of about 10 percentage points. Fig. 3 further reveals the relationship between reducing excess oxygen and combustion efficiency through fuel consumption [20]. Excess air to achieve highest possible efficiency for some common fuels is as follows [21]:

5–10% for natural gas; 5–20% for fuel oil; 15–60% for coal.

Although it may be possible to monitor and manually adjust the air-to-fuel ratio on a daily basis, it is not practical. In reality, by installing

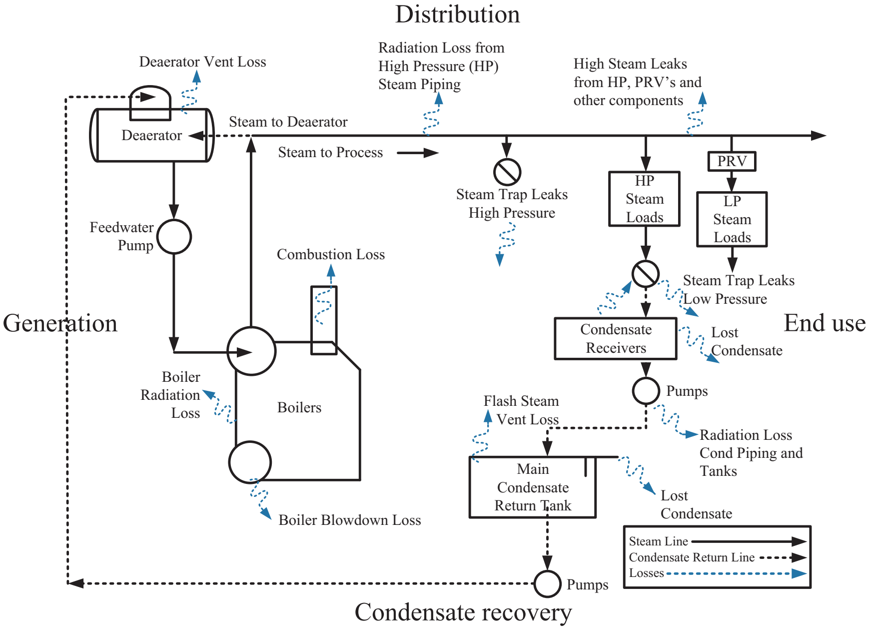


Fig. 1. Illustration of steam system losses (adapted from [16]).

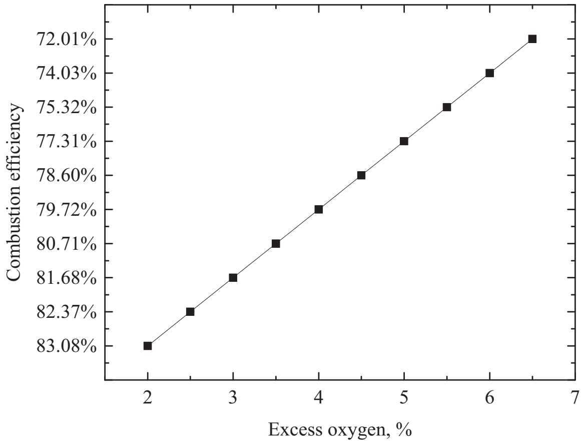


Fig. 2. Excess air effect on combustion efficiency for boilers equipped with economisers and air heaters [19].

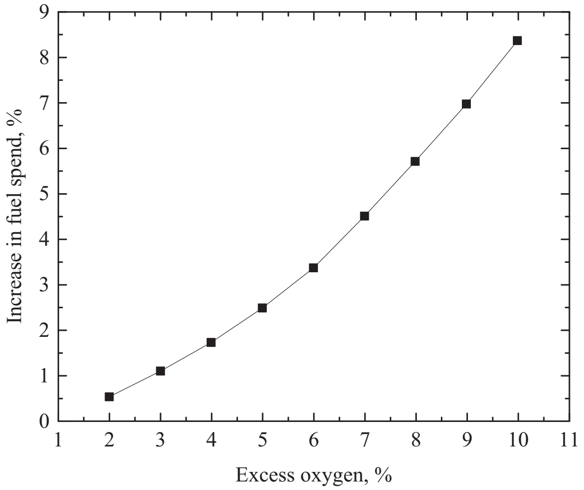


Fig. 3. Increase in fuel spend by oxygen level in boiler operations [20].

an automatic O_2 system, generically called 'O_2 Trim Systems' [22], the free oxygen concentration in a boiler flue can be continuously measured. A controller then regulates the air rate to maintain the best combustion conditions at all time. Oxygen trim control systems can be fitted on their own, but are now more commonly installed as part of a broader digital combustion control package, sometimes along with new burners. The equipment costs for O_2 Trim varies only a little with boiler size. Investment costs will vary mainly due to the torque requirements for the servomotors and types of O_2 analysers. An example of estimating payback from the installation of O_2 trim is listed in Table 2 [23].

Thermal efficiency relates to the thermal transfer of energy contained in the fuel to the water in the boiler. If the boiler tubes are not kept scale and deposit free, then the thermal transfer surfaces will be compromised and the design output will never be achieved irrespective of how good the combustion process is. Fig. 4 shows the potential improvement of boiler efficiency through water treatment. From the figure it can be seen that a scale thickness as little as 0.75 mm of calcium sulphate will result in an efficiency loss of 3% and an increase in metal temperature of 60 °C: efficiency losses due to scale of between 5% and 10% are not uncommon with the root cause being the way chemicals are added and how the feed and boiler water are monitored [20].

There are two approaches to keep the boiler scale and deposits free. One is off-line cleaning by stripping down the boiler and treating the affected surfaces with acid; another one is online cleaning the boiler tubes with dispersants. The choice of approach depends on specific cases. The main factor that determines water treatment technology and costs is pressures [24,25]. The payback time of such systems is to be expected within 1–2 years. Apart from pressure, water quality also affects the design of a water treatment programme. There is no standard treatment for water that all steam system operators can apply, that is because of variations in the quality of the water being supplied by water utilities. To enable a water treatment programme to be created for a steam system, the impurities in the water supply must first be analysed. An effective water treatment programme could bring more savings on chemical and fuel costs in the areas with high water hardness.

Heat losses relates to the loss from steam boilers through the flue gas, blowdown and radiation to the boiler's surroundings, in which flue gas loss accounts for more than 70% [26]. To reduce the flue gas loss, flue economiser is a widely accepted technology, which can be either used to retro-fit existing boilers that have no any form of heat recovery built in (e.g. non-condensing boilers) or can be a built-in technology to new boilers (e.g. condensing boilers). The net thermal efficiency can be increased by up to 5% by using a non-condensing economiser or by up to 15% by using a condensing economiser [26]. The main applications of the flue economiser are to pre-heat boiler feed water and combustion air [27]. To pre-heat boiler feed water, the economiser (water jacket) is normally fitted around the flue stack. The relatively cool boiler feed water is pumped through the heat exchanger tubes, where it absorbs heat from the hot flue gas before being pumped into the boiler (Fig. 5(a)); to pre-heat combustion air, ambient outside air is drawn through the boiler flue economiser, where it absorbs heat from the hot flue gas before being ducted to the burner air input (Fig. 5(b)).

For the boiler with an annual spend on gas of around £15,000, an investment of £6000–£8000 to retro-fit a boiler flue economiser could see a payback in four to five years. The payback will be far more quick than retrofitting if replacing a boiler with one that already contains economiser technology [26].

2.1.2. Distribution

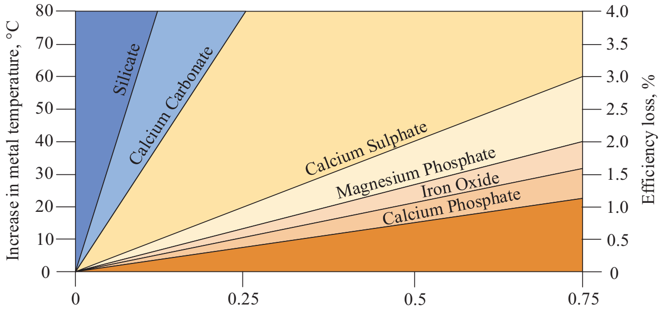
One of the effective measures to reduce energy loss in steam distribution network is steam pressure reduction. By this measure, the pressure reduction valve (PRV) can adjust the pressure at a low level to the set points and thus directly reduce the PRV associated losses. An example of the potential saving from the steam pressure reduction in this case is listed in Table 3. However, as each steam boiler is designed to operate under rated conditions, the boiler will encounter a few negative consequences when operating at lower pressures, e.g. boiler carryover (wet steam), overheating. Thus, boiler owners who are considering steam pressure reduction should consult their boiler supplier.

In contrast to steam pressure reduction, another way to increase steam system efficiency is by using a noncondensing or backpressure steam turbine to perform the same pressure-reducing function as a PRV while converting steam energy into electrical energy [28]. Fig. 6 can be used to estimate the potential power output at a PRV, which shows lines of constant power output as a function of turbine inlet and exhaust pressures. Typically, turbo-generator systems cost about £680/kW for a 150-kW system to less than £150/kW for a 2000-kW system, and the

Table 2
Estimating payback from the installation of O_2 trim [23].

Boiler parameters	
Boiler capacity, kg steam/h	6350
Fuel input, MW h/yr	15,716
Operating hours, h/week	120
Natural gas cost, p/kW h	2.5
O_2 trim systems	
Equipment cost, £[a]	20,000
Fuel saving, %	6.4
Savings, £/year	25,145
Payback time, year	< 1

[a] An oxygen trim control system is installed as part of a broader digital combustion control package.



Note: Chemical constituents of boiler scale can be any one or a combination of all of the above.

Fig. 4. Graphical representation of the effects of scale on thermal efficiency [20].

installation costs account for 75% of equipment costs [28]. Payback time of such turbo-generator system is estimated to be 1–2 years, while the system is designed for a 20-years minimum service life.

Besides the above ways, another measure to reduce the energy loss in steam distribution network is to use insulated steam distribution and condensate return lines [29]. Table 4 shows typical heat loss from uninsulated steam distribution lines. Insulation can typically reduce energy losses by 90%. However, for a specific case, the insulating layer is not always the thicker the better, but has an optimal thickness [30]. If an insulating layer is thicker than its optimal thickness, increased expenditure to improve the level of insulation cannot be justified by the additional savings which would arise [30]. The combined effect of increased expenditure due to increasing the thickness of the insulating layer, and increased cost saving, for a specific set of operating conditions, is illustrated in Fig. 7. The minimum cost shown is the lowest combined cost of insulation and heat loss over a given period.

2.1.3. End use

When the steam reaches the intended destination, it provides the latent energy to the end use until it condenses to water (condensate). Steam trap is the key equipment of a steam system, which is used to prevent steam from passing beyond its point of use and to return the condensed steam (water) back to the boiler. Even one failed trap can have steam leakage resulting in losses of hundreds of pounds per year [31] and any industrial-scale steam system easily has a few thousand steam traps. The average performance level of a steam trap station should be a failure rate below 3%; the energy loss from failed steam trap stations is estimated at 3.6% [17]. Although obvious leaks are easily found in steam distribution lines, a big contributor to energy loss could be from a problem of steam traps and usually not identifiable. Attention should be paid to steam trap maintenance.

Table 3
Potential saving from steam pressure reduction [16].

Combustion loss	0.6% of fuel input
Boiler radiation and convection loss	0.2% of fuel input
Boiler blowdown loss	0.1% of fuel input
High pressure steam trap leakage	0.6% of fuel input
Enthalpy savings effect	4.1% of fuel input
High pressure steam piping heat loss	Increasing with the length of pipe

Note: the operating pressure at the boiler was reduced from 130 psig to 80 psig.

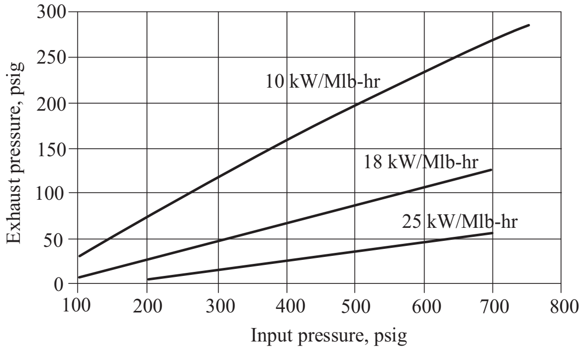


Fig. 6. Backpressure turbo-generator generating potential, kW/Mlb-h [28].

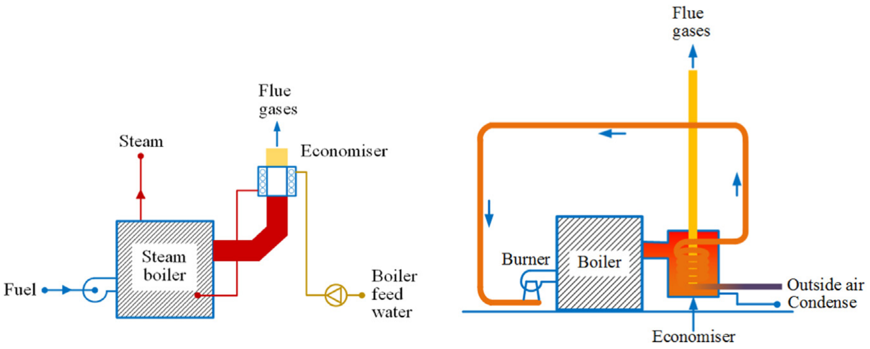
Table 4
Heat loss per 100 ft of uninsulated steam line [29].

Distribution line diameter, in.	Heat loss per 100 ft of uninsulated steam line, MMBtu/yr Steam pressure, psig			
	15	150	300	600
1	140	285	375	495
2	235	480	630	840
4	415	850	1120	1500
8	740	1540	2030	2725
12	1055	2200	2910	3920

Based on horizontal steel pipe, 24 °C ambient air, no wind velocity, and 8760 operating hours pegr year.

In industrial processes, savings in the end use of steam can be made by replacing large shell and tube heat exchangers with more compact plate heat exchangers. In terms of design, plate heat exchangers are fundamentally different from shell/tube heat exchangers. The shell/tube heat exchanger does not allow for 'temperature cross' [32] but the plate heat exchanger does allow. As shown in Fig. 8, for a typical shell/tube heat exchanger, the outlet of the cold side generally has a certain temperature difference to the outlet of the hot side. In contrast, for a typical plate heat exchanger, the cold side outlet temperature can get close to the hot side inlet temperature.

Thus, plate heat exchangers are up to five times more efficient than shell/tube designs with approach temperatures as close as 1 °C. Due to



(a) (b)

Fig. 5. Non-condensing gas-to-water economiser fitted to boiler flue [26].

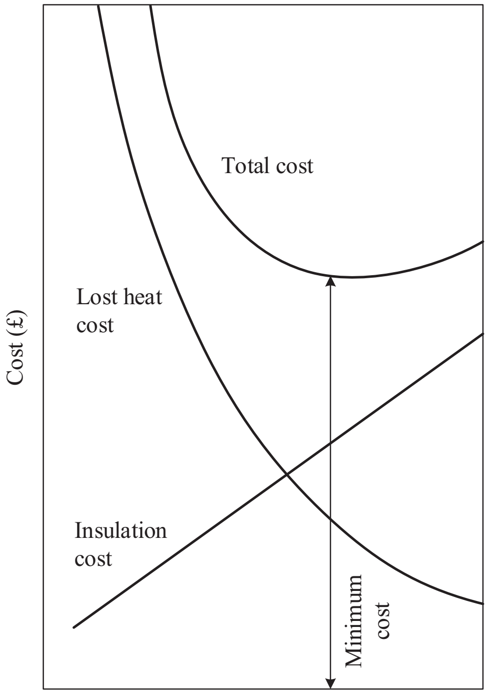


Fig. 7. Economic thickness of insulation [30].

the compact size, plate heat exchangers are ideal for installations where space is limited. Their stack structure means the heat transfer surfaces are easily accessible for inspection or mechanical cleaning and makes it easy to adjust capacity to meet changing needs. But above all, these features make the plate heat exchanger have lower capital and maintenance costs compared with traditional shell/tube heat exchangers.

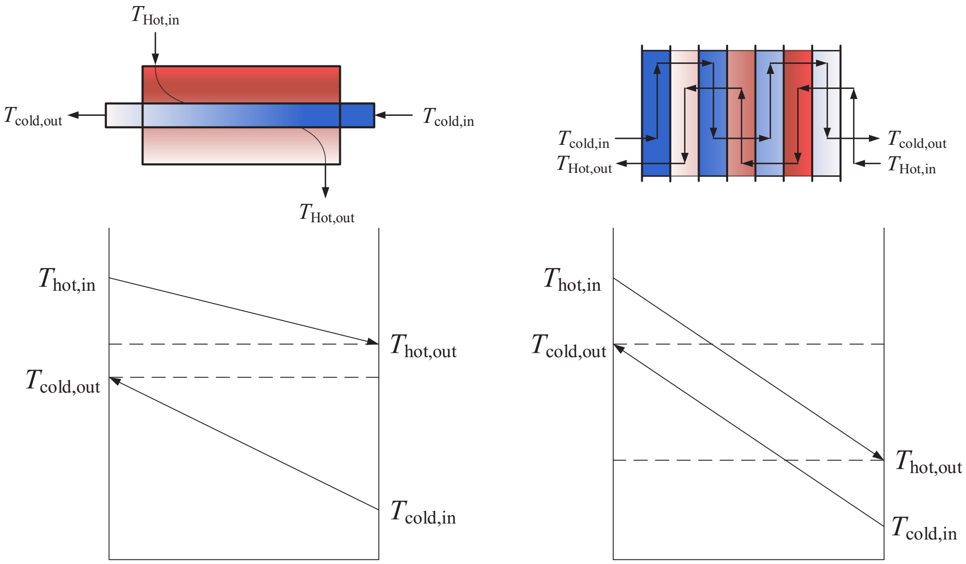
2.1.4. Condensate recovery

After releasing latent energy to the process, high pressure condensate still contains around a quarter of the energy in the steam vapour (sensible energy) and not recovering this energy will result in a significant loss [33]. Although there are only a few sites in the UK without any form of condensate recovery system, many sites could do more. Flash steam vessels are effective equipment used to recover steam from high pressure condensate lines [34]. By removing steam from the condensate, flash steam vessels can provide an efficient source of steam to low-pressure end uses, such as space heating and preheating. The discharged condensate will be sent to the boiler house for a next steam generation cycle. However, in fact, condensate cannot be 100% recovered. Condensate that is not returned must be compensated for by the addition of makeup water. Reducing the amount of makeup water will bring several benefits to the steam system. As water and energy are the two key resources used to generate steam for industrial processes, condensate recovery is one of the most effective resource-saving measures for most steam system sites.

For applications in which condensate is not returned to the boiler due to either operational reasons or a risk consideration, such as the condensate from food processing and the contaminated condensate, that is wastewater. Typically, wastewater temperatures in the UK vary from 12 to 20 °C. If only 5 °C worth of this heat energy were recovered, it would equate to 1.8 times the amount of energy gained through methane production and over 200 times that generated by small-scale hydro-systems [35]. Hence, heat recovery from wastewater, whilst not traditionally viewed as an energy source, should not be overlooked.

2.2. Heat recovery from industrial processes

Heat recovery is the collection and re-use of heat arising from any process that would otherwise be wasted. Heat can be recovered after heating processes or as a by-product heat that is produced when systems convert energy contained in fuels to mechanical work or electric energy. This heat might be from above 1000 °C to less than 100 °C. The waste heat can be defined according to their temperatures such as high (> 650 °C), medium (230–650 °C) and low (< 230 °C) [11]. Recovering the waste heat can help to reduce the overall energy consumption of the process itself, or provide useful heat for other purposes. The potential for heat recovery is governed by technical and economic factors. Some of these factors are the nature of waste heat sources and heat sinks, the compatibility of the sources and sinks (e.g. temperatures, capacity, timing, location), available heat recovery technologies (costs and efficiency), energy/carbon prices, investor priorities and site- or industry-specific issues [12]. Increasing the application of heat recovery is therefore very important to construct technology mapping and develop overall solutions and business models.



(a) Shell/tube heat exchanger (b) Plate heat exchanger

Fig. 8. Comparing shell/tube heat exchanger with plate heat exchanger.

2.2.1. Technology mapping

Heat recovery technologies may be classified as either passive or active (see Fig. 9). The passive heat recovery follows the convection/diffusion law that heat spontaneously passes from a higher temperature source to a lower temperature stream by using heat exchangers of various types. Due to the spontaneous nature, passive heat recovery technologies do not require significant mechanical or electrical input for their operation, except for auxiliary equipment such as pumps or fans. In contrast, since heat can never pass from a lower temperature source to a higher temperature stream without some other cost, active heat recovery technologies require the input of energy (e.g. waste heat). Some examples of both passive and active heat recovery technologies are shown in Fig. 9.

Table 5 lists the available heat recovery technologies for industrial applications, including some of their techno-economic characteristics either from models or experiments. The selection of appropriate heat recovery technology for a particular application, primarily, depends on heat source grades (e.g. temperature), quantity (e.g. flow rate), efficiency and payback period. In general, the passive heat recovery technologies are used for various preheating processes, direct heat to electricity conversion or thermal energy storage applications. For preheating processes, the target (waste heat) temperature is usually greater than 60 °C, such as preheating of air and boiler make-up water. Heat distribution is particularly suitable for recovering waste heat of hot streams, like steam (100–140 °C) and hot water (50–90 °C), to district heating; redundant hot water can also be stored for future use. One of the passive ways of heat recovery technology is thermal energy storage using a Phase Change Materials (PCMs) system which absorbs energy when heating and releases energy when cooling. Although PCMs can be used as both latent and sensible heat storage units, the latent heat storage PCMs offers a more efficient and greater energy storage density than the sensible heat storage PCMs [36]. PCMs are therefore designed to recover energy from different temperature ranges heat sources: from as low as 15 °C to above 90 °C. The high temperature PCMs are mainly employed to industrial waste heat recovery applications where a heat source temperature could typically higher than 90 °C [37]. Unlike other passive heat recovery technologies, the direct energy conversion technologies such as thermoelectric generator and thermophotovoltaic convert heat energy into electricity directly. The thermoelectric generator is a solid-state semiconductor or conductor device, which generates electricity through the Seebeck effect when a temperature difference across the device is imposed. The conversion efficiency of thermoelectric generators is in the range of 1–5% while the operating temperature is within 150–600 °C [38,39], and they are therefore suitable to low and medium grade heat recovery applications. In the case of high grade heat sources in industry, typically with temperatures of 1000 °C and above, a thermophotovoltaic device, which is a collection of photovoltaic cells that absorb infrared radiation from a high temperature heat source and converts it into electricity, can be used. It has been reported that the thermophotovoltaic has an efficiency potential of up to 20% at a heat source temperature of 1800 °C [40,41].

The active heat recovery strategies mainly refer to recovering waste heat for heating, cooling, and mechanical work. Some of the active heat recovery technologies, their operating conditions and techno-economic performances are provided in Table 5. Among them, closed-cycle mechanical heat pumps are suitable for heat recovery from waste heat streams up to about 110 °C, depending on the working fluid. Heat pump is particularly suited for moist exhaust stream as it can not only recover the heat associated with the temperature – 'sensible heat' but also the heat associated with the humidity – 'latent heat'. Absorption refrigerators and adsorption chillers are often used to recover waste heat from turbine and engine exhausts but do not rely on electrical power. In addition to the pumps and valves, they mainly consist of heat exchangers with the features of low noise and little vibration. In recent years, these two technologies have been widely used in central air conditioning to replace traditional compression refrigeration systems. In contrast, various thermodynamic cycles can be used to recover low-grade waste heat to obtain mechanical work and then drive generator to generate electricity. Organic Rankine cycle (ORC) has been developed based on traditional Rankine cycle (TRC) but using different organic working fluids which depends on specific conditions, such as waste heat temperature and cycle operating pressure [42,43]. Depending on working pressure, an ORC can operate at a subcritical or supercritical pressure. The subcritical ORC is the one that is traditionally used in small-scale waste heat recovery applications. However, recent studies show that a supercritical ORC is capable of producing higher power output and thermal efficiency than a conventional subcritical cycle [44–49]. Kalina cycle is the improved version of the Rankine cycle, in which the ammonia-water mixture is used as the working fluid and the evaporation segment of the cycle is non-isothermal. The non-isothermal evaporation feature can reduce the irreversibility and improve the utilisation of heat sources, and make the Kalina cycle usually 20–40% more efficient than the Rankine cycle in practice. From the various published models of the Kalina cycle system (KCS11, KCS34, KCS34g) [50], they are for utilisation of sensible heat part of the waste heat, mainly to recover the gas turbine exhaust heat or make use of geothermal to generate background power. Supercritical CO_2 cycle is another version of the Rankine cycle, which utilises CO_2 in place of water/steam as the working fluid, with the features of being more compact and environmental friendly [51]. Compared with Rankine cycle, supercritical CO_2 system requires less work for compression because the working fluid will be compressed at a liquid state. Trilateral cycle based systems use light hydrocarbons as the working fluid, in which expansion starts from the saturated liquid, rather than the saturated, superheated or supercritical vapour phase, with almost perfect temperature matching. The Trilateral cycle is 14–85% more efficient than the organic Rankine cycle, and it is conceived primarily as a means of recovering power from hot liquid streams in the 100–200 °C [52]. The Thermofluidic oscillator is a kind of temperature difference (as low as 30 °C) driven emerging heat recovery technology and particularly well suited to the conversion of low grade heat to produce useful (hydraulic) work for fluid pumping, heating and/or cooling and niche power generation applications [53]. Although Thermofluidic oscillators have a relatively low Carnot efficiency, the simple construction (few moving parts or dynamic seals) makes them have low capital and maintenance costs [54]. Stirling engine is one of the thermodynamic heat engines that can be used for low and medium grade heat recovery purposes which converts heat energy into mechanical rotations by continuous compression and expansion of a working fluid, usually air, helium or hydrogen, in a cylinder. The efficiency of the Stirling engines can vary from 13% to 36% depending on the temperature difference between a heat source and sink [40].

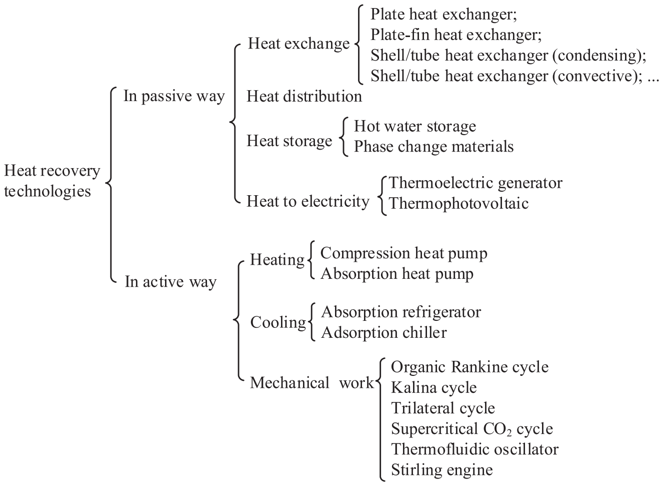


Fig. 9. Classification of heat recovery technologies.

Table 5
Heat recovery technologies for industrial applications.

Methods	Heat recovery technologies	Driving temperature (°C)	Efficiency or U-value	Media	Costs	Ref.
Passive way	Heat exchangers (HE)	100–650/50–250 (plate HE)	0.06–0.28 kW/m^2 K	steam-steam; steam-water	£180/m^2	[12]
		60–90 (plate-fin HE)	0.06 kW/m^2 K	steam-water	£4/m^2	[12]
		100–500 (shell-tube HE, cond.)	0.11–0.85 kW/m^2 K	steam-steam; steam-gas; steam-water; gas-steam; gas-gas; gas-water.	£180–220/m^2	[12]
		40–500 (shell-tube, conv.)	0.11–0.57 kW/m^2 K	water-gas; water-water; water-steam; steam-steam; steam-gas; gas-gas; gas-steam.	£170–180/m^2	[12]
	Heat distribution	100–140	0.82 K/km	steam	£740k/km	[12]
		50–90	0.4 K/km	hot water	£188k/km	[12]
	Hot water storage	50–90	0.08 kW/m^2	hot water	£36/kW h	[12]
	PCM	600–700	85–90%	molten salt (Na)	£8–32/kW h$_{th}$	[55]
	Thermoelectric generator	150–600	1–5%$_{th}$	Lead/bismuth telluride	£7325/kW$_e$	[38]
	Thermophoto-voltaic	1000–1800	10–20$_{th}$	Gallium antimonide/ silicon/Indium gallium arsenide		[41]
Active way	Heat pumps	35–110 (compression HP)	COP: 5	water-water	£200/kW$_{th}$	[12]
		30–110 (compression HP)	COP: 3.3	gas-water	£370/kW$_{th}$	[12]
		50–110 (absorption HP)	O/I: 1.6	water-water	£230/kW$_{th}$	[12]
	Absorption refrigerator	55–90	COP: 0.35–0.70	silica gel-H_2O		[56]
	Adsorption chiller	65–90	COP: 0.63–0.77	H_2O-LiBr; H_2O–LiCl; H_2O–NH_3		[57]
	Organic Rankine cycle	90–150 (low temp.)	8%$_{net}$	Organic fluids	£2200/kW$_e$	[12]
		300–550 (high temp.)	16–17%$_{net}$	ammonia-water	£2600/kW$_e$	[12]
	Kalina cycle	149–177 (geothermal)	8–12%$_{th}$ [50]	ammonia-water	£1645/kW$_e$	[58]
		200–400	20–40%[a]	ammonia-water	£1150/kW$_e$	[59]
	Supercritical CO_2 cycle	150–300	6–10%[b]	CO_2	£1000–650/kW$_e$	[60]
	Trilateral cycles	100–250	14–85%[c]	light hydrocarbons	£1300/kW$_e$	[52]
	Thermofluidic oscillator	from 30[d]	9.5%$_{carnot}$	organic working fluid		[53]
	Stirling engine	100–700	13–36%$_{th}$	hydrogen/helium/air		[40]

[a] The Kalina cycle is 20–40% more efficient than the Rankine cycle.
[b] The efficiency is based on optimum thermo-economic operating point.
[c] The Trilateral cycle is 14–85% more efficient than the organic Rankine cycle.
[d] Temperature difference between heat source and sink that associates with low grade heat.

2.2.2. Overall heat recovery solutions

According to spatial distribution and energy conversion form, overall heat recovery solutions can be broadly classified into three strategies, as shown in Fig. 10: (a) recovering waste heat from a process and recycling the recovered energy back into the process through heat exchange of various types; (b) recovering waste heat for other process uses or hot water storage through heat distribution network and heat exchange; (c) using it to pass heat from a lower temperature source to a higher temperature stream (e.g. refrigeration or heat pump) or generate electricity in power systems (e.g. thermodynamic cycle or heat engine).

Industrial processes are sets of procedures that involve thermal, physical, mechanical, chemical and electrical actions to produce a target item, for instance a steam generating process. An industry is comprised of many individual process and sub processes in different

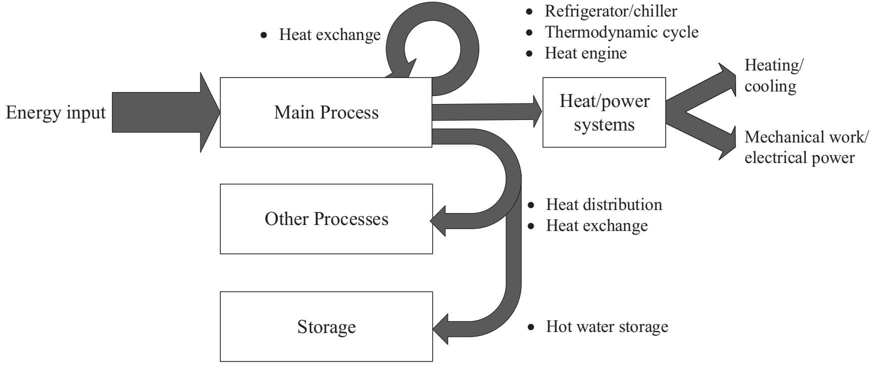


Fig. 10. Illustration of overall heat recovery solutions.

operating temperatures. The most efficient way of recovering waste heat from a process is to reuse the heat by feeding back to the main process. A common example of waste heat reuse within a process is boilers. In industrial boilers, the combustion exhaust can be used to preheat combustion air and feed water which eventually saves fuel costs and increases boiler efficiency. A list of industrial processes, temperatures and potential in-process reuse options is listed in Table 6.

The second most efficient option for the utilisation of waste heat in industry is to use the heat in other nearby processes. Waste heat from high temperature processes can be transferred to other lower temperature processes via heat exchangers. Some examples where heat exchangers used are space heating, hot water for domestic use, in plant absorption refrigeration system, heating of evaporative systems or over the fence heat sinks such as district heating [63]. In addition, waste heat from different processes can also be stored for future use by various storage technologies with carrier fluids such as water, thermal oil, PCMs, etc. The thermal energy storage could be an effective way of reducing waste heat, especially when the waste heat from any process is intermittent in nature and utilisation of this excess heat in other processes is not viable. The third and final stage of the solution is to recover a waste heat either using heating and cooling systems or via power generation systems. Although, numerous technologies for this purpose are commercially available and ready to use, a process specific waste heat recovery technology should be assessed according to the quantity and quality of heat source. Hammond and Norman [9] conducted such an analysis to show the heat source characteristics required by different technologies to be used for waste heat recovery applications. For instance, heat pumps can be used with a heat source temperature less than 100 °C. On the other side, an on-site heat recovery is preferable if the temperature of heat source is higher than 100 °C. Heat to chilling is suitable for a heat source temperature in between 100 and 300 °C and all heat sources with temperatures greater than 100 °C can be used for electricity generation [9].

2.3. Bioenergy/waste utilisation

Bioenergy and bio-waste utilisation is a broad and very active area in sustainable energy studies. Some novel and emerging waste to energy conversion technologies utilise feedstock generated on site or within a group of neighbouring sites to keep transportation costs and emissions low. These technologies include anaerobic digestion, pyrolysis and gasification [64]. In the EU Waste Framework Directive [65], bio-waste is defined as *"biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants, but does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood"*. There are two types of agricultural crop residues: field residues are materials left in an agricultural field or orchard after the crop has been harvested, which can be ploughed directly into the ground, or burned first to sustain the fertility of the soil; process residues are materials left after the crop is processed into a usable resource. Because of the high carbohydrate content, crop residues can be considered as an appropriate bio-waste feedstock to produce biofuels [66–69]. Globally the total bio-energy potential of crop residues, animal waste and municipal waste (Fig. 11) are estimated to grow from 14,000 TW h to 36,300 TW h from 1990 to 2050 based on estimates given in [70]. The highest increase rate is projected to be in energy from municipal waste. Such energy increases with the population and wealth growth and fast diffusion of food waste recycling and collection practices in society. In the same study, it is reported that only 20% of the total bioenergy potential (after the energy crops and wood is included) was used in 1990.

The study by *Global Energy Perspective* [71], explored six global primary energy supply description scenarios, in which one of the scenarios (Scenario A3) is based on the vision of the highest absolute contribution of bioenergy. Based on that scenario it is estimated that as the energy supply will increase over time the percentage contribution of the bioenergy in the total energy supply will also increase up to 12.5% by the year 2020 and up to 15% by 2050 (Fig. 12). These figures imply that bioenergy is expected to replace some portion of the non-renewables (e.g. coal, oil) energy supplies.

The UK is obligated to apply a waste hierarchy dictated by the revised EU Waste Framework Directive. The framework orders the options as prevent, reuse or recycle to reduce greenhouse gas emissions [65]. In this hierarchy energy recovery is an option for waste that would otherwise go to landfill and create landfill methane emissions. Direct combustion or incineration is a conventional technology to generate heat and power using steam turbines or combined heat and power systems. A more environment friendly and efficient alternative to direct combustion is combustion of waste derived fuel such as the methane released from bio-waste. Recovering the energy as waste derived fuel becomes more common owing to improving technologies in the bioenergy sector and the advantages of storability and transportability of the produced energy.

2.3.1. Energy recovery through anaerobic digestion

Anaerobic digestion (AD) is currently one of the most popular and promising conventional energy recovery technologies in the bioenergy sector [72], as shown in Fig. 13. AD is a natural process in which microorganisms break down the biodegradable matter found in wet biomass waste (such as sewage sludge, animal manure and slurry and waste food) in an oxygen-free environment. The AD process produces biogas (mainly a mixture of around 60% methane and 40% carbon dioxide) and nutrient rich digestate which is comprised of up to 95% water and

Table 6
Heat recovery through in process reuse options [11,61–63].

Industry type	Process type	Process temperature (°C)	Heat quality	Process reuse options
Iron & Steel Ceramics Cement Glass Chemicals	Furnaces	650–1650	High	Combustion air preheating
Chemicals	Steam boilers	230–480 < 230	Medium Low	Combustion air preheating Water preheating
Food & drink	Baking	150–250	Low to Medium	Combustion air preheating
Food & drink Pulp & Paper Ceramics	Medium temperature drying	230–590	Medium	Air preheating
Cement Chemicals Oil refinery	Low temperature drying	90–230	Low	
Food & drink Pulp & Paper Ceramics	Hot water boilers	60–230	Low	Water preheating
Cement Glass Chemicals Oil refinery	Boilers	200–300	Low to Medium	Combustion air preheating
Food & drink Pulp & Paper Ceramics	Space heating	60–230	Low	Water preheating
Cement Glass Chemicals Oil refinery				Combustion air preheating

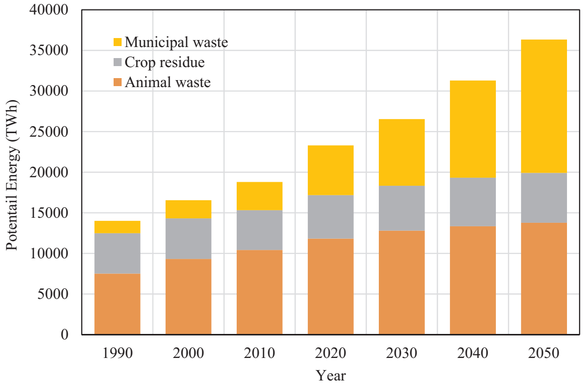


Fig. 11. Energy capacity of global bio-waste based on estimates in [70].

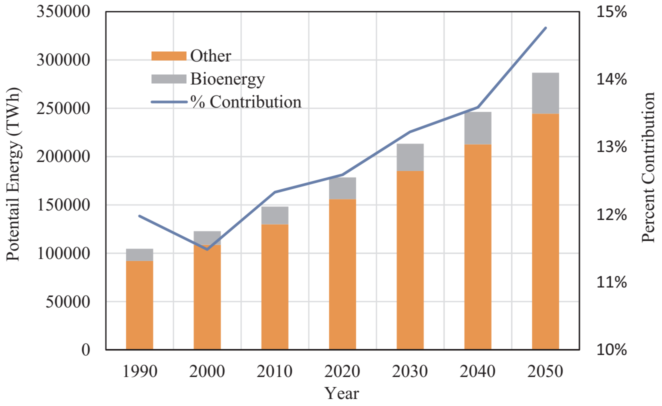


Fig. 12. Global energy supply and contribution of bioenergy based on IIASA-WEC Scenario A3 projections [71].

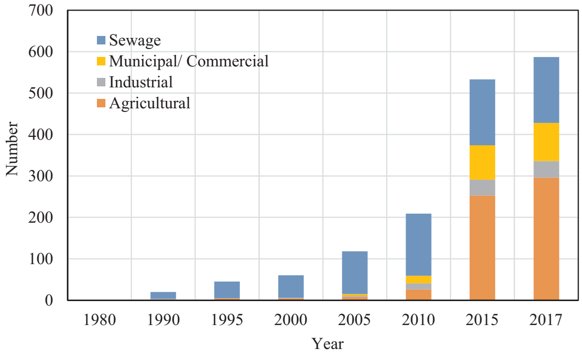


Fig. 14. Number of operational AD plants in the UK based on data from the official information portal on anaerobic digestion [84].

the remaining undigested solids. The energy recovered through the AD process helps towards the decarbonisation of the UK electricity grid [73]. Anaerobic digestion has the potential to reduce the environmental impact of energy production through such displacement of fossil fuels [74]. Benefits have been observed not only to replace fossil fuels for heat, but also for electricity generation and transport fuel [75]. Since bio-gas can be stored, or upgraded for insertion into the distribution network/infrastructure, AD may contribute to energy security by offering a demand orientated solution to the erratic nature of other renewable energy sources such as wind or solar [76,77].

Anaerobic digestion plants have been operating within the UK for decades (mostly fed by sewage sludge), but only recently the number of plants fed by other feedstock types has increased considerably, in part due to the subsidies supported Feed-in Tariff (FiT), the Renewable Heat Incentive (RHI) or the Renewables Obligation (RO) [78]. The ability of AD to offer solutions aligned with energy system interests (low carbon electricity and heat) means that growth in the sector can now largely be associated with energy policy [79]. This has allowed the number of AD plants to grow from 209 to 587 (Fig. 14) and the energy production capacity to grow from 273 to 664 MWe (Fig. 15) between 2010 and 2017 alone. In a detailed assessment of a micro-scale AD Plant fed by urban organic waste the specific biogas yield is reported as 220 m^3 per ton of fresh food waste [80]. In a similar assessment of a large-scale AD Plant the specific yield is reported as 156 m^3 per ton of fresh food waste [81]. Considering the biofuel contains around 60% methane with a lower calorific value of 11.1 kW h per cubic metre, the specific energy yield of fresh food waste through AD process can be calculated as around 1040–1465 kW h per ton. In 2015 the estimated amount of household food waste (HHFW) in the UK was 7.3 million tons [82], which has a potential of 10.95 TW h of equivalent energy. In the UK, currently AD plants with a wide range of types and sizes operate on multiple different feedstocks and generate 664 MWe of energy in total. It is estimated that 2 TW h of bio-methane was injected into the national grid in 2015 and the potential that could be generated from wastes and residues was 35 TW h in total. This potential would make up approximately 4–12% of the projected UK gas needs in 2050 (300–800 TW h) [83].

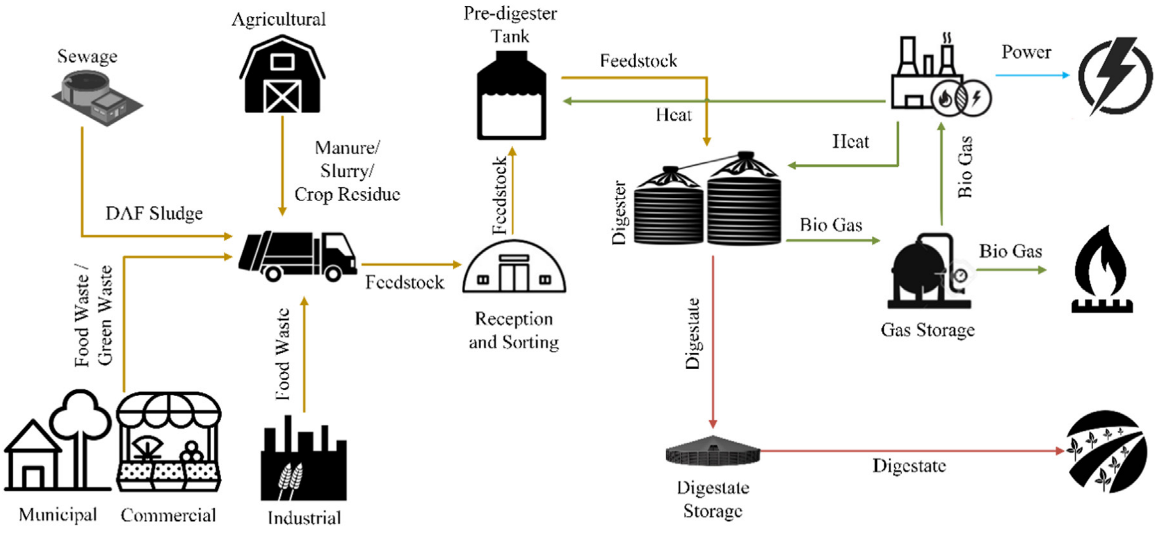


Fig. 13. Illustration of a typical feedstock collection and AD plant operation.

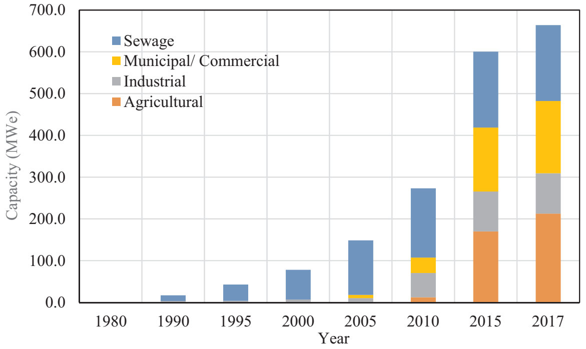


Fig. 15. Energy capacity of operational AD plants in the UK based on data from the official information portal on anaerobic digestion [84].

The AD plants in the UK range from a small scale, not-for-profit community plant (< 1 kW) fed by food waste from local restaurants, to a medium scale crop based plant (50 kW) built using novel construction techniques, and up to large commercial plants (> 1 MW) that are operated over multiple sites and fed by their own food waste collection logistics. Understanding the motivation of stakeholders behind the existing barriers in the AD industry is important to project the potential growth of AD [85]. The drivers behind the different plants vary with the intensity of subsidies: some are fully dependent on FiT as the main source of income; some hold a power purchase contract with the local distribution network operator; others benefit from the savings made from avoided waste disposal costs or purchased fertilizer costs. In fact, AD expansion is currently losing its momentum within the UK. At present, AD plants only receive subsidies for the energy which they generate and not the other side products such as digestate. Due to the low economic value and high transportation cost, digestate is often seen as a burden to the plants producing it, with many paying for it to be taken away [86]. The subsidy levels are in the process of being reduced, and are at the edge where a significant proportion of future plants seems to be not feasible [87]. This must be compared against already high perceived barriers of cost to installing AD [88]. Hence, the number of new plants to be commissioned is expected to reduce significantly in the coming years [87].

2.3.2. *Emerging bio-energy recovery technologies*

Besides AD technology, there are a number of advanced technologies emerging such as pyrolysis and gasification with higher conversion efficiencies than the conventional energy recovery technologies. Pyrolysis is a thermochemical decomposition of organic material into bio-char and bio-oil at very high temperatures (200–500 °C) in the absence of oxygen (or any halogen). There are various methods developed based on the pyrolysis for producing fuel (bio-oil) from biomass. Slow pyrolysis has been used traditionally for the conversion of biomass (commonly wood) into charcoal. In slow pyrolysis the biomass is heated slowly to temperatures between 300 °C and 400 °C with long reaction times up to several days [89]. Although charcoal is the main product of the slow pyrolysis, the process also generates lower yields of bio-oil and gaseous products. In the past 30 years fast pyrolysis has become of considerable interest as a method for producing higher yields of bio-oil. The fast pyrolysis process is carried out at temperatures around 500 °C and with very short reaction times between 1 and 5 s. Fast pyrolysis is meant to convert biomass into a maximum quantity of bio-oil with significantly higher energy density than the original biomass. Normally around 65% of the weight is converted into bio-oil in addition to 20% bio-carbon and 15% gas. Depending on the type of the pyrolysis and the biomass used in the process the energy conversion performance varies considerably [90]. The typical yields from fast pyrolysis process and highly dependent on the reaction temperature [91].

The biomass feedstock used in the process may be specifically grown energy crops (non-food) as well as biological waste products [92]. The sustainability constraints for each type of bioenergy feedstock is analysed and classified for future UK bioenergy supply [93]. Pyrolysis technique is also used to recover energy from non-biological carbon-based wastes such as car tyres [94]. Pyrolysis can be performed at relatively small scale and at remote locations which enhance energy density of the biomass resource and reduce transport and handling costs. Conversion of biomass to bio-oil near the biomass source using modular/mobile fast pyrolysis plants can further reduce the cost of biomass harvesting and handling [95]. Pyrolysis offers a flexible and attractive way of converting solid biomass into an easily stored and transported liquid, which can be successfully used for the production of heat, power and chemicals.

Gasification is a process that converts organic or fossil fuel based materials into carbon monoxide, hydrogen and carbon dioxide. Gasification can also be fed by materials which would otherwise have been disposed, such as bio-waste [96]. Similar to pyrolysis, gasification is achieved by reacting the material at very high temperatures (> 700 °C), without combustion, with a controlled amount of oxygen and/or steam. The resulting gas mixture is called syngas (synthesis gas of H_2 and CO) which itself is a fuel. The advantage of gasification is that using the syngas is potentially more efficient than direct combustion of the original fuel (if a fuel is used as beginning material), because it can be combusted at higher temperatures or even in fuel cells [97]. In addition, the high-temperature process refines out corrosive ash elements such as chloride and potassium, allowing clean gas production from otherwise problematic fuels [98]. Gasification is also used as next step of process after pyrolysis to purify the recovered bio-oil [99].

3. Industrial sector studies

Final energy demand of UK industry has been reduced by nearly 40% from 1990 to 2016 [100]. While iron and steel accounted for 18% of total industrial final energy use in 1990, with changes in the economic structure of the UK economy and increasing imports, it reduced its energy use the most (i.e. 86% reduction) by 2016. As a sector producing goods that are embedded in many other finished goods such as automotive or construction industries, iron and steel has been seen as a strategic sector for the UK economy [101]. On the other hand, the food, drinks and tobacco sector has accounted for nearly 12% of UK's final energy consumption from 1990 until 2016 [102]. According to the food and drink federation, the sector contributes £28.2 billion to the UK economy [103]. Overall these two sectors represent different characteristics in terms of types of end use services energy is used for (Fig. 16). While high-temperature processes account for 60% of energy needs of iron steel sector, low temperature processes are the main driver of energy use in the food, drinks and tobacco sector.

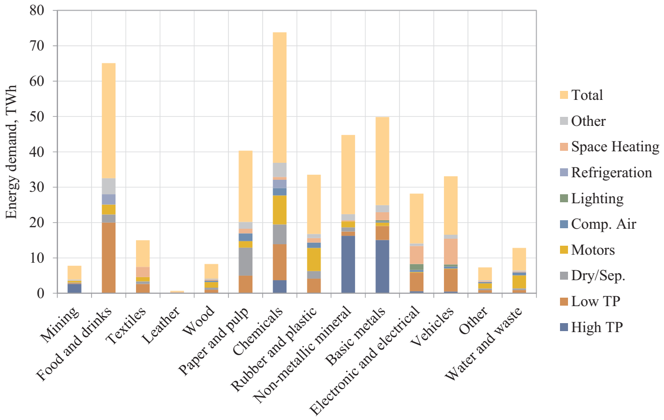


Fig. 16. Final UK energy demand by different end-use services in 2016 [100].

3.1. Iron and steel industry

Rising concern about reducing both energy demand and CO_2 emissions is pushing more efforts to achieve sustainable development in energy intensive industries. The iron and steel industry is energy-intensive accounting for 18% of the world's total industry final energy consumption in 2013 (latest available data at https://www.iea.org). According to statistical data of the International Energy Agency published in 2012, the iron and steel industry has the technical potential to reduce its current total energy consumption by approximately 20% by applying the best available technology, where more energy-efficiency technologies/measures could be implemented in steel plants. In the UK, Iron and steel production accounts for 26% of CO_2 emissions [104] and 7.5% of annual industrial energy consumption [105]. To reduce the levels of CO_2 by at least 80% by 2050, the UK government has supported a series projects and aims to address this challenge by working closely with some key industrial collaborators. Its objective is to demonstrate the potential to achieve energy demand and carbon emission reductions of more than 15%. The iron and steel industry is expected to be one of the principal beneficiaries.

Globally, steel is produced via two main routes: blast furnace-basic oxygen furnace (BF-BOF) route and electric arc furnace (EAF) route. Variations and combinations of production routes also exist depending on product mix, available raw materials, energy supply and investment capital etc. In BF-BOF route, firstly raw materials, coal and iron ore, are pre-treated in coking and sintering processes respectively; then, sintered iron, coke, and flux (e.g. limestone) are added into a blast furnace to produce molten pig iron; next, together with scrap iron/steel, molten iron turns into steel in a blast oxygen furnace without any external energy sources, but only the heat of the molten iron itself and the heat generated from the reactions between the molten iron components; finally, liquid steel will go through continuous casting process and hot rolling process sequentially before it becomes a finished steel. Due to the inclusion of coke making and sintering operations, BF-BOF route is highly energy intensive, with average of 5.2 MW h per tonne crude steel [106]. Comparatively, EAF route has significantly lower energy intensity, with an average of 1.87 MW h per tonne crude steel, due to the omission of these two processes. Currently, about 70% of steel is produced using the BF-BOF route [107]. Gas from iron and steelmaking (e.g. coking, BF and BOF) has high calorific value, which can be used internally to produce steam if being cleaned. These gases can be fully reused within the steel production site, and can provide up to 60% of the site’s power [107].

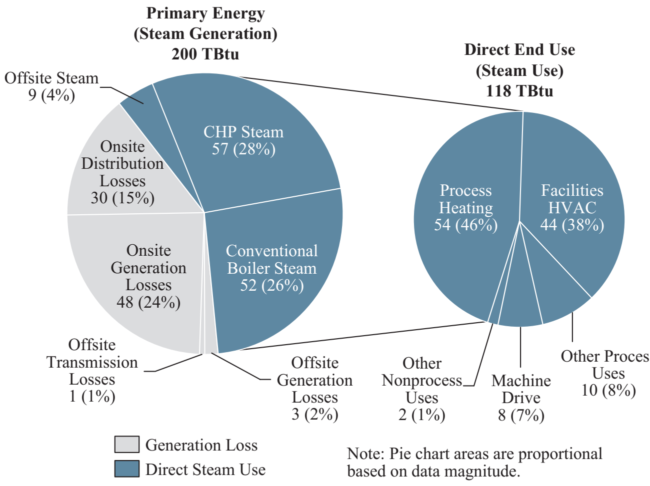
3.1.1. Steam generation and uses in the iron and steel industry

In iron and steel plants, steam is produced through one of three methods: offsite steam that is transferred into plants or purchased through the local utility or other sources, steam generated using CHP units, and steam generated using conventional boilers. Typical steam generation and direct end use in the iron and steel plants are shown in Fig. 17. About 42% of steam produced is lost through offsite generation and transmission losses, onsite generation and distribution losses. Process heating applications use 46% of steam, with 38% used in facility HVAC, 8% used in other process uses, 7% used in machine-driven applications, and 1% used in other non-process uses.

Steam consumption accounts for around 10% of total energy consumption in the iron and steel industry [109], and recoverable waste heat steam is also considerable which accounts for around 7% of total energy consumption the industry [110]. The energy consumption and running cost can be reduced by improving the recovery and utilisation of steam. However, more attention was given to the optimised utilisation of by-product gases [111,112]. For example, Tata Steel is to invest £53 million in cutting the power needed by its steel-making plant in Port Talbot [113]. A new cooling system will create steam, allowing the plant to generate up to 10 MW of electricity. The new cooling system would cut the BOF demand by about 15% and improve Port Talbot's productivity and energy efficiency.

Currently, besides new cooling systems, like Tata Steel adopted to cut the BOF energy demand, other technologies used in the iron and steel industry to recover waste heat to generate steam mainly include coke dry quenching [114], sinter plant cooler waste heat recovery [115], oxygen converter gas recovery [116], EAF waste heat recovery [117], and reheating furnace evaporative cooling [118]. Typical parameters of the waste heat steam generated using these technologies are listed in Table 7. However, such steam parameters are quite similar worldwide, as modern steel production facilities have been modernised to maintain their competitiveness. According to the figures in Table 7, the steam grades are currently low, and this limits the application scope of the steam. On the other hand, due to the low steam grade, most waste heat steam in the iron and steel industry is saturated steam and it is easy to get condensed. If heat loss occurs in transport, droplets or liquid moist will be formed and this will further reduce the temperature and pressure of the steam. Especially, the distribution of waste heat sources in the iron and steel industry is relatively dispersed, which will inevitably lead to humidity and transportation difficulties. These difficulties play a negative role on the utilisation of waste heat steam in the iron and steel industry.

The waste heat is obtained mainly from the by-product gas of iron- and steel making processes, therefore the waste heat steam generation is inevitably affected by these processes. However, due to process requirements, iron- and steel making processes are intermittent, fluctuant, and periodic. Therefore, waste heat sources in the iron and steel industry also have these characteristics. Energy recovery systems in the iron and steel industry have to be both efficient and responsive. Taking the blast- and electric arc furnaces as examples, which are major sources of energy consumption in the steel manufacturing process, they have their own operating cycles. In practice, blast furnace operators commonly use fixed cycles due to the difficulty of operating blast-furnace stoves in cycles of different durations. However, this practice inevitably leads to fuel losses and destabilizes the temperature of the blast and is likely to produce a blast temperature below the required level [119]. In converter steelmaking operation, gas flow rate and temperature also significantly changes with operating steps, including scrap and hot metal charging, oxygen blowing, and auxiliary operations, as shown in Fig. 18. Due to inherent operation cycles existing with various processes, waste heat steams vary with their host, instantaneous steam production rate might be much higher than the mean production rate. Although steam accumulators [120] between steam sources and steam pipe networks successfully solved the fluctuation problem of steam production, it is at the expense of lowering steam grade and loss of exergy.



Note: Pie chart areas are proportional based on data magnitude.

Fig. 17. Steam generation and direct end use in the iron and steel sector (adapted from [108]).

Table 7
Typical parameters of the waste heat steam in iron and steel plants [110].

Process	Temperature, °C	Pressure, MPa	Superheated?
Coke dry quenching	450	3.82	Yes
Sinter plant waste heat recovery	375	1.95	Yes
Oxygen converter gas recovery	240	3.2	No
EAF waste heat recovery	200	1.6	No
RF waste heat recovery	175	0.8	No

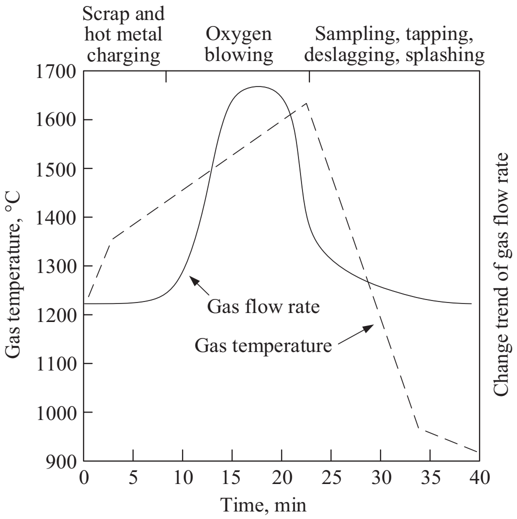


Fig. 18. Gas flow rate and temperature profile in converter operation (adapted from [110]).

For the use of steam, iron and steel plants usually only set up one or two sets of steam pipeline network systems [121]. The steam from different supply sources is connected by pipe line networks and transmitted to the end user of different production processes. Due to the variation in steam quality that end users require, high quality steam often has to be degraded by pressure reduction valve (PRV) before reaching the end users rather than being used in a cascade way. Therefore, exergy loses seriously in the pressure reduction process [122]. Fig. 19 shows the status of steam generation and uses in an iron and steel plant. The overall steam utilisation ratio is 82%, and rest of the steam is lost in the distribution pipe network. The uses of low pressure steam are dominant, and account for 48% of the total, mainly used for auxiliary production and district heating etc.; relatively, the medium to high pressure steam mainly used for energy intensive processes, such as blast furnace blower [123] and ladle vacuum treatment [124]. As a result, 16% higher pressure steam is degraded to medium pressure for use; and 13% medium pressure steam is degraded to low pressure for use. The mismatched uses of high quality steam caused a huge waste. Due to distribution loss and mismatched uses, the exergy efficiency of existing system is usually lower than 50% [125]. Therefore, there is a large space for further improving the efficiency of steam pipe networks. The authors also note that the cases shown in Figs. 18 and 19 are from Chinese iron and steel plants. However, they believe that these cases can also reflect on the situation in the UK because there is no significant difference between the Chinese and British iron and steel plants from a technical point of view.

Since district heating accounts for a larger portion of the use of low pressure steam and the demand of heating varies significantly with seasons, seasonal supply and demand of most steam systems is somewhat unbalanced, especially in regions with large seasonal temperature difference. Fig. 20 shows annual energy supply for heating in the UK in 2010. It is obvious that heat demand is seasonally based. From November to January is the peak time of steam use; in contrast, from June to July is the off-peak time of steam use. The peak to off-peak ratio of heat demand over the year is up to 5. As the majority of low pressure steam is used for heating, that implies that if the steam supply can satisfy the demand in peak time then it necessarily exceeds the demand in off-peak time. This is because although the steel production is intermittent, the seasonal difference is not significant. Fig. 21 shows monthly crude steel production in the UK in 2015. Although the production generally decreased over the year (declining from approximately 1.1 million tonnes in January 2015 to 603,140 tonnes in December 2015), this is nothing to do with seasonal effect. In many iron and steel industrial processes, waste heat steam systems also play the role of cooling. Therefore, waste heat steam systems must keep running throughout the year. Due to the reduced demand in summer, part of the waste heat steam has to be exhausted into the atmosphere directly.

In addition, in iron and steel enterprises, steam sources and consumers usually cover a large region. The steam system is enormous, that not only provides the steam for production but also for living. Fig. 22 shows the main lines of steam pipe network at Tata Steel's Port Talbot Integrated works in South Wales. Due to the sheer scale of the steelworks (approx. 4 km by 1.5 km), the total length of steam pipe exceeded 26 km. In reality, the steam pipe network is generally more complex because the historical development of the steelworks. In the process of technology upgrading or retrofitting, it brought the problem of unreasonable local design and piping, which are the main cause of energy losses in the pipe network. In practice, there are five common pipe sizing problems [128]:

(1) Incorrectly sized distribution piping, from not optimising steam velocity;
(2) Oversized distribution piping, from altered boiler operating conditions;
(3) Undersized piping downstream of pressure reducing valves, from failing to consider changes in steam velocity and specific volume;
(4) Undersized condensate piping downstream of traps, ignoring the presence of two-phase flow;
(5) Improperly sized condensate return-lines, from failure to differentiate between pressurised and pumped condensate.

To monitor steam generation and use over the entire system, each producer and customer should be equipped with steam flowmeters. However, due to various reasons, many places are not equipped with steam flowmeters, even if some places are equipped with them but due to lack of management, the steam flow data is either not available or not accurate. This results in steam generation and consumption of the process is not clear. To ensure accurate and consistent performance from a steam or condensate flowmeter, it is essential that it is correctly matched to intended applications [130].

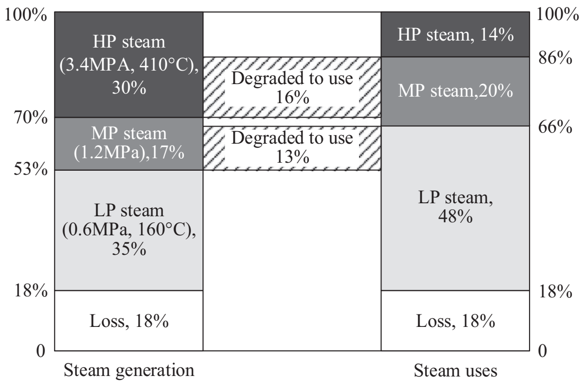


Fig. 19. Steam generation and uses in an iron and steel plant (adapted from [110]).

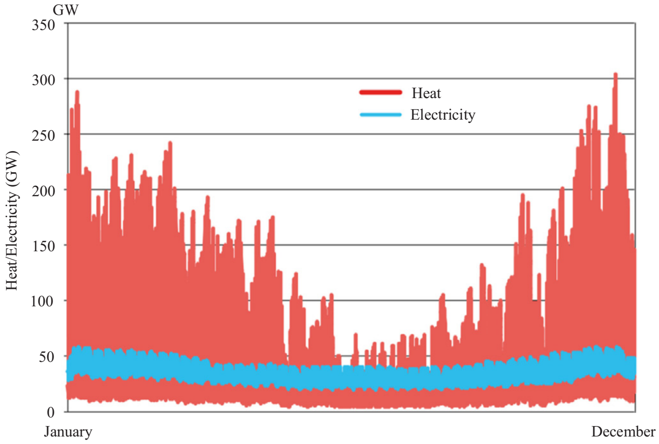


Fig. 20. Annual energy supply for heating in the UK in 2010 [126].

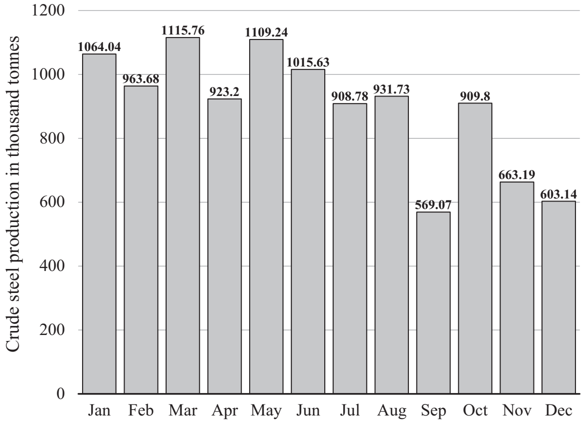


Fig. 21. Monthly crude steel production in the UK in 2015 [127].

3.1.2. Heat recovery potential from the iron and steel industry

Energy interdependent relationship within modern iron and steel enterprises is a complex system. Fig. 23 illustrates an example of the energy flows in an integrated steelwork. Although the dominant inputs are coal (more than 65% of primary source of energy), heavy oil and coke (if bought from an external supply), most of them are used to produce coke in the coke oven plant and as reducing agents in the blast furnace. The materials that constitute the basis of the energy system are the process gases, including coke oven gas, blast furnace gas, and basic oxygen furnace gas. Heat recovery is an effective way to enable that most of the energy demand can be satisfied by these gases, while minimising the remaining part that must be balanced with purchased energy, normally electrical power and natural gas. Despite the widespread development of heat recovery technologies within process stages (individual process or plant level), larger savings may be obtained by using a wider integrated network of heat exchange across various processes along the supply chain (integrated system level). McBrien et al. [131] investigated the potential for energy savings by heat recovery in an integrated steel supply chain using pinch analysis. Table 8 lists potential heat recovery methods currently available and average energy saving obtained if implemented in the blast furnace – basic oxygen furnace integrated (BF-BOF) route steelmaking process.

According to the current situation described in [131], theoretically a maximum energy saving for heat recovery of 1.2 MW h per tonne of hot rolled steel (h) has been calculated through pinch analysis of the entire system. Based on existing heat recovery technologies (excluding heat recovery from solid streams), overall process heat recovery can only save approximately 0.5 (MW h/t h), integrated heat recovery with conventional heat exchange could save 0.7 MW h/t h; if including heat recovery from solid streams (hot steel), it could save 0.83 MW h/t h. In addition, limited additional savings may be obtained from the integration of the steel supply chain with other supply chains involving heating. Based on an average energy consumption of 5.3 MW h/t for primary steel production in the BF-BOF route reported by worldsteel Associate [133], if the industry moves from an average value to the values as the studied scenarios, energy-saving potential for the BF/BOF route is 9.4%, 13%, 15.6% respectively.

3.1.3. Bioenergy/waste utilisation in the iron and steel industry

Although energy efficiency measures are able to effectively reduce production energy consumption per tonne of steel for the time being, they are not enough to offset the growth in energy demand resulting from increasing steel production in the long run. Fossil fuels coal and coke represent the main source of energy in the iron and steel industry. Total or partial substitution with a fuel with a lower carbon content, e.g. biomass, can reduce the dependence on fossil fuels. The extent to which coal can be replaced is dependent on the iron- and steelmaking process. The biomass products can be applied in several processes as shown in Fig. 24: (i) coke making for production of bio-coke or

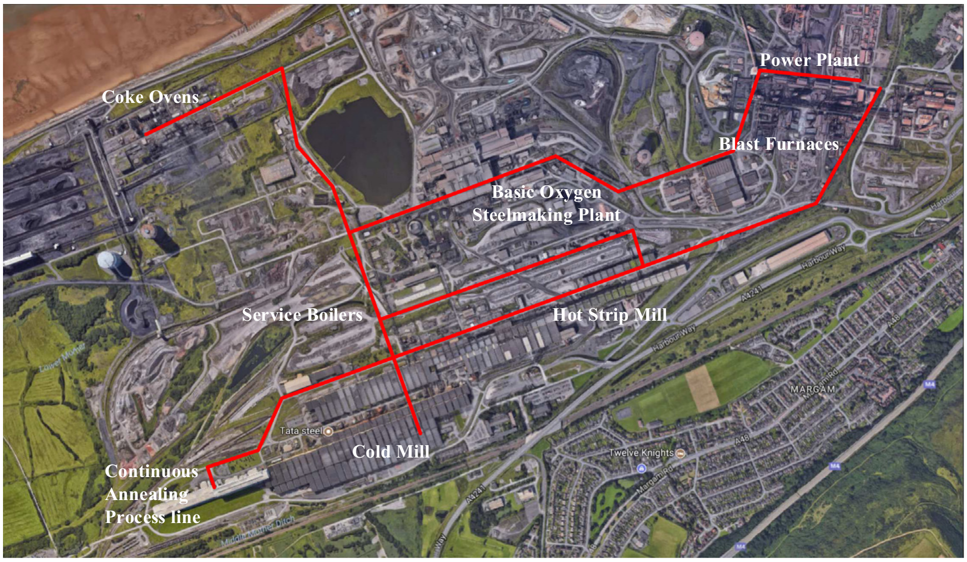


Fig. 22. Tata Steel's Port Talbot Integrated works in South Wales [129].

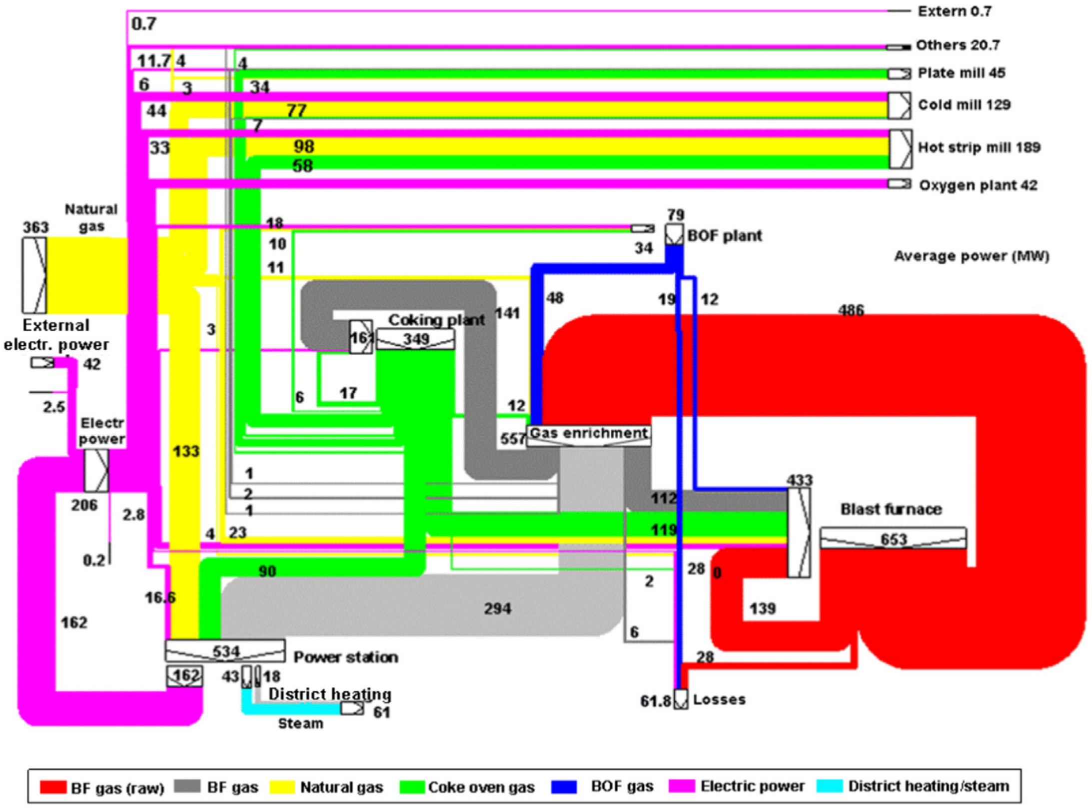


Fig. 23. Example of energy flow in an integrated steelwork [132].

Table 8
List of hot outputs from the steel supply chain with potential heat recovery methods currently available and average energy saving obtained if implemented [131].

Process	Output	Temp (°C)	Thermal energy (MW h/t)	Other energy (MW h/t)	Heat recovery method	Energy saving (MW h/t)
Coking	Coke oven gas	700	0.05	0.19	District heating	0.04
	Coke	1100	0.15	–	Coke dry quenching to generate steam	0.16
	Flue gas	250	0.02	–	Fuel preheating	0.01
Sintering	Sinter	700	0.25	–	Dry cooling – preheated air input	0.09
	Stack exhaust	350	0.09	–	Recirculation	0.05
Ironmaking	BF gas	180	0.1	1.14	Dry cleaning and top recovery turbine	0.05
	Blast stove exhaust	250	0.02	–	Incoming air preheat	0.02
	BF slag	1500	0.14	–	Dry granulation – air used to generate steam	0.06
Steelmaking	BOF exhaust	1700	0.05	0.03	Waste heat boiler to generate steam	0.05
	BOF slag	1700	0.01	–	Dry granulation – air used to generate steam	0.00
Casting	Steel	1200	0.19	–	–	–
	Steel latent heat	1200	0.09	–	–	–
Hot rolling	Reheat exhaust	700	0.05	–	Recuperative or regenerative burners	0.03
	Steel out	900	0.15	–	Space heating (hypothetical)	0.003
Total (MW h/t)			1.36	1.36		0.56

charcoal; (ii) sintering process for production of bio-sinter; (iii) partial replacement of nut coke, coke or PC in blast furnace; (iv) pelletising/briquetting for production of bio-composites and/or bio-briquettes; (v) replacement of pulverised coal injected as a fuel in the blast furnace; and (vi) bio-recarburisation of steel in ladle furnace [134].

Due to much lower mechanical strength of bio-coke compared to coke, in practice it is impossible to operate large blast furnaces with 100% substitution of bio-coke for coke, with substitution rates up to 20% being considered reasonable [135]. Typical carbon material addition rates of other processes in different steelmaking routes are shown in Table 9.

However, the sustainable production of bio-coke from planted trees needs large amounts of land. Producing 500 metric tons of hot metal requires over 40,000 ha (400 km^2) [138]. Therefore, there is also the competition with land for food production and with other industrial users, such as the power generating industry, that will lead to increased biomass costs. These factors limit the role of biomass in reduction of energy demand in the countries with low land availability. Fortunately, apart from biomass derived from timber plantations, there are other sources of biomass that potentially could be used for bio-coke production, such as wood processing residues, pulp and paper residues and forestry residues [139].

3.2. Food and drink industry

The food chain in the UK consists of several energy consuming

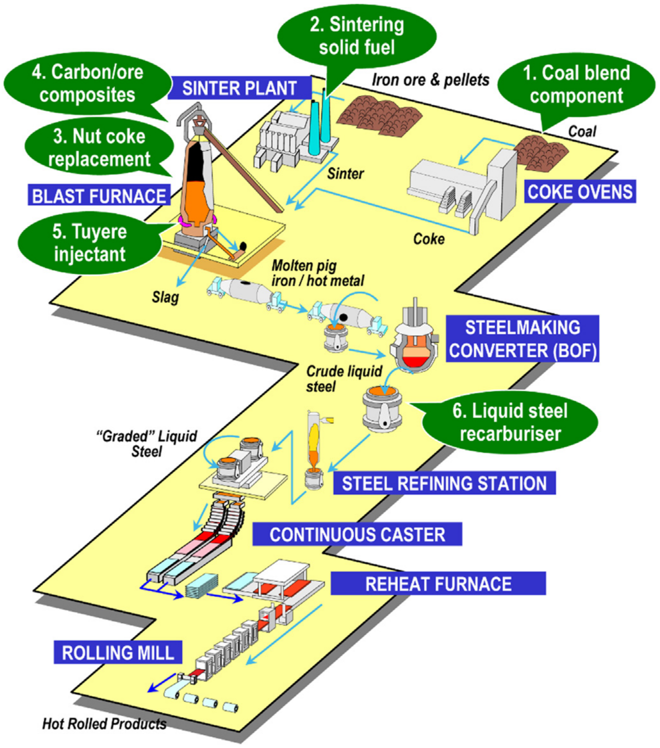


Fig. 24. Biomass applications in BF-BOF route [136].

members, mainly agricultural activities, manufacturing plants, distribution centre, retailers, catering service provider, consumers and waste disposal activities [140]. In 2011, total energy consumption across the UK agri-food chain was estimated to be 396.58 TW h [141]. The energy consumption at each stage of the food chain and their corresponding available emissions data are shown in Fig. 25. The entire food chain is responsible for 18% of total UK energy consumption and emits 176 $MtCO_2e$ GHG to the environment and leaves 15 Mt of food waste [141]. Tassou et al. [140] reviewed the energy consumptions and emissions from individual level of the food chain and summarised opportunities available and approaches for energy demand reduction. However, in this review paper, we are focused on the food and drink manufacturing sector rather than the entire food chain. In 2016, the food and drink manufacturing sector consumed 32.33 TW h energy, of which 61% of energy was supplied from natural gas, 31% from electricity, 5% from oil and rest of the energy supplied from coal [142]. This consumption led to an equivalent estimated GHG emissions of 8 $MtCO_2e$ from the sector.

The UK food and drink manufacturing sector is a highly diverse and disperse sector as it has many sub-sectors and produces varieties of products using different manufacturing processes across the country. The industry comprises of different sizes of companies mainly, bakery, meat and poultry, brewing and malting, fruits and vegetable processing and preservation, dairy and cheese production, sugar and confectionary, oil and fat, beverage, etc. The energy consumption can vary depending on the type of product and size of the manufacturing plant. The variation of energy consumption for different subsectors is shown in Fig. 26. The figure shows that the top five subsectors namely: bakery, meat and poultry, brewing and malting, fruit and vegetable and dairy and cheese, are responsible for 65% of the energy consumption of the total food and drink manufacturing sector. According to the UK Food and Drink Federation, emissions from different sub-sectors vary according to the consumption of fossil fuels and electricity profiles. Overall, the distribution of emissions for the whole sector based on the end use of energy are as follows: boilers 49%; direct heating from fuel combustion 19%; motors 16%; direct electrical heating 8%; refrigeration and air conditioning 6%; and compressed air responsible for 2% of the sector's energy used [143]. These percentages indicate the fact that most of the energy uses and emissions are directly linked to either steam generating processes through boilers or heat intensive processes through combustions. For instance, food canning is a steam intensive process which uses 70% of energy for boiler; baking of bread in a bakery requires around 60% of its total energy use for ovens [143]. Since the bulk of the energy is consumed by these two ways, energy consumption and carbon emission can be reduced by installing energy efficient technologies, better controls to ensure process optimisation, and by recovery and utilisation of steam and waste heat in the food and drink manufacturing sector. It is also worth taking into account that the food and drink sector also contributes to around 10 Mt of waste through

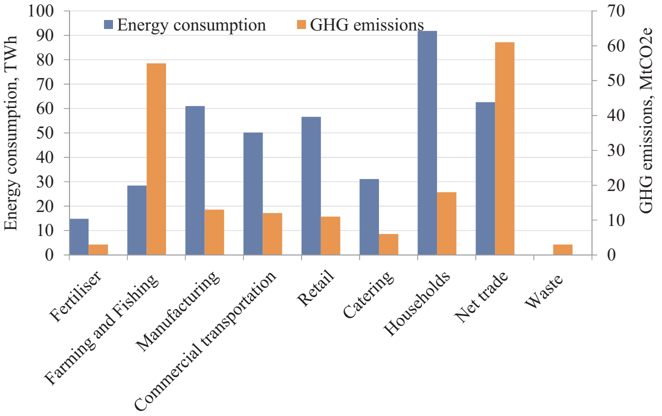


Fig. 25. Energy consumption and GHG emissions in the UK agri-food sector [141].

Table 9

Proposed applications for biomass-derived chars within BF-BOF and EAF steelmaking routes (adapted from Tables 1 and 2 in [137]).

BF-BOF route	
Sintering solid fuel,	50–100% replacement of coke breeze or anthracite at 45–60 kg-coke/anthracite/t-sinter (and 1.7 t-sinter/t-HM);
Cokemaking blend component,	2–10% of coking coal blend, with coke used at 300–350 kg-coke/t-HM;
BF tuyere fuel injectant,	100% replacement of injected coal (PCI) at 150–200 kg-coal/t-HM;
BF nut coke replacement,	50–100% replacement of 45 kg-nuts/t-HM;
BF carbon/ore composites or BOF pre-reduced feed,	5–10% of iron in charcoal/ore pellets to BF or charcoal-based pre-reduced feed to BF or BOF;
Steelmaking recarburiser,	100% replacement of 0.25 kg-char/t-crude steel.
EAF route	
Charge carbon,	50–100% replacement of 12 kg-coke/t-crude steel;
Raw materials, electrodes, etc.,	0% replacement of 4.5 kg-C/t-crude steel;
Natural gas heating,	0% of 3 N m^3/t-crude steel (0.54 t-C/t-crude steel);
Slag foaming agent,	50–100% replacement of 5 kg-coke/t-crude steel;
Steel recarburiser,	50–100% replacement of 1.4 kg-char/t-crude steel.

Notes: HM is hot metal; PCI is pulverised coal injection; PCI coal assumed to be 75% C; coke, coke breeze, anthracite and recarburiser are assumed to be 85% C; coke, foaming agent and recarburiser assumed to be 85% C; no improvements in electrical usage are considered here.

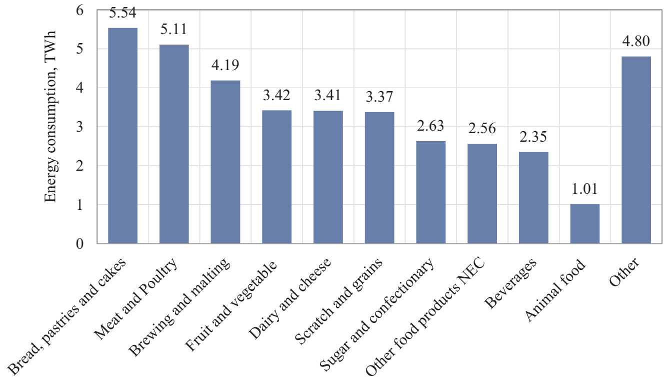


Fig. 26. Energy consumption in the UK food and drink subsectors, 2007 [142].

the entire chain [144]. The waste from the sector offers opportunities to convert the waste into bio-energy through anaerobic digestion, pyrolysis and gasification, which would reduce the cost of production and promote a cleaner environment. Otherwise, if the waste is dumped in landfills, it will cause adverse environmental impacts such as groundwater pollution and release of methane and greenhouse gases.

3.2.1. *Steam generation and uses in food and drink industry*

The food and drink processing sector is one of the most steam using sectors, consuming around 49% of the total sector's energy demand to generate steam for different processes [143]. A boiler is generally installed in every food and drink manufacturing site to deliver the required amount and quality of steam for process heating such as cooking, sterilising, humidifying, drying, etc. A list of typical steam application processes in the food and drink sector is provided in Table 10.

Boilers with a capacity of 2000–20,000 kg/h and operating at a pressure of up to 10 bar are common in the Food and drink manufacturing industry [143]. In an industrial boiler, generally 65–85% of fuel heat is converted into steam, while 10–30% heat is lost as flue gas, the rest of the heat is lost by blow down or through radiation [152]. Moreover, steam systems which deliver steam to different processes account for 15% of the heat loss. The Carbon Trust [153] investigated the potential for energy saving through implementing regular boiler maintenance, retrofitting different technologies such as waste heat recovery from flue gas, process optimisation through automatic control and steam distribution system improvement. The report suggested that applying all the options available in the market can reduce an estimated 10–30% of total energy consumption by the boilers in the UK food and drink manufacturing sector. Which is equivalent to a reduction of 1.58–4.75 TW h in boilers energy use, 382.77–1148.33 ktCO$_2$e reduction and 4.9–14.7% total energy consumption reduction in the UK food and drink manufacturing sector in 2016. The potential energy saving and corresponding CO$_2$ reduction through proposed individual energy saving measure is listed in Table 11. Furthermore, if an old boiler system is completely replaced with a state-of-the-art boiler or with an alternative option, e.g. combined heat and power (CHP) unit, it is possible to save a further 25% of the energy consumption in the industry [143]. It was estimated that installation of CHP in the food and drink sector could deliver 11 TW h of thermal power and 8 TW h of electrical power per year [154]. Griffin et al. [10] argued that the full use of the CHP in this sector could save 4.6 TW h energy which equates to a 854 ktCO$_2$e reduction per year.

Table 11
Estimated energy saving and CO$_2$ reduction in food and drink sector by adopting energy saving measures for boilers (adapted from [155]).

Measures	Energy saving[a], TW h	CO$_2$ reduction[b], ktCO$_2$e	Energy saving potential[c] (%)
Operation and maintenance of boiler	0.792	191.38	~ 5%
Combustion control and oxygen trim	0.792	191.38	~ 5%
Economiser	0.792	191.38	~ 5%
Blowdown heat recover	0.633	153.08	~ 4%
Combustion air preheating	0.32	76.55	~ 2%
Water treatment and water conditioning	0.32	76.55	~ 2%
Total dissolved solids (TDS) and blowdown control	0.32	76.55	~ 2%
Flue gas shut-off dampers	0.16	38.27	~ 1%

[a] The total energy consumption in 2016 was 32.33 TW h, which is considered as the baseline to calculate the energy saving. It is also assumed that 49% of this energy was used by the boilers.

[b] Assumed all the energy are delivered as natural gas and UK Government carbon emission conversion factors: 241.6 ktCO$_2$e/TW h has been adopted to calculate potential carbon reduction [156].

[c] The potential saving is possible if the corresponding measure is taken. The total saving cannot be calculated by simply adding all the measures.

3.2.2. *Heat recovery potential in food and drink industry*

As stated before, the Food and drink manufacturing industry is one of the largest energy consumers within UK industry. Because of thermodynamic limitation or equipment or process inefficiency, a significant amount of waste heat is released and lost by the sector in every year. It has been estimated that UK industry produces around 11.4 TW h/year of recoverable waste heat of which 2.8 TW h is from the food and drink manufacturing processes [63]. Utilisation of this waste heat can reduce 514.08 ktCO$_2$e emissions and save £70 million per year. Unlike the heat source from the Iron and Steel industry, the waste heat from food and drink processes is predominantly low grade energy

Table 10
Typical steam applications in food and drink manufacturing industry.

Process	Industry	Process Temp (°C)	Purpose	Ref.
Bread Proving	Bakery	40	Humidity control	[145]
Bread Baking	Bakery	230–270	Humidity control/glaze effect	[145]
Steam cooking tunnels	Vegetables	96	Cooking	[146]
	Rice and grains	96	Cooking	[146]
	Seafood	75–95	Cooking	[146]
Meat cooking	Meat and poultry	85–90 for full steam cooking 180–200 for quarter steam + heat cooking	Cooking	[146]
Superheated Steam drying	Food processing	160–200	Drying	[147]
UHT milk sterilisation	Dairy	135–150	Sterilisation	[148]
Multi-effect Evaporators	Dairy	140–150	Heating	[149]
Bottles sterilisations	Drink	100–116	Sterilisation	[150]
Sugar juice concentrating/evaporation	Sugar	120	Heating	[151]
Sugar cane mills	Sugar	250	Milling/cogeneration	[151]

whose temperature is typically below 260 °C. In the food and drink industry, about 64% of the energy is used for low temperature processes [63]. Heat recovery from the moderate temperature (200–400 °C) heat sources is more cost effective today with the increasing energy prices, technological development by equipment manufacturers and decreasing equipment costs. The heat recovery with a temperature less than 60 °C is not economical in light of the current technological development stage yet. In order to recover the low grade heat from the industrial processes three criteria should be met: a) the processes must generate a waste heat at a reasonable temperature that a heat sink can use the waste heat, b) the heat transfer from a low grade heat source to a heat sink should be economically sound, c) a heat sink must be available to absorb the waste heat during the main process operation [157]. Since the sector is highly diverse in terms of types of processes and products used to manufacture, there is limited accurate data available on the heat source and sink temperatures, waste heat quantity and potential to heat recovery using a specific heat recovery method. Therefore, an approximate temperature of different processes has been adopted to summarise the opportunities that are available for waste heat recovery from the food and drink manufacturing sector, which is presented in Table 12.

A recent study conducted by Hammond and Norman [9] shows that around 0.75 TW h of waste heat at temperatures up to 200 °C is available from the UK food and drink sector. The available waste heat is used to derive the potential heat recovery opportunities using different methods as follows: a) on-site heat recovery, b) heat recovery by heat pumps, c) Heat utilisation in chilling process, d) electricity generation from waste heat, e) Heat transportation for over the fence use, and f) combination of different recovery options.

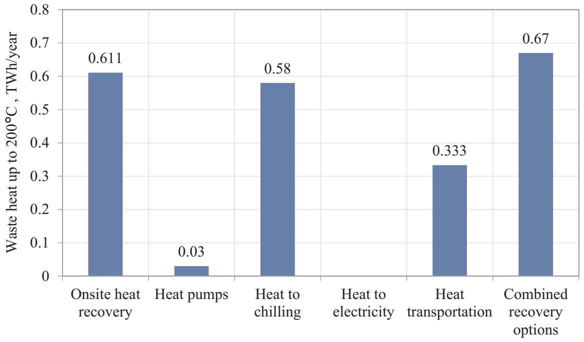


Fig. 27. Annual heat recovery potential using different heat recovery methods [9].

Fig. 27 shows an indicative potential for the heat recovery from the food and drink manufacturing sector. It can be seen that onsite heat recovery has the potential to recover a maximum of 0.611 TW h/year, which is highest among the individual waste heat recovery method used in the study. It was also reported that over 85% of the food and drink manufacturing sites have the capability to adopt an on site heat recovery option [9]. Heat pumps on the other hand represent the lowest opportunities with a potential of 0.03 TW h/year. The study could not find any opportunities for the use of the waste heat in electricity generation in the food and drink sectors. This is because of the low temperature heat sources that could not potentially generate a minimum of 0.5 MW_e, which is the minimum limit to be considered as the potential waste heat recovery method in the analysis [9]. The heat to chilling was suggested to be the second highest potential method with a contribution of 0.58 TW h/year. Heat transportation to neighbour industries, within 10 km distance, with 50% efficiency has the potential to recover 0.333 TW h/year. In order to maximise the heat recovery potential, a combination of different waste heat recovery methods was applied and the result shows that the combined option has the maximum potential which is 0.67 TW h/year [9].

3.2.3. Bioenergy/waste utilisation in food and drink industry

Bioenergy in relation to the food and drink industry can be classified into two broad streams: bioenergy that is generated from agricultural commodities, e.g. sugarcane, corn and bioenergy which is extracted

Table 12
Heat sources from food and drink manufacturing processes with potential heat recovery methods currently available [62,63].

Process/source	Industry	Heat source temp. (°C)	Heat source type	Heat recovery method(s)
Air compressors (water cooling)	Food & drink	60	Water	Process water heating
Air compressors (air cooling)	Food & drink	40	Air	Space heating
Cooking	Food & drink	110–115	Vapour	Space heating Water for in plant use
Boiler flue	Food & drink	~ 200	Gas	Economiser for water preheating Condensing economiser Air preheating Heat pumps Thermoelectric generator Organic Rankine cycle Kalina cycle Absorption refrigeration cycle Micro co-generation
Spent cooling water	Food & drink	Up to 90	Water	Water for in plant use
Condensate return	Food & drink	Up to 90	Water	Water for in plant use
Ovens	Bakery	150–250	Gas/vapour	Air preheating Space heating Water heating Thermodynamic power cycles
Fryers	Meat & poultry	Up to 200	Gas/vapour	Air preheating Space heating
Dryers	Food	160	Air/vapour	Preheating dryer air inlet
Evaporation and distillation	Drink	~ 100	Water vapour	Heat pumps
Refrigeration	Food	~ 60	Water	In plant hot water supply
Pasteurisation	Dairy	~ 70	Water/liquid	Hot water supply
UHT process	Dairy	135	Water/liquid	Space heating Hot water for in plant use
Sterilisation	Food & drink	140–150	Water	Space heating

from waste biomass or litters/sludge arising in food and drink manufacturing sites. In both cases, bioenergy reduces the grid energy demand and carbon emission, by replacing fossil fuels or natural gas. The use of crops for bioenergy generation raises the issue of food security as they are cultivated on soil that would otherwise be used for crops for food production [158]. Similarly, the second type of bioenergy also has an impact on food security since the use of food waste as a biomass source for the generation of green energy leaves a feedstock shortage for the production of animal feed [15]. It is therefore recommended to carry out a full life cycle assessment (LCA) approach to see the effect of using bio waste as a low-carbon biomass for energy generation on food security, which is out of the scope of this paper. But it is more obvious that the use of the UK food chain's waste will bring a great emission reduction and perfectly fit into the context of the government's decarbonisation roadmap to 2050.

In 2015, around 1.7 Mt of waste was generated from the UK food and drink manufacturing sector that equates to a value of £1.2 billion a year [144]. It was also estimated that around 0.9 Mt of food waste from the manufacturing sector is believed to be avoidable; around 0.66 Mt of the finished food is also classed as redistributable through charity routes and, around 0.5 Mt of food is identified as divertible for animal feed [144]. These waste preventing options are the most preferable according to the food products flow hierarchy as shown in Fig. 28.

When the prevention is not an option in the industry, the recycle and recovery strategy can be used to convert the waste into bioenergy using AD, composting and thermal treatment. The food and drink industry produces a variety of waste that is generally in three types: segregated food waste, packaging waste and non-segregated or mixed waste. The segregated food waste represents 76%, the segregated packaging waste represents 18% and the mixed waste represents about 6% of the total food waste in the industry [160]. In 2015, it was estimated that about 0.5 Mt of the food waste from the UK food and drink manufacturing sector were sent to AD plants, which represents about 30% of the total food waste. While around 1.2 Mt of the food waste were processed through incineration that recover heat energy and land spreading that benefits agricultural land. A very small portion, around 0.002 Mt (0.11%), of the food waste was dumped in landfills, which is the least preferable option as per as the food hierarchy concern [159].

4. Energy efficiency markets

At the end of the 1970s and in the early 1980s price pressures from oil disruptions forced the introduction of a series of energy efficiency solutions and commitments from both industry and state, spawning various energy service companies (ESCOs) that provide energy efficiency services. During the energy crisis period, energy services business experienced a rapid rise due to deregulated energy markets [161]. ESCOs which had emerged in the 1970s focusing on demand business (providing energy efficiency) started to expand into the supply business (providing energy). Utilities realized this competitive threat and began to supplement their traditional supply services with for-profit demand-side energy efficiency services and to cut down on not-for-profit demand-side management spending. In fact, ESCOs provided energy efficiency services to utility customers in order to fulfil various regulatory requirements; and utilities in turn provided the non-regulated services, such as transmission services (wires, billing, etc.), to ESCOs who were looking to supply energy in deregulated markets (Fig. 29). However, ESCOs gradually faded from energy users' horizon in the late 1990s due to an emphasis on energy supply [146] and historically low energy prices (thus discouraging energy efficiency investments) [162].

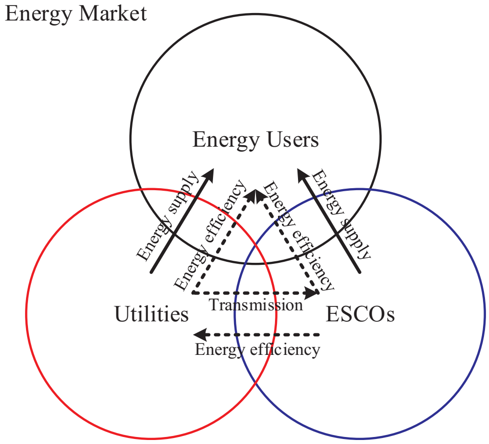


Fig. 29. The services between energy users, utilities, ESCOs.

With increasing concerns about global climate change and the environment, there is a renewed emphasis on energy efficiency. This market change has created a new dynamic in both the ESCO and the utility. For ESCOs, the new market is similar to the original market of high energy prices in the 1970s that led to the creation of the industry but now the market is also driven by the existing 'demand pull' policy including regulation, economic incentives, informative policies, and direct public sector purchasing [163]. For utilities, an equally significant opportunity also presented itself. Energy efficiency spending is viewed as a regulatory investment. If the utilities spend more money on energy efficiency programmes, the regulators will allow rate increases for capital improvements, operating costs, inflation, or general profitability [164]. Facing these opportunities, service providers including both utilities and ESCOs in energy markets are increasingly being called upon again to adapt their business models and business operations to incorporate the provision of cost-effective energy efficiency. Furthermore, the UK government's Energy Efficiency Strategy recognises that

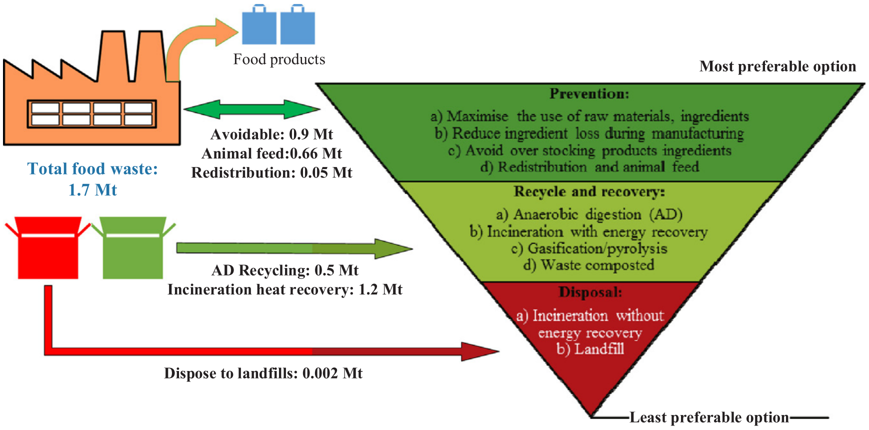


Fig. 28. Diversion of food waste from UK manufacturing sector in 2015 and food products advised flow hierarchy (adapted from [159]).

energy efficiency can deliver economic and environmental benefits and states that demand reduction is the first and most important action in making the transition to a low-carbon economy [165]. Under the energy efficiency obligations frame – the EU Energy Services Directive [166], the UK government is being committed to catalysing the adoption of energy-efficient business practices by developing a stronger understanding of the drivers and barriers encountered by energy users including individual firms, particularly small and medium-sized enterprises. Currently, nearly 80% [167] of investments in commercial energy efficiency measurement in the UK are financed on a company's own balance sheet with costs recouped through bill savings; and the remaining part (nearly 20%) is financed either through third party financing such as a bank loan or direct investment via energy service markets or through a combination approach. Further detailed data on the proportion of different business models in specific applications is not available. Therefore, to further realize the potential of energy efficiency, diverse business models need to be explored in the UK and the drivers and barriers that influence energy consuming businesses engaging in energy efficiency need to be understood.

4.1. Business models for energy efficiency projects

Business models and business operations are structured by the concept of the 'value chain' which is based on the premise that value is created by transforming inputs into products at each step of the chain [168]. Consideration of the breadth of the scope of the value chain suggests that an energy user and an ESCO (or that is sub-company created by a utility, providing energy efficiency services, the same hereinafter) could occupy several different value chain positions, so several business models appear to be possible. According to the type of project development and construction contract, business models for energy efficiency might fall into four broad categories: Engineering-Procurement-Construction (E-P-C), Build-Operate-Transfer (B-O-T), energy performance contracting, and energy service contracting (Table 13). All listed business models are potentially applicable to all major energy users' types, covering energy use from retail to commercial and even industrial scale. The choice of a specific business model depends on the size of energy efficiency projects, the energy user's financial situation, drivers and barriers, etc. Following a discussion of these models, their scope for the utilisation of biomass energy is considered. As the effectiveness of these business models depend on a number of technical, economic and organisational factors, drivers and barriers are discussed afterwards.

4.1.1. Engineering-Procurement-Construction (E-P-C)

E-P-C is a popular business model in industry. Energy service providers undertake the system planning and design, civil construction, equipment procurement, equipment installation, system commissioning, and are fully responsible for the quality, safety, duration, and cost of a project [169]. The entire system is handed over to the energy users on completion thus turnkey operates. The E-P-C business model has some derivative forms. For the Engineering (E) service model [170], the ESCO provides technical solutions and design, but the energy users arrange their own equipment procurement, construction, and management. In the E model, the ESCO occupies only one value chain position, so some of the large ESCOs are reluctant to provide this model of service, thus the proportion of this business model is declining year by year. For the Engineering-Procurement (E-P) service model, the ESCO not only provides technical solutions and design, but also arrange equipment procurement, construction, and management for the energy users. The E-P service is widely used for energy efficiency projects or non-core business. Other energy users adopt the E-P-C service model in the project phase and then commission the ESCO to operate the energy system in the operation phase, that is, the E-P-C & Commission service model. The application and promotion of the E-P-C & Commission service model has some inevitability as energy efficiency projects often have different technical requirements compared to the energy users' core business. They are often complicated in structure and have a wide range of highly technical content. After project completion, the operation, maintenance and management of the new energy system require personnel with high technical capabilities. Due to the lack of relevant professional and technical personnel as well as other organisation barriers as discussed in Section 4.2, in most cases energy users cannot operate the energy system under optimum conditions. Furthermore, due to technical barriers and other reasons, when determining the general contractor, it is difficult for the energy user to determine the pros and cons of E-P-C project work and the effect this will have on operational efficiency from the written materials. In either case, the E-P-C & Commission service model allows the project risk to be handed over to the operations contractor and the energy user can concentrate on its core business.

4.1.2. Build-Operate-Transfer (B-O-T)

B-O-T business models establish a special purpose corporation which may involve an ESCO designing, building, financing, owning and operating the energy system for a defined period of time and then transferring this ownership across to the energy user [171]. Energy users enter into long term supply contracts with the B-O-T operator and are charged accordingly to the service delivered. The service charge includes capital and operating cost recovery and project profit. The step change toward sustainable energy development and utilisation in industry and manufacturing sectors will drive the change in business models, for example, the change from E-P-C to B-O-T to integrate build and operating costs. Energy efficiency projects of industrial park scale often have characteristics of large volume, high professionalism, great public influence and long duration. These characteristics create challenges for the E-P-C service model particularly for capital investment, project management, and post-operation. Such large energy efficiency changes do not only increase the relative additional value of energy users but also alter the custom of blindly emphasizing construction and despising operation prevalent in the past. Therefore, the B-O-T service model is conducive for energy users to obtain sustained and steady benefits. As for the E-P-C service model, the B-O-T service model also has some derivative forms with discernible characteristics: for the Build-Own-Operate (B-O-O) service model [172], the ESCO builds and operates an energy efficiency project in accordance with the concession granted by the energy user, but the ownership is vested in the ESCO and the project related infrastructure is not transferred to the energy user; for the Build-Transfer (B-T) service model [173], compared to the B-O-O service model, the ESCO will transfer the project related

Table 13
Potential energy efficiency business models.

Engineering-Procurement-Construction (E-P-C)	Engineering (E) Engineering-Procurement (E-P) Engineering-Procurement-Construction (E-P-C) E-P-C & Commission
Build-Operate-Transfer (B-O-T)	Build-Own-Operate-Transfer (B-O-O-T) Build-Own-Operate (B-O-O) Build-Transfer (B-T) Build-Transfer-Operate (B-T-O) Build-Lease-Transfer (B-L-T)
Energy performance contracting (EPC)	Shared Saving Guaranteed Saving Chauffage First out Leasing
Energy service contracting (ESC)	Customer infrastructure Fee-for-service Green power

infrastructure to the energy user immediately after the completion of the project when the energy user pays in installments for the project price, using project operating income; the Build-Transfer-Operate (B-T-O) service model [174] adds to the B-T service model as the energy user entrusts the ESCO to operate and manage the project after acquiring ownership of the project; for the Build-Lease-Transfer (B-L-T) model [174], the energy user grants concessions to the ESCO allowing the ESCO to own and operate the project during the project's operation period and obliging the energy user to become the project's renter and to receive the assets after the lease term expires.

4.1.3. Energy performance contracting

Energy performance contracting refers to business models in which the ESCO, through signing energy performance based contracts, provides energy users with services related to energy saving retrofit which recover investment and create ongoing benefits from energy savings [175]. The ESCO calculates the energy saving potential for energy users, proposes the schemes of energy saving retrofit, and implements them using their funds, equipment and technology. Energy performance contracting models can greatly reduce the financial and technological risks of energy saving retrofit for energy users and fully arouse their enthusiasm for energy saving retrofit. In the Shared Saving model, the ESCO shares energy-saving benefits with energy users in accordance with an agreed ratio during the contract and after the contract expires, the ownership of energy efficiency projects is transferred to the energy user; In the Guaranteed Saving model, energy users provide funds for the energy saving retrofit project in phases, cooperating with project implementation, whilst the ESCO provides the entire service and commits the contracted energy saving performance. Energy saving benefits can make up for all project repayments and all the testing, inspection operation and maintenance services provided by the ESCO. If the project does not meet the promised energy saving, the ESCO undertakes the corresponding responsibilities and accepts economic losses as agreed in the contract. The energy user and the ESCO can share the excess return if the savings achieved are more than project repayments. In the ‘chauffage’ model, the ESCO takes on the responsibility for providing the improved level of energy service for a reduced bill. The fee paid by the energy user under a ‘chauffage’ arrangement is calculated on the basis of its existing energy bill minus a percentage saving (often in the range of 5–10%), or a fee may be charged per square metre of conditioned space. Thus, the more efficiently and cheaply it can do this, the greater its earnings. However, in ‘first out’ model, the ESCO is paid 100% of the energy savings until the project costs, including the ESCO profit, are fully paid [176]. The exact duration of the contract will depend on the level of savings achieved: the greater the savings, the shorter the contract. Another attractive alternative is the leasing model because lease payments tend to be lower than loan payments [176]. For example, for energy efficiency equipment, the ESCO can negotiate and arrange an equipment lease-purchase agreement with a financing institution. If the ESCO is not affiliated to an equipment manufacturer or supplier, it can raise an invitation to tender, conduct a supplier competitive analysis and arrange the equipment.

4.1.4. Energy Service Contracting

Energy Service Contracting focuses on energy efficiency services sold directly to customers on a paid service basis, which allows energy user shareholders to profit from the provision of ESCO-type services [177]. The ESCO can provide energy efficiency services for energy users who desire or see value in additional expenditures for the service. In the customer infrastructure model, the ESCO contracts with an energy user for delivery of specified energy services, such as heating or cooling, and potentially assumes ownership or direct operation of customer energy infrastructure. This model helps the ESCO get as close as possible to the energy user. However, in the ‘fee-for-service’ model, the ESCO does not assume ownership or direct operation of customer energy infrastructure and therefore has less opportunities to manage cost/risk. Neither model involves regulatory mechanisms or performance-based contracting. They are used to meet the increased demand for these services. The green power model focuses on offering green power to energy users who are willing to pay the full incremental cost of green power. To simultaneously solve the dilemma of energy demand, waste management, and greenhouse gas emission for industry and manufacturing sectors globally, the bioenergy/waste-to-energy supply as a new energy system should be a viable method toward energy efficiency adopting a circular economy philosophy. There are significant opportunities to develop new forms of green power business models.

4.1.5. Business models for utilisation of biomass energy

Novel and integrated business models and global energy service approaches are required to facilitate the use of biomass for heat and power. In this context, the role of ESCOs will be crucial to facilitate the widespread use of biomass for stationary applications, in combination with energy efficiency measures and demand side management tools. Moreover, segmentation of energy demand can be useful to assess the niche markets where the ESCO approaches are more promising and to investigate the bottlenecks and barriers for bioenergy based services. Biomass energy can play a significant role in the achievement of the energy policy targets at EU level by 2020 [178]. Negative carbon emissions from heat generation from biomass make it becomes an ideal substitute to the limited resource [179]. In some cases, the incomplete industrial chain structure and high upfront costs of biomass utilisation projects are major barriers for the implementation of such projects by final end users. For example, due to the incomplete industrial chain productions often lack uniform technical specifications and quality certification standards. If quality supervision and information service fail to follow up in a timely manner, the entire market will be at risk for disorder. There is less literature by far in the specific field of biomass-ESCO business models [180]. Only the small scale biomass CHP systems operated within an ESCO supply scenario have been reported [181]. The results show that ESCOs might be an effective means to facilitate the utilisation of biomass. Within realistic ESCO operating scenarios, biomass CHP shows good competitiveness even in the case of no capital subsidies; while energy users could also enjoy discounted energy tariffs similar to those provided by mainstream utility companies. Various business models of bio-energy in European countries are presented in [182], including best practice examples and common recommendations for successful bio-energy stories.

4.2. Drivers and barriers for energy efficiency

Understanding the drivers and barriers that influence energy consuming businesses engaging in energy efficiency is key to developing policy that encourages and supports them in doing so [183]. The drivers to energy efficiency as defined by Thollander and Ottosson [184] are seen as factors that motivate or promote the adoption of energy-efficient and economically efficient decisions and behaviours. Drivers are an indirect means to boost energy efficiency implementation in the organisation. In the scope of effective climate policy, Bataille et al. [185] equates deep decarbonisation as the process of replacing inefficient and carbon-intensive infrastructure and end-use equipment with more efficient and lower-carbon technologies that provide the same (or better) energy services.

The barriers to energy efficiency are considered a mechanism that inhibits energy and/or economically efficient decisions and behaviours within an organisation [186,187]. Barriers are not only purely technical and economic, but also social and cultural: that is, expectations, conventions and decision-making processes will play roles alongside costs and practicalities [188]. There is a need to understand the taxonomy of drivers and barriers and to appreciate the synergies and tensions between them.

4.2.1. Taxonomy of drivers and barriers

Many studies exist on the drivers and barriers for energy efficiency adoption in industries [186,189–193]. However, a general comparison of the existing different literature studies into energy efficiency barriers and drivers is a highly problematic task since they are usually categorised in many overlapping ways [186]. This issue stems from the fact that there are multiple ways to understand, classify and interpret barriers and drivers. In earlier work, a taxonomy of barriers to energy efficiency made by Sorrell et al. [186] was categorised into four main theoretical frameworks: economic non-market failure, economic market failure, behavioural and organisational. Following this, Cagno et al. [192] made further refinements to the taxonomy in seven perspectives: technology related, information, economic, behavioural, organisational, competence related, and awareness, indicating important aspects of external actors. This later analysis is important since barriers to energy efficiency often stem from the factors external to the organisation. Taking a whole systems perspective, this paper does not focus on the narrow, single view of the individual categories and areas of the various barriers and drivers [184,186,187,192]. Rather, it identifies the drivers and barriers as components of an holistic system-thinking approach [194,195]. This approach is refined to reflect the top-down and bottom-up industrial sector modelling approaches identified in [104,196] bringing out a focus on scale by highlighting the associated process, plant and national energy efficiency driver and barrier levels of the various industrial organisations.

The terms: process, plant and national are next defined within the context of this work. The process level is considered as the disaggregated lower order subsectors that define the necessary procedures used within the industrial sector. According to Griffin et al. [104], the lower order subsectors can also be the plant level or industrial subsector in terms of energy usage as incorporating different processes, the plant level efficiencies emerge from the physically proximate arrangement of equipment and processes such that waste heat output of one can be an input to the other. The further aggregation of industrial subsector electricity demands reflects spatial and temporal opportunities to benefit from shifting loads to contribute to network congestion or balancing supply and demand at distribution or transmission networks in the national or grid level. It should be noted our classification has parallels to Reddy's [197] taxonomy of micro (end user), meso (organisation) and macro (market). His approach focuses on actors that are responsible for the emergence of drivers and barriers whereas our approach focuses on the scale where they come about.

The need to embrace not only the external factors to the organisation but also the internal factors can be well illustrated using the process, plant and national level energy efficiency drivers. Tables 14, 15 identify some of the key drivers and barriers to energy efficiency within the various interacting levels of industrial organisations respectively. As presented in Table 14, cost reductions from lower energy use, rising energy prices and international competition are market related factors that are applicable across all levels. Among the organisational and behavioural factors, a company's environmental profile encompasses all plants and sites, such that it is relevant at national level. Environmental management systems refer to the use of resources beyond energy (e.g. water) as well as management and control of by-products of activities, requiring a plant level focus. Long term energy strategy can utilise differences in geographical location of different plants (e.g. being close to a windy area) as well as defining a blue print of future energy related activities at aggregate level. Depending on the size of the company, an energy manager at a plant level or overseeing across all the plants can make a significant contribution in pushing forward an energy efficiency agenda. Some energy efficiency improvements can enable improved working conditions (e.g. capturing of waste heat can improve comfort level of labour) at a process or plant level. Finally, networks within the company or sector can make contributions achieving plant or grid level efficiencies by sharing knowledge and information. Policies such as investment subsidies in energy efficient technologies stand to provide drive efficiency across all levels whereas energy audits can specifically improve plant level efficiency. Other schemes such as emissions trading scheme or renewable energy incentives will contribute to energy efficiency at grid level.

The taxonomy of barriers is a lot more contentious compared to that of drivers as the extent to which underpinning economic theories (e.g. transaction cost vs orthodox economics) are employed varies significantly (for a detailed discussion see [186]). Focusing especially on the scale (process, plant, grid) where these barriers might come about as before, factors, such as costs and risks to production are highlighted. Other market related barriers which might influence attainment of energy efficiency across all levels include access to capital, especially to cover high initial costs, hidden costs (e.g. overhead costs for management, costs associated with gathering data and identifying inefficiencies) and verification of suppliers' performance claims, while propriety of technical characteristics might influence at both process and plant levels. Distortions in the price of energy due to taxes or subsidies might blur the opportunities at plant and grid level. Difficulties in accessing external skills in the market place are a factor that can affect the opportunities across all levels. A key concept that underlines behavioural aspects of barriers to energy efficiency is inertia or bounded rationality which argues that the quality of decision making may not necessarily build on the provision of accurate information. More specifically, decision making processes, lack of interest in energy efficiency, lack of time (or presence of other priorities) and shared objectives are behavioural and organisational factors that deter the uptake of plant and grid level energy efficiency actions. Lack of awareness about energy efficiency, divergent interests (e.g. costs incurring to one department within the organisation whereas benefits are shared) and imperfect evaluation criteria (e.g. short term vs long term assessment of benefits) can put off energy saving actions across all levels. The time lag between taking an energy efficiency decision, its implementation and emergence of benefits mean that the diffusion of technologies and relevant information can be rather low. If such information is not shared within an industrial sector or company, the attainment of process and plant level efficiencies can be dampened. Lack of fiscal and energy policy coordination across different government departments and regulatory frameworks can create challenges for the realisation of grid level benefits.

4.2.2. A new approach to drivers and barriers for energy efficiency

Highlighted from this multi-scale breakdown at process, plant and national level of energy efficiency barriers and drivers it can be seen

Table 14
Taxonomy of the drivers to industrial energy efficiency from a disaggregated systems perspective [184,192].

Driver type	*Internal*		*External*
	Process	Plant	Grid
Market related factors			
- Cost reductions from lower energy use	X	X	
- International competition	X	X	X
- Rising energy prices	X	X	X
Organisational and behavioural factors			
- Company environmental profile			X
- Environmental management systems		X	
- Energy managers with real ambition		X	X
- Improved working conditions	X	X	
- Long-term energy strategy		X	X
- Networks within company/sector		X	X
Policy factors			
- Emissions trading scheme			X
- Investment subsidies for energy efficient technologies	X	X	X
- Publicly financed energy audits		X	
- Renewable energy incentives			X

Table 15
Taxonomy of the barriers to industrial energy efficiency from a disaggregated systems perspective [186,187,192].

Barrier type	*Internal*		*External*
	Process	Plant	Grid
Market related factors			
- Costs to production disruptions	X	X	
- Difficulty in gathering external skills	X	X	
- Energy price distortion		X	X
- Hidden costs	X	X	X
- High initial costs/payback	X	X	X
- Lack of access to capital	X	X	X
- Risks to production disruptions	X	X	
- Technical characteristics not adequate	X	X	
- Verification of technology suppliers performance claims	X	X	X
Organisational and behavioural factors			
- Complexity of decision making		X	X
- Divergent interests	X	X	X
- Imperfect evaluation criteria	X	X	X
- Inertia (bounded rationalities)	X	X	X
- Lack of awareness or ignorance	X	X	X
- Lack of time/other priorities		X	X
- Lack of sharing the objectives		X	X
- Lack of interest in energy efficiency		X	X
Policy factors			
- Distortion in fiscal policies			X
- Distortion in energy policies			X
- Lack of proper regulation			X
- Low diffusion of technologies	X	X	
- Low diffusion of information	X	X	
- Scarce communication skills	X	X	

that the most of drivers and barriers are at plant level, and the least are at the process level. This does not imply that less work should be done to overcome energy efficiency adoption at the process level but that for the industrial sector much more of the intrinsic complexities of energy efficiency adoption lie at the plant level. From a UK perspective, a low carbon economy will need to include significant levels of renewable energy generation which need to be balanced via flexible generation, demand side response, storage or interconnection [198,199]. This means the industrial and commercial sectors can create extra value by taking part in various system balancing and ancillary services at grid level, which is currently under development stage. The authors believe that including renewable energy generation at grid level will bring more drivers to energy efficiency in the future. Yet, there is need for more detailed research to understand the industry's willingness to take part in such services as they are not necessarily their core business. However, this needs critical and urgent assessment in light of anticipated increases in the price of energy in a low carbon economy where there are new loads on the networks due to electrification of transport and heating sectors.

5. Conclusions

The UK industry and manufacturing sector is one of the biggest energy consumers and greenhouse gas emitters. In order to tackle the high energy consumption and emission issues, the Government has adopted decarbonisation roadmaps to promote the realisation of the energy demand reduction targets. Energy efficiency opportunities from UK industry have been identified by many previous studies, yet most of the opportunities remain unimplemented due to technical, economic and social factors. This research therefore reviewed recent literature and explored a connection amongst energy efficiency opportunities offered by the industry with the factors affecting the adoption of energy efficiency and business models. Since around 73% of the energy consumed in the industry is used as heat while approximately 35% of the energy is used for steam systems, the focus of the review was on these sectors. Both the steam and heat related processes result in significant losses due to the processes inefficiencies or thermodynamic limitations which represent a greater percentage of total energy wasted in the industry. Therefore, we explore the scope of steam and the waste heat recovery processes and the contributions they can make towards UK's energy efficiency and emission reduction targets. Furthermore, we also included bioenergy/waste utilisation in this paper as it is widely acknowledged for its significant role in reducing grid dependency, ensuring the energy sustainability and reducing landfill-related pollution.

This paper provides technology mapping for a wide range of heat sources from UK industry and summarises them according to their techno-economic performances. In particular, the available energy saving technologies for the steam system in generation, distribution, end use and condensate recovery were summarised. Overall waste heat recovery solutions provided with the methods of on-site heat recovery including the reuse in main processes, transfer to surrounding processes, and heat conversions and storage. A complete energy management will enable to optimise and conserve the heat energy in the industry. Additionally, the recent trend of bioenergy and waste utilisation using anaerobic digestion, pyrolysis and gasification was discussed to make readers aware of their role in the industrial energy efficiency.

The review was then extended to cover the iron and steel and food and drink industries with respect to energy efficiency improving opportunities in steam systems, waste heat recovery, and bioenergy and waste to energy conversion technologies. Although the potential energy efficiency opportunities are clear and in-line with recent studies in this area, the potential business models discussed in this paper to help the adoption of the energy efficient and waste heat recovery technologies are the key to accelerate and meet the carbon and energy reduction targets.

Although, there are no common business models for energy efficiency in the industry present at this moment, the adaptation of well-known USCOs and ESCOs business models to incorporate energy efficiency measures can help to bridge the gap. While our review identified a number of different business models, energy saving potentials they can offer are likely to vary depending on the sector, types of technologies and fuels used as well as the broader socio-technical framework including policy and regulation. This emerges as an important area for future research as potentially they can also help to reduce the barriers of energy efficiency described in this paper. With the current study, the potential of energy demand reduction in the future can be better understood by optimising the integrated energy systems across multiple pathways and scales. From a social point of view, successful business models can help the business succeed in finding high-value operations and processes, offering significant value to customers, and delivering significant margins, and therefore contribute to overcoming barriers and encourage the adoption of emerging energy efficient and demand reduction technologies.

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References

[1] Parliament of the United Kingdom. Climate Change Act 2008. London; 2008.
[2] International Energy Agency Energy technology perspectives: scenarios & strategies to 2050 2010 doi: 10.1049/et:20060114.
[3] IPCC Climate change 2014: mitigation of climate change 2014 doi: 10.1017/CBO9781107415416.
[4] DECC. Digest of UK Energy Statistics 2011. London; 2011.
[5] DECC. The Future of Heating: Meeting the challenge. London; 2013.
[6] DECC. 2014 UK Greenhouse Gas Emissions. London; 2015.

[7] Committee on Climate Change(CCC). UK Emissions by Sector; 2013.
[8] DECC. Energy Consumption in the UK 2010. London; 2010.
[9] Hammond GP, Norman JB. Heat recovery opportunities in UK industry. Appl Energy 2014;116:387–97. https://doi.org/10.1016/j.apenergy.2013.11.008.
[10] Griffin P, Hammond G, Norman J. Industrial energy use from a bottom-up perspective: developing the usable energy database (beta version). UK Energy Res Cent 2013.
[11] U.S. DOE. Waste heat recovery. Washington, DC: Technology and Opportunities in U.S. Industry; 2008.
[12] DECC. The potential for recovering and using surplus heat from industry. London; 2014.
[13] DBEIS. Digest of UK energy statistics 2017. London; 2017.
[14] DECC. UK Bioenergy Strategy. London; 2012.
[15] DECC, DBIS. Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050: Cross Sector Summary. London; 2015.
[16] U.S. DOE. Steam pressure reduction : opportunities and issues. Washington, DC; 2005.
[17] Swagelok Energy Advisors. Steam System Thermal Cycle Efficiency—Part One; 2011.
[18] Tiwari AG, Jane SS, Katoke P, Talmale K, Dongre K. Case study on efficiency of boiler and factors affecting it. Int J Sci Res Dev 2017;5:1790–3.
[19] Energy Solution Centre. Oxygen Control. Energy Solut Cent; 2017. 〈http://cleanboiler.org/learn-about/boiler-efficiency-improvement/efficiency-index/oxygen-control〉, [Accessed 19 June 2017].
[20] Controls4Steam. Boiler Efficiency & Combustion Efficiency. Controls4Steam; 2015. 〈http://www.controls4steam.co.uk/knowledge-sharing-platform/72-boiler-efficiency-combustion-efficiency〉, [Accessed 19 June 2017].
[21] The Engineering ToolBox. Combustion efficiency and excess air; 2017. 〈http://www.engineeringtoolbox.com/boiler-combustion-efficiency-d_271.html〉, [Accessed 26 June 2017].
[22] Saidur R. Energy savings and emission reductions in industrial boilers. Therm Sci 2011;15:705–19. https://doi.org/10.2298/TSCI091014046S.
[23] Carbon Trust. How to implement oxygen trim control; n.d. 〈https://www.carbontrust.com/media/147167/j8054_ctl147_how_to_implement_oxygen_trim_control_aw.pdf〉, [Accessed 28 June 2017].
[24] SAMCO. How much does a boiler Feed water treatment system cost? (pricing, factors, etc.); 2016. 〈https://www.samcotech.com/much-boiler-feed-water-treatment-system-cost-pricing-factors-etc〉, [Accessed 26 June 2017].
[25] Preising K Save $91,000 annually in low pressure boiler water treatment chemical and fuel costs using a dealkalizer. NALCO Pretreat Solut; 2015. 〈http://www.reskem.com/dealkalizers/〉, [Accessed 26 June 2017].
[26] Carbon Trust. Heat recovery; 2017. 〈https://www.carbontrust.com/media/31715/ctg057_heat_recovery.pdf〉, [Accessed 28 June 2017].
[27] Madhav D, Ramesh L, Naveen M. Heat recovery through boiler blow down tank. Int J Eng Trends Technol 2013;4:1597–600.
[28] U.S. DOE. Energy Tips : STEAM Replace Pressure-Reducing Valves with Backpressure Turbogenerators. Washington, DC; 2012.
[29] U.S. DOE. Energy Tips: Insulate Steam Distribution and Condensate Return Lines. Washington, DC; 2012.
[30] Department of the Environment (UK). The Economic Thickness of Insulation For Hot Pipes; 1994.
[31] TLV. Steam trap losses – what it costs you; 2017. 〈http://www.tlv.com/global/UK/steam-theory/cost-of-steam-trap-losses.html〉, [Accessed 11 July 2017].
[32] Kuppan T. Heat exchanger design handbook. 2nd ed. Boca Raton: CRC Press; 2013.
[33] Spirax Sarco. Condensate recovery in industrial steam systems; 2012.
[34] U.S. DOE. Improving steam system performance. Washington, DC: A Sourcebook for Industry; 2012.
[35] Hawley C, Fenner R. The potential for thermal energy recovery from wastewater treatment works in southern England. J Water Clim Chang 2012;3:287–99. https://doi.org/10.2166/wcc.2012.013.
[36] Pielichowska K, Pielichowski K. Phase change materials for thermal energy storage. Prog Mater Sci 2014;65:67–123. https://doi.org/10.1016/j.pmatsci.2014.03.005.
[37] Liu M, Saman W, Bruno F. Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems. Renew Sustain Energy Rev 2012;16:2118–32. https://doi.org/10.1016/j.rser.2012.01.020.
[38] Johansson MT, Söderström M. Electricity generation from low-temperature industrial excess heat-an opportunity for the steel industry. Energy Effic 2014;7:203–15. https://doi.org/10.1007/s12053-013-9218-6.
[39] Dughaish ZH. Lead telluride as a thermoelectric material for thermoelectric power generation. Phys B Condens Matter 2002;322:205–23. https://doi.org/10.1016/S0921-4526(02)01187-0.
[40] Broberg Viklund S, Johansson MT. Technologies for utilization of industrial excess heat: potentials for energy recovery and CO_2 emission reduction. Energy Convers Manag 2014;77:369–79. https://doi.org/10.1016/j.enconman.2013.09.052.
[41] Bauer T, Forbes I, Pearsall N. The potential of thermophotovoltaic heat recovery for the UK industry. Int J Ambient Energy 2004;25:19–25. https://doi.org/10.1080/01430750.2004.9674933.
[42] Chowdhury JI, Nguyen BK, Thornhill D. Modelling of evaporator in waste heat recovery system using finite volume method and fuzzy technique. Energies 2015;8:14078–97. https://doi.org/10.3390/en81212413.
[43] Chowdhury JI, Nguyen BK, Thornhill D, Hu Y, Soulatiantork P, Balta-Ozkan N, et al. Fuzzy nonlinear dynamic evaporator model in supercritical organic rankine cycle waste heat recovery systems. Energies 2018;11:901. https://doi.org/10.3390/en11040901.
[44] Schuster A, Karellas S, Aumann R. Efficiency optimization potential in supercritical organic rankine cycles. Energy 2010;35:1033–9. https://doi.org/10.1016/j.energy.2009.06.019.
[45] Gao H, Liu C, He C, Xu X, Wu S, Li Y. Performance analysis and working fluid selection of a supercritical organic rankine cycle for low grade waste heat recovery. Energies 2012;5:3233–47. https://doi.org/10.3390/en5093233.
[46] Shu G, Yu G, Tian H, Wei H, Liang X. A multi-approach evaluation system (MA-ES) of organic rankine cycles (ORC) used in waste heat utilization. Appl Energy 2014;132:325–38. https://doi.org/10.1016/j.apenergy.2014.07.007.
[47] Chowdhury JI, Nguyen BK, Thornhill D. Dynamic model of supercritical organic rankine cycle waste heat recovery system for internal combustion engine. Int J Automot Technol 2017;18:589–601. https://doi.org/10.1007/s12239-017-0059-8.
[48] Chowdhury JI, Nguyen BK, Thornhill D. Investigation of waste heat recovery system at supercritical conditions with vehicle drive cycles. J Mech Sci Technol 2017;31:923–36. https://doi.org/10.1007/s12206-017-0145-x.
[49] Chowdhury JI. Modelling and control of waste heat recovery system. Belfast, United Kingdom: Queen's University Belfast; 2017.
[50] Zhang X, He M, Zhang Y. A review of research on the Kalina cycle. Renew Sustain Energy Rev 2012;16:5309–18.
[51] Chen Y, Lundqvist P, Johansson A, Platell P. A comparative study of the carbon dioxide transcritical power cycle compared with an organic rankine cycle with R123 as working fluid in waste heat recovery. Appl Therm Eng 2006;26:2142–7. https://doi.org/10.1016/j.applthermaleng.2006.04.009.
[52] Smith I, Stosic N, Aldis C, Lan Smith NS, Aldis C. Trilateral flash cycle system a high efficiency power plant for liquid resources. Proc World Geotherm Congr 1995;3:2109.
[53] Markides CN, Smith TCB. A dynamic model for the efficiency optimization of an oscillatory low grade heat engine. Energy 2011;36:6967–80. https://doi.org/10.1016/j.energy.2011.08.051.
[54] Kirmse CJW, Oyewunmi OA, Taleb AI, Haslam AJ, Markides CN. A two-phase single-reciprocating-piston heat conversion engine: non-linear dynamic modelling. Appl Energy 2017;186:359–75. https://doi.org/10.1016/j.apenergy.2016.05.140.
[55] Jacob R, Belusko M, Inés Fernández A, Cabeza LF, Saman W, Bruno F. Embodied energy and cost of high temperature thermal energy storage systems for use with concentrated solar power plants. Appl Energy 2016;180:586–97. https://doi.org/10.1016/j.apenergy.2016.08.027.
[56] Wang D, Zhang J, Tian X, Liu D, Sumathy K. Progress in silica gel-water adsorption refrigeration technology. Renew Sustain Energy Rev 2014;30:85–104. https://doi.org/10.1016/j.rser.2013.09.023.
[57] Ghafoor A, Munir A. Worldwide overview of solar thermal cooling technologies. Renew Sustain Energy Rev 2015;43:763–74. https://doi.org/10.1016/j.rser.2014.11.073.
[58] Leibowitz H, Markus D. Economic performance of geothermal power plants using the Kalina cycle technology. Geotherm Resour Counc Trans 1990;14:1037–42.
[59] Mirolli MD. The Kalina cycle for cement kiln wast heat recocery power plant. IEEE Power 2005:330–6.
[60] Mirkhani N, Amini A, Ashjaee M. Thermo-economic analysis of transcritical CO_2 cycles with bounded and unbounded reheats in low-temperature heat recovery applications. Energy 2017;133:676–90. https://doi.org/10.1016/j.energy.2017.05.162.
[61] DECC. The potential for recovering and using surplus heat from industry – appendix. London; 2014.
[62] Brückner S, Liu S, Miro L, Radspieler M, Cabeza LF, Lävemann E. Industrial waste heat recovery technologies: an economic analysis of heat transformation technologies. Appl Energy 2015;151:157–67.
[63] Law R, Harvey A, Reay D. Opportunities for low-grade heat recovery in the UK food processing industry. Appl Therm Eng 2013;53:188–96. https://doi.org/10.1016/j.applthermaleng.2012.03.024.
[64] Thorneloe S State of Practice for Emerging Waste Conversion Technologies. Washington, DC; 2012.
[65] European Parliament and Council. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. Off J Eur Union 2008:3–30. [doi:2008/98/EC; 32008L0098].
[66] Parawira W, Read JS, Mattiasson B, Björnsson L. Energy production from agricultural residues: high methane yields in pilot-scale two-stage anaerobic digestion. Biomass Bioenergy 2008;32:44–50. https://doi.org/10.1016/j.biombioe.2007.06.003.
[67] Hills DJ, Roberts DW. Anaerobic digestion of dairy manure and field crop residues. Agric Wastes 1981;3:179–89. https://doi.org/10.1016/0141-4607(81)90026-3.
[68] Aditiya HB, Mahlia TMI, Chong WT, Nur H, Sebayang AH. Second generation bioethanol production: a critical review. Renew Sustain Energy Rev 2016;66:631–53. https://doi.org/10.1016/j.rser.2016.07.015.
[69] Aditiya HB, Chong WT, Mahlia TMI, Sebayang AH, Berawi MA, Nur H. Second generation bioethanol potential from selected Malaysia's biodiversity biomasses: a review. Waste Manag 2016;47:46–61. https://doi.org/10.1016/j.wasman.2015.07.031.
[70] Fischer G, Schrattenholzer L. Global bioenergy potentials through 2050. Biomass Bioenergy 2001;20:151–9. https://doi.org/10.1016/S0961-9534(00)00074-X.
[71] Nakicenovic NN, Grübler A, McDonald A. Global energy perspectives. Cambridge, United Kingdom: Cambridge University Press; 1998.
[72] Holm-Nielsen JB, Al Seadi T, Oleskowicz-Popiel P. The future of anaerobic digestion and biogas utilization. Bioresour Technol 2009;100:5478–84. https://doi.org/10.1016/j.biortech.2008.12.046.
[73] Tagliaferri C, Evangelisti S, Clift R, Lettieri P, Chapman C, Taylor R. Life cycle assessment of conventional and advanced two-stage energy-from-waste

technologies for methane production. J Clean Prod 2016;129:144–58. https://doi.org/10.1016/j.jclepro.2016.04.092.
[74] Bacenetti J, Fiala M. Carbon footprint of electricity from anaerobic digestion plants in Italy. Environ Eng Manag J 2015;14:1495–502.
[75] Styles D, Dominguez EM, Chadwick D. Environmental balance of the of the UK biogas sector: an evaluation by consequential life cycle assessment. Sci Total Environ 2016;560–561:241–53. https://doi.org/10.1016/j.scitotenv.2016.03.236.
[76] Ertem FC, Martinez-Blanco J, Finkbeiner M, Neubauer P, Junne S. Life cycle assessment of flexibly fed biogas processes for an improved demand-oriented biogas supply. Bioresour Technol 2016;219:536–44. https://doi.org/10.1016/j.biortech.2016.07.123.
[77] O'Shea R, Wall D, Murphy JD. Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times. Bioresour Technol 2016;216:238–49. https://doi.org/10.1016/j.biortech.2016.05.050.
[78] Edwards J, Othman M, Burn S. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renew Sustain Energy Rev 2015;52:815–28. https://doi.org/10.1016/j.rser.2015.07.112.
[79] Raven RPJM, Verbong GPJ. Boundary crossing innovations: case studies from the energy domain. Technol Soc 2009;31:85–93. https://doi.org/10.1016/j.techsoc.2008.10.006.
[80] Walker M, Theaker H, Yaman R, Poggio D, Nimmo W, Bywater A, et al. Assessment of micro-scale anaerobic digestion for management of urban organic waste: a case study in London, UK. Waste Manag 2017;61:258–68. https://doi.org/10.1016/j.wasman.2017.01.036.
[81] Banks CJ, Chesshire M, Heaven S, Arnold R. Anaerobic digestion of source-segregated domestic food waste: performance assessment by mass and energy balance. Bioresour Technol 2011;102:612–20. https://doi.org/10.1016/j.biortech.2010.08.005.
[82] Quested T, Parry A. Household Food Waste in the UK; 2015, 2017.
[83] Parkin D. The future of gas-supply of renewable gas. Natl Grid 2016:24.
[84] NNFCC. The Official Information Portal on Anaerobic Digestion; 2017.
[85] Hoolohan C, Larkin A, McLachlan C, Falconer R, Soutar I, Suckling J, et al. Engaging stakeholders in research to address water–energy–food (WEF) nexus challenges. Sustain Sci 2018:1–12. https://doi.org/10.1007/s11625-018-0552-7.
[86] WRAP. A survey of the UK anaerobic digestion industry in 2013. Banbury, UK: Prepared by LRS Consultancy; 2014.
[87] More O, Noyce C. AD market report summary. 2016.
[88] Tranter RB, Swinbank A, Jones PJ, Banks CJ, Salter AM. Assessing the potential for the uptake of on-farm anaerobic digestion for energy production in England. Energy Policy 2011;39:2424–30. https://doi.org/10.1016/j.enpol.2011.01.065.
[89] Axelsson L, Franzén M, Ostwald M, Berndes G, Lakshmi G, Ravindranath NH. Jatropha cultivation in southern India: assessing farmers' experiences. Biofuels Bioprod Bioref 2012;6:246–56. https://doi.org/10.1002/bbb.
[90] Biochar for Carbon Capture. Biochar Production: Fast and Slow Pyrolisis; n.d. ⟨http://biocharforcarboncapture.com/research/fast-and-slow-pyrolisis⟩, [Accessed 9 January 2018].
[91] Meier D, Van De Beld B, Bridgwater AV, Elliott DC, Oasmaa A, Preto F. State-of-the-art of fast pyrolysis in IEA bioenergy member countries. Renew Sustain Energy Rev 2013;20:619–41. https://doi.org/10.1016/j.rser.2012.11.061.
[92] Jablonski S, Strachan N, Brand C, Bauen A. The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergy scenarios. Energy Policy 2010;38:5799–816. https://doi.org/10.1016/j.enpol.2010.05.031.
[93] Thornley P, Upham P, Tomei J. Sustainability constraints on UK bioenergy development. Energy Policy 2009;37:5623–35. https://doi.org/10.1016/j.enpol.2009.08.028.
[94] Williams PT. Pyrolysis of waste tyres: a review. Waste Manag 2013;33:1714–28. https://doi.org/10.1016/j.wasman.2013.05.003.
[95] Badger PC, Fransham P. Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs – a preliminary assessment. Biomass- Bioenergy 2006;30:321–5. https://doi.org/10.1016/j.biombioe.2005.07.011.
[96] Fatih Demirbas M, Balat M, Balat H. Biowastes-to-biofuels. Energy Convers Manag 2011;52:1815–28. https://doi.org/10.1016/j.enconman.2010.10.041.
[97] LI M, Rao AD, Brouwer J, Samuelsen GS. Design of highly efficient coal-based integrated gasification fuel cell power plants. J Power Sources 2010;195:5707–18. https://doi.org/10.1016/j.jpowsour.2010.03.045.
[98] E4tech. Review of technologies for gasification of biomass and wastes. 2009. https://doi.org/10.1016/j.dsr2.2004.06.026.
[99] Czernik S, Bridgwater AV. Overview of applications of biomass fast pyrolysis oil. Energy Fuels 2004;18:590–8. https://doi.org/10.1021/ef034067u.
[100] DBEIS. Energy consumption in the UK, 2017 update. London; 2017.
[101] Rhodes C.UK steel industry: statistics and policy; 2017.
[102] DBEIS. Energy consumption in the UK 2016. London; 2016.
[103] UK Food and Drink Federation. UK food and drink federation's statistics at a glance. Food Drink Fed; 2017. ⟨https://www.fdf.org.uk/statsataglance.aspx⟩, [Accessed 20 July 2012].
[104] Griffin PW, Hammond GP, Norman JB. Industrial energy use and carbon emissions reduction: a UK perspective. Wiley Interdiscip Rev Energy Environ 2016:5. https://doi.org/10.1002/wene.212.
[105] DBEIS. Digest of UK Energy Statistics 2016: Chapter 1. London; 2016.
[106] Wu C-C, Reimink H. Energy intensity online measurement and benchmarking system; 2016.
[107] Worldsteel Association. Fact Sheet – Energy use in the steel industry; 2016.
[108] U.S. DOE. U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis. Washington, DC; 2012.
[109] Ma G, Cai J, Zhang L, Sun W. Influence of steam recovery and consumption on energy consumption per ton of steel. Energy Procedia 2012;14:566–71. https://doi.org/10.1016/j.egypro.2011.12.976.
[110] Yang M. The state of the art and development direction of steam utilization in iron and steel plants. In: Proceedings of the Natl. Symp. Energy Saving, Emiss. Reduct. Low Carbon Technol. Dev. Metall. Ind. Tangshan, Hebei; 2011.
[111] Hou SS, Chen CH, Chang CY, Wu CW, Ou JJ, Lin TH. Firing blast furnace gas without support fuel in steel mill boilers. Energy Convers Manag 2011;52:2758–67. https://doi.org/10.1016/j.enconman.2011.02.009.
[112] Kong H, Qi E, He S, Li G. MILP model for plant-wide optimal by-product gas scheduling in iron and steel industry. J Iron Steel Res Int 2010;17:34–7. https://doi.org/10.1016/S1006-706X(10)60153-7.
[113] BBC. Tata £53m in steel steam power in Port Talbot. BBC News; 2011. ⟨http://www.bbc.co.uk/news/uk-wales-13192091⟩.
[114] Steel Plantech. Solutions of Steel Plantech; 2013. ⟨http://steelplantech.com/en/product/⟩.
[115] Tian WY, Zhang JY, Dai CD, Long XY. Recovery of waste heat from sinter cooling process: simulation and optimisation. Ironmak Steelmak 2015;42:97–104. https://doi.org/10.1179/1743281214Y.0000000203.
[116] Lin T. Converter gas and waste water treatment by OG-system in steel smelting industry. Kokkola, Finland: Centria University of Applied Sciences; 2013.
[117] Gandt K, Meier T, Echterhof T, Pfeifer H. Heat recovery from EAF off-gas for steam generation: analytical exergy study of a sample EAF batch. Ironmak Steelmak 2016;43:581–7. https://doi.org/10.1080/03019233.2016.1155812.
[118] Carsten B, Ralf G. Waste heat – the biggest source for energy efficiency optimisation. Millenn Steel India 2014:39–42.
[119] Zhi L, Zhi W, Fu-Yong S. Analysis of efficient operating cycles for blast-furnace stoves. Metallurgist 2013;56:799–806. https://doi.org/10.1007/s11015-013-9654-8.
[120] Spirax Sarco. Steam Accumulators; 2017. ⟨http://www.spiraxsarco.com/Resources/Pages/Steam-Engineering-Tutorials/the-boiler-house/steam-accumulators.aspx⟩.
[121] Luo X, Liu S, Xu M, Huang Y Modeling and simulation of steam pipeline network with multiple supply sources in iron & steel plants. In: Proceedings of the 28th Chinese control Decis. conference. Yinchuan, China: IEEEXplore; n.d., p. 4667–71.
[122] Cesar CPFrança GAC. Energetic and exergetic analysis of a thermal system aiming cogeneration. In: Proceedings of the 18th international Congr. Mech. Eng. Novemb. 6–11. Ouro Preto, MG; 2005.
[123] Sun W, Zhao Y, Wang Y. Electro- or turbo-driven?—analysis of different blast processes of blast furnace. Processes 2016;4:28. https://doi.org/10.3390/pr4030028.
[124] Barraclough K. The applications of vacuum technology to steelmaking. Vacuum 1972;22:91–102. https://doi.org/10.1016/0042-207X(72)90467-8.
[125] Rian AB, Ertesvåg IS. Exergy analysis of a steam production and distribution system including alternatives to throttling and the single pressure steam production. Energy Convers Manag 2011;52:703–12. https://doi.org/10.1016/j.enconman.2010.07.049.
[126] DECC. The Future of Heating: A strategic framework for low carbon heat in the UK. London; 2012.
[127] Monthly crude steel production in the United Kingdom (UK) in 2015. World Steel Assoc; 2016.
[128] Spirax Sarco. Design of fluid systems; 2017.
[129] Williams CL. A waste heat recovery strategy for an integrated steelworks. Cardiff, United Kingdom: Cardiff University; 2015.
[130] Spirax Sarco. Types of steam flowmeter; 2017. ⟨http://www.spiraxsarco.com/Resources/Pages/Steam-Engineering-Tutorials/flowmetering/types-of-steam-flowmeter.aspx⟩.
[131] McBrien M, Serrenho AC, Allwood JM. Potential for energy savings by heat recovery in an integrated steel supply chain. Appl Therm Eng 2016;103:592–606. https://doi.org/10.1016/j.applthermaleng.2016.04.099.
[132] EUROFER. Contribution to the energy management section; 2007.
[133] IISI. Energy Use in the Steel Industry. Brussels; 1998.
[134] Mousa E, Wang C, Riesbeck J, Larsson M. Biomass applications in iron and steel industry: an overview of challenges and opportunities. Renew Sustain Energy Rev 2016;65:1247–66. https://doi.org/10.1016/j.rser.2016.07.061.
[135] Norgate T, Haque N, Somerville M, Jahanshahi S. Biomass as a source of renewable carbon for iron and steelmaking. ISIJ Int 2012;52:1472–81. https://doi.org/10.2355/isijinternational.52.1472.
[136] Jahanshahi S, Deev A, Haque N, Lu L, Mathieson J, Norgate T, et al. Recent progress in R&D on use sustainable biomass/designer chars for steel production. Proc Iron Steel Ind Tokyo Jpn Ironmak Jpn Soc Promot Sci 2014.
[137] Mathieson J, Rogers H, Somerville M, Ridgeway P, Jahanshahi SS. Use of biomass in the iron and steel industry – an Australian perspective. In: Proceedings of the 1st international conference energy Effic. CO_2 Reduct. Steel Ind. (EECR Steel 2011) – Inc., METEC InSteelCon 2011; 2011, p. 1–10.
[138] Carpenter A. CO_2 abatement in the iron & steel industry. 2012. https://doi.org/10.1021/ef900064c.
[139] Fung PYH, Kirschbaum MUF, Raison RJ, Stucley C. The potential for bioenergy production from Australian forests, its contribution to national greenhouse targets and recent developments in conversion processes. Biomass Bioenergy 2002;22:223–36. https://doi.org/10.1016/S0961-9534(01)00069-1.
[140] Tassou SA, Azapagic A, Fryer P, Gowreesunker B, Stojceska V, Kolokotroni M, et al. Energy demand and reduction opportunities in the UK food chain. Proc ICE – Energy 2014;167:162–70. https://doi.org/10.1680/ener.14.00014.
[141] DEFRA. Food Statistics Pocketbook 2013. London; 2013.
[142] DBEIS. Energy consumption in the UK July 2017. London; 2017. ⟨http://dx.doi.org/10.1073/pnas.1423686112⟩.

[143] UK Food and Drink Federation. Carbon management best practice in food and drink manufacturing guidance prepared as part of FDF's five-fold environmental ambition. 2008.
[144] DEFRA. Food Statistics Pocketbook 2016. London; 2016.
[145] Carbon Trust. Industrial Energy Efficiency Accelerator – Guide to the paper sector; 2011.
[146] AEG. Steam cooking guide; n.d. 〈https://hndgwww2.blob.core.windows.net/www2/products/061-appliances/cooking-appliances/Steam+Cooking+Guide.pdf〉.
[147] Mujumdar AS. Handbook of industrial drying. 4th ed. USA: CRC Press; 2014.
[148] Earle RL. Unit operations in food processing. Web Ed. Oxford, United Kingdom: Pergamon Press; 1983.
[149] Bylund G. Dairy processing handbook. Lund, Sweden: Tetra Pak; 1995.
[150] Spirax Sarco. Food and Beverage best practice guide to managing steam quality; 2012.
[151] Ogden J, Hochgreb S, Hylton M. Steam economy and cogeneration in cane sugar factories. Int Sugar J 1990;92:131–6.
[152] Jayamaha L. Energy-efficient building systems: green strategies for operation and maintenance. New York, United State: McGraw-Hill Education; 2007.
[153] Carbon Trust. Food and drink processing; 2012.
[154] DEFRA. Analysis of the UK potential for Combined Heat and Power. London; 2007.
[155] Carbon Trust. Steam and high temperature hot water boilers; 2012.
[156] DBEIS. Greenhouse gas reporting: conversion factors 2017; 2017. 〈https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017〉.
[157] Ammar Y, Joyce S, Norman R, Wang Y, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. Newcastle upon Tyne, UK: Sustainable Thermal Energy Management in the Process Industries International Conference; 2011.
[158] Popp J, Lakner Z, Harangi-Rákos M, Fári M. The effect of bioenergy expansion: food, energy, and environment. Renew Sustain Energy Rev 2014;32:559–78. https://doi.org/10.1016/j.rser.2014.01.056.
[159] WRAP. Estimates of Food Surplus and Waste Arisings in the UK; 2016.
[160] Castella T, Parfitt J. Food and drink federation members' waste survey. 2014.
[161] British Embassy Tokyo. UK Energy Innovation – The history and current status of the UK's electricity and gas markets; 2016.
[162] Pearson P, Watson JJ. UK Energy Policy 1980–2010: A history and lessons to be learnt; 2012.
[163] Hannon MJ, Foxon TJ, Gale WF. "Demand pull" government policies to support product-service system activity: the case of Energy Service Companies (ESCos) in the UK. J Clean Prod 2015;108:1–16. https://doi.org/10.1016/j.jclepro.2015.05.082.
[164] Frank A. ESCOs and Utilities: Shaping the Future of the Energy Efficiency Business. GreenBiz; 2008. 〈https://www.greenbiz.com/news/2008/04/13/escos-and-utilities-shaping-future-energy-efficiency-business〉, [Accessed 2 October 2017].
[165] DECC. The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK; 2012.
[166] European Parliament. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. [L315/1]. Off J Eur Union2012:1–56. https://doi.org/10.3000/19770677.L_2012.315.eng.
[167] Aldersgate Group. Increasing investment for commercial energy efficiency. London; 2018.
[168] Olschewski D, Fragidis GG. Review of Business Models & Energy Management Strategies – FP7 – 609082 – Collaborative Project; 2014.
[169] Pícha J, Tomek A, Löwitt H. Application of EPC contracts in international power projects. Procedia Eng 2015;123:397–404. https://doi.org/10.1016/j.proeng.2015.10.061.
[170] Tasker P, Shaw A, Kelly S. Standards for engineering services. Procedia CIRP 2014;22:186–90. https://doi.org/10.1016/j.procir.2014.07.153.
[171] Chen C, Doloi H. BOT application in China: driving and impeding factors. Int J Proj Manag 2008;26:388–98. https://doi.org/10.1016/j.ijproman.2007.07.002.
[172] U.S. DOE. Combined Heat and Power (CHP) Financing Primer. Washington, DC; 2017.
[173] Shen L, Tam VWY, Gan L, Ye K, Zhao Z. Improving sustainability performance for public-private-partnership (PPP) projects. Sustainability 2016:8. https://doi.org/10.3390/su8030289.
[174] Algarni AM, Arditi D, Polat G. Build-operate-transfer in infrastructure projects in the United States. J Constr Eng Manag 2007;133:728–35.
[175] Shang T, Zhang K, Liu P, Chen Z. A review of energy performance contracting business models: status and recommendation. Sustain Cities Soc 2017;34:203–10. https://doi.org/10.1016/j.scs.2017.06.018.
[176] Bertoldi P, Rezessy S. Energy service companies in Europe – status report. 2005.
[177] King M, Meehan G, George GR, Olson WP. Making a business of energy efficiency: sustainable business models for utilities; 2007.
[178] Scarlat N, Dallemand J-F, Monforti-Ferrario F, Banja M, Motola V. Renewable energy policy framework and bioenergy contribution in the European Union – an overview from national renewable energy action plans and progress reports. Renew Sustain Energy Rev 2015;51:969–85. https://doi.org/10.1016/j.rser.2015.06.062.
[179] Bui M, Fajardy M, Mac Dowell N. Bio-energy with carbon capture and storage (BECCS): opportunities for performance improvement. Fuel 2018;213:164–75. https://doi.org/10.1016/j.fuel.2017.10.100.
[180] Pantaleo A, Candelise C, Bauen A, Shah N. ESCO business models for biomass heating and CHP: profitability of ESCO operations in Italy and key factors assessment. Renew Sustain Energy Rev 2014;30:237–53. https://doi.org/10.1016/j.rser.2013.10.001.
[181] Wood SR, Rowley PN. A techno-economic analysis of small-scale, biomass-fuelled combined heat and power for community housing. Biomass Bioenergy 2011;35:3849–58. https://doi.org/10.1016/j.biombioe.2011.04.040.
[182] Kleinhappl R. Best practice business models for bio-energy success stories; 2009.
[183] DECC. Research to Assess the Barriers and Drivers to Energy Efficiency in Small and Medium Sized Enterprises. London; 2014.
[184] Thollander P, Ottosson M. An energy efficient Swedish pulp and paper industry – exploring barriers to and driving forces for cost-effective energy efficiency investments. Energy Effic 2008:21–34. https://doi.org/10.1007/s12053-007-9001-7.
[185] Bataille C, Waisman H, Colombier M, Segafredo L, Jotzo F, Bataille C, et al. The need for national deep decarbonization pathways for effective climate policy. Clim Policy 2016;16:6–26. https://doi.org/10.1080/14693062.2016.1173005.
[186] Sorrell S, Mallett A, Nye SS. Barriers to industrial energy efficiency: a literature review. Vienna; 2011.
[187] Sorrell S, O'Malley E, Schleich J, Scott S. The economics of energy efficiency: barriers to cost-effective investment. Cheltenham: Edward Elgar; 2004.
[188] Sherriff G. Drivers of and barriers to urban energy in the UK: a Delphi survey. Local Environ 2014;19:497–519. https://doi.org/10.1080/13549839.2013.836164.
[189] Apeaning RW, Thollander P. Barriers to and driving forces for industrial energy efficiency improvements in African industries e a case study of Ghana's largest industrial area. J Clean Prod 2013;53:204–13. https://doi.org/10.1016/j.jclepro.2013.04.003.
[190] Thollander P, Backlund S, Trianni A, Cagno E. Beyond barriers – a case study on driving forces for improved energy efficiency in the foundry industries in Finland, France, Germany, Italy. Appl Energy 2013;111:636–43. https://doi.org/10.1016/j.apenergy.2013.05.036.
[191] Trianni A, Cagno E, Thollander P, Backlund S. Barriers to industrial energy efficiency in foundries: a European comparison. J Clean Prod 2013;40:161–76. https://doi.org/10.1016/j.jclepro.2012.08.040.
[192] Cagno E, Trianni A, Worrell E, Miggiano F. Barriers and drivers for energy efficiency: different perspectives from an exploratory study in the Netherlands. Energy Procedia 2014;61:1256–60. https://doi.org/10.1016/j.egypro.2014.11.1073.
[193] Trianni A, Cagno E, Farnè S. An empirical investigation of barriers , drivers and practices for energy efficiency in primary metals manufacturing SMEs. Energy Procedia 2014;61:1252–5. https://doi.org/10.1016/j.egypro.2014.11.1071.
[194] Forrester JW. Industrial dynamics. Cambridge: MIT Press; 1961.
[195] Senge PM. The fifth discipline: the art and practice of the learning organization. New York: Random House Business; 1990.
[196] Dyer CH, Hammond G, McKenna RC. Engineering sustainability: energy efficiency, thermodynamic analysis and the industrial sector. In: Proceedings of the international conference Eng. Sustain. Perth; 2008.
[197] Sudhakara Reddy B. Barriers and drivers to energy efficiency – a new taxonomical approach. Energy Convers Manag 2013;74:403–16. https://doi.org/10.1016/j.enconman.2013.06.040.
[198] DECC. The Carbon Plan: Delivering our low carbon future. London; 2011.
[199] National Grid. Future Energy Scenarios. London; 2017.