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The role of pumped and waste heat technologies in a high-efficiency sustainable energy future for the UK

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Abstract

This paper begins with an overview of the current supply and demand characteristics of primary energy for the provision of heat and power in the UK. This is followed by a brief review of a variety of solutions that are being proposed towards the establishment of a sustainable energy landscape, including clean coal, wind and solar energy. The discussion extends to the economics and performance of various renewable energy systems in comparison to fossil fuel equivalents. Placed in this context, the study then focuses specifically on the role of pumped heat, CHP schemes, and options for the recovery and conversion of waste heat into useful work, all of which have a potential to contribute towards the creation of a 'high-efficiency sustainable energy future'. It is concluded that although the problem is complex, the relative costs of competing technologies are not prohibitive, but comparable, leading to an inability to make a decisive choice and delaying progress. CHP and pumped heat are found to be similar in terms of overall efficiency, with the load factor (heat-to-power demand ratio) being of critical importance. Various waste heat systems are also found to be similar in terms of the important indicator of power per unit cost.

Keywords: energy efficiency, low grade heat, waste heat, heat engines, heat pumps, heat and power

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1. Introduction

In this section the case is made for a *high-efficiency sustainable* energy future. The energy problem is considered from an economic, environmental, health and security perspective. An important realisation concerns the potential of various energy options to impact meaningfully on these diverse aspects. Some options, although quite capable of adequately addressing a number of them, fail to address others. These limitations must be borne in mind during strategic decision-making processes. This leads, in Section 2, to an overview of a wide range of technologies that are being considered as viable means for the provision of such an energy landscape in the United Kingdom.

1.1. Fossil fuels, combustion and energy

Mankind has been burning fossil fuels for light, heat and power for a very long time, and for good reason. On combustion, fossil fuels release substantial amounts of heat at high temperature and are thus associated with high energy and exergy densities. The latter in particular makes them ideal candidates for use in heat engines for the production of power, whether this is directly for motion (i.e. transportation) or conversion to electricity via generators, since the efficiency of any such engine will increase with the temperature of the available heat source. Fossil fuels are, and will remain, the most important energy carrier over the next few decades.

In the UK, oil, gas and coal accounted collectively for 90% of all the consumed primary fuel sources in 2009, including fossil, nuclear, wind, hydro- and imported electricity (see Fig. 1 [1]). Fossil fuels were also responsible for approximately 75% of the electricity generated in 2008 and 2009 [1]. Yet, along with high-grade (i.e. high-temperature) heat, the combustion of fossil fuels also produces gases such as oxides of carbon (commonly, CO_x), nitrogen (NO_x) and sulphur (SO_x), as well as water vapour. Imperfect combustion also produces unburnt hydrocarbons (UHC) and particulate matter (PM) such as soot. Increasing attention over the past 15–20 years is being paid to these various emissions and their possible effects on human health and the Earth's climate [2].

1.2. Emissions, climate change and health effects

Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are considered to be the primary greenhouse gases (GHGs) in the Earth's atmosphere [2, 3]. According to the Department of Energy and Climate Change [4], *if one excludes H_2O vapour*, CO_2 accounts for >99% of the weight and ~85% of the global warming potential of all GHGs. With this

understanding in mind, it is possible to refer to GHG and CO₂ emissions (almost) interchangeably, though the significance of excluding H₂O is recognised and noted.

Hence, considerable interest is being shown in CO₂ in particular and a variety of ‘decarbonised’ strategies that would promote the reduction of CO₂ emissions over the next few decades are being considered. A hypothetical road map for the worldwide curbing of CO₂ emissions with estimated contributions from various practices and technologies has been published by the International Energy Agency (IEA) [5] and can be seen in Fig. 2(a). Note here: (i) the equal expectations from carbon capture and storage (CCS) and renewable technologies, which have been identified as having a similar potential towards this goal of between 17 and 19%; and (ii) the 43% combined potential assigned to energy efficiency in various forms, a 2.5-fold higher potential.

The UK Government has made a legally binding international commitment directly with respect to total GHG (and hence CO₂) emissions, currently (2009 figures) at 570 Mt CO₂ of which 470 Mt are associated with CO₂ [4]. In 1997 it adopted the Kyoto protocol that stipulates a reduction in total GHG emissions by 12.5% below 1990 levels (780 Mt CO₂ [4, 6]) by 2008–2012. Subsequently, in the Climate Change Act of 2008 it pledged to cut emissions by 80% relative to 1990 levels by 2050 and by at least 34% by 2020, though GHG/CO₂ emissions had already dropped by 20%/11% between 1990 and 2008 [4], in line with the Kyoto targets. To this end it has been imposing progressive caps on GHG emissions through 5-year ‘Carbon budgets’, the first of which covers the period from 2008–2012 and stipulates a reduction of 22% below 1990 levels.

The historical evolutions of the emissions of CO₂ and of the total GHG emissions weighted by global warming potential since 1980 are shown in Fig. 2(b). Also shown here are the Kyoto and first Carbon budget targets. Both targets have been broadly met, however, the economic downturn caused by the financial crisis has acted as a catalyst in this direction. In particular note the sudden drop in emissions after the contraction of 2008 and the slight rebound in 2010.

Nevertheless, the IEA observes that “Current energy and CO₂ trends run directly counter to the repeated warnings sent by the United Nations Intergovernmental Panel on Climate Change (IPCC), which concludes that reductions of at least 50% in global CO₂ emissions compared to 2000 levels will need to be achieved by 2050 to limit the long-term global average temperature rise to between 2.0 °C and 2.4 °C” [5]. It proceeds to note that “Recent studies suggest that climate change is occurring even faster than previously expected and that even the ‘50% by 2050’ goal may

be inadequate to prevent dangerous climate change". Clearly there is an element of uncertainty with regards to the effect of the *human-based* release of CO₂ into the atmosphere on the Earth's climate, the science of which is highly complex and not well understood. The conventional approach of the majority of the scientific and policy communities has been a precautionary one.

In addition, beyond the possible contribution of the release of combustion products to the greenhouse effect, NO_x and SO_x emissions have been associated with other detrimental aspects of climate change, such as acid rain, while air pollution from PM, aerosols and even O₃ have been linked to adverse effects on human health. Specifically for instance, PM has been implicated in damage to the heart and lungs [7]. A growing body of both legislation and research over the past 15 years has been dedicated to the control of these emissions, with noteworthy success.

1.3. Development, security, sustainability and economics

At the same time, energy security in the face of finite resources of oil and gas, but also of coal (the UK is already a net importer of all three), demands the identification and implementation of more sustainable (i.e. in this context, long term) energy solutions. Declining reserves will lead eventually to escalating energy prices and increased propensity for economic slow-downs, recessions and even depressions [8, 9], as well as issues related to energy security when the commodities become scarce and need to be imported to cover demand. In fact, domestic electricity costs in both the UK and the EU have shown an increase by a factor of 1.9 in the last decade, while industrial sector costs have increased by 2.4 and 2.9, respectively [10, 11]. This trend is set to continue, if not accelerate.

When discussing energy resources and sustainability it is necessary to consider the energy use per capita and population growth. On the one hand there is a significant correlation between the use of energy per capita (and consequently also, the emissions per capita) and a country's standard of living [12, 13] that is quantified typically through the UN's Human Development Index, or HDI. Referring to Fig. 3, this trend tends to level out at the highest levels of the HDI, associated with highly industrialised advanced economies where the energy use is also highest [12]. A country's historical per capita demand for energy is thus a crucial guide in imposing limitations on what energy policy can achieve and, eventually, in determining a viable and realistic future energy strategy. Another factor of prime importance is population growth. The population of the UK has been increasing at average rate of approximately 0.5% over the past 30 years; but this aggregate figure hides the fact that the growth has accelerated from a rate of 0.3% over the first half of this

period to a rate of 0.6% over the past decade [14]. The doubling times associated with these two piece-wise exponential growth curves are 230 and 115 years, respectively. Predictions indicate that the increasing growth trend is likely to continue for another decade, during which time the growth rate should be $\sim 0.7\%$ with a population doubling time of just under 100 years. At the same time society has become more efficient. The UK's average energy use increased from about 3.4 tonnes of oil equivalent (TOE) per capita in the early 1980s to a peak of close to 3.8 TOE in the late 1990s, and decreased again to about 3.2 TOE per capita since then [15, 16]. Thus, the overall final energy consumption increased from the early 1980s to the mid-2000s at a rate of close to 0.9% per year with a doubling time of 80 years, but has *dropped* in the last 5 years by 1.5%. The task of lowering the total energy use is clearly made more difficult in a growing population.

In summary, dwindling resources and rising energy prices, together with a growing public acceptance and even demand for Government regulation to address sustainable development, environmental and health concerns, fuel economy and energy security issues are acting, and will continue to act, as major and *intensifying* drivers for the widespread application of energy efficiency schemes and the utilisation of alternative energy sources to fossil fuels. The UK has already signed up to the EU Renewable Energy Directive, which includes a UK target of 15% of energy from renewables by 2020, a seven-fold increase in UK renewable energy consumption relative to 2008 levels. One may argue that, due to scarcity of supply and increasing demand for energy and fossil fuels, self-regulating market forces will lead away from a globalised world that favours low-cost labour towards local economies that favour low-cost transportation and energy usage [8, 9]. Or, perhaps, a sustainable future will arise as a consequence of public opinion, or on the basis of national security or economic competitiveness. This paper discusses techno-economically feasible solutions and systems that will be required to deliver a 'high-efficiency, sustainable (and hence also decarbonised) energy future', irrespective of the underlying forces that might give rise to it.

2. High-efficiency sustainable energy futures

Having established the drivers for a high-efficiency sustainable energy future, the aim in this section is to present relevant technologies that are being proposed in order to achieve this. As our starting point we consider options that coincide with those in MacKay [17]. These are presented briefly before a shortlist is made that will be discussed in detail in Sections 3 and 4.

2.1. Energy options and combinations

It is important to recognise the great uncertainty in the ever-expanding dialogue concerning the advantages and disadvantages of various energy futures. The excellent book by MacKay [17] has been an invaluable contribution to this discussion in the area of energy and efficiency, by pointing out the importance of *quantifying realistically* the benefits and potential of competing technologies. MacKay focuses on the combined domestic/residential and transport sectors in the UK and this can be justified on the basis that 65% of the total consumed energy is used up in these two sectors [1]. The present paper is a simple, complementary analysis to that of MacKay, concerned with the direct comparison of specific energy solutions and systems that address the issues raised above. The starting points for the present study are the five plans for the future supply of energy in the UK that appear in the book, repeated here in Fig. 4.

2.2. Generation, supply and consumption framework

Two opposing hypothetical scenarios are imagined in the context of energy provision: a ‘centralised’ scenario in which electricity, and possibly heat, would be produced at large point sources/plants and distributed via a grid to the domestic level; and a ‘decentralised’ one in which distributed individual energy units would aim to become self-sufficient with respect to heat and power, via cogeneration or other means. In effect the former is a decarbonised upgrade of the present situation, plus (potentially) district heating. Electricity and also (possibly) heat would be produced by renewables, or otherwise, at large point sources/plants and distributed via a grid out to the end-users. The decentralised scenario describes an approach that is conceptually exactly the opposite to this, with distributed generation matching demand. Heat and power (i.e. electricity) are produced at the level of a household, a group of households, large buildings (schools, hospitals, etc.), a small community, or even a small ‘energy farm’.

A realistic energy solution is sought for heat and electricity provision that is ‘sustainable’ (i.e. long term) and decarbonised. In this sense, even though its characterisation as a ‘sustainable’ energy source is debatable, the nuclear option is not rejected. In Fig. 4 one can identify 8 potential energy sources, which in order of potential are [17]: (1) nuclear; (2) wind; (3) solar (both solar thermal and photovoltaic-PV); (4) clean coal; (5) pumped heat; (6) waste and biomass (wood, biofuels, biogas); (7) tidal and wave; and (8) hydroelectricity. Waste/biomass, tidal/wave and hydroelectricity (and also geothermal) are not considered further here, on the grounds of reduced capacity for the provision of the total required energy in the UK. In Ref. [17] a generous application of these solutions, allocated a collective potential towards meeting the required total energy demand of only 15–20% from all of these sources combined. It is emphasised that this does not imply that hydroelectricity, for example, is to be rejected. On the contrary, it should be harnessed wherever and whenever this is possible. However, it is simply the case that the potential of this source to provide a significant fraction of the overall UK’s national energy need is limited.

2.3. Renewable versus conventional energy option costs

The levelised electricity cost (LEC) includes all aspects of the initial investment, the capital costs, the fuel cost, and operational and maintenance costs over the complete lifetime of the system, which is usually specified as being between 20–30 years or up to 40 years for solar thermal. It also takes into account the capacity or load factor/duty of the system. The well-known LEC studies by Lazard [18] and Emerging Energy Research (EER) [19] (Fig. 5) paint a similar picture, as do the 2010 global study by the International Energy Agency [20] and UK-specific studies by Parsons Brinckerhoff [21] and Mott MacDonald [22] (Fig. 6), and others.

An inspection of Figs. 5 and 6, while noting that deviations between sources [18–23] often amount to 20–40% (sometimes 50–60% in projected LECs), reveals that: (i) the LEC for most technologies (conventional or renewable) is, even now, to a great extent comparable, with the possible exception of tidal and crystalline PV; and (ii) there is general agreement that renewables are on a decreasing cost curve, while non-renewables are on an increasing one, with grid parity expected in the next 5–20 years depending on the technology. Taking a figure of £100/MWh (± 20 –40%) as indicative, the supply of the UK’s total current electricity need (350 TWh/year [24]) over 20 years is associated with a total cost of £700 Bn, or £35 Bn per year for 20 years. This represents 5% of annual Government spending. It also represents an amount smaller than the official £850 Bn

sum used recently for the bailout of the financial sector in the UK. The total costs of the bank bailouts, including indirect liabilities and long term debt, are estimated to be closer to $\sim$ £1.5 Tn.

2.4. *Clean coal*

The Coal Authority, the UK's regulatory body responsible for the licensing of coal mines and the owner of the vast majority of coal and coal mines, has indicated that "in 2005 coal resources at existing deep mines and existing, planned and known potential surface mining sites were in the order of 900 million tonnes" [25]. In addition, it states that "recoverable tonnages considered to be potentially available from new or expanded deep-mining operations amounted to almost 1.4 billion tonnes" [25]. If we take a generous figure of 5 billion tonnes of coal (i.e. double the sum of the two figures provided by the Coal Authority) and a 1.9 MWh/ton conversion based on coal-fired power plants with 40% thermal efficiency and 10% point efficiency penalty to CCS [26], the total reserves represent 25–30 years of the UK's need in electricity at *current* demand, which is $\sim$ 350 TWh per year (averaged over the period 2005–2008 [24]). This demand accounts for 18% of the total current energy use in the UK [1]. For higher efficiency (up to 2.4 kWh/kg [26]) advanced clean coal technologies based on supercritical coal (SCC) power plants with CCS, this figure improves to $\sim$ 35 years. However, these results would be reduced by any growth leading to greater consumption.

It is possible to suggest that clean coal would not replace all fossil fuel powered electricity generation, which then leaves a question mark concerning the supply of the remaining required oil and/or gas. Nevertheless, even if coal covered as little as 50% of the current fossil fuel electricity share (currently at 16% [1]), provisions would only stretch to about 50–55 years for the case of non-SCC with CCS. This "stop-gap" role of clean coal has also been identified by MacKay [17]. Yet it is also likely that road transport (responsible for 70% of all transport, and 25% of the total current energy use [1]) will evolve to displace internal combustion engines (ICEs) and to embrace technologies that require an additional supply of electricity. The electrification of transport, or 'electromobility', can be achieved for example either directly with battery electric vehicles (BEVs), or indirectly with fuel cell electric vehicles (FCEVs) through an intermediate vector such as hydrogen (H_2), or otherwise. Even with a modest 50% market penetration of such a scenario into the transport sector, coal provisions would fall back down to 25–30 years. Hence, there exist non-trivial energetic grounds to reflect carefully a move to clean coal.

In summary, although centralised coal-fired power coupled with CCS presents an option that

addresses adequately the issue of emissions, assuming a successful roll out of CCS technology on a large scale and reliable storage with little or no leakage, it cannot provide a future in which the UK is not increasingly and eventually entirely reliant on imports. Thus, it fails to address energy security in the long term and as such cannot be classed as a truly sustainable energy option.

Furthermore, the release of considerable quantities of methane during coal mining is often ignored, as are the additional emissions associated with the supply of coal, including mining and transportation. Methane has a global warming potential 25 times higher than that of CO₂ over a 100 year horizon [27]. There is evidence from studies such as that shown in Fig. 7(a) that coal will have considerably higher total GHG emissions than renewables even with the adoption of CCS ($\sim 3\text{--}10\times$ at 150–250 gCO₂/kWh), mainly due to the processes of mining and coal supply [28], while any level of continuous CO₂ leakage would act to exasperate this differential. In addition, Fig. 7(b) from the same study predicts that the LEC of renewables is expected to become comparable to that of clean coal as early as the coming decade (see Section 2.3).

CCS may yet have a role to play, but it will have to extend beyond coal-fired power generation to other targeted large emission point-sources. *Returning to Section 2.2 and Fig. 4 we retain: onshore and offshore wind, solar thermal and PV, pumped heat and possibly nuclear.*

2.5. Wind energy

Wind energy appears consistently as one of the cheapest renewable options in various LEC studies, such as those mentioned above and shown in Figs. 5 and 6. Nevertheless, given a UK load factor of $\sim 30\%$ [29], the management of transient wind-generated electricity becomes a crucial aspect of this option. In fact, wind's load factor profile is considerably worse than that of solar where daytime generation more closely matches the demand (although in the UK this remains sub-optimal, as discussed in the next section) and for which thermal storage can be made available more readily [30, 31]. Addressing this issue requires farm over-capacity or load-levelling (e.g. in Fig. 6(a) by oil-firing in open cycle gas turbine-OCGT plants [21], or otherwise). Depending on the action this can increase the cost and emissions, or decrease the total energy supply potential per unit area. In the future load factor variations may be overcome with advanced electricity storage schemes (e.g. pumped thermal [32] or other [33, 34]), but many of these are still under development. Wind remains a serious energy option for the UK and can deliver a reasonable part of the total energy demand as part of a mix of technologies. This will however hinge crucially on

a reliable and affordable solution to the transient management problem.

2.6. Solar energy

We turn now to solar energy, both thermal and PV. In the UK, PV technologies have largely displaced solar thermal from the energy discussion, to the extent that PV is often made synonymous with solar energy while bypassing any mention of solar thermal. It is important to realise from Figs. 5 and 8 that *current* LEC for concentrating solar thermal (CST) systems are basically either on par or slightly cheaper than PV (both in the range $\sim$ £100–200/MWh [19, 23, 35]) and have an edge in terms of efficiency [19, 30, 31]. Cradle-to-grave GHG from the solar options are also comparable, with CST again (perhaps) having a small lead. A brief meta-analysis over a number of sources [36–40] gives, for PV: thin-film CdTe 18–67 g, Si 32–104 g; and for CST: trough 14–90 g, receiver 21–60 g, dish 22–58 gCO₂/kWh. Furthermore, unlike PV, large-scale (>100 MW) CST installations have been in operation since the mid-80s, while up to 15-hr heat storage can be provided for demand matching and load factor enhancement at a fraction of the cost of batteries [23, 30, 31]. Thin-film (e.g. CdTe) and concentrator PV show promise in either LEC, efficiency or GHGs, but gains in one aspect typically lead to losses in another, while improvements to the estimated values are often well within the bounds of their uncertainty.

Unfortunately, the seasonal characteristics of solar intensity in the UK are not favourable for these technologies, even excluding climatic conditions (cloud coverage). The daily load factor varies strongly between summer and winter, with the peak demand at 6 pm in January when solar intensity is almost zero. Therefore, as with wind, solar electricity will require significant storage to be effective and for this reason it will be considerably more expensive than predictions in generic LEC studies that are based in more favourable geographic locations. Often solar technologies do not even appear in UK specific studies (e.g. see Fig. 6 [21, 22]). Although controversial (e.g. for security reasons), it is the author’s opinion that *imported* solar power from Southern Europe and North Africa is the most viable large-scale solar option for the UK [17, 41, 42], along the lines of the current DESERTEC proposal [41–43]. This proposal involves a network of CST and to lesser extent PV systems and wind farms, and a high-voltage DC transmission grid capable of providing Europe with up to 15% of its need in electricity. Indicative projected LECs should be in the range €80–200/MWh to begin with, falling with time [41–43], but the large scale of the project leads to a considerable total cost of $\sim$ €500 Bn.

Finally, it is often forgotten that beyond electricity solar thermal can also provide up to 50–70% of the hot water demand in households in the UK [44], as well as some space heating. The McKinsey cost curve analysis commissioned by the Confederation of British Industry (CBI) identified solar hot water as the leading solution in terms of potential for GHG abatement, albeit at a cost [45].

Having presented briefly a number of relevant options, it is possible to conclude that a high-efficiency sustainable UK energy landscape could include a mix of wind, pumped heat and (possibly) imported solar and nuclear. Thus, pumped heat, but also combined heat and power (CHP) and waste heat recovery for overall efficiency improvement and primary energy usage minimisation are key solutions for the provision of heating and power in such an energy future; and if a transition to this future is to take place these options should play a central role in the process. Section 3 below examines specifically the role of CHP and pumped heat, while Section 4 discusses the scope for recovery and conversion of waste heat to power.

3. Heating: central heating boilers, CHP and heat pumps

Current heat-to-electricity consumption ratios (H/E) in the UK domestic/residential sector are of the order of about 4 (mostly in the range 3.5–5.3), and as such heating is a major energy sink in the UK in need of close attention. The purpose here is to propose actions beyond simple energy efficiency schemes (e.g. thermal insulation, etc.) that certainly need to be employed given the relative ease and speed with which they can be implemented. Clearly, the combustion of natural gas in boilers for domestic heating is exergetically wasteful. More efficient alternatives to this practice are heat pumps and combined heat and power (CHP). It was suggested in Ref. [17] that heat pumps may have an edge over CHP plants, and by extension smaller, distributed micro-CHP units for heat provision. In this section we will reconsider this comparison.

Before this is done it is worth mentioning the UK Government Renewable Heat Incentive (RHI). The RHI policy was announced in early 2011 and is a noteworthy development that recognises the need to address how heat is generated, managed and used. Under this scheme, tariff support is provided currently to large emission sources in the non-domestic sector; from small business and community heating projects to large-scale commercial, industrial and public sector heating. It is intended that the RHI support target will be broadened at a later stage (from 2012) to include the domestic sector, with eligibility extended to households that have installed suitable installations since mid-2009. Under the policy in its current form neither waste heat recovery and re-use nor CHP are eligible for this incentive, which is only granted (over 20 years) if the heat is generated from renewable sources; and this even though the Government readily acknowledges that these do represent more productive ways of using fossil fuel resources. It should be noted that *small-scale* (>2 kW) gas-fired CHP (or micro-CHP) units, suitable almost exclusively for the domestic market, are eligible under the Feed-in Tariffs (FITs) payment scheme for the electricity produced, with an additional bonus for exporting to the grid. Given that the renewable generation of heat currently makes only a marginal contribution to the overall need, and will continue to do so in the short-term, there is room for improvement here. A more carefully balanced and inclusive policy could see a wider and accelerated drive towards the more efficient utilisation of fossil fuels for the (possibly consolidated) provision of both heating and power relative to current levels in the shorter term, paving the way for more serious changes further down the line. Certainly, solar thermal projects for hot water at the domestic scale (Section 2.6) are relatively simple, effective and easily realisable,

and have the potential to make an impact on the energy consumption in this sector (28% of the overall primary energy [1] and $\sim 14\%$ of all emissions [4] are attributed to domestic use). Their timely inclusion in the RHI policy would be a useful outcome in this direction.

In Fig. 9(a), following Ref. [17], the thick line shows the *current best* achievable heat and electrical efficiency, involving a mix of heat from a high-efficiency condensing boiler (95% fuel-to-heat conversion) and electricity from a high-efficiency CCGT plant (50% fuel-to-electricity conversion; including a 7–9% point electricity transmission and distribution loss, averaged over the period 1980–2000 [46]). The dashed lines denoted by ‘H/E’ enclose the region $H/E = 3.5\text{--}5.3$. The steep dashed ‘HP’ line shows the *current best* heat and electrical efficiency that can be achieved with a mix of heat from high-efficiency heat pumps with a coefficient of performance (COP) of 4 (400% electricity-to-heat conversion) and electricity from CCGT plants.

The shallower ‘CHP’ line indicates the typical performance of CHP after deducting a 10% heat and 8% point electricity transmission loss. The open circles were obtained for a hypothetical steam cycle CHP plant with a boiler temperature and pressure of 550 °C and 100–150 bar, respectively, and a gradual increase in the heat rejection temperature from 60 to 120 °C. The maximum electrical efficiency of this plant is 35% (27% after the losses), when rejecting heat at the lowest temperature of 60 °C. Note that this electrical efficiency is 15% points lower than that used above in the CCGT/heat pump scenario. The highest electrical efficiency operating point has the lowest H/E ratio of the CHP option, so if the demanded H/E ratio is lower than this the overcapacity with respect to the generated heat would lead to heat being rejected to the environment, as indicated by the vertical line. The ‘CHP’ line that passes through the points is associated with a ‘total efficiency’ (heat plus electrical) of about 80%.

Now, if we look at the performance of these solutions between the dashed ‘H/E’ lines in the region $H/E = 3.5\text{--}5.3$ we observe that the heat pump/CCGT combination has a higher total efficiency ($\sim 125\%$) than the *current best* and CHP solutions (both $\sim 80\%$; dashed circle). However, a decarbonised future will have three effects: (i) a reduced maximum possible electrical efficiency (a move away from CCGT); (ii) a more energy efficient housing stock in which heat losses are significantly abated leading to a reduction in the demanded heat; and (iii) a replacement of ICE vehicles with electric alternatives, such that the H/E consumption ratio could drop as low as 0.5–0.8. This shifts the H/E operation regime (solid ‘H/E’ lines) and the heat pump/power combination

performance (solid 'HP' line) to a total efficiency of $\sim 45\%$ (solid circle). Clearly, the CHP and pumped heat solutions are now almost identical.

Proceeding further, Fig. 9(b) addresses the potential improvements from higher efficiency electricity generation. The effect of the higher efficiency CHP plant is to extend the vertical limit to the right. The filled circles are for actual CHP plants and studies by the Carbon Trust [17]. The dashed line is an extrapolation from the hypothetical CHP plant. The fact that it passes through all points implies that the total efficiency (heat plus electrical) of about 80% used earlier is a reasonable estimate for CHP performance. A 45% efficient electrical power plant would improve both the heat pump and the CHP options to operating points within the required H/E operation regime with a total efficiency of $\sim 65\%$. The two solutions remain identical. Hence, the incentive for maximising efficiency is substantial and independent of the solution employed for heat provision.

4. Energy efficiency through waste heat conversion

Once heat has been made available it is more thermodynamically sensible to use this energy directly as heat, rather than to convert it to electricity for which a significant exergetic penalty is paid. This however does not take into account the relative demand for heat and electrical power. In this section we address scenarios and settings in which electricity is required and heat is easily available in quantities significantly larger than the levels of demand.

The relevant Government payback scheme for the generation of “green electricity” are the Feed-in Tariffs (FITs). FITs were implemented in 2010 with the intention of supporting renewable electricity generation at scales up to 5 MW and over a period of 20 years. As mentioned previously in Section 3, gas-fired micro-CHP (<2 kW) is also eligible for FITs, but only for 10 years. Although strictly speaking it is a non-renewable form of electricity generation, it appears that the policy does recognise *to some extent* the improvement offered over current domestic gas-fired boilers.

It was stated in Section 1.1 with reference to Fig. 1 that fossil fuels account for 90% of all primary energy supplies in the UK. They also account for 80% of all energy consumption [1]. With renewables amounting currently to only a few % points of the same energy supply and consumption, high-efficiency energy solutions will be a necessity if a real impact is to be made in decarbonising the energy landscape. In the interim, increased efficiency will allow current fossil fuel supplies to last for longer, thus proving a time buffer necessary for the development and deployment of this desired future energy infrastructure.

According to the IEA [5] and as discussed earlier in Section 1.2 in relation to Fig. 2(a): (i) the largest opportunity for emission reductions comes from improved efficiency, which encompasses end-use fuel and electricity efficiency, as well as power generation efficiency, accounting for about 43% of the overall possible reductions; and (ii) renewables have as much potential as CCS schemes, with each of these two having 40% of the potential for emission reductions compared to that of improved efficiency. Clearly, a sustainable and decarbonised energy future is synonymous with a high-efficiency energy future, whichever energy scenario emerges.

The term ‘high efficiency’ has several implications with regards to waste heat. Heat recovery and re-use to displace fossil fuel burning for heating where this is possible and required is by far a better use of waste heat compared to conversion to power. This arises due to the low thermal efficiencies associated with the conversion of low temperature heat (20% at best; see Table 1). Yet, as stated

above, the purpose here is to propose options *beyond* passive energy (heat) efficiency schemes (e.g. thermal insulation), or end-use energy (heat) reuse or minimisation. Options include: (i) bottoming cycles that recover heat rejected from power-producing systems, for increased overall efficiency; or (ii) stand-alone systems for waste heat conversion to useful work, either fluid pumping (circulation or compression) or electrical power. Suitable systems employ a wide array of technologies based, amongst other, on: (i) subcritical, ‘modified’ and supercritical Rankine or Kalina cycles; or (ii) gas-phase thermoacoustic, Stirling-based and two-phase equivalent cycles.

Thermoelectric generators (TEGs) that convert heat directly into electrical energy by using the Seebeck effect are not considered here. TEGs are compact, simple and have long lifetimes, but also have lower efficiencies than thermodynamic heat engines and higher costs in large systems, restricting their employment to specific small-scale applications. TEGs are being developed in the automotive sector for the conversion of waste heat from IC engines (exhaust gas and cooling water) [47]. Typical *current* thermal efficiencies η_{th} when using heat in the range 200–250 °C are about 5–6%, with associated exergetic efficiencies around $\eta_{ex} \sim 15\%$.

A major advantage of waste heat conversion systems arises from the easy access to and abundant availability of waste heat as an energy source, leading to low operating expenses. Low-grade heat, i.e. heat at ‘low’ temperature (with respect to the original process from which the heat was rejected), is rejected to the environment in vast quantities from a host of power generating and other industrial applications, and even domestic settings. Unfortunately, the conversion of this low-exergy heat to additional useful power (electricity or otherwise) with the use of appropriate heat engines is inevitably associated with low thermodynamic efficiencies. Their usefulness and wider deployment are thus highly dependent upon minimising the capital expense associated with their installation, and the achievement of high efficiencies per unit cost and power densities for rapid cost payback. This is especially true for devices that are capable of operating with marginal energy sources and close to ambient temperatures.

4.1. Heat supply and removal stream matching

Consider Fig. 10(a) in which T – S diagrams of standard subcritical ORC (dark), supercritical (SC-) ORC (light) and Kalina cycles (medium shading) are overlaid; both ‘dry’ (solid) and ‘wet’ (dashed) working fluids are shown. Systems based on these cycles have been targeted for use primarily with geothermal heat, heat from the combustion of biomass and to a lesser extent wasted heat (mostly

from IC engines). Neglecting thermodynamic irreversibilities, the area within each cycle represents the net heat flow into the cycle, which is also equal to the net work produced by that cycle. Hence, there is an incentive to maximise this area. The arrow from top-right to bottom-left represents the hot stream from which waste heat is extracted as this is taken up by the cycle. This imposes a limitation on the area of the cycle that must remain at all times below this curve by at least 5–10 °C in order to drive the heat from the hot stream into the working fluid as this undergoes the heat addition processes of the thermodynamic cycle. The point at which the cycle and the curve are closest is the well-known ‘pinch point’. It is clear that matching the cycle diagram to the evolving temperature of the hot stream from which the waste heat is recovered is a crucial issue for the efficient utilisation of this heat. Fig. 10(a) identifies the potential advantages that SC-ORC and Kalina cycles have over the standard ORC with respect to the maximisation of the cycle area. In addition, Fig. 10(b) indicates a second important point. As well as matching a varying waste heat source temperature, it may also be that the heat sink temperature varies as heat from the cycle is rejected to the cooling stream. Thermofluidic oscillators (see Section 4.2), dry-fluids and reheating with regeneration can go some way towards taking advantage of this process.

The exergetic or second law efficiency η_{ex} is a key and often-quoted thermodynamic performance indicator. It compares the actual thermal efficiency η_{th} of a cycle to the best attainable efficiency η_{max} of a theoretical equivalent (Carnot) cycle,

$$\eta_{\text{ex}} \equiv \eta_{\text{th}} / \eta_{\text{max}} ; \quad (1)$$

where η_{max} is the thermal efficiency of the equivalent Carnot cycle operating across the same hot and cold temperatures. Given its importance, it is instructive to investigate the effects of the varying waste heat and cooling stream temperatures on η_{max} .

Figures 11(a) and (b) show the effects of a decreasing heat source temperature T_{hot} and an increasing heat sink temperature T_{cold} on the maximum theoretical thermal efficiency η_{max} and output work W_{net} of an ideal (Carnot) cycle, respectively. In Fig. 11(a) the Carnot efficiency η_{th} (top surface) is shown for constant temperature hot and cold reservoirs. This is the maximum attainable efficiency η_{max} . The other two surfaces underneath this are calculated by integrating over an infinite array of infinitesimal Carnot engines operating between changing source T_{hot} and sink T_{cold} , with a source temperature drop parameter or ‘heat fraction’ θ . Assuming equal heat

434 duties (mc_p) for both streams for simplicity, gives,

$$435 \quad \eta_{\max} = 1 - f/\Delta T_{\text{hot}} ; \quad (2)$$

$$436 \quad W_{\text{net}} = \eta_{\max} mc_p \Delta T_{\text{hot}} ; \quad (3)$$

437 where $\Delta T_{\text{hot}} = \theta T_{\text{hot},\text{in}}$ is the temperature drop of the hot stream through the heat engine, and,

$$438 \quad f = -T_{\text{cold},\text{in}} \ln(1 - \theta) , \quad (4)$$

439 for a hot stream with a decreasing temperature $\Delta T_{\text{hot}} > 0$ and a cold stream at a constant
440 temperature, or

$$441 \quad f = \Delta T_{\text{cold}} = T_{\text{cold},\text{in}} \theta / (1 - \theta) , \quad (5)$$

442 for a hot stream with a decreasing temperature $\Delta T_{\text{hot}} > 0$ and a cold stream with a increasing
443 temperature $\Delta T_{\text{cold}} > 0$.

444 We observe that at a given hot supply temperature $T_{\text{hot},\text{in}}$, $\eta_{\max}$ decreases with increasing θ , as
445 the area of the thermodynamic cycle in the T - S is progressively restricted. At the same time W_{net}
446 *increases*, revealing a central optimisation problem in the design of these systems. Interestingly
447 we also observe at low $T_{\text{hot},\text{in}}$ that W_{net} shows a non-monotonic trend with θ . At a constant hot
448 temperature supply $T_{\text{hot},\text{in}}$, W_{net} first increases and then decreases again as θ is increased. Two
449 opposite effects combine to give rise to this behaviour in W_{net} , both of which are described by Eq. 3.
450 As the value of θ increases: (i) the drop in the temperature of the hot stream ΔT_{hot} increases,
451 and consequently, the heat supply to the cycle also increases; and (ii) the thermal efficiency $\eta_{\max}$
452 decreases as the temperature range within which the cycle is found is restricted. The competition
453 between these two effects is won by the former at lower values of θ , whereas the latter effect
454 dominates increasingly at higher values of θ .

455 Hence, working fluid selection and careful matching to the available heat source and sink are
456 crucial to the ultimate performance of these systems, as is the design of the heat exchangers required
457 to operate over the small temperature differences, component (pumps, turbines, etc.) performance
458 and materials compatibility. Conventional ORC systems [48, 49] are relatively established and
459 commercially available (typically, from a few hundred kW to a few MW). GE and Pratt & Whitney
460 have entered the waste heat market and systems have been in operation successfully for many years.

Capital costs are plant size dependent, but amount approximately to £1.5–4/W (£15–35/MWh over 25 years; ~4000–4500 hr/yr) with 10–20 years for payback. This is a conservative estimate, with manufacturers stating costs around the £1–3/W mark and payback periods down to 3–5 years [50–52]. These figures can be compared with the £100/MWh used indicatively in Section 2.3. In addition, operational and maintenance costs of about £5–10/MWh are expected. Referring to Table 1, standard operation from 100–300 °C heat gives $\eta_{th} = 8\text{--}20\%$ and $\eta_{ex} = 25\text{--}45\%$. SC-ORCs [49, 53, 54] can reach $\eta_{th} = 10\text{--}25\%$ and $\eta_{ex} = 30\text{--}50\%$ over the same temperature range, but the high pressures result in higher LEC of £25–40/MWh over a 20-year life.

For an ammonia-water Kalina system operating between ~500 °C and 70–100 °C, a η_{th} of 30–35% and corresponding η_{ex} of 50–60% have been predicted [55], while a low-temperature (90–150 °C) geothermal heat-powered plant is now capable of 15/35% [56]. Typically [57–59], we would expect to operate with heat in the low-to-medium 100–200 °C range and 10–20/40–50% efficiencies. Special materials are needed to deal with corrosion and added components lead to increased system complexity. Still, capital investment is modest at £1.5–2.5/W (£15–25/MWh over 25 years) with an 8–18 year payback depending on plant size, but higher operational and maintenance costs are expected than for the ORC which is more common and generally better known.

4.2. Two-phase thermofluidic oscillators

Thermofluidic oscillators (TFOs) include devices such as thermoacoustic engines [60–62], dry free-liquid-piston (Fluidyne) engines and free-piston Stirling engines [63–68], pulse-jets and pulse-tubes [69–72]. These devices are not expected to play a crucial role in the short-term, except perhaps in niche areas, as they have not yet emerged from their development stages. Nevertheless, they are particularly well-suited to the conversion of low-grade heat and hence of interest to the present discussion, also as a benchmark for the rest of the waste heat technologies. In effect TFOs exchange construction simplicity for operation simplicity. They consist of a network of interconnected chambers and tubes, usually with few mechanical moving parts, and sometimes with a liquid piston in place of a mechanical displacer. Within this very simple layout fluids are subjected to complex time-varying flow and heat transfer processes, driven by the working fluid as it undergoes a thermodynamic cycle. TFOs have many dynamic similarities with analogue electronic oscillator circuits, and thus, electrical analogies have been used to predict approximate stability/instability criteria and to estimate first order heat and work flows, and efficiencies (e.g. [60, 62, 69]). Their

complicated operating nature has meant that analysis and design has proved challenging, but modern computational methods, rapid prototyping techniques, advances in materials and working fluids are allowing significant progress to be made. Two-phase thermofluidic oscillators, if designed properly, can have advantages over gas cycle equivalents because phase change allows smaller surface areas (A_{hx}) and temperature differences (ΔT) to drive the heat supply/removal ($\dot{Q}$) required by the cycle. This conclusion arises from the higher heat transfer coefficients (h) associated with phase change (by orders of magnitude) relative to that of forced convection between a gas a solid surface, $\dot{Q} = hA_{\text{hx}}\Delta T$. Smaller surface areas lead to compact heat exchangers, with simpler designs not requiring the extensive use of fins. Since heat exchangers are the most expensive components of these devices, this has a great effect on reducing the overall cost.

A promising low-grade heat conversion technology that has attracted attention recently as a result of potential reliability advantages as well as reduced capital and maintenance costs, on account of its few moving parts relative to mechanical heat engines, is the NIFTE as proposed in Refs. [73, 74]. The NIFTE is as a two-phase TFO in which persistent and reliable thermodynamic oscillations are generated and sustained by external temperature differences ΔT_e . These oscillations are driven by and give rise to heat and fluid flows, which involve the evaporation and condensation of the working fluid. The NIFTE can produce useful *hydraulic* work for fluid pumping, heating and/or cooling and niche power generation applications; in a variety of solar thermal and energy recovery settings, and in combined heat and power/pumping schemes. It has been demonstrated as being capable of operating across ΔT_e between a heat source and sink down to 30 K. At these low temperatures, $\eta_{\text{ex}} = 5\%$ has been reported [73, 74], while projections from recent modelling studies [75–77] indicate that, with careful design, the potential exists for considerable improvements to be made, with operation possible at ΔT_e as low as 10 K. Performance characteristics are summarised in Table 1, the main conclusion being that there is not a great deal of difference between the various options *per unit cost*. It is emphasised that important a key indicator of performance for these waste heat conversion systems is that of power per unit cost.

5. Further discussion and conclusions

It is acknowledged that the Government has shown sensitivity towards energy issues [1, 4] and made noteworthy steps in a variety of directions over the last decade [26, 46, 78]. This has certainly been supported (in some cases driven) by the sense of purpose that permeates public discourse on these matters and the public's desire for decisive action(s) to be taken. Interestingly, the general consensus that has been established has arisen from a diverse range of environmental, health, security and other motives discussed in Section 1. However, Government and industry have yet to embrace and to commit firmly and consistently to a specific energy solution [30]. The industrial sector alone is a ~30% contributor to all primary energy use (with transport at 37% and domestic use at 28%) [1], and also a ~60% contributor to all emissions (the transport sector is at 20–22% and the residential sector at 14%) [4]. Instead, the *status quo* has been to keep the discussion concerning the multitude of energy options alive and to drift by uncertainty or inaction towards a diverse, but unknown future energy landscape. While keeping the majority of stakeholders with their diverse interests engaged, in the long term this strategy may prove problematic.

Though energy diversity and decentralisation are desirable and will emerge naturally to some extent led by end-users and market forces, they cannot be relied upon for the bulk of the change that is required if a sustainable energy future is to be attained. A shift is required in which the Government must lead the way with a careful mix of incentives and taxation, including breaks where necessary. The cost of power from alternative energy is expected to become competitive to that from fossil fuel sources soon. Investment in R&D and embracing any technology on a large scale will shorten this timescale. And, although technical improvements are possible, many technologies are mature and ready to be implemented. At this stage progress is being held up by an inability to decide on a particular (mix) of energy solution(s) and to take action, perhaps because the ultimate differences between competing technologies are small and of the order of their estimated potential and cost [21, 22, 29]. Considering the time-lag required by the EPC process, a coherent energy vision based on sound techno-economic principles must be defined and offered to the public for consultation soon if the ambitious targets we have set ourselves are to be met.

544 Figures

Figure 1: (a) UK production and consumption of primary fuels in 2009. Includes non-energy use of petroleum and gas. Differences between consumption and production are made up by foreign trade, marine bunkers and stock changes. (b) UK energy consumption of breakdown in 2009. Taken from Ref. [1]

545 (1) Includes services and agricultural sectors.

546 (2) Includes coal, manufactured fuels, biomass etc.

Figure 2: (a) Envisaged contributions of various strategies towards a global reduction of CO₂ emissions; taken from Ref. [5]. (b) UK GHG and CO₂ emission history from 1980 to 2010, with progress towards the Kyoto budget for total GHG emissions and the UK Government first Carbon budget (2008–2012)

Figure 3: (a) The United Nations' Human Development Index (HDI) as a function of the electricity use per capita in 60 selected countries in 1997; taken from Ref. [12]. (b) HDI as a function of CO₂ emissions in 2005; taken from Ref. [13]

Figure 4: Five plans for future energy supply in the UK proposed by MacKay; taken from Ref. [17]

Figure 5: (a) US-based LEC (light blue) with fuel price sensitivity (dark blue) study by Lazard in 2008 [18]. Darkened areas in horizontal bars represent low end and high end levelised cost of energy corresponding with $\pm 25\%$ fuel price fluctuations. (b) US- and (c) EU-based LEC and predicted cost evolution (right); study by EER in 2010 [19]

(a) Low end represents single-axis tracking crystalline. High end represents fixed installation.

(b) Represents a leading solar crystalline company's targeted implied levelised cost of energy in 2010, assuming a total system cost of \$5.00 per watt. Company guidance for 2012 total system cost of \$4.00 per watt would imply a levelised cost of energy of \$90 per MWh.

(c) Represents the leading thin-film company's targeted implied levelised cost of energy in 2010, assuming a total system cost of \$2.75 per watt. Company guidance for 2012 total system cost of \$2.00 per watt would imply a levelised cost of energy of \$62 per MWh.

(d) Low end represents solar tower. High end represents solar trough.

(e) Represents retrofit cost of coal plant.

(f) Estimates per National Action Plan for Energy Efficiency; actual cost for various initiatives varies widely.

(g) High end incorporates 90% carbon capture and compression (CCC).

(h) Does not reflect potential economic impact of federal loan guarantees or other subsidies.

(i) Based on advanced supercritical pulverized coal. High end incorporates 90% CCC (see Point (g)).

Figure 6: (a) UK LEC (p/kWh) for various electricity technologies (legend from left); taken from Ref. [21]. (b) Predicted LEC (£/MWh = 0.1 p/kWh) evolution in the UK; taken from Ref. [22]. Levelised costs for the main technologies under different project start dates and FOAK/NOAK (first-of-a-kind/nth-of-a-kind) status

Figure 7: (a) GHG emission comparison for pulverised coal (PC), natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) power plants with and without CCS, and renewables (offshore wind and solar thermal electricity). (b) LEC for different fuel price scenarios for PC, NGCC and IGCC power plants, both with and without CCS, and comparison with renewables in Germany. CCS has a CO_2 capture rate of 88% for post- and pre-combustion and of 99.5% for oxyfuel combustion. Taken from Ref. [28]

Figure 8: (a) CSP and PV efficiency comparison. (b) CSP and PV air and water usage. Taken from Ref. [19]

Figure 9: (a) Basic steam cycle CHP scheme and comparison with 'best CCGT' pumped heat. (b) High-efficiency cycles for both CHP and pumped heat

Figure 10: (a) Waste heat supply stream matching: subcritical and supercritical ORC, and Kalina cycle. (b) Waste heat supply and removal stream matching: subcritical ORC and two-phase TFO cycle

(a)

(b)

Figure 11: (a) Effect of heat source cooling and sink heating on maximum cycle efficiency with $T_{\text{cold,in}} = 25 \text{ }^{\circ}\text{C}$. (b) Effect of both heat source cooling and sink heating on maximum cycle power with $T_{\text{cold,in}} = 25 \text{ }^{\circ}\text{C}$

Figure Captions

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608 **Tables**Table 1: Comparison of typical performance characteristics of waste heat technologies (η_{ex} based on Carnot)

Technology	η_{th} [%]	η_{ex} [%]	$T_{\text{hot,in}}^*$ [°C]	Relative Cost
Organic Rankine Cycles (ORC) [48, 49]	8–20	25–45	100–300	Intermediate
Supercritical (SC-) ORC [49, 53, 54]	10–25	30–50	100–300	High
Kalina Cycles [55–59]	10–20	40–50	100–200	Intermediate
Thermofluidic oscillators (TFO) [73–77]	1–5	5–20	30–150	Low

*Note: With $T_{\text{cold,in}}$ at 10–30 °C

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