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Assessing the sustainability of the UK society using thermodynamic concepts: Part 2

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ABSTRACT

By building on the first part of our analysis, this second part attempts to provide a further understanding of the UK society's metabolism, its impact and offer policy suggestions that could promote a shift towards sustainability. The methodologies employed in this second part include Exergy Analysis (EA) and Extended Exergy Analysis (EEA). Exergy inputs and outputs amounted to 17423.9 and 11888.7 PJ, respectively, with energy carries, mainly fossil fuels, being both the predominant inputs (15597.1 PJ) and outputs (5147.1 PJ). Exergy consumption and efficiency for various economic sectors and subsectors have been calculated with the residential and service sector showing the lowest exergy conversion efficiencies (11.2% and 12.3%, respectively) while certain industrial subsectors, such as the aluminium and iron/steel industries showed the highest exergy conversion factors (67.0 and 62.1%). Extended exergy efficiencies were somewhat different owing to the different calculation procedure. Extended exergy efficiencies were 91.4% for the extraction sector, 38.9% for the conversion sector, 49.1% for the agriculture sector, 31.5% for the transportation sector, 38.6% for the industrial sector and 80.0% for the tertiary sector.

Contents

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1. Introduction

Exergy (or available energy) is a thermodynamic property of a system that has been widely used by engineers to study and improve the efficiency of chemical and thermal processes. Even though this concept has a long history stemming from the work of S. Carnot and W. Gibbs, the term was only coined in the mid-1950s by Z. Rant. Over the past years exergy has also gained popularity amongst engineers and ecologists for the study of complex human systems such as societies and economic sectors [1–3].

Exergy is defined as the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state. Thus, the exergy of an energy form is an entropy free form of energy that can be perceived as a measure of its usefulness or quality or potential to cause change. Exergy, in contrast to energy, is not subject to a conservation law except for ideal or reversible processes but is rather consumed or destroyed due to the unavoidable irreversibilities within any real process. In fact, the concept of exergy derives from a combination of the first two laws of thermodynamics [2] since it is a measure of both the quantity (first law) and the quality (second law) [4] of different energy sources.

Exergy accounting is a useful methodology that can provide insights of the metabolism of a system (materials, energy and in some cases labour and capital) and the effect of the system on the environment using a common denominator. It can thus play a significant role for the provision of policy advice on energy planning and sustainable development as it [4]:

- can address the impact of energy utilisation on the environment;
- is ideal for the design and analysis of energy systems as its methodology combines the conservation of mass and energy with the second law of thermodynamics;
- quantifies waste and energy losses so it can provide important information for more efficient resource use.

Central to exergy analysis is the concept of exergy efficiency. Generally speaking an increase of exergy efficiency implies a decrease of environmental impact (exergy conversion with fewer losses) and an increase in sustainability (process approaches reversibility) [5].

The most attractive feature of exergy accounting is the fact that it is based on a well-defined and robust methodology that is universally accepted and has been used in a wealth of case studies. Exergy can be obtained from the laws of thermodynamics, which allows precise measurement while it can be applied universally to assess the degradation of all possible physical processes [6]. Another strong point is its ability to detect the irreversibilities in a production chain but on the other hand it fails to provide any information about their causes [7].

Exergy is only defined subject to a reference environment and a key criticism of exergy analysis revolves around the definition of a meaningful reference state (environment). The main problem, as perceived by critics, is that the choice of the reference state affects the outcome of an exergy analysis given that different reference states for the same study system will inevitably produce different results. This introduces a sense of relativity in every exergy analysis [7]. Additionally, the reference state is usually considered static (i.e. constant temperature, pressure, chemical properties, etc.) in order to assist the calculations. However the static reference state is just a convenience that is not encountered in natural systems. Nevertheless, certain attempts have been made to utilise non-static reference states in the past, e.g. [8].

Three main methodologies for the quantification of exergy consumption/production patterns within economic sectors and the society as a whole have been proposed in the literature: Reistad's, Wall's and Sciubba's

Reistad's	USA [9], OECD/World/non-OECD [10], Saudi Arabia [11–15]
Wall's	China [1], Norway [16], Italy [17], Japan [18]
Sciubba's	Italy [19], Norway [20]

Reistad's approach only quantifies the use of energy carriers within an economy. Wall's approach further quantifies the exergy content of other flows such as metals, minerals, biomass as well as the waste and atmospheric emissions resulting from the economic activity. Sciubba's approach builds on Wall's approach by further considering capital and labour as production factors. Further details on the Wall's and Sciubba's approaches are discussed in the following section.

Eco-exergy is another example of an exergy technique. It has been developed by Jorgensen [3] and has several conceptual differences than the techniques discussed earlier (e.g. different calculation procedure, different reference state). Even though eco-exergy offers potential for similar analyses it has not yet been applied in any comprehensive case study at the national or sectoral level.

2. Methodology

The aim of this study is to apply Wall's and Sciubba's approaches in order to analyse the production and consumption patterns within the UK for the year 2004. Thus, as in the first part of our analysis, the UK (Great Britain and Northern Ireland) is considered as the boundary and exergy is calculated for a number of production activities within the system as well as for some of the main imports and exports. Our analysis supplements an earlier exergy analysis of the UK [21] that only quantified the use of energy carriers (Reistad's approach).

Even though, the underlying philosophy of the Wall and Sciubba approaches are quite similar there are certain differences in their methodologies that should be clarified. The most striking difference stems from their different approach towards calculating the exergy conversion efficiency. In Sciubba's approach only the sectoral output that is actually transferred to other economic sectors is considered useful and is actually accounted for. Wall's approach puts emphasis on the conversion of the exergy input by accounting for all useful output including lighting and space heating that is not actually transferred to other sectors [20]. Hence the discrepancies between the exergy efficiencies found in the first part of our study with those reported in Tables 17–22. All R- and N-flows in these tables are based on calculations presented in Section 3 of this paper.

The Extended Exergy Analysis (EEA) of the UK is included in Section 4 and follows the methodology presented in [19,20]. In particular the UK economic system and its surrounding was divided into nine subsystems (refer below) and flows of resources, products, capital, labour and waste between the aforementioned subsystems were subsequently quantified.

ag	Agriculture and related activities (includes livestock production, fishing, forestry and the food industry)
ex	Extraction (includes fuel and mineral extraction, quarrying, refining and manufacturing of fuel)
co	Conversion (including electricity plants and heat production)
in	Industry (includes various industries and construction but excludes food and energy industry that are accounted for in the agriculture and extraction sectors, respectively)
tr	Transportation
te	Tertiary (includes private and public sector services)
do	Domestic sector
e	Environment
a	Abroad

The relevant flows considered are the following:

R	Resources such as primary and secondary fuels, electricity, ores, etc. (R-flows)
N	Natural resources such as agricultural products, livestock, wood, etc. (N-flows)
P	Products and services (P-flows)
T	Trash fluxes deposited in the environment (waste) (T-flows)
D	Discharges to the environment (atmospheric emissions) (D-flows)
W	Paid work, labour (W-flows)
C	Capital (C-flows)

It is worth mentioning here that these sectors and flows are aggregates of several subsectors and sub-flows that can be found in the official statistics publications. Notations such as Rex,ag which are used throughout our EEA indicates a resource flow from the extraction to the agricultural sector. Following [19,20] the exergetic value of labour (Ew) and capital (Ec) is calculated as

$$\mathrm{Ew} = \frac{n \times \mathrm{Ein}}{\mathrm{ntot}} \tag{1}$$

$$\mathrm{Ec} = \frac{C \times \mathrm{Ein}}{\mathrm{Cref}} \tag{2}$$

Table 1
Lower heating values and exergy factors of the main fuels

	LHVs[a]	Exergy factors[b]
Coal	26.0 GJ/t	1.06
Crude oil	43.4 GJ/t	1.06
Petroleum products	43.6 GJ/t	1.06
Natural gas	35.6 MJ/m^3	1.04
Coke	29.8 GJ/t	1.05
Coke oven gas	16.2 MJ/m^3	1.04
Electricity	–	1
Fuelwood (20% humidity)	10.0 GJ/t	1.11
Landfill and sewage gas	21.0 MJ/m^3	1.13

[a] *Source*: [23,29].
[b] *Source*: [16,24,25].

where Ein is the exergy inflow to the society (sum of extracted and imported exergy minus exported exergy), n is the amount of work-hours from/to a sector, n_{tot} the overall amount of work-hours in the society, C the capital flow from/to a sector and Cref a reference amount of money which in our case study is the "broad money" (M4) [22].

Diverse inputs such as fuels, minerals, biomass, waste as well as labour and capital flows are quantified by using exergy as a common denominator. Exergy values for natural renewable sources (wind, hydro, sun) are calculated on the basis of the electricity generated. Table 1 contains the lower heating values (LHVs) and exergy quality factors of the main fuels that are considered in our study. LHVs were collected from [23] and exergy quality factors from [16,24,25]. In particular the choice of exergy factors for crude oil, petroleum products and natural gas from the study of Norway [16] seems quite reasonable considering that the majority of both UK's and Norway's fuels (crude oil and natural gas) are extracted from the N. Sea so the chemical composition is expected to be quite similar.

Exergy content of food is set equal to the energy content of the contained nutrients. Exergy values for other chemical species are calculated following [24,26] while calculations for certain other inputs/outputs such as igneous rock, glass, metal products, etc. are conducted as designated in [27]. Exergy content of waste streams was set equal to their LHV as a first approximation (refer to [1,24]) given the difficulty of designating an average chemical composition for such a diverse stream. Waste LHVs were calculated averaging relevant data from the PHYLLIS Database [28].

Aggregated results found in the text and in the tables of Section 4 are reported in PJ (10^{15} J). Entries in tables relevant to Section 3 are in J given that some of their content is several orders of magnitude lower than 1 PJ.

3. Exergy analysis

3.1. Renewable energy

The unplanned benefit of solar energy for passive heating and lighting in UK buildings is estimated to be 522 PJ [23]. Even though this figure is very approximate and has never been included in the Department for Trade and Industry's (DTI) energy balance sheets that have been used in this study, it is however indicative of the importance of this ecological service to the UK economy. To appreciate the magnitude of this figure it should be noted that it is approximately equal to the exergy content of the coal mined within the UK (refer to Section 3.3).

Active solar heating on the other hand employs solar collectors predominantly for heating water (domestic hot water systems, swimming pools, etc.). According to [29] for the year 2004 an estimated 0.97 PJ of exergy was consumed. Of these, 0.25 PJ were used in domestic hot water systems, 0.44 PJ for swimming pools and 0.28 PJ for other similar uses (refer also to Table 10). There was also a quite small installed capacity of photovoltaic (8.2 MW) with an overall generation of approximately 0.01 PJ of exergy. Given the approximate nature of the passive solar heating estimates and the negligible value of the photovoltaic input only the active solar heating values will be used for the ensuing sectoral analyses (Sections 3.6.4, 3.7 and 3.8).

According to [23] the UK's offshore wind resources are vast and can provide more than the UK's current electricity demand. The first offshore project started operating in 2003 north of Wales. As of 2004 offshore wind projects produced 0.7 PJ of exergy. All onshore projects were responsible for inputting 6.3 PJ of exergy to UK economy bringing the total exergy from wind power to 7.0 PJ.

Table 2
Exergy content of 15 major harvested crops and livestock (96.8% of total exergy)

Commodities	Exergy (J)	Fraction
Total	4.88E+17	100.0
Wheat	2.22E+17	45.4
Barley	8.61E+16	17.6
Milk, whole, fresh	3.90E+16	8.0
Rapeseed and mustard seed	3.16E+16	6.5
Potatoes	1.82E+16	3.7
Sugar beet	1.63E+16	3.3
Chicken meat	1.20E+16	2.5
Oats	1.02E+16	2.1
Pig meat	9.01E+15	1.8
Bovine meat	8.02E+15	1.6
Pulses, nec	7.24E+15	1.5
Animal fats	3.93E+15	0.8
Sheep and goat meat	3.60E+15	0.7
Bird eggs (incl. hen eggs)	3.40E+15	0.7
Broad beans, horse beans, dry	2.28E+15	0.5

Large-scale hydroelectricity plants with capacities over 5 MWe amounted for most of the hydroelectricity with the majority of the plants located in Scotland and Wales. There was an installed capacity of approximately 1368 MWe (excluding pumped storage stations) for large-scale hydroelectric schemes with 16.7 PJ of exergy actually being produced in 2004. Small-scale hydroelectricity plants (<5 MWe) are mainly used for domestic/farm purposes as well as for local sale to electricity supply companies. In 2004 there was an installed capacity of 136 MWe and these schemes were responsible for generating 10.2 PJ of exergy. Overall exergy production due to hydroelectric schemes amounted to 27.3 PJ of exergy (including pumped storage) with 0.39 PJ being used on works and 26.9 PJ being supplied.

As of 2004 there was only one geothermal scheme operating in the UK, located in Southampton, with its main use being in community heating systems. This scheme provided approximately 0.03 PJ energy (0.01 PJ exergy) [23]. This geothermal source, given its negligible size, is excluded from the ensuing calculations.

3.2. Agricultural production and related activities

In our analysis this sector includes all activities relevant to agriculture, forestry, livestock production, fishing and the food processing industry. Activities falling within the food retail industry have been included in the tertiary sector.

Inputs to this sector include fuels, electricity, minerals, seeds, animal feed and fertilizers. Fuels used were mainly natural gas and petroleum products as well as small amounts of coal and renewable resources (poultry litter, meat and bone, biomass). Renewable energy sources contributed less than 1.5% of the total fuel input in the sector [23].

Exergy values for the major inputs include coal (1.4 PJ), petroleum products (27.6 PJ), natural gas (114.5 PJ), electricity (59.6 PJ), minerals (0.15 PJ—mainly limestone, dolomite, chalk and silica sand), feed and seed (179.0 PJ) and fertilizer (37.8 PJ).

Agricultural, livestock and fishery production for the year 2004 was in the order of 488.0 PJ (62,411 kt approximately) while forests produced 150.5 PJ of wood (8,700,000 and 510,000 green tonnes of softwood and hardwood, respectively) [30]. Agricultural production was calculated based on the analysis of the flows of over 200 agricultural commodities retrieved from the statistical database of the United Nations Food and Agriculture Organisation [31]. Production statistics are calculated for the year 2004 while feed and seed statistics are for the year 2003. Energy content of the different commodities was retrieved from the US Department of Agriculture [32]. The main results are summarised in Tables 2 and 3. Exergy of the food consumed amounted to 52.7% of the production and the net imports.

Mineral statistics were retrieved from [33] and fertilizer statistics from [34]. It should be mentioned that exergy of potash and phosphorus fertilizers is calculated as the equivalent exergy of K_2O and P_2O_5, respectively, and for nitrogen fertilizers as the equivalent exergy of NH_4^+.

Table 3
Exergy content of major food categories, their source and their end use

	Production (J)	Imports (J)	Exports (J)	Feed and seed (J)	Other net uses (J)	Food consumption (J)
Livestock and fish products	8.63E+16	4.51E+16	2.23E+16	5.37E+15	5.49E+15	9.87E+16
Cereals	3.19E+17	8.39E+16	1.04E+17	1.49E+17	3.59E+16	1.14E+17
Fruits and vegetables	1.86E+15	3.47E+16	2.51E+15	1.04E+14	4.51E+15	2.95E+16
Tea, coffee, spices and nuts	3.39E+13	2.14E+16	3.82E+15	0.00E+00	5.46E+15	1.22E+16
Legumes and starchy roots	4.76E+16	5.33E+16	1.30E+16	1.76E+16	6.18E+15	6.42E+16
Oil and oilseeds	3.27E+16	1.62E+17	1.89E+16	7.26E+15	1.06E+17	6.25E+16
Total	4.88E+17	4.00E+17	1.65E+17	1.79E+17	1.63E+17	3.81E+17

Table 4
Exergy balance sheet for the primary energy resources produced within the UK

	Coal		Crude oil		Natural gas	
	Raw data (1000 t)	Exergy (J)	Raw data (1000 t)	Exergy (J)	Raw data (GWh)	Exergy (J)
Production	25,096	6.94E+17	95,374	4.64E+18	1,116,554	4.18E+18
Imports	36,153	1.05E+18	62,516	3.03E+18	133,035	4.98E+17
Exports	−622	−1.99E+16	−65,504	−3.13E+18	−114,111	−4.27E+17
Stock changes	−60	−2.49E+15	−133	−6.61E+15	−6235	−2.33E+16
Energy industry and transformation	57,639	1.63E+18	89,821	4.35E+18	438,670	1.64E+18
Losses	0	0.00E+00	0	0.00E+00	10,690	4.00E+16
Final consumption	2,810	8.77E+16	0	0.00E+00	646,990	2.42E+18
Difference	118	2.93E+15	2,432	1.78E+17	4.36E+04	1.63E+17

Source: [23].

Table 5
Volume and exergy content of the main extracted minerals

Mineral	Raw data (t or m^3)	Exergy (J)
Igneous rock	53,037,000	3.94E+16
Peat (m^3)	1,262,000	1.57E+16
Clays	15,405,000	1.18E+16
Limestone	81,641,000	4.12E+15
Sand and gravel	97,333,000	3.08E+15
Salt	5,800,000	1.42E+15
Dolomite	12,226,000	1.00E+15
Sandstone	18,844,000	5.96E+14
Chalk	7,997,000	4.03E+14
Potash	912,000	2.37E+14
Silica sand	5,011,000	1.58E+14
Gypsum	1,686,000	8.42E+13
Fluorspar	50,000	7.30E+12
Iron ore	275	1.02E+12
Barytes	61,000	8.89E+11
Lead ore	500	5.62E+11
Talc	4,000	3.85E+11
Total		7.79E+16

Source: [33].

3.3. Primary fuel and mineral extraction

Large quantities of primary fuels such as coal, crude oil and natural gas were extracted in the UK during 2004. Primary fossil fuel and mineral extraction statistics are included in Tables 4 and 5 and were retrieved from [23,29,33].

Inland coal production amounted to 694.4 PJ which was almost equally divided between deep and opencast mines. Specifically there were eight major deep mines and four smaller ones with one closing down in January 2004 [23]. Surface mine output in the UK has declined over the past years as a result of the difficulty in obtaining necessary planning permissions [23]. As a result there has been an increasing trend towards importing coal. Coal imports amounted to 36,153,000 t with an equivalent exergy of 1048.2 PJ.

Crude oil production in 2004 amounted to 95,374,000 t with equivalent exergy of 4639.8 PJ. Imports amounted to 3027.3 PJ and exports to 3129.4 PJ. Natural gas production amounted to 4180.4 PJ of exergy with imports and exports reaching 498.1 and 427.2 PJ, respectively, making the UK a net natural gas importer.

3.4. Mineral extraction

Other major extracted material included igneous rock, clay, dolomite and limestone. While the volume of the extracted minerals was quite high, the similar chemical composition of these minerals to the reference environment meant low chemical exergies and resulted in their relatively low overall exergy content of 77.9 PJ (Table 5). Mineral extraction statistics were retrieved from [33].

3.5. Electricity generation

Electricity in the UK is mainly produced through thermal processes. The overall electricity generated from thermal processes was 1423.1 PJ (of which 28.4 PJ came from thermal renewables such as biofuels and non-biodegradable wastes) compared with just 34.3 PJ produced from non-thermal renewables such as hydro and wind (2.4% of the total). Data for electricity production within the UK for the year 2004 were retrieved from [23] and are summarised in Table 6.

Exergies for coal, oil, gas, thermal renewables and other thermal sources used were equivalent to the chemical exergy of the input fuels that were actually used. Given that nuclear fuel

Table 6
Electricity fuel use, generation and supply for thermal processes

Fuel	Fuel used	Generation	Used on works	Supplied	Other losses	Efficiency
Coal						
Raw data (GWh)	364,010	131,822	6100	125,722	–	
Exergy (J)	1.39E+18	4.75E+17	2.20E+16	4.53E+17	–	0.342
Petr. products						
Raw data (GWh)	13,041	4873	567	4306	–	
Exergy (J)	4.98E+16	1.75E+16	2.04E+15	1.55E+16	–	0.353
Gas						
Raw data (GWh)	340,517	157,338	3339	153,999	–	
Exergy (J)	1.27E+18	5.66E+17	1.20E+16	5.54E+17	–	0.444
Nuclear						
Raw data (GWh)	211,248	79,999	6317	73,682	–	
Exergy (J)	7.60E+17	2.88E+17	2.27E+16	2.65E+17	–	0.379
Renewables[a]						
Raw data (GWh)	32,383	7878	511	7368	–	
Exergy (J)	1.09E+17	2.84E+16	1.84E+15	2.65E+16	–	0.260
Other thermal[b]						
Raw data (GWh)	18,284	3878	140	3738	–	
Exergy (J)	6.45E+16	1.40E+16	5.04E+14	1.35E+16	–	0.216
Non-thermal renewables[c]						
Raw data (GWh)	9518	9518	107	9410	–	
Exergy (J)	3.43E+16	3.43E+16	3.85E+14	3.39E+16	–	1.000
Total						
Raw data (GWh)	989,001	395,306	17,081	378,225	34,225	
Exergy (J)	3.68E+18	1.42E+18	6.15E+16	1.36E+18	1.23E+17	0.386

Source: [23].
[a] Includes biofuels and non-biodegradable wastes.
[b] Includes coke oven gas, blast furnace gas and waste products from chemical processes.
[c] Includes hydro, wind and solar photovoltaics.

Table 7
Outputs of the iron and steel industry

Item	Raw data (t)	Exergy (J)
Pig iron	10,179,600	6.69E+16
Crude steel	957,100	6.39E+15
Steel alloys	12,806,600	8.46E+16
Total		1.58E+17

Source: [33,35].

mass figures are confidential the exergy input of nuclear fuel was considered equal to the equivalent electricity with such figures being available in [23]. All other exergies in Table 6 were calculated for electricity.

Exergy efficiencies were calculated on the basis of total electricity generated and not of electricity actually supplied to end users with the overall exergy efficiency of the conversion sector being at the order of 38.6%. If electricity used on works and other energy losses through transmission through the grid the overall exergy efficiency is even lower and is in the order of 33.6%.

3.6. Industry

3.6.1. Iron and steel industry

The iron and steel industry constitutes one of the most energy and resource intensive sectors of the UK economy. For this reason it has been analysed in depth. The exergy of all inputs totalled 254.4 PJ while the exergy of the output totalled 157.9 PJ. This amounts to an efficiency of 62.1%. Tables 7 and 8 summarise the main inputs and outputs of the sector. Raw data were retrieved from [33,35].

3.6.2. Aluminium industry

Fuel exergy input amounted to 11.9 PJ (0.04 PJ coal, 1.0 PJ petroleum products, 5.5 PJ natural gas, 5.4 PJ electricity). Material input included 14.6 PJ of scrap (447.9 Mt) (data for 2001) and 1.0 PJ of aluminium compounds and bauxite (505.8 Mt aluminium compounds, 0.55 Mt bauxite).

Aluminium production amounted to 11.7 PJ (359.6 Mt) from primary aluminium production and 6.7 PJ (205.4 Mt) from secondary aluminium production. Thus the overall exergy efficiency is at the order of 67.0%. Raw data were retrieved from [33,36–38].

Table 8
Inputs to the iron and steel industry

Item	Raw data (t or J)	Exergy (J)
Iron ore		
Home produced	500	1.85E+12
Imported	16,013,000	6.69E+16
Iron and steel scrap	5,037,000	3.06E+16
Pig iron	10,010,000	6.58E+16
Alloy metals		
Ni	16,800	6.66E+13
Mo	2100	1.60E+13
V	100	1.42E+12
Cr	53,900	5.64E+14
Ferro alloys		
FeMn	95,500	9.84E+14
FeSiMn	23,100	2.89E+14
FeSi	37,300	8.50E+14
Dolomite	262,600	2.15E+13
Limestone	2,067,900	1.04E+14
Lime	583,800	2.95E+13
Zn (galvanising)	52,300	2.71E+14
Sn (tinplating)	2600	1.19E+13
Manufactured fuels[a]	2.94E+16	3.05E+16
Petroleum	1.47E+15	1.55E+15
Natural gas	3.50E+16	3.64E+16
Electricity	1.95E+16	1.95E+16
Total		2.54E+17

Source: [33,35].
[a] Includes oven coke, coke breeze, coke oven gas and blast furnace gas.

Table 9
Exergy input, output and efficiencies for different activities and fuels within the other industry sector

	Exergy consumption (J)	Consumption ratio (%)	Exergy efficiency (%)	Exergy output (J)
High temperature process	5.51E+15	2.2	44.7	2.46E+15
Coal	4.44E+14	0.2	33.8	1.50E+14
Petr. products	7.10E+14	0.3	39.8	2.83E+14
Natural gas	4.35E+15	1.7	46.6	2.03E+15
Low/medium temperature process	1.01E+17	39.8	20.2	2.04E+16
Coal	5.17E+15	2.0	16.6	8.60E+14
Petr. products	1.22E+16	4.8	18.0	2.20E+15
Natural gas	4.88E+16	19.2	18.5	9.04E+15
Electricity	3.49E+16	13.7	23.9	8.33E+15
Lighting	1.29E+16	5.1	9.4	1.21E+15
Incandescent	8.35E+15	3.3	4.5	3.76E+14
Fluorescent	4.50E+15	1.8	18.5	8.32E+14
Space heating	1.01E+17	39.9	6.4	6.44E+15
Petr. products	1.23E+16	4.8	5.7	6.98E+14
Natural gas	4.88E+16	19.2	6.4	3.13E+15
Electricity	4.01E+16	15.8	6.5	2.61E+15
Motors	7.35E+15	2.9	50	3.68E+15
Petr. products	1.22E+15	0.5	50	6.09E+14
Electricity	6.14E+15	2.4	50	3.07E+15
Other	2.58E+16	10.2	6.3	1.63E+15
Natural gas	2.02E+16	8.0	6.1	1.23E+15
Electricity	5.61E+15	2.2	7.1	3.98E+14
Total	2.54E+17	100	14.1	3.58E+16

Table 10
Exergy input, output and efficiencies for different activities and fuels within the domestic sector

	Exergy consumption (J)	Consumption ratio (%)	Exergy efficiency (%)	Exergy output (J)
Space heating	1.28E+18	61.1	6.3	8.11E+16
Solid fuel[a]	3.00E+16	1.4	5.1	1.53E+15
Petr. products	1.10E+17	5.3	5.7	6.27E+15
Natural gas	1.06E+18	50.6	6.4	6.83E+16
Electricity	7.21E+16	3.4	6.5	4.69E+15
Wood	7.06E+15	0.3	4.3	3.07E+14
Water heating	4.92E+17	23.4	6.9	3.39E+16
Solid fuel[a]	1.39E+16	0.7	2.6	3.57E+14
Petr. products	3.39E+16	1.6	3.5	1.18E+15
Natural gas	3.91E+17	18.6	7.2	2.81E+16
Electricity	5.23E+16	2.5	8.1	4.25E+15
Solar	9.73E+14	0.0	8.0	7.81E+13
Cooking	5.80E+16	2.8	14.5	8.42E+15
Solid fuel[a]	4.89E+14	0.0	4.5	2.22E+13
Petr. products	6.80E+14	0.0	5.9	4.04E+13
Natural gas	2.98E+16	1.4	11.1	3.32E+15
Electricity	2.46E+16	1.2	19.8	4.89E+15
Wood	2.42E+15	0.1	6.5	1.58E+14
Lighting and appliances (electricity)	2.67E+17	12.7	41.6	1.11E+17
Lighting	6.44E+16	3.1		0.00E+00
Incandescent	4.18E+16	2.0	4.5	1.88E+15
Fluorescent	2.25E+16	1.1	18.5	4.17E+15
Refrigeration	5.45E+16	2.6	0.9	5.01E+14
Recreation[b]	6.24E+16	3.0	75.0	4.68E+16
Wet	4.66E+16	2.2	70.0	3.26E+16
Others	3.93E+16	1.9	64.0	2.51E+16
Total	2.10E+18	100.0	11.2	2.34E+17

[a] Assumed coal.
[b] Assumed TV and computer.

3.6.3. Wood, paper and pulp industry

Fuel input to the wood, paper and pulp industry was in the order of 98.1 PJ exergy including 4.3 PJ from coal, 26.8 PJ from petroleum products, 43.5 PJ from natural gas, 23.2 PJ from electricity and 0.3 PJ from heat. Other raw material included 128.8 PJ of UK grown wood (7,364,000 green tonnes softwood and 515,000 green tonnes of softwood), 245.8 PJ of imported sawn wood, 27.8 PJ of imported pulp and 65.5 PJ of recirculated paper. Outputs included 78.3 PJ of sawnwood, 85.0 PJ of wood-based panels, 0.5 PJ of exported pulp and 106.1 PJ of paper and paper products. Thus the exergy efficiency was 47.6%.

Intermediate products (e.g. pulp and sawmill products) were excluded from this study in order to avoid double counting. Relevant raw data and conversion factors were retrieved from [30,31,36,39,40]. Energy contents of wood and timber products (including paper) was retrieved from [28] and the exergy content of pulp/paper products (17 PJ/Mt) from [16,41].

3.6.4. Other industry

In our study this subsector included industrial activities such as textiles, wearing apparel, leather, fabricated metal products, machinery/equipment, office machinery/computers, electrical machinery/equipment, transport equipment, furniture and recycling.

Exergy inputs amounted to 253.8 PJ of which 5.6 PJ came from coal, 26.5 PJ from petroleum products, 122.2 PJ from natural gas and 99.5 PJ from electricity. The majority of this input was used for high/medium/low temperature processes, lighting, space heating, and mechanical energy. The overall efficiency was calculated to be of the order of 14.1% and thus the total output was 35.8 PJ (Table 9). Efficiencies for the different end uses were calculated following [10,25,42]. More details are given in the ensuing sections.

We should note here that the raw data contain separately the overall consumption by fuel and by end use [36]. In our study we attempt to make a breakdown of fuels by end use. Albeit our analysis is based on realistic assumptions the end result is quite uncertain and should be treated with caution.

3.7. Residences

The domestic sector consumed 2101.6 PJ of exergy in 2004 which was the second highest energy consumption by sector in the UK for that year. Exergy inputs included 32.5 PJ from coal, 11.7 PJ from manufactured fuel, 1484.2 PJ from natural gas, 415.9 PJ from electricity, 0.5 PJ from heat, 144.9 PJ from petroleum products and 11.8 PJ from renewables. Of these renewables 9.5 PJ came from fuel wood, 1.0 PJ from solar sources and 1.4 PJ from waste. Exergy from heat and waste is not included in this ensuing sectoral analysis.

Exergy in the domestic sector is used for space heating, water heating, lighting and appliances. The exergy efficiency was calculated to be 11.2% so the total exergy output was 234.5 PJ. It is worth mentioning that the overall energy input (excl. heat and waste), energy efficiency and energy output of that sector was 2031.4 PJ, 84.2% and 1710.9 PJ, respectively.

Table 10 summarises the exergy consumption by the aforementioned activities as well as their overall significance (fraction) and efficiencies. Raw data were obtained from [23] while most exergy efficiencies were calculated following [25]. Energy efficiencies for certain activities and fuels such as cooking (solid fuel and petroleum products) and water heating (solid fuel and petroleum products) were retrieved from [10].

3.8. Services, commerce and public administration

The tertiary sector contains diverse economic activities ranging from commercial offices, education, government, health, hotels/catering, retail, sport and leisure to warehouses among others.

Table 11
Exergy input, output and efficiencies for different activities and fuels within the tertiary sector

	Exergy consumption (J)	Consumption ratio (%)	Exergy efficiency (%)	Exergy output (J)
Space heating	4.02E+17	49.8	6.4	2.56E+16
Petr. products	3.94E+16	4.9	5.7	2.24E+15
Natural gas	3.13E+17	38.8	6.4	2.01E+16
Electricity	4.93E+16	6.1	6.5	3.21E+15
Water heating	7.59E+16	9.4	7.0	5.29E+15
Petr. products	7.19E+15	0.9	3.5	2.49E+14
Natural gas	5.70E+16	7.1	7.2	4.09E+15
Electricity	1.17E+16	1.4	8.1	9.47E+14
Catering[a]	8.39E+16	10.4	15.7	1.32E+16
Petr. products	4.20E+15	0.5	5.9	2.50E+14
Natural gas	3.34E+16	4.1	11.1	3.72E+15
Electricity	4.63E+16	5.7	19.8	9.19E+15
Computing (electricity)	1.89E+16	2.3	75.0	1.42E+16
Lighting (electricity)	1.38E+17	17.1	9.4	1.30E+16
Incandescent	8.97E+16	11.1	4.5	4.04E+15
Fluorescent	4.83E+16	6.0	18.5	8.93E+15
Cooling and ventilation	3.37E+16	4.2	2.2	7.40E+14
Refrigeration (petr. products)	1.86E+14	0.0	0.3	5.28E+11
Refrigeration (natural gas)	1.47E+15	0.2	0.9	1.27E+13
Refrigeration (electricity)	2.13E+16	2.6	0.9	1.96E+14
Air conditioning (electricity)	1.07E+16	1.3	5.0	5.30E+14
Other	5.42E+16	6.7	50.2	2.72E+16
Mechanical work (petr. products)	6.12E+15	0.8	50.0	3.06E+15
Mechanical work (natural gas)	4.74E+16	5.9	50.0	2.37E+16
Appliances (electricity)	7.14E+14	0.1	64.0	4.57E+14
Total	8.06E+17	100.0	12.3	9.91E+16

[a] Assumed cooking.

Exergy input in the tertiary sector was 814.9 PJ of which 0.5 PJ came from coal, 410.8 PJ from natural gas, 341.7 PJ from electricity, 3.8 PJ from heat, 51.5 PJ from petroleum products and 6.6 PJ from renewables. Of these renewables 2.5 PJ came from sewage gas and 4.1 PJ from waste. Energy from heat and renewables ($\approx$1% of the total) is not included in the raw data reported in [36] and are excluded from the following in depth analysis of exergy consumption within the sector.

The exergy efficiency was calculated to be 12.3% so the total exergy output was 99.1 PJ. The overall energy input (excl. heat and renewables), energy efficiency and energy output of that sector was 788.8 PJ, 65.8% and 516.9 PJ, respectively.

Table 11 summarises the main exergy conversion activities within the sector. The exergy efficiencies were calculated according to [25] following the same assumptions as for the domestic sector.

3.9. Transport

The transport sector constituted the most important final exergy consumption sector. Total exergy consumption was in the order of 2558.9 PJ of which 2549.2 PJ came from petroleum products and 9.7 PJ from electricity.

Transportation modes tend to have almost the same energy and exergy efficiencies. The effective operating efficiencies calculated according to [21] are used in this study and the main results are included in Table 12. Given that the overall efficiency of the sector was 19.7% the final exergy output was 503.4 PJ.

3.10. Atmospheric pollution and waste

In our calculations only the chemical exergy of the atmospheric pollutants was considered and was calculated as the product of the quantity of a certain pollutant emitted in a year (in mol) and its chemical exergy (in J/mol). Pollutants that were considered include CO_2, CH_4, N_2O, NH_3, SO_2, HCl, CO, C_6H_6, NOx (assumed as NO), HF, As, Cd, Ca, Cr, Cu, Pb, Mg, Hg, Ni, K, Se, Na, V and Zn. The exergy of particulate matter (PM) and non-methane volatile organic compounds (NMVOCs), apart from C_6H_6, was not quantified due to lack of information on their composition. According to our results (Table 13) the exergy of atmospheric emissions is almost uniformly divided between the different sectors with the conver-

Table 12
Exergy input, output and efficiencies for the transport sector

Mode	Energy consumption (J)	Exergy consumption (J)	Fraction	Exergy efficiency	Exergy output (J)
Road	1.77E+18	1.87E+18	73.2	17	3.19E+17
Air	5.51E+17	5.84E+17	22.8	27	1.58E+17
Water	5.00E+16	5.30E+16	2.1	25	1.33E+16
Rail	4.60E+16	4.82E+16	1.9	29	1.40E+16
Petroleum	3.63E+16	3.85E+16			
Electricity	9.72E+15	9.72E+15			
Total	2.41E+18	2.56E+18	100.00	19.7	5.03E+17

Source: [21,23].

Table 13
Atmospheric emissions by sector

	Ag (J)	Co (J)	Do (J)	Ex (J)	In (J)	Te (J)	Tr (J)	Total (J)
CO_2	2.52E+15	7.74E+16	3.98E+16	1.88E+16	4.57E+16	1.19E+16	5.81E+16	2.54E+17
CH_4	4.67E+16	1.78E+14	1.44E+15	2.72E+16	8.53E+14	5.11E+16	4.89E+14	1.28E+17
N_2O	2.12E+14	8.05E+12	1.20E+12	2.29E+12	4.25E+13	1.03E+13	4.29E+13	3.20E+14
NH_3	6.04E+15	5.36E+11	4.45E+13	3.35E+12	1.05E+14	2.56E+14	2.11E+14	6.66E+15
SO_2	2.03E+13	2.43E+15	1.61E+14	3.88E+14	8.41E+14	2.41E+13	2.16E+14	4.08E+15
HCl	4.87E+10	4.61E+13	7.40E+12	8.34E+10	1.55E+13	5.61E+11	6.95E+09	6.96E+13
CO	4.30E+14	6.64E+14	5.00E+15	3.44E+14	7.84E+15	3.38E+14	1.42E+16	2.88E+16
C_6H_6	1.31E+12	3.81E+11	2.32E+14	7.32E+13	8.93E+13	4.42E+13	1.71E+14	6.12E+14
NOx[a]	2.59E+14	9.82E+12	1.47E+12	2.79E+12	5.18E+13	1.22E+13	5.27E+13	3.90E+14
HF	4.00E+09	1.15E+13	4.88E+11	2.10E+12	4.75E+12	4.00E+10		1.89E+13
Metals	1.23E+12	1.01E+13	1.36E+13	8.87E+12	5.75E+13	1.02E+13	1.04E+13	1.12E+14
Total	5.62E+16	8.07E+16	4.67E+16	4.69E+16	5.56E+16	6.37E+16	7.35E+16	4.23E+17
Fraction	13.3	19.1	11.0	11.1	13.1	15.1	17.4	100.0

Source: [43].
[a] Assumed NO.

Table 14
Work-hour allocation and extended exergy equivalent for different sectors

Sector	Work-hours (h)	Fraction (%)	Extended exergy (J)
Ag	1.76E+09	3.7	440.1
Ex	2.10E+08	0.4	52.5
Co	1.32E+08	0.3	33.0
In	9.44E+09	19.8	2359.2
Tr	1.42E+09	3.0	353.6
Te	3.46E+10	72.8	8650.5
Total	4.76E+10	100	

Source: [46].

sion and transport sectors being slightly more significant polluters with 19.1% and 17.4% of the total exergy emissions. Data for atmospheric emissions and sectoral breakdown was collected from [43].

As has already been mentioned the exergy content of the diverse waste streams was set equal to the LHV as a first approximation. The relevant LHVs were calculated from data contained in the PHYLLIS Database [28]. Aggregated waste data was collected from [44] which was the data reported to the EU as a requirement of the Waste Framework Directive. Sectoral breakdown of the waste arising in 2004 was provided by DEFRA after personal communication by the authors. We should note here that a certain level of double counting is inevitable as a result of the reporting format required by the European Commission. In our calculations there was a conscious attempt to minimise this double counting and as such our results should be treated with caution.

The overall exergy content of the waste was approximately 1050.0 PJ of which 122.4 PJ were produced by the agricultural, 28.0 PJ by the extraction sector, 228.5 PJ by the industrial, 416.9 PJ by the tertiary, 6.8 PJ by the conversion and 247.4 PJ by the domestic sector. Of this waste (1050.0 PJ) approximately 350.2 PJ (33.3%) was recycled, 39.6 PJ (3.8%) was burnt for energy recovery, 27.6 PJ (2.6%) was incinerated on land while the rest 632.7 PJ (60.3%) was disposed to the environment by either being deposited on land or being treated and released in water bodies.

Table 15
Capital input and its extended exergy equivalent for different sectors

	Production (M£)	Capital disposals (M£)	Subsidies (M£)	Cin (M£)	Extended exergy (PJ)
Ag	179928.4	669.0	103.0	180700.4	1821.8
Ex	120902.6	805.5		121708.1	1227.1
Co	30914.7	327.5		31242.2	315.0
In	900286.7	4191.0		904477.7	9119.0
Tr	80743.6	2188.0	99.0	83030.6	837.1
Te	1304898.9	24019.0		1328917.9	13398.3

Table 16
Capital output and its extended exergy equivalent for different sectors

	Consumption (M£)	Comp. of employees (M£)	Taxes (M£)	Capital acquisitions (M£)	Return to owners (M£)	Cout (M£)	Extended exergy (PJ)
Ag	54581.0	17718.0		2948.0	12717.0	87964.0	886.9
Ex	35369.0	6747.0	446.0	6121.5	15673.0	64356.5	648.8
Co	23300.0	2618.0	724.0	3184.5	3862.0	33688.5	339.7
In	312915.0	119390.0	2781.0	16829.0	52698.0	504613.0	5087.6
Tr	36423.0	21347.0		9542.0	2212.0	69524.0	700.9
Te	645080.0	480897.0	13105.0	79083.0	205924.0	1424089.0	14357.8

Table 17
Extended exergy analysis of the extraction sector (ex)

Fluxes	Energy (PJ)	Exergy (PJ)	Extended exergy (PJ)	Comments
Input				
Resources				
Re,ex	9051.9	9514.6	9514.6	Energy carriers
Re,ex		77.9	77.9	Minerals
Ra,ex	4125.7	4317.7	4317.7	Energy carriers
Rco,ex	33.3	32.9	32.9	Energy carriers
Products				
Pin,ex	11.6	13.9	13.9	Industrial products
Ptr,ex	5.6	5.9	5.9	Passengers, freight
Work				
Wdo,ex			52.5	Labour
Capital			1227.1	Capital
Total input	13228.0	13963.0	15242.6	
Output				
Resources				
Rex,a	4855.7	5138.8	5138.8	Energy carriers
Rex,a		2.2	2.2	Minerals
Rex,co	2602.1	2726.5	2726.5	Energy carriers
Rex,ag	130.6	136.3	136.3	Energy carriers
Rex,ag		0.1	0.1	Minerals
Rex,in	1116.3	1173.2	1173.2	Energy carriers
Rex,in		75.6	75.6	Minerals
Rex,tr	1848.9	1959.8	1959.8	Energy carriers
Rex,te	432.5	450.6	450.6	Energy carriers
Rex,do	1555.3	1620.0	1620.0	Energy carriers
Capital			648.8	Capital
Total output	12541.5	13283.1	13932.0	
Tex,e	6.2	28.0	28.0	Waste
Dex,e		46.9	46.9	Atmospheric emissions
Efficiency (%)	94.8	95.1	91.4	

Table 18
Extended exergy analysis of the conversion sector (co)

Fluxes	Energy (PJ)	Exergy (PJ)	Extended exergy (PJ)	Comments
Input				
Resources				
Re,co	34.3	34.3	34.3	Energy carriers
Ra,co	855.5	904.7	904.7	Energy carriers
Rex,co	2602.1	2726.5	2726.5	Energy carriers
Products				
Pin,co	4.1	5.0	5.0	Industrial products
Ptr,co	0.4	0.4	0.4	Passengers, freight
Pte,co	115.8	127.0	127.0	Waste
Work				
Wdo,co			33.0	Labour
Capital			315.0	Capital
Total input	3612.2	3797.8	4145.7	
Output				
Resources				
Rco,a	8.3	8.3	8.3	Energy carriers
Rco,ex	33.3	32.9	32.9	Minerals
Rco,ag	59.7	59.6	59.6	Energy carriers
Rco,in	407.3	381.2	381.2	Energy carriers
Rco,tr	30.4	30.4	30.4	Minerals
Rco,te	356.9	345.5	345.5	Energy carriers
Rco,do	418.1	416.4	416.4	Minerals
Capital			339.7	Capital
Total output	1313.9	1274.4	1614.1	
Tex,e	0.8	6.8	6.8	Waste
Dex,e		80.7	80.7	Atmospheric emissions
Efficiency (%)	36.4	33.6	38.9	

4. Extended exergy analysis (EEA)

4.1. Product flows (P-flows)

Harvest output from the agricultural sector included 381.4 PJ for food consumption (N-flow to tertiary sector), 163.3 PJ for other uses (N-flow to industry) and 179.0 PJ for feed and seed that was a non-useful output as it was consumed within the agricultural sector. Of the 381.4 PJ for food consumption transferred to the tertiary sector 260.8 PJ was resold in the domestic sector (P-flow) and the rest was used within the tertiary sector (non-useful output) in hotels, restaurants, etc. These two figures were based on relevant statistics provided in [45].

In order to determine the useful output of the transport sector data on passenger habits, passenger transport and freight transport were analysed, in more detail. Data on passenger transport energy consumption [36], passenger habits [36] and work-hour allocation between the different economic sectors (from [46] and personal communication with the Office for National Statistics) were used in order to determine the useful output of passenger transport. Due to lack of relevant data it was assumed that freight transport energy/exergy consumption relevant to each economic sector was directly proportional to the demand of each economic sector for road transport in economic terms. Furthermore it was assumed that passenger transport for each sector was proportional to the amount of work-hours in each sector. Detailed data on the amount of fuel used for transport of passengers and freight for road and rail transport were found in [36]. However, such data are missing for air and water transport. In our analysis we assumed that air transport was solely responsible for the movement of passengers while sea transport solely responsible for the movement of freight. Our results are included in Table 20 and even though they are based on realistic assumptions they are quite uncertain. It should be noted here that the total output of the transport sector in Table 20 is lower than that calculated in Table 12 because a small fraction of output was used from the transport sector itself (non-useful output).

Another challenge is presented during the allocation of the different industrial products between the different economic sectors. In this study the overall exergy output (P-flow) was considered equal to the difference between the exergy of the input (fossil fuel for non-energy use, minerals, ores, metals, timber, paper, recycled material, agricultural products, etc.) either domestic or imported and the exergy content of the exported output (metals, wood products, papers, etc.) for which detailed data existed [30,33,36,39,40]. The value of this P-flow was in the order of 1211.9 PJ. Subsequently the industry P-flow was allocated to the different economic sectors based on their intermediate consumption that was calculated from monetary input/output tables [47]. In particular 13.9 PJ (1.1%) went to the extraction sector, 5.0 PJ (0.4%) to conversion, 35.9 PJ (3.0%) to agriculture, 12.3 PJ (1.0%) to transport, 366.3 PJ (30.2%) to tertiary and 778.4 PJ (64.2%) was exchanged between the industrial subsectors (non-useful output).

4.2. Labour and capital flows (W- and C-flows)

Labour was accounted for as an output of the domestic sector. Labour flows in total work-hours and work-hours by economic sector were recovered from the National Statistics [46] and from

Table 19
Extended exergy analysis of the agricultural sector (ag)

Fluxes	Energy (PJ)	Exergy (PJ)	Extended exergy (PJ)	Comments
Input				
Resources				
Ra,ag	6.8	7.2	7.2	Energy carriers
Rex,ag	130.6	136.3	136.3	Energy carriers
Rex,ag		0.1	0.1	Minerals
Rco,ag	59.7	59.6	59.6	Energy carriers
Natural resources				
Ne,ag	488.0	488.0	488.0	Harvest
Ne,ag	135.6	150.5	150.5	Wood
Na,ag	400.1	400.1	400.1	Harvest, feed, seed, etc.
Products				
Ptr,ag	12.9	13.7	13.7	Passengers, freight
Pin,ag	29.9	35.9	35.9	Industrial products
Pte,ag	0.1	0.1	0.1	Waste
Work				
Wdo,ag			440.1	Labour
Capital			1821.8	Capital
Total	1263.8	1291.7	3553.5	
Output				
Natural resources				
Nag,a	165.0	165.0	165.0	Harvest, food, etc.
Nag,a	9.0	10.0	10.0	Wood
Nag,in	163.3	163.3	163.3	Harvest
Nag,in	116.0	128.8	128.8	Wood
Nag,te	381.4	381.4	381.4	Food
Nag,do	8.5	9.5	9.5	Fuel wood
Capital			886.9	Capital
Total	843.2	857.9	1744.7	
Tag,e	100.8	122.4	122.4	Waste
Dag,e		56.2	56.2	Atmospheric emissions
Conversion efficiency (%)	66.7	66.4	49.1	

Table 20
Extended exergy analysis of the transportation sector

Fluxes	Energy (PJ)	Exergy (PJ)	Extended exergy (PJ)	Comments
Input				
Resources				
Ra,tr	556.0	589.4	589.4	Energy carriers
Rex,tr	1848.9	1959.8	1959.8	Energy carriers
Rco,tr	30.4	30.4	30.4	Energy carriers
Products				
Pin,tr	10.3	12.3	12.3	Industrial products
Work				
Wdo,tr			353.6	Labour
Capital			837.1	Capital
Total	2445.5	2591.9	3782.6	
Output				
Ptr,ag	12.9	13.7	13.7	Passenger, freight
Ptr,ex	5.6	5.9	5.9	Passenger, freight
Ptr,co	0.4	0.4	0.4	Passenger, freight
Ptr,in	57.1	60.5	60.5	Passenger, freight
Ptr,te	171.8	182.0	182.0	Passenger, freight
Ptr,do	215.6	228.4	228.4	Passenger, freight
Capital			700.9	Capital
Total	463.3	490.9	1191.9	
Tag,e	0.0	0.0	0.0	Waste
Dag,e		73.5	73.5	Atmospheric emissions
Efficiency (%)	18.9	18.9	31.5	

Table 21
Extended exergy analysis of the industrial sector

Fluxes	Energy (PJ)	Exergy (PJ)	Extended Exergy (PJ)	Comments
Input				
Resources				
Ra,in	204.7	217.0	217.0	Energy carriers
Ra,in		102.9	102.9	Minerals, ores, etc.
Rex,in	1116.3	1173.2	1173.2	Energy carriers
Rex, in		75.6	75.6	Minerals, ores, etc.
Rco,in	407.3	381.2	381.2	Energy carriers
Natural resources				
Na,in	475.3	536.6	536.6	Wood, pulp, etc.
Nag, in	163.3	163.3	163.3	Harvest
Nag, in	116.0	128.8	128.8	Wood
Products				
Ptr,in	57.1	60.5	60.5	Passenger, freight
Pte,in	309.8	350.2	350.2	Recycled material
Pte,in	11.1	12.4	12.4	Waste for energy
Work				
Wdo,in			2359.2	Labour
Capital			9119.0	Capital
Total	2860.8	3201.7	14680.0	
Output				
Products				
Pin,a		82.1	82.1	Metals, minerals
Pin,a	55.8	63.4	63.4	Wood products
Pin,ag	29.9	35.9	35.9	Industrial products
Pin,ex	11.6	13.9	13.9	Industrial products
Pin,co	4.1	5.0	5.0	Industrial products
Pin,tr	10.3	12.3	12.3	Industrial products
Pin,te	304.9	366.3	366.3	Industrial products
Capital			5087.6	Capital
Total	416.5	579.0	5666.5	
Tag,e	122.6	228.5	228.5	Waste
Dag,e		55.6	55.6	Atmospheric emissions
Exergy loss				
Conversion efficiency (%)	14.6	18.1	38.6	

personal communication with the Office of National Statistics. The total amount of the work-hours invested in the UK economic system was 47588.5 Mh (Table 14). Even though the raw data in most cases agreed with our sectoral breakdown, in a few cases some adjustments were required. Such cases included the data from the electricity/gas/water supply sector: 64% of total work-hours were attributed to the conversion sector (electricity supply), 21% to tertiary (water supply) and 15% to extraction (gas supply). Another example was transport/storage/communication sector of which 42% of the total work-hours were considered relevant to the transportation sector (transport) and 58% to the tertiary sector (storage/communication). Our estimates were based on employee and employee compensation data published in the 2004 Business Inquiry [46]. Given that a significant portion of the economic activity in the tertiary sector is associated with services to the public a separate W-flow from the tertiary sector to the domestic sector was considered. This W-flow encompassed all the relevant activities of hotels/restaurants, community/social work, social security, public administration, education and health. The overall flow amounted to 15179.4 Mh, with an equivalent exergy of 3792.2 PJ (43.8% of the total).

Capital input to an economic sector was considered the sum of the total demand of a sector's products/services by other economic sectors and final users (e.g. residences, abroad, etc.), the capital disposals to other sectors and the net product subsidies (if positive). Capital output was equal to the sum of the intermediate consumption of that sector (products/services), compensation of employees, net product taxes (if positive), capital acquisitions and capital return to owners (gross operating surplus plus capital disposals minus capital acquisitions). All relevant data were collected from [46,47] and are included in Tables 15 and 16.

4.3. EEA results

EEA results are included in Tables 17–23. In our calculations exergy conversion efficiencies were taken as the ratio between the outflow R/N/P-flows and the input R/N/P-flows. Extended exergy efficiencies also included relevant W- and C-flows. In most cases the extended exergy efficiency is higher than the exergy efficiency. This is due to the fact that in sectors such as transport, industry and the tertiary the capital inflow/outflow was significant. We should note here the imported figures considered in Section 3.6.3 contained only raw materials and not any other finished products such as wood-based panels or paper. However, data contained in Table 21 also contain finished materials such as those mentioned earlier.

The extended exergy of labour and capital was 248.3 MJ/h while that of capital was 10 MJ/£. The former was quite close to the value designated in [19] for Italy (18.18 MJ/USD).

5. Discussion

The greatest exergy input in the UK economy was fossil fuels by a wide margin. This over reliance on these forms of energy might have negative effects in the future especially considering that over the past 2 years the UK has become a net importer of both crude oil and natural gas.

Table 22
Extended exergy analysis of the tertiary sector

Fluxes	Energy (PJ)	Exergy (PJ)	Extended exergy (PJ)	Comments
Input				
Resources				
Ra,te	11.5	12.2	12.2	Energy carriers
Rex,te	432.5	450.6	450.6	Energy carriers
Rco,te	356.9	345.5	345.5	Energy carriers
Natural resources				
Nag,te	381.4	381.4	381.4	Food
Products				
Pa,te	16.8	16.8	16.8	Waste
Ptr,te	171.8	182.0	182.0	Passenger, freight
Pin,te	304.9	366.3	366.3	Industrial products
Work				
Wdo,te			8650.5	Labour
Capital			13398.3	Capital
Total	1675.8	1754.9	23803.6	
Output				
Product				
Pte,a	55.5	65.5	65.5	Recirculated paper
Pte,in	309.8	350.2	350.2	Waste for mat. recovery
Pte,in	11.1	12.4	12.4	Waste for en. recovery
Pte,co	115.8	127.0	127.0	Waste for en. recovery
Pte,ag	0.1	0.1	0.1	Waste for en. recovery
Pte,do	1.0	1.1	1.1	Waste for en. recovery
Pte,do	260.8	260.8	260.8	Food
Pte,do	80.7	15.3	15.3	Energy by services
Pte,do	47.2	56.5	56.5	Resale of industrial prod.
Work				
Wte,do			3792.2	Labour
Capital			14357.8	Capital
Total	882.0	888.7	19038.8	
Tex,e	239.4	416.9	416.9	Waste
Dex,e		63.7	63.7	Atmospheric emissions
Efficiency (%)	52.6	50.6	80.0	

Table 23
Total inputs and outputs from the UK

Flows	Energy (PJ)	Exergy (PJ)	Extended exergy (PJ)	Comments
Re,ex	9051.9	9514.6	9514.6	Energy carriers
Re,ex		77.9	77.9	Minerals
Ra,ex	4125.7	4317.7	4317.7	Energy carriers
Re,co	34.3	34.3	34.3	Energy carriers
Ra,co	855.5	904.7	904.7	Energy carriers
Ra,ag	6.8	7.2	7.2	Energy carriers
Ra,tr	556.0	589.4	589.4	Energy carriers
Ra,in	204.7	217.0	217.0	Energy carriers
Ra,in		102.9	102.9	Minerals, ores, etc.
Ra,te	11.5	12.2	12.2	Energy carriers
Ra,do	50.3	53.4	53.4	Energy carriers
Ne,ag	488.0	488.0	488.0	Harvest
Ne,ag	135.6	150.5	150.5	Wood
Na,ag	400.1	400.1	400.1	Harvest, feed, seed, etc.
Na,in	475.3	536.6	536.6	Wood, pulp, etc.
Pa,te	16.8	16.8	16.8	Waste
Total—input	16412.6	17423.9	17423.9	
Rex,a	4855.7	5138.8	5138.8	Energy carriers
Rex,a		2.2	2.2	Minerals
Rco,a	8.3	8.3	8.3	Energy carriers
Nag,a	165.0	165.0	165.0	Harvest, food, etc.
Nag,a	9.0	10.0	10.0	Wood
Pin,a		82.1	82.1	Metals, minerals
Pin,a	55.8	63.4	63.4	Wood products
Pte,a	55.5	65.5	65.5	Recirculated paper
Total—output	5149.3	5535.2	5535.2	
Total within country	11263.3	11888.7	11888.7	Ein
T (incl. domestic)	539.8	1050.0	1050.0	Waste
D (incl. domestic)		423.3	423.3	Atmospheric emissions

One way to promote the sustainability of the UK is to focus on the improvement of electricity generation (conversion sector) considering the relatively low exergy efficiency of 38.6%. Focusing on that sector might also help decrease its gaseous emissions which, according to Table 13, are higher than any other sector. A possible way to achieve this is through switching to natural gas as the main fuel for electricity generation. A second path is to increase electricity production from renewable exergy which, at the moment, is discouragingly low as compared with thermal processes.

Energy and material intensive sectors such as the iron/steel, aluminium and wood/paper/pulp industries show high exergy efficiencies which is an encouraging sign. Two sectors that ought to receive attention are the residential and tertiary sectors as according to our exergy analysis have the lowest overall exergy efficiencies of 11.2% and 12.3%, respectively. Appliance efficiencies are relatively difficult to be improved so it might be more appropriate to tackle issues of efficiency in these sectors through familiarisation of residents and workers with energy saving procedures. Also government incentives might also influence the diffusion of energy saving devices such as energy saving lamps.

Results from the extended exergy analysis are quite different stemming from the different method used to calculate exergy efficiency. For the extraction, conversion and industrial sectors exergy and extended exergy efficiencies were quite similar. In the agricultural, transport and tertiary sectors there was a significant difference between exergy and extended exergy efficiencies resulting from the inclusion of capital and labour as production factors. The most striking case is that of the tertiary sector where the exergy efficiency was 50.4% and extended exergy efficiency was 80.0% (refer to Table 22). This was due to the fact that capital and labour flows accounted for almost 100% of the inputs/outputs from the sector.

Another interesting finding is the atmospheric and waste emissions by sector (Table 13, Section 3.10). Atmospheric emissions seem, with little variance, be equally distributed among the economic sectors. However waste emissions were far greater from the industrial, domestic and tertiary sectors. Interestingly enough agriculture, despite being a relatively small part of the overall economic activity within the UK, seems to be producing a significant amount of waste. That is because the majority of agricultural waste is of organic nature which has high exergetic content per unit mass.

6. Conclusions

The analysis presented in this paper utilised two distinct exergy methodologies to understand the metabolism of the UK system. Fossil fuels dominated the exergy inputs in the UK society for the year 2004. Efficiency calculations with both methodologies showed that the conversion, domestic and transport sectors have low exergy efficiencies which is quite troubling considering that these sectors constitute the most important exergy consumptions sectors. We believe that a focus on increasing the exergy efficiency in these sectors would be of great benefit for a shift towards sustainability in the UK by reducing both the amount of resources lost as well as the atmospheric and waste emissions and their subsequent environmental impact. However in order to ensure that shift towards sustainability the increase of exergetic efficiency in the different economic sectors should not be the only policy objective/priority given that increasing the efficiency of resource use may lead, in the medium to long term, to an increase in the consumption of that resource (Jevon's paradox).

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