



Understanding China's past and future energy demand: An exergy efficiency and decomposition analysis



Paul E. Brockway*, Julia K. Steinberger, John R. Barrett, Timothy J. Foxon

Sustainability Research Institute, School of Earth and Environment, University of Leeds, LS2 9JT, UK

HIGHLIGHTS

- We complete the first time series exergy and useful work study of China (1971–2010).
- Novel exergy approach to understand China's past and future energy consumption.
- China's exergy efficiency rose from 5% to 13%, and is now above US (11%).
- Decomposition finds this is due to structural change not technical leapfrogging.
- Results suggests current models may underestimate China's future energy demand.

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ABSTRACT

There are very few useful work and exergy analysis studies for China, and fewer still that consider how the results inform drivers of past and future energy consumption. This is surprising: China is the world's largest energy consumer, whilst exergy analysis provides a robust thermodynamic framework for analysing the technical efficiency of energy use. In response, we develop three novel sub-analyses. First we perform a long-term whole economy time-series exergy analysis for China (1971–2010). We find a 10-fold growth in China's useful work since 1971, which is supplied by a 4-fold increase in primary energy coupled to a 2.5-fold gain in aggregate exergy conversion efficiency to useful work: from 5% to 12.5%. Second, using index decomposition we expose the key driver of efficiency growth as not 'technological leapfrogging' but structural change: i.e. increasing reliance on thermodynamically efficient (but very energy intensive) heavy industrial activities. Third, we extend our useful work analysis to estimate China's future primary energy demand, and find values for 2030 that are significantly above mainstream projections.

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1. Introduction

As the world's economic powerhouse and largest energy consumer [1], much effort is spent understanding China's historical energy consumption (e.g. [2–4]) and future energy demand [5–7]. However these studies typically examine primary or final energy data, rather than useful work values obtained using an exergy analysis based technique. This is the research gap that this paper seeks to address. Exergy analysis takes a broader, whole system approach to energy analysis, giving "a measure of the thermodynamic quality of an energy carrier" (p. 686, [8]), thereby enabling a robust view of useful work consumed in provision of energy services. Exergy analysis also has the benefit of taking into account more aspects of the energy supply chain than traditional energy

analysis, and in a more consistent way. A flow visualisation of primary exergy to useful work is given in Fig. 1.

A key assumption in this study is that useful work is a better 'energy parameter' than primary energy on which to analyse end energy use and economic activity, since – as Fig. 1 shows – it is the last thermodynamic place where energy is measured before it is exchanged for energy services. We are not alone in this view. Numerous authors (e.g. [8–10]) suggest second law exergy analyses can help understand national-scale energy use. For economic insights, Percebois [11] suggested in 1979 that energy intensity metrics (i.e. energy consumption relative to GDP) were better undertaken at the energy output stage, since it "allows us to analyse structural change in energy supply and situates our analysis at the level of satisfied needs". Serrenho et al. [12] recent work on useful work intensity supports this assertion. Meanwhile, Warr and Ayres [13], Santos et al. [14] and Guevara et al. [15], all found empirical evidence suggesting useful work is a better candidate as

* Corresponding author.

E-mail address: eepr@leeds.ac.uk (P.E. Brockway).

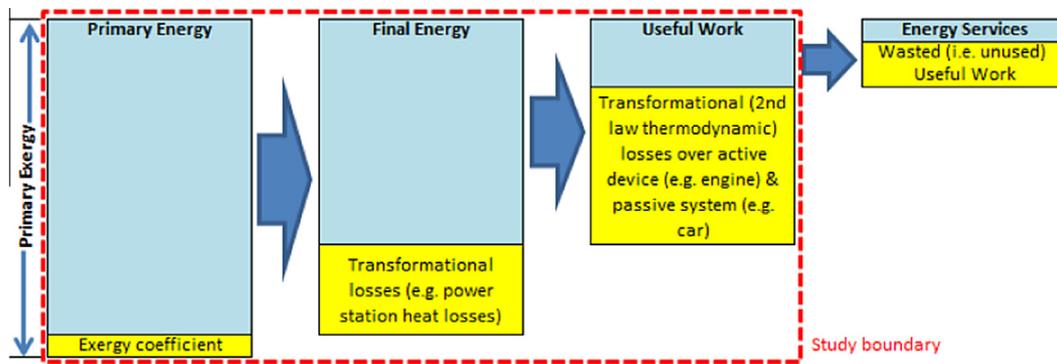


Fig. 1. Conceptual diagram of primary exergy to useful work.

a factor of production (than primary energy) to explain economic growth. This gets us to the crux of our argument: if it is useful work and not primary energy that supplies economic needs, then we should conduct energy and economic analyses at that level.

The few published time-series studies of useful work accounting have focussed largely on industrialised countries including the US, UK and Japan (e.g. [16–18] and later all EU-15 countries [12]). Somewhat curiously, these country-scale analyses typically focus on economic implications and linkages, rather than energy-based conclusions. Brockway et al. [19] set out to address this imbalance, by undertaking a 50 year time-series analysis (1960–2010) of the US and UK. They found the US and UK may no longer be increasing their aggregate exergy efficiency, as increases in process level efficiencies are offset by efficiency dilution taking place [19], following the case of Japan [17]. In short: individual technology gains in efficiency are being overtaken by using increasing amounts of less efficient processes, such as air-conditioning. This raises the question: could the same be happening in China?

Numerous Extended Exergy Accounting (EEA) studies have been published on China (e.g. [20–32]). EEA is a biophysical exergy analysis method, developed largely by Wall and Sciubba in the 1990s (e.g. [33–35]) to examine the embedded exergy of all natural resources inputs (e.g. energy, natural materials) and associated outputs of the economy (e.g. food, materials, wastes). This valuable technique helps understand societal exergy consumption. It is complementary to the useful work accounting method applied here, which is based on an “energy carriers for energy use” approach [36] introduced at a national-scale by Reistad [37] in 1975, which examines the exergy destruction of energy conversion processes from primary exergy to end useful work. The key distinction is that EEA is akin to a mass-balance analysis (except it studies

start, we undertake the first historical exergy efficiency and useful work analysis for China, covering the period 1971–2010. Next, we adopt an index decomposition analysis to identify the key drivers of change in China’s useful work. Last, we develop a useful work based method for projecting China’s primary energy demand to 2030, and also test implications of potential future declines in the rate of exergy efficiency improvement.

The paper proceeds as follows. After the Introduction, Section 2 contains Methods and Data, Results and Discussions are in Section 3, with Conclusions in Section 4.

2. Methods and data

2.1. Historical useful work analysis (1971–2010)

2.1.1. Method Summary

Reistad [37] defined exergy as ‘available energy’. As depicted in Fig. 1, at a country-scale, primary exergy of energy carriers (e.g. coal, oil, gas, renewables, food and feed) is transformed into ready to use ‘final energy’ (e.g., diesel or electricity), which is then used to provide ‘useful work’ (i.e. through heat, mechanical drive, manual labour or electrical devices), to ultimately provide energy services (e.g. warmth, light, cooling, sustenance). Carnahan et al. [39] defined task-level ‘useful work’ (U_{ij}) as “the minimum exergy input to achieve that task work transfer”. For our purposes, task-level means sub-class (j) (e.g. diesel road transport or low temperature heat) levels nesting within overall main classes (i) of energy use (i.e. heat, muscle work, transport, mechanical drive). Task-level exergy efficiency (ϵ_{ij}) represents the second law thermodynamic efficiency of the energy conversion from primary exergy to end useful work, defined by Carnahan et al. [39] as:

$$\epsilon_{ij} = \frac{\text{Useful work, } U_{ij}}{\text{Primary Exergy, } E_{ij}} = \frac{\text{The minimum exergy input to achieve that task work transfer}}{\text{Maximum amount of reversible work done as system reaches equilibrium}} \quad (1)$$

exergy content not mass) whereas Reistad’s approach estimates the thermodynamic work done by the energy system to deliver energy services. It is the latter approach we require for detailed energy system analysis – and such national-scale useful work accounting studies for China are rare (e.g. [38]), and none to date examine a long time-series.

To address the lack of exergy-based analyses in China which examine time-series results through an energy demand lens, we pose the following research question: *What new insights can useful work analysis provide for historical and future energy demand in China?* In response, we provide three novel, linked analyses. To

Primary exergy values at task-level (E_{ij}) are then multiplied with their associated task-level exergy efficiencies (ϵ_{ij}) to give an estimate for task-level useful work (U_{ij}). When summed, we derive an overall estimate for the total national-scale useful work ($U_{tot} = \sum U_{ij}$) via Eq. (2). Finally, national exergy (second law) efficiency (ϵ_{tot}) is given by Eq. (3), which – following Carnahan et al. [39] – we adopt as a country-scale measure of energy efficiency, and use it as a term throughout this paper for consistency. Eq. (2) also reveals the obvious (but important, as we see later) observation that useful work changes are supplied by changes in primary exergy and/or exergy efficiency.

$$\sum U_{ij} = \sum (E_{ij}\epsilon_{ij}) \quad (2)$$

$$\epsilon_{\text{tot}} = \frac{\sum U_{ij}}{\sum E_{ij}} \quad (3)$$

Our country-scale useful work accounting approach builds on the methodology developed by numerous authors including Reistad [37], Wall [40], Ayres and Warr [41], and more recently Serrenho et al. [42], who introduced a consistent International Energy Agency (IEA) based input energy mapping framework. Brockway et al. [19] made further advances to electricity applications and mechanical drive classes, which is also used in this study for consistency and comparability. We apply these advances to produce a first time-series analysis of China. Fig. 2 gives an overview of the basic stages:

2.1.2. Input data

Primary exergy inputs, E_{ij} , are first derived. IEA energy datasets 1971–2010 (1) for fossil fuel and biomass (combustible renewables) provided much of the base data. IEA primary energy values are converted to primary exergy inputs using chemical exergy coefficients [43]. At an aggregate level, total primary exergy is around 5% higher than the IEA's Total Primary Energy Supply (TPES) values. The inputs E_{ij} are then mapped to three main classes (heat, mechanical drive and electricity) and to task-levels where possible (e.g. Low Temperature Heat (LTH)), following recent approaches [19,42]. The task-levels are listed in Appendix A. In some cases, we extend the IEA end energy use breakdown to more granular levels (e.g. road fuel split between transport modes) by supplementing Chinese end consumption data in three key areas: buildings [3,44–48]; transport [49–53]; and industry [54–58].

Next, task-level exergy efficiencies (ϵ_{ij}) for transport, heat, and electricity are added. Previous US–UK values [19] are modified by Chinese data as follows. For transport, local fuel economy data was used for road and rail [52,53,59,60]. For calculating Carnot efficiencies (for heat exergy efficiencies), for external temperatures we used 1971–2010 China monthly air temperature data [61], whilst indoor temperatures (for LTH efficiencies) were weighted for China's city/rural split and assume a 20 year lag in comfort levels versus UK data [62]. LTH first law efficiencies are based on Warr et al. [18], Chen et al. [30] and Edwards et al. [63]. Steel and ammonia industries are adopted (as with US–UK study) as representative of High Temperature Heat (HTH) efficiencies, by virtue of having the two highest proportions of Chinese industrial energy use [58]. Process (GJ/tes) efficiency data for steel [54–57,64,65] and ammonia (taken as 75% of UK values, based on average values from Phylipsen et al. [65]) and the IEA [66] are combined with temperature data to calculate time-series exergy efficiencies. For electricity application efficiencies, values of 80% of those from the US–UK

analysis were typically used, based on evidence that China's average devices were 10–20 years behind US–UK values across industry, commerce and residential sectors [3,67].

Then, we calculated primary exergy and useful work values for a fourth main class: muscle work. For human labour, estimates follow Brockway et al. approach [68]: using manual labour population [69,70], food intake data [71,72], and Smil's estimated 13% conversion efficiency of food to human useful work [73]. For draught animals, we assumed 100 million draught animals in China in 1990 [74], and a 1% annual decline in numbers from 1971 to 2010, mirroring India [75]. For animal useful work outputs, we assumed 400 W average power output for a 5 h working day over 120 working days/year, based on published data [74,76,77]. Estimates of intake feed requirements were based on Ramaswamy and Krausmann [74,78].

Last, a note on data quality. For input energy data, two systematic discrepancies mean our national-level datasets underestimate actual primary energy use. First, at a national-scale, IEA-based TPES values are ~5% lower than those of Lawrence Berkeley National Laboratory (LBNL) China Energy Databook [46]. Second, reported aggregate primary energy consumption in China is ~10% higher from aggregated regional versus national datasets [79]. However, these differences are expected to be systematic, and thus have limited overall effect for our trends analysis. For task-level efficiencies, whilst the China data sources are weaker in many instances than the previous US–UK studies [19], overall trends and comparison to US–UK results remain valid.

2.1.3. Useful work accounting outputs

Appendix A shows the task-level outputs of useful work, primary exergy and exergy efficiency. This data serves as task-level inputs to the Logarithmic Mean Divisia Index (LMDI) decomposition analysis, or is summed to give useful work or exergy efficiencies at main class level (i.e. heat, mechanical drive, electricity and muscle work) and country-scale.

2.2. LMDI decomposition (1971–2010)

LMDI decomposition is now the mainstream Index Decomposition Analysis (IDA) technique for analysing drivers of changes in CO₂ emissions (e.g. [80,81]) and sectoral energy use such as manufacturing and transport (e.g. [82,83]). Using the LMDI approach, we develop a new approach to reveal the relative contribution of energy and efficiency drivers to China's historical useful work (U). First, we expand Eq. (2) ($U = \sum E_{ij}\epsilon_{ij}$) to yield Eq. (4), which is based on task-level useful work (U_{ij}) and primary exergy (E_{ij}), enabling the historical results to act as the input data for the LMDI analysis. Eqs. (5)–(9) give the four drivers of useful work changes: Input Exergy (D_{ex}); Main class structure (D_{str});

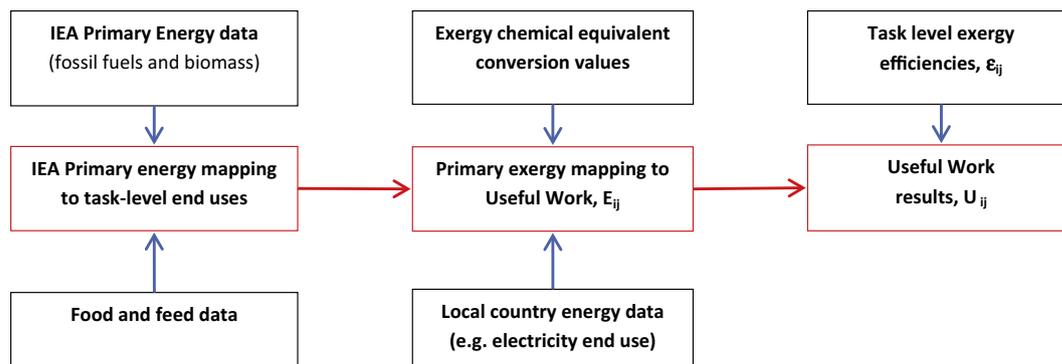


Fig. 2. Useful work analysis flowchart.

sub-class (i.e. task) level structural change (D_{dil}); and task-level efficiency (D_{eff}). This shows how LMDI decomposition can be used to breakdown the overall exergy efficiency changes (from the main analysis results in Section 3.1) into three parts (D_{str} , D_{dil} , D_{eff}).

$$U = \sum_{ij} U_{ij} = \sum_{ij} E \frac{E_i}{E} \frac{E_{ij}}{E_i} \frac{U_{ij}}{E_{ij}} \quad (4)$$

$$D_{tot} = U^T / U^0 = D_{ex} D_{str} D_{dil} D_{eff} \quad (5)$$

$$D_{ex} = \exp \left(\sum_{ij} \hat{w}_{ij} \ln \left(\frac{X_{ij}^T}{X_{ij}^0} \right) \right) \quad (6)$$

$$D_{str} = \exp \left(\sum_{ij} \hat{w}_{ij} \ln \left(\frac{S_{ij}^T}{S_{ij}^0} \right) \right) \quad (7)$$

$$D_{dil} = \exp \left(\sum_{ij} \hat{w}_{ij} \ln \left(\frac{L_{ij}^T}{L_{ij}^0} \right) \right) \quad (8)$$

$$D_{eff} = \exp \left(\sum_{ij} \hat{w}_{ij} \ln \left(\frac{F_{ij}^T}{F_{ij}^0} \right) \right) \quad (9)$$

$$\hat{w}_{ij} = \left(\frac{(U_{ij}^T - U_{ij}^0) / (\ln U_{ij}^T - \ln U_{ij}^0)}{(U^T - U^0) / (\ln U^T - \ln U^0)} \right) \quad (10)$$

where

- E = Primary exergy input to economy
- E_i = Main class exergy input
- E_{ij} = Task-level exergy input
- U_{ij} = Task-level useful work output
- \hat{w}_{ij} = log mean weighting function
- X = Exergy input
- S = Main class share of exergy input (E_i/E)
- L = Task-level share of exergy input within main class (E_{ij}/E_i)
- F = Task-level exergy efficiency (U_{ij}/E_{ij})
- D_{ex} = change in overall exergy input (E)
- D_{str} = change in share of exergy inputs between main classes (E_i)
- D_{dil} = change in task-level shares (E_{ij}) of exergy inputs within each main class

2.3. China energy demand scenarios 2010–2030

After conducting the historical and decomposition analyses, we develop and trial a new useful work-based methodology to estimate primary energy demand to 2030, based on projections of GDP and extrapolations of task-level exergy efficiencies under illustrative constant and declining exergy efficiency growth rate scenarios. Four steps were required. The first estimates China's useful work requirement for 2010–2030. To do this, 1971–2010 overall useful work energy intensity (UW/GDP) – calculated from historical GDP data [84] – is extrapolated using a best-fitting curve to 2030. Using World Bank forecasts of GDP for 2011–2030 [85] – see also the [Supplementary Information – Section S1](#), China's total useful work (to deliver that GDP) in 2030 is then estimated.

Second, total projected useful work to 2030 is allocated to task-levels. To start, useful work proportions from main classes are estimated based on historic trend comparison in UK, US and China. China and US allocations are shown in [Fig. 3](#). Then, task level allocations are derived, also based on comparisons to previous US-UK values, which place China as ~40 years behind US-UK allocations. These results at task-level are given in the [Supplementary Information – Section S2](#).

Third, task-level exergy efficiencies are projected to 2030 under two illustrative scenarios which have different efficiency gains assumptions. In Scenario 1 (constant efficiency gains), China's 1990–2010 task-level exergy efficiency changes are extended to 2010–2030. Typically this places China's task-level efficiencies in 2030 as those of average US-UK values in 2010. In Scenario 2 (declining efficiency gains), only half of China's 1990–2010 efficiency gains are extended to 2010–2030, with two thirds of these reduced gains assumed to occur in 2010–2020. There is some justification for the declining gains scenario, as Brockway et al. [19] found that efficiency gains in important task-levels (e.g. residential electricity and LTH) slowed or reversed in 1990–2010 (versus 1970–1990). Assuming an average 20 year lag for China, this could mean similar effects exhibited in China by 2030. More detailed efficiency results at task-level are given in the [Supplementary Information – Section S3](#). Whilst other efficiency scenarios are possible (and indeed probable), our two selected cases are intended to represent the possible envelope of task-level efficiencies for 2010–2030, and are thus valid to study the effects of declining efficiency gains.

Fourth, estimates of total primary energy demand for 2010–2030 are made at task-level (Eq. (11)) and aggregate level (Eq. (12)). Suffix 1 and 2 refer to Scenario 1 and 2. Finally, the chemical exergy conversion ratios [43] are removed to reveal primary

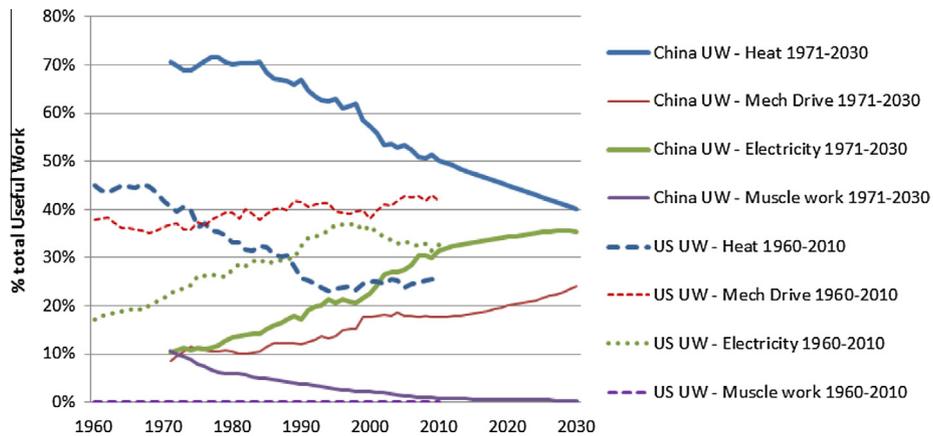


Fig. 3. China (1971–2030) and US (1860–2010) useful work allocations.

energy (i.e. TPES) projections to 2030 under these two scenarios, with differences suggesting impacts of declining exergy efficiency gains on primary energy demand.

$$E_{1ij} = \frac{U_{ij}}{\varepsilon_{1ij}}; \quad E_{2ij} = \frac{U_{ij}}{\varepsilon_{2ij}} \quad (11)$$

$$E_1 = \sum E_{1ij}; \quad E_2 = \sum E_{2ij} \quad (12)$$

3. Results and discussion

3.1. 1971–2010. useful work accounting results

Table 1 summarises useful work, primary exergy and exergy efficiency results for 1971–2010, with task-level results given in Appendix A for 1971 and 2010. China's end useful work has increased 10-fold since 1971, with electricity applications and HTH industrial uses growing from 30% to 53% of total useful work. Conversely, muscle work and low temperature heat have together declined from 40% of total useful work to 8%.

Aggregate exergy efficiency has grown almost linearly from 5.3% to 12.5%. Table 1 (together with Appendix A) suggest a key factor is the structural shift from (low efficiency) muscle work

and low temperature heat (20 °C) to (high efficiency) HTH. Fig. 4 illustrates a second reason: the strong growth in mechanical drive and heat class efficiencies – which make up over half of total primary exergy inputs. The question of whether this linear aggregate efficiency trend can continue is considered via the future scenario analysis in Section 3.3.

Fig. 4 also compares China's aggregate efficiency growth to the stable US (10–11%) values from the previous US-UK study [19]. China's exergy efficiency overtakes the US by around 2004. At first, it is tempting to see China's overtaking of the US's aggregate efficiency as 'technological leapfrogging' (e.g. [86]) – i.e. rapidly adopting high-efficiency technologies without having to deal with the legacy of past low efficiency capital stock. In fact this is not the case, since task-level exergy efficiencies are generally lower than the US (except mechanical drive, which is a small component of China's energy use). This result implies structural differences make a significant contribution to China's increasing efficiency: i.e. its production-focused industrial economy uses more high temperature heat and industrial processes versus the US's mature consumer economy. The index decomposition results in Section 3.2 support this view. In turn, this implies as China's economy also matures and its structure shifts towards that of the US, that this may have a diluting effect on future overall exergy efficiency, as seen later in Section 3.3.

Table 1
Summary of useful work analysis results 1971–2010.

Useful work analysis: output category	1971		1980		1990		2000		2010	
	PJ	% of total								
<i>Useful work</i>										
Direct heat	1087	71	1848	71	2787	68	3901	59	7602	51
Mechanical Drive	126	8	268	10	477	12	1140	17	2633	18
Electricity end uses	154	10	343	13	684	17	1460	22	4665	31
Muscle work	157	10	151	6	148	4	137	2	127	1
Total	1524	100	2610	100	4096	100	6638	100	15027	100
<i>Primary exergy</i>										
Direct heat	15370	54	21560	56	28271	55	31504	49	51983	43
Mechanical Drive	1090	4	1971	5	2988	6	5625	9	12720	11
Electricity end uses	1592	6	3519	9	6283	12	13951	22	42507	35
Muscle work	10661	37	11760	30	13489	26	13398	21	13159	11
Total	28713	100	38810	100	51032	100	64478	100	120,369	100
<i>Exergy efficiency (useful work/primary exergy)</i>										
Main category end use	% efficiency									
Direct heat	7.1		8.6		9.9		12.4		14.6	
Mechanical Drive	11.6		13.6		16.0		20.3		20.7	
Electricity end uses	9.7		9.7		10.9		10.5		11.0	
Muscle work	1.5		1.3		1.1		1.0		1.0	
Total	5.3		6.7		8.0		10.3		12.5	

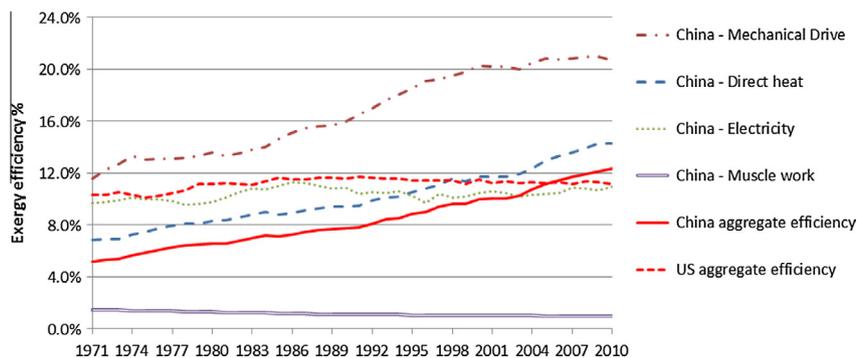


Fig. 4. China's exergy efficiency by end use 1971–2010, compared to US aggregate efficiency.

Few comparative estimates are available of aggregate Chinese efficiencies. Chen and Chen [30] calculate a value of 20%, twice that of our 10% value for China in 2000. The main reasons are due their exclusion of muscle work, and higher industry efficiency (e.g. 78% for the chemical sector). Nakicenovic [87] estimated reforming countries (e.g. China) exergy efficiencies in 1990 to be $\sim 10\%$, of a similar order to our 8% estimate for 1990.

Fig. 5 shows how China's 10-fold useful work growth was supplied by a 4-fold increase in primary energy coupled to a 2.5-fold gain in aggregate exergy efficiency: from 5% to 12.5%. In other words, if China's exergy efficiency had stayed at 5%, a 10-fold gain in primary exergy would have been required to achieve the same useful work supply level.

Finally, to understand the overall flow of exergy to end useful work, and the exergy losses that occur during the various conversion processes, useful work-based Sankey diagrams of China are constructed for 1971 and 2010, as shown in Appendix B. They show the transformation of China in 40 years from a largely agricultural to industrial economy. By 2010, China is dominated by energy dense fossil fuel inputs (versus food and feed for muscle work) and energy intensive end uses, particularly in industry, which underpins the rise in overall exergy efficiency.

3.2. LMDI decomposition results 1971–2010

The multiplicative factors are summarised in Table 2 for the period 1971–2010, comparing three countries: China, the UK and US. For China, the largest contribution to useful work growth is primary exergy, confirming the result of Fig. 5. Importantly, the overall efficiency gain factor (2.5) is now split into three parts. First, the main class structural change (1.39) tracks the move from less efficient (i.e. muscle work) to more efficient (i.e. heat) main classes. Second, we find sub-class structural change (1.19) is above 1.00, which means that within each main class there has also been an efficiency 'concentration' effect. (In contrast note the efficiency 'dilution' values of 0.87–0.88 for the US and UK). This is due to China's transition from agricultural society to industrial powerhouse, causing structural shifts within main classes from lower to higher efficiency categories (e.g. LTH to HTH). Third, task-level efficiency gains (1.48) are the largest of the three efficiency gain factors.

The value of using the LMDI approach is also highlighted by Table 2. Firstly, it confirms and quantifies the assertion stated in Section 3.2: that overall structural change (1.66) is at least as important to overall efficiency gains as task-level efficiency gains (1.48). Secondly, we can directly compare factors to other countries. In this case, we see that China has not reached the point of efficiency 'dilution' that can be seen in the US and UK – where D_{dil} would be below 1.00 – as found earlier by Williams et al. [17] for Japan. China's improvements to task-level efficiencies (1.48) are similar to US (1.29) and UK (1.58) values, confirming that instead of technological leapfrogging, it is overall structural change

Table 2

Summary of LMDI decomposition factors 1971–2010 for China, US, UK.

Country	U Useful work	D _{ex} Primary Exergy	D _{str} Main class structural change	D _{dil} Sub-class structural change	D _{eff} Task-level efficiency
China	9.76	3.96	1.39	1.19	1.48
US	1.53	1.32	1.03	0.88	1.29
UK	1.43	1.01	1.04	0.87	1.58
Country	U Useful work	D_{ex} Primary exergy	$D_{str} * D_{dil}$ Overall structural change	D_{eff} Task-level efficiency	
China	9.76	3.96	1.66	1.48	
US	1.53	1.32	0.90	1.29	
UK	1.43	1.01	0.90	1.58	

(1.66 for China versus 0.90 for US and UK) that has been responsible for China's rise in overall aggregate efficiency to overtake the US.

3.3. Future exergy efficiency: impacts on primary energy projections

3.3.1. Step 1 – Useful work projection to 2030

China's useful work and primary energy intensities (of economic activity) are shown in Fig. 6, based on constant price GDP. It shows a 66% reduction in useful work intensity from 12.0 (GJ/2005\$US) in 1971 to 3.9 (GJ/2005\$US) in 2010, compared to an 86% reduction in primary energy intensity (210.7 to 29.8 GJ/2005\$US) – the standard metric for energy intensity (e.g. [88]) – over the same period. The greater stability of useful work intensity suggests useful work is more closely linked to GDP than primary energy – supporting the key assumption noted earlier. Useful work and primary energy intensities are projected to 2030 using best-fitting trendlines as shown in Fig. 6.

The World Bank's GDP forecast for China in 2030 [85] is \$13.5 Trillion(US2005), a 3.5-fold increase from the \$3.8 Trillion(US2005) value in 2010. Using the useful work intensity projection of 2.45 (GJ/US\$2005) for 2030, this gives a useful work estimate of 33.1EJ in 2030 (just over double the 15.0EJ consumed in 2010) – to deliver that level of GDP.

3.3.2. Step 2 – Allocation of task-level useful work

Fig. 7 shows the projected annual useful work growth to 2030 is almost linearly ~ 27 – 28 Mtoe/year. This is due to two effects cancelling each other out: a slowdown in GDP growth mirroring useful work intensity reductions. At a main class level, as China's economy matures, a slowdown in heat's contribution to useful work is offset by growth in electricity and mechanical drive (mainly transport) classes. This appears broadly consistent with other economic forecasts for China used in energy modelling (e.g. [6]).

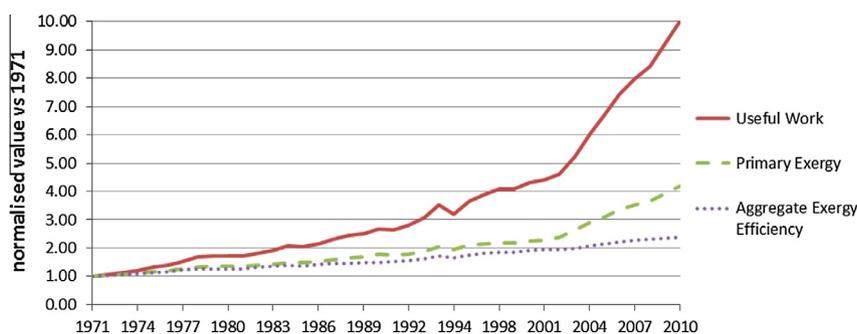


Fig. 5. China 1971–2010 useful work analysis results vs 1971 datum.

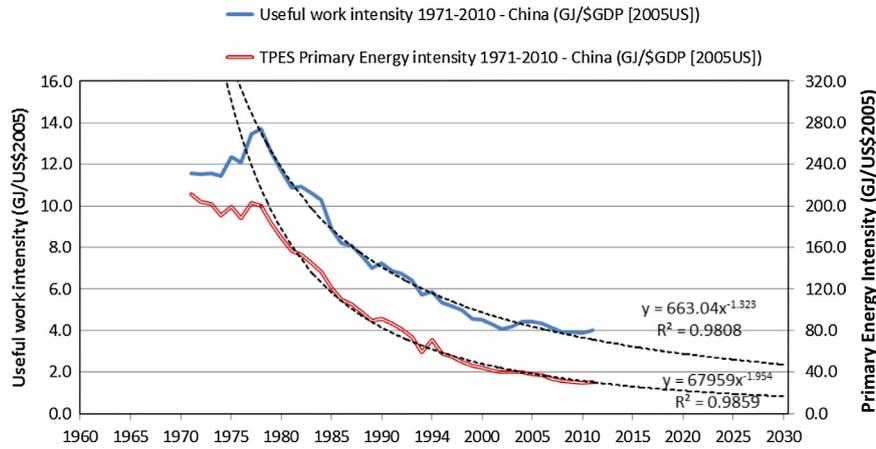


Fig. 6. Comparison of China primary energy and useful work intensities.

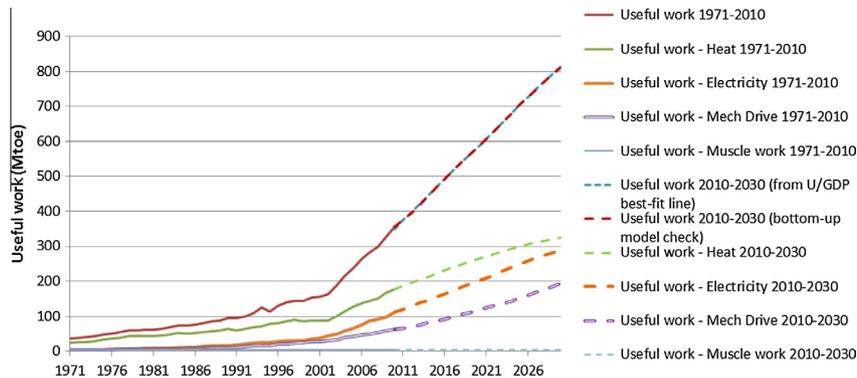


Fig. 7. China – useful work projection to 2030.

3.3.3. Step 3 – Task-level exergy efficiencies

Next, task-level exergy efficiencies are projected based on the linear and declining gains scenarios described earlier – see [Supplementary Information](#). The results at main class level are shown in [Fig. 8](#). In Scenario 1, stable gains in task-level exergy efficiencies are combined with structural change in China in 2011–2030 – moving towards a more service sector-based economy, with associated decreases in higher efficiency processes (e.g. high temperature heat) and increases in low-efficiency activities (e.g. residential and commercial electricity), as shown earlier in [Fig. 3](#). This results in only a small increase in national aggregate exergy efficiency from 12.5% to 13.0% in 2030. The green wedge in [Fig. 8](#) illustrates the effect of this structural change, compared to a simple extrapolation of China’s 1990–2010 aggregate efficiency, which would result in aggregate exergy efficiency of around 17% in 2030.

In Scenario 2, which includes both structural change and slowing of task-level efficiency gains, aggregate exergy efficiency peaks at 12.8% before 2025, then reduces to 12.5% by 2030. Therefore most of the reduction in overall efficiency is due to assumed structural change than the difference in task-level efficiencies under the two scenarios.

For heat and mechanical drive classes, the projected efficiency dilution is so strong (i.e. less industrial usage and more consumer/commercial use), their efficiencies decline by 2030 under both scenarios. As electricity provides an increasing share of useful work by 2030, this accelerates the slowdown (scenario 1) and decline (scenario 2) in overall exergy efficiency. Mechanical drive efficiency stagnates in this analysis under both scenarios, since it balances task-level efficiencies that were increasing (e.g. static motors and aviation) and decreasing (e.g. road transport – due to more

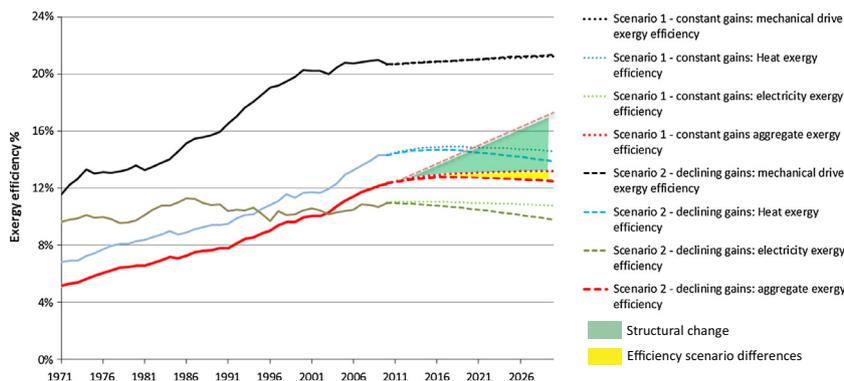


Fig. 8. China – exergy efficiency scenario results.

cars/less motorcycles, and more heavy duty-trucks). However, as the smallest of the three main classes, this effect has limited impact on the aggregate exergy efficiency.

3.3.4. Step 4 – Primary end demand in 2030

Finally, the useful work-based primary energy estimates are calculated based on the assumed efficiency scenarios. The results are compared in Fig. 9 to five published reference (i.e. current policies) scenarios [67,89–92] and a top-down primary energy intensity (TPES/GDP) based estimate (derived econometrically via the best-fit TPES/GDP projection shown earlier in Fig. 6). By 2030, our Scenario 1 (6000 Mtoe/year) requires 900 Mtoe/year more primary energy than the econometric estimate, whilst Scenario 2 – due to assumed declining efficiency gains – requires an additional 300 Mtoe/year (compared to Scenario 1). The TPES/GDP derived primary energy estimate (as with the other five reference projections) slows over time, following the assumed slow-down in GDP growth. In contrast, our useful work derived projections show more linear increases, as with flat overall exergy efficiencies (shown earlier in Fig. 8), the linear projected growth in useful work required (see earlier Fig. 7) is passed on to required primary energy inputs.

Our useful work-based projections are significantly higher than the five reference cases. The three reference scenarios using a 2010 base year [89–91] produce estimates of 4300–5000 Mtoe/year in 2030, whilst the two scenarios with a 2005 base year [67,92] estimate primary energy consumption as 3200 Mtoe in 2030. A key aspect therefore appears the choice of base year, with the 2005 base year models missing China's step up in energy consumption, and so undercut the projections of later base year models. Perhaps this illustrates how tricky energy forecasting is, as Smil [93] notes: “long-range energy forecasters have missed every important shift of the past 2 generations..[and they]..will continue to be wrong”.

Nevertheless, the fact remains the traditional energy models give lower estimates of primary energy than our simple useful work-based approach – so it's worth reflecting on this. Most importantly, we base our projections on a different energy intensity metric versus mainstream models – ours is based on useful work (U/GDP), as this measures the energy level delivered to economic activities, rather than on primary energy (TPES/GDP) entering the economy. Moreover, our TPES/GDP based projection is 20% below our U/GDP based projections – showing that this distinction is an important one. The GDP projections that we use are consistent with other models (e.g. [6]). Our methodology is also top-down: it starts from an aggregate demand estimation, and then builds up its constituent elements from task-share trends. Other energy models tend to be bottom-up, using demand and technology trends of various sectors. We attach more detailed scenario data in the [Supplementary Information](#).

Whilst we believe the useful work based approach to primary energy forecasting is justified by the observed links between aggregate economic activity and useful work, significant caveats exist around the accuracy of the underlying data to our energy projection conclusions. For the useful work calculations for 1971–2010, though the primary exergy data is relatively robust (relying mainly on IEA energy balance data), the task-level efficiencies have greater uncertainty, being based on often partial data. In turn, projecting task-level useful work allocations and exergy efficiencies to 2030 amplifies any data inaccuracies. However the driving rationale of the paper was to develop a new technique based on useful work. The result highlights the possible importance of this method and thus mandate for further study.

4. Conclusions

To address the lack of time-series exergy analyses for China which examine energy demand drivers and implications, we set the following research question: *What new insights can useful work analysis provide for historical and future energy demand in China?* First, our historical analysis found China's exergy efficiency grew linearly from 5.3% (1971) to an impressive 12.5% (2010), placing it between the US (11%) and the UK (15%). In addition, a striking 10-fold rise in China's useful work occurred from 1971 to 2010, supplied by a 4-fold increase in primary exergy and a 2.5-fold increase in exergy efficiency. Second, using LMDI decomposition we found efficiency growth was split evenly between task-level efficiency gains and structural change (e.g. moving from muscle work to mechanical drive). Third, a new useful work-based energy forecasting technique is developed and trialled, which – based on two illustrative exergy efficiency scenarios – projects China's 2030 primary energy demand in the range of 6000–6300 Mtoe, significantly higher than the 4500–5200 Mtoe estimates from published sources using traditional energy models which use the same 2010 baseline year.

The results allow several key insights. Firstly, if China's exergy efficiency had stayed at 5%, a 10-fold (rather than 4-fold) gain in primary exergy would have been required to achieve the same useful work supply level. Through the mechanism of the macro-economic rebound effect, however, as Ayres et al. [94] and Schipper and Grubb [95] established, lower efficiency gains may in fact translate to lower economic growth, and hence lower required useful work. Second, the application of LMDI decomposition to useful work results provided robust insights: revealing China's efficiency rise above the US was not due to technological leapfrogging, but greater use of energy intensive (yet more exergy efficient) industrial processes. Third, in common with the US and UK, China may approach an asymptotic exergy efficiency maximum by 2030, as its economy matures and efficiency dilution starts. Such dilution is already

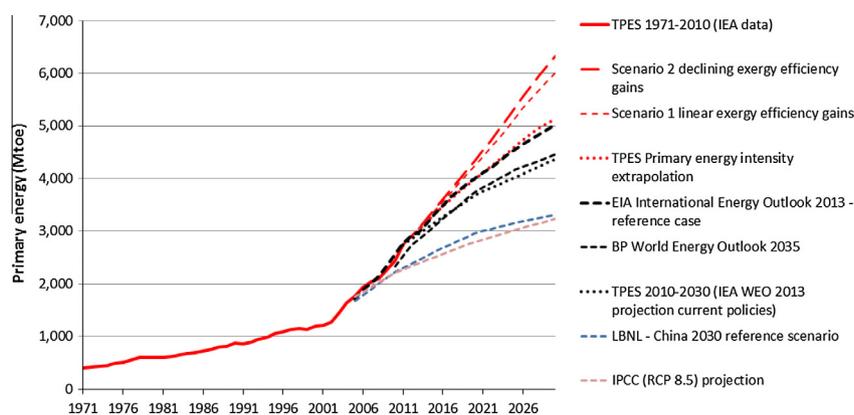


Fig. 9. China – primary energy (TPES) forecasts to 2030.

forecast: the modal shift to cars [67] will reduce mechanical drive exergy efficiency; a rapid increase in residential electricity [3]; and a peaking in the share of HTH allied to a shift to greater residential LTH. Fourth, our extension of useful work based technique projects higher primary energy demand in China by 2030 versus traditional bottom-up energy model estimates (i.e. based on primary or final energy). Further studies investigating the possible reasons (e.g. differences in assumed future energy efficiency savings, structural consumption, energy rebound and efficiency dilution) would therefore be beneficial.

Overall, the useful work method appears a valuable technique to give new insights into Chinese energy consumption and efficiency – past, present and future. Given the implications to future energy demand and associated policies, further research is encouraged. First, work to improve the consistency of the useful work method would be of benefit – such as the treatment of renewables, non-energy use, active/passive system efficiencies, or extending the analysis boundary to include energy services, as others suggest [38,87,96]. Second, contrast the construction of traditional (primary and final energy) versus useful work energy models, to uncover the reasons for energy projection differences. Third, undertake further economic analysis to test the key assumption underpinning this work: that useful work is a more suitable parameter for energy and economic analysis than primary energy. Lastly, policy implications

could be explored – such as how to meet higher (than expected) primary energy demand, or how to amend micro-efficiency policies to capture energy savings before rebound occurs.

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Appendix A. Useful work accounting outputs: China – 1971, 2010

(see Table A1)

Table A1
Useful work accounting outputs: China – 1971, 2010.

Main class, <i>i</i>	Task level, <i>j</i>	1971			2010		
		Useful work U_{ij} PJ	Primary exergy E_{ij} PJ	Exergy efficiency ϵ_{ij} (%)	Useful work U_{ij} PJ	Primary exergy E_{ij} PJ	Exergy efficiency ϵ_{ij} (%)
Heat	LTH (Low Temperature Heating 20 °C)	435	10,103	4.3	973	20,281	4.8
	MTH1 (Medium Temperature Heating 100 °C)	30	247	12.1	592	4428	13.4
	MTH2 (Medium Temperature Heating 200 °C)	301	2657	11.3	1913	10,506	18.2
	HTH (High Temperature Heating 600 °C)	283	2362	12.0	3963	16,695	23.7
	Sub total	1049	15,370	6.8	7441	51,910	14.3
Mechanical Drive	Mechanical drive – Gas/diesel oil (assume diesel road vehicles)	20	114	17.3	821	3728	22.0
	Mechanical drive – Domestic Aviation fuel, jet fuel	0	0	n/a	158	642	24.6
	Mechanical drive – Gasoline fuel (Petrol road vehicles)	42	242	17.3	691	3920	17.6
	Mechanical drive – Diesel/gas oil fuel (Boat engines)	2	17	13.0	188	915	20.5
	Mechanical drive – Industry static motors (diesel engines)	28	118	23.5	522	1934	27.0
	Mechanical drive – Gas/diesel fuel (diesel trains)	1	8	13.0	64	310	20.5
	Mechanical drive – Gas/diesel fuel (tractors)	26	255	10.2	88	799	11.0
	Mechanical Drive – bio-diesel/bio-gasoline (road transport)	0	0	n/a	16	80	n/a
	Mechanical drive – bio-diesel/bio-gasoline (road transport)	0	0	n/a	0	0	n/a
	Mechanical drive – Gas/diesel oil (assume diesel cars)	0	1	20.4	85	385	22.0
	Mechanical drive – Gas fired engines (for pipeline transport)	0	0	n/a	2	7	n/a
	Mechanical drive – Coal (steam powered trains)	7	333	2.2	0	0	n/a
	Mechanical drive – Coal (steam powered boats)	0	0	n/a	0	0	n/a
	Mechanical drive sub-total	126	1090	11.6	2633	12,720	20.7
Electricity	Lighting	1	84	0.8	46	2836	1.6
	Domestic/commercial – Space heating	0	31	1.3	57	3303	1.7
	Domestic – Hot water/cooking	1	21	3.0	47	1272	3.7
	Industry – HTH process heating	16	199	7.9	443	4537	9.8
	Electrolytic end use – Industry	11	153	7.5	370	3490	10.6
	Communications/electric devices	0	0	0.1	1	267	0.3
	Refrigeration/air conditioning	4	307	1.4	144	8221	1.7
	Domestic – Wet/dry motor driven appliances	0	0	10.0	17	138	12.6
	Other mechanical drive motors	123	797	15.4	3537	18,442	19.2
	Electricity – Sub-total	156	1592	9.8	4662	42507	11.0
Muscle work	Human	26	5432	0.5	38	9626	0.5
	Draught animals	131	5229	2.5	88	3533	2.5
	Muscle work – Sub-total	157	10,661	1.5	127	13,159	1.0
Total	Grand total	1488	28,713	5.2	14,863	120,296	12.4

Appendix B. Primary exergy to useful work E-Sankey flowmaps: China – 1971 and 2010

(see Figs. B1 and B2)

China 1971 Primary exergy to useful work flow map

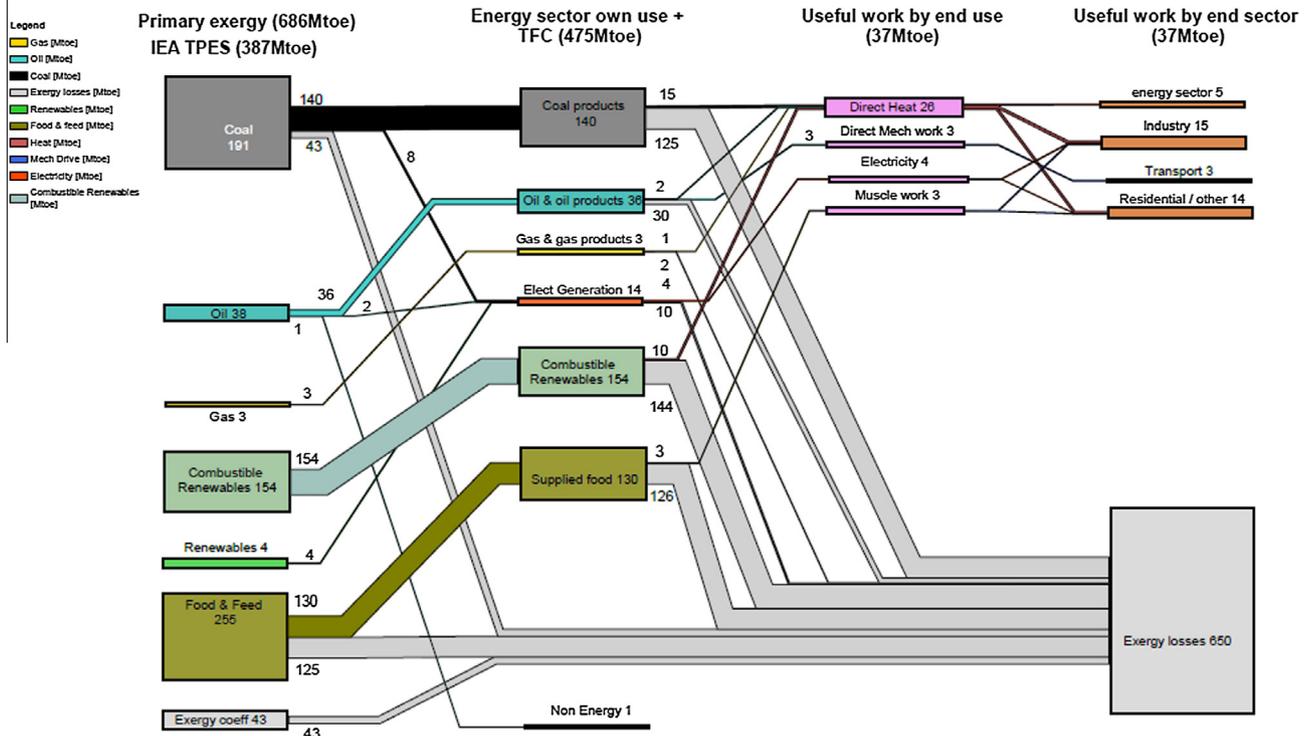


Fig. B1. China E-Sankey Diagram (1971).

China 2010 Primary exergy to useful work flow map

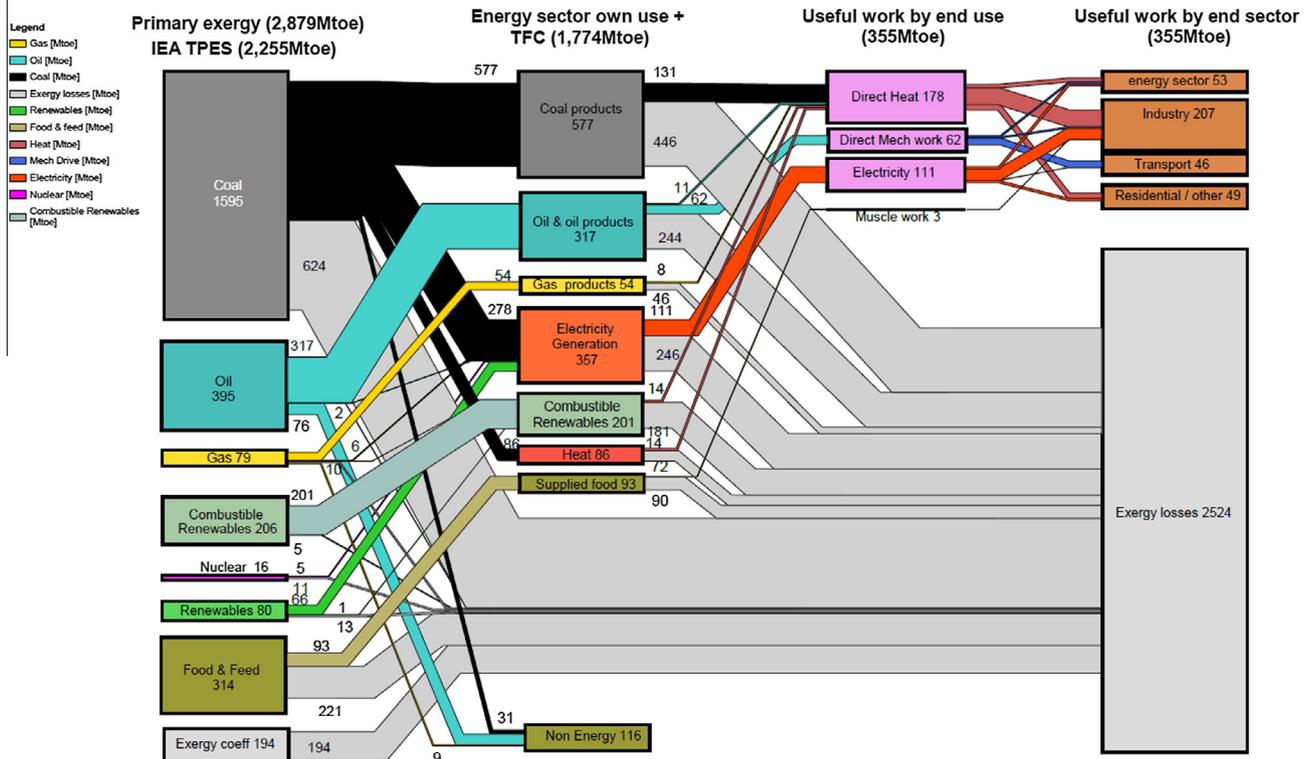


Fig. B2. China E-Sankey Diagram (2010).

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2015.05.082>.

Appendix D. Data Statement. Supplementary material

A complete results file, produced following the methodology and sources described in this paper, has been deposited at the University of Leeds Data Repository at <http://doi.org/10.5518/7>.

References

- [1] International Energy Agency (IEA). Extended world energy balances, IEA World energy statistics and balances (database); 2013. <http://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances/extended-world-energy-balances_data-00513-en>.
- [2] International Energy Agency (IEA). Energy technology perspectives 2012: Pathways to a clean energy system; 2012 <<http://www.iea.org/etp/etp2012/>>
- [3] Letschert VE, Mcneil MA, Zhou N. Residential electricity demand in China – can efficiency reverse the growth? Lawrence Berkeley National Laboratory (LBNL); 2010.
- [4] Energy Foundation China. Background report: vehicle fuel economy in china; 2001 <<http://www.efchina.org/Reports-en/reports-efchina-20030630-2-zh>>.
- [5] International Energy Agency (IEA). Energy technology perspectives 2010: scenarios & strategies to 2050. IEA, France; 2010.
- [6] International Energy Agency (IEA). World energy model documentation 2013 Version; 2013 <http://www.worldenergyoutlook.org/media/weowebiste/2013/WEM_Documentation_WEO2013.pdf>.
- [7] Organisation for Economic Co-operation and Development (OECD). Energy and climate policy: bending the technological trajectory. OECD studies on environmental innovation. OECD Publishing; 2012.
- [8] Hammond GP. Industrial energy analysis, thermodynamics and sustainability. Appl Energy 2007 Jul;84:675–700.
- [9] Rosen MA, Dincer I, Kanoglu M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Pol 2008;36(1):128–37.
- [10] Groscurth HM, Kummel R, van Gool W. Thermodynamic limits to energy optimisation. Energy 1989;14(5):241–58.
- [11] Percebois J. Is the concept of energy intensity meaningful? Energy Econ 1979.
- [12] Serrenho AC, Sousa T, Warr B, Ayres RU, Domingos T. Decomposition of useful work intensity: the EU (European Union) – 15 countries from 1960 to 2009. Energy 2014;76:704–15.
- [13] Warr BS, Ayres RU. Evidence of causality between the quantity and quality of energy consumption and economic growth. Energy Elsevier Ltd 2010;35(4):1688–93.
- [14] Santos J, Domingos T, Sousa T, Aubyn MS. Useful work & economic growth: Portugal. TBC; 1960–2009.
- [15] Guevara Z, Sousa T, Domingos T. An approach for a better evaluation of energy efficiency trends using index decomposition analysis and useful work accounting. Energy Econ 2014.
- [16] Ayres RU, Warr B. Accounting for growth : the role of physical work. Struct Chang Econ Dyn 2005;16:181–209.
- [17] Williams E, Warr B, Ayres RU. Efficiency dilution: long-term exergy conversion trends in Japan. Environ Sci Technol 2008;42(13):4964–70.
- [18] Warr B, Ayres R, Eisenmenger N, Krausmann F, Schandl H. Energy use and economic development: a comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. Ecol Econ. Elsevier B.V 2010;69(10):1904–17.
- [19] Brockway PE, Barrett JR, Foxon TJ, Steinberger JK. Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. Environ Sci Technol 2014;48:9874–81.
- [20] Chen B, Chen GQ. Resource analysis of the Chinese society 1980–2002 based on exergy—Part 4: Fishery and rangeland. Energy Pol 2007;35(4):2079–86.
- [21] Chen GQ, Chen B. Extended-exergy analysis of the Chinese society. Energy. Elsevier Ltd 2009;34(9):1127–44.
- [22] Dai J, Chen B. Extended exergy-based ecological accounting of China during 2000–2007. Procedia Environ Sci 2011;5:87–95.
- [23] Chen B, Chen GQ. Exergy analysis for resource conversion of the Chinese Society 1993 under the material product system. Energy 2006;31(8–9):1115–50.
- [24] Dai J, Chen B, Sciubba E. Extended exergy based ecological accounting for the transportation sector in China. Renew Sustain Energy Rev. Elsevier 2014;32(19):229–37.
- [25] Dai J, Chen B, Sciubba E. Ecological accounting based on extended exergy: a sustainability perspective. Env Resour Econ 2014;48:9826–33.
- [26] Chen B, Dai J, Sciubba E. Ecological accounting for China based on extended exergy. Renew Sustain Energy Rev. Elsevier; 2014.
- [27] Dai J, Fath B, Chen B. Constructing a network of the social-economic consumption system of China using extended exergy analysis. Renew Sustain Energy Rev Elsevier 2012;16(7):4796–808.
- [28] Dai J, Fath B, Chen B. Constructing a network of the social-economic consumption system of China using extended exergy analysis. Renew Sustain Energy Rev Elsevier 2012;16(7):4796–808.
- [29] Ji X, Chen GQ. Exergy analysis of energy utilization in the transportation sector in China. Energy Pol 2006;34(14):1709–19.
- [30] Chen B, Chen GQ, Yang ZF. Exergy-based resource accounting for China. Ecol Modell 2006;196(3–4):313–28.
- [31] Chen B, Chen GQ. Modified ecological footprint accounting and analysis based on embodied exergy – a case study of the Chinese society 1981–2001. Ecol Econ 2006;61:355–76.
- [32] Chen GQ, Qi ZHH. Systems account of societal exergy utilization: China 2003. Ecol Modell 2007 Nov;208(2–4):102–18.
- [33] Wall G. Exergy conversion in the Japanese society. Energy 1990;15(5):435–44.
- [34] Wall G, Sciubba E, Naso V. Exergy use in the Italian society. Energy 1994;19(12):1267–74.
- [35] Sciubba E. Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems. Exergy Int J 2001 Jan;1(2):68–84.
- [36] Ertesvag IS. Society exergy analysis : a comparison of different societies. Energy 2001;26:253–70.
- [37] Reistad G. Available energy conversion and utilization in the United States. ASME Trans Ser J Eng Power 1975;97:429–34.
- [38] Ma L, Allwood JM, Cullen JM, Li Z. The use of energy in China : tracing the flow of energy from primary source to demand drivers. Energy Elsevier Ltd 2012;40(1):174–88.
- [39] Carnahan W, Ford KW, Prosperetti A, et al. Technical aspects of the more efficient utilization of energy: Chapter 2 – Second law efficiency: the role of the second law of thermodynamics in assessing the efficiency of energy use. Am Inst Phys Conf Ser 1975;25:25–51.
- [40] Wall G. Exergy – A useful concept. PhD Thesis, Chalmers Univ Technol Univ Göteborg; 1986 <www.exergy.se/ftp/ex77c.pdf>.
- [41] Ayres RU, Ayres LW, Warr B. Exergy, power and work in the US economy, 1900–1998. Energy 2003;28(3):219–73.
- [42] Serrenho AGCH. Useful Work as an Energy End-Use Accounting Method: Historical and Economic Transitions and European patterns. PhD Thesis, Univ Lisboa; 2014.
- [43] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical and metallurgical processes. New York: Hemisphere; 1988.
- [44] Amecke H, Deason J, Hobbs A, Novikova A, Xiu Y, Shengyuan Z. Buildings energy efficiency in China, Germany, and the United States. San Francisco, USA: Climate Policy Initiative; 2013.
- [45] Murata A, Kondou Y, Hailin M, Weisheng Z. Electricity demand in the Chinese urban household-sector. Appl Energy 2008;85:1113–25.
- [46] Lawrence Berkeley National Laboratory (LBNL). China Energy Databook v8.0; 2013. <<http://china.lbl.gov>>.
- [47] Pachauri S, Jiang L. The household energy transition in India and China. Energy Pol 2008 Nov;36(11):4022–35.
- [48] Catania P. China's rural energy system and management. Appl Energy 1999 Sep;64:229–40.
- [49] Hao H, Wang H, Ouyang M. Fuel consumption and life cycle GHG emissions by China's on-road trucks: Future trends through 2050 and evaluation of mitigation measures. Energy Pol Elsevier 2012;43:244–51.
- [50] Huo H, He K, Wang M, Yao Z. Vehicle technologies, fuel-economy policies, and fuel-consumption rates of Chinese vehicles. Energy Pol Elsevier 2012;43:30–6.
- [51] He K, Huo H, Zhang Q, et al. Oil consumption and CO₂ emissions in China's road transport: current status, future trends, and policy implications. Energy Pol 2005;33(12):1499–507.
- [52] Qunren L, Yushi M. China's transportation and its energy use. Energy Sustain Dev Int Energy Initiat Inc. 2001;5(4):92–9.
- [53] Wang M, Huo H, Johnson L, He D. Projection of Chinese motor vehicle growth, oil demand, and CO₂ emissions through 2050. US: Energy Systems Division, Argonne National Laboratory; 2006.
- [54] Hasanbeigi A, Price L, Aden N. A comparison of iron and steel production energy use and energy intensity in China and the U.S.; 2011 <<http://china.lbl.gov/sites/all/files/lbl-5746e-steel-ei-comparisonjune-2012.pdf>>.
- [55] He F, Zhang Q, Lei J, Fu W, Xu X. Energy efficiency and productivity change of China's iron and steel industry Accounting for undesirable outputs. Energy Pol Elsevier 2013;54:204–13.
- [56] Price L, Sinton J, Worrell E, Phylipsen D, Xiulian H, Ji L. Energy use and carbon dioxide emissions from steel production in China. Energy 2002;27:429–46.
- [57] Hasanbeigi A, Jiang Z, Price L. Analysis of the past and future trends of energy use in key medium- and large-sized Chinese steel enterprises, 2000–2030. Berkeley, USA; 2013 <http://china.lbl.gov/sites/all/files/steel_decom_analysis.pdf>.
- [58] Hasanbeigi A, Price L, Fino-chen C, Lu H, Ke J. Retrospective and prospective decomposition analysis of Chinese manufacturing energy use, 1995–2020; 2013 <http://eetd.lbl.gov/sites/all/files/6028e_decom_analysis.060313.pdf>.
- [59] Hao H, Wang H, Ouyang M. Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China's passenger vehicle fleet. Energy Elsevier Ltd 2011;36(11):6520–8.
- [60] Teter J. China transport efficiency data. UC Davis data sent by email to author; 2014.

- [61] National Climatic Data Centre. National climatic data centre – climate data online: dataset discovery; 2014 <<http://www.ncdc.noaa.gov/cdo-web/datasets>>.
- [62] Department of Energy & Climate Change (DECC). Energy Consumption in the UK: 2013; 2013 <<http://www.decc.gov.uk/en/content/cms/statistics/publications/ecuk/ecuk.aspx>>.
- [63] Edwards RD, Smith KR, Zhang J, Ma Y. Implications of changes in household stoves and fuel use in China. *Energy Pol* 2004;32:395–411.
- [64] Ross M, Feng L. The energy efficiency of the steel industry of China. *Energy* 1991;16(5):833–48.
- [65] Phylipsen D, Blok K, Worrell E, De Beer J. Benchmarking the energy efficiency of Dutch industry : an assessment of the expected effect on energy consumption and CO₂ emissions. *Energy Pol* 2002;30:663–79.
- [66] Saygin D, Patel M, Tam C, Gielen D. Chemical and petrochemical sector: potential of best practice technology and other measures for improving energy efficiency. IEA Inf Pap; 2009 <http://www.iea.org/publications/freepublications/publication/chemical_petrochemical_sector.pdf>.
- [67] Fridley D, Zheng N, Zhou N, Ke J, Hasanbeigi A, Price L. China energy and emissions paths to 2030 (2nd Edition). Lawrence Berkeley National Laboratory (LBNL); 2012.
- [68] Brockway PE, Barrett JR, Foxon TJ, Steinberger JK. Supporting information – divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. *Environ Sci Technol* 2014;48:S1–S39.
- [69] Laux R, Werner B, Knight I, Djerf K. Modernising China's labour market statistics. *Labour Mark Trends* April 2003;2003:203–11.
- [70] Brooks R, Tao R. China's labor market performance and challenges. International Monetary Fund (IMF) working paper WP/03/210; 2003.
- [71] Wirsenius S. Human Use of Land and Organic materials: Modeling the Turnover of Biomass in the Global Food System [Internet]. PhD Thesis, Chalmers Univ Technol; 2000 <<http://publications.lib.chalmers.se/records/fulltext/827.pdf>>.
- [72] Food and Agricultural Organisation of the United Nations (FAOSTAT). Food supply kcal/day; 2013 <http://faostat3.fao.org/faostat-gateway/go/to/download/C/*E>.
- [73] Smil V. Energy in world history. Boulder (Colorado, USA): Westview Press; 1994.
- [74] Ramaswamy NS. Draught animals and welfare. *Rev Sci Tech Off Int Epiz* 1994;13(1):195–216.
- [75] Down to Earth. 65 million draught animals; 2004 <<http://www.downtoearth.org.in/node/11947>>.
- [76] Wilson RT. The environmental ecology of oxen used for draught power. *Agric Ecosyst Environ* 2003;97:21–37.
- [77] O'Neill DH, Kemp DC. A comparison of work outputs of draught oxen. *J Agric Engng Res* 1989;43:33–44.
- [78] Krausmann F, Erb K, Gingrich S, Lauk C, Haberl H. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. *Ecol Econ* 2007;65:471–87.
- [79] Guan D, Liu Z, Geng Y, Lindner S, Hubacek K. The gigatonne gap in China's carbon dioxide inventories – supporting information. *Nat Clim Chang* 2012.
- [80] Wang C, Chen J, Zou J. Decomposition of energy-related CO₂ emission in China: 1957–2000. *Energy* 2005;30(1):73–83.
- [81] Xu X, Zhao T, Liu N, Kang J. Changes of energy-related GHG emissions in China: an empirical analysis from sectoral perspective. *Appl Energy Elsevier Ltd* 2014;132:298–307.
- [82] Liu L-C, Fan Y, Wu G, Wei Y-M. Using LMDI method to analyze the change of China's industrial CO₂ emissions from final fuel use: an empirical analysis. *Energy Pol* 2007 Nov;35(11):5892–900.
- [83] Zhang M, Li H, Zhou M, Mu H. Decomposition analysis of energy consumption in Chinese transportation sector. *Appl Energy Elsevier Ltd* 2011;88(6):2279–85.
- [84] World Bank. GDP (constant 2005 US\$); 2014 <<http://data.worldbank.org/indicator/NY.GDP.MKTP.KD>>.
- [85] World Bank, The Development Research Center of State Council the People's Republic of China. China 2030: Building a Modern, Harmonious, and Creative Society; 2012 <<http://www.worldbank.org/content/dam/Worldbank/document/China-2030-complete.pdf>>.
- [86] Goldemberg J. Viewpoint leapfrog energy technologies. *Energy Pol* 1998;26(10):720–41.
- [87] Nakicenovic N, Gilli PV, Kurz R. Regional and global exergy and energy efficiencies. *Energy* 1996;21(3):223–37.
- [88] Liddle B. Revisiting world energy intensity convergence for regional differences. *Appl Energy Elsevier Ltd* 2010;87(10):3218–25.
- [89] International Energy Agency (IEA). World energy outlook 2013. Paris, France; 2013.
- [90] US Energy Information Administration (USEIA). World primary energy consumption. *Int Energy Outlook 2014*; 2014 [cited 2014 Nov 5] <<http://www.eia.gov/oiiaf/aeo/tablebrowser/#release=IEO2013&subject=1-IEO2013&table=1-IEO2013®ion=0-0&cases=Reference-d041117>>.
- [91] British Petroleum (BP) Ltd. World Energy Outlook 2035 – Excel Tables. *World Energy Outlook 2035*; 2014 [cited 2014 Nov 5] <<http://www.bp.com/en/global/corporate/about-bp/energy-economics/energy-outlook/energy-outlook-downloads.html>>.
- [92] IIASA. MESSAGE LIMITS-base (RCP 8.5) Total Primary Energy Consumption data. LIMITS Scenar. Database (version 1.0.0); 2014 [cited 2014 Nov 5] <<https://tntcat.iiasa.ac.at/LIMITSPUBLICDB/dsd?Action=htmlpage&page=series>>.
- [93] Smil V. Perils of long-range energy forecasting : reflections on looking far ahead. *Technol Forecast Soc Change* 2000;65:251–64.
- [94] Ayres RU, Turton H, Casten T. Energy efficiency, sustainability and economic growth. *Energy* 2007;32:634–48.
- [95] Schipper L, Grubb M. On the rebound? Feedback between energy intensities and energy uses in IEA countries. *Energy Pol* 2000;28(6–7):367–88.
- [96] Ayres RU. Eco-thermodynamics: economics and the second law. *Ecol Econ* 1998 Aug;26(2):189–209.