BIEE Conference Paper: *How peaking of exergy efficiency may lead to rising energy demand in OECD countries and an underestimate of non-OECD energy consumption growth*

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Abstract

As the world's largest consumer of energy, China is of key significance to global energy systems and policies. It is therefore important to use a wide range of energy analysis techniques to gain different perspectives on China's historic and predicted energy use. Such diversity includes the study of useful work – i.e. energy used at the energy services stage – which we employ to address a central research question: *what are the drivers of China's energy efficiency and the implications for China's energy supply in 2030?*

To start, the longest time-series yet (1971-2010) of China's exergy efficiency and useful work is calculated. This finds a 10-fold growth since 1971 in China's useful work, which in turn has been supplied by a 4-fold increase in primary energy coupled to a 2.5-fold gain in aggregate exergy efficiency: from 5% to 12%. This places China midway between the US (11%) and UK (15%), suggesting possible 'technological leapfrogging' – i.e. adopting high efficiency devices. However, by using structural decomposition, the weighting of energy efficiency drivers are identified, and shows instead China's position is based on 'efficiency concentration': i.e. increasing reliance on efficient - but still very energy intensive - heavy industrial activities.

The implications of efficiency drivers on future energy demand are tested via two distinct efficiency scenarios for China to 2030. First, a 'stable efficiency gains' scenario projects a growth of exergy efficiency for the period 2010-2030 at the same rate as that for 1990-2010. The primary energy required in 2030 in this scenario matches closely the IEA's 'current trends' forecast. Second, under a 'declining efficiency gains' scenario, exergy efficiency stabilises at around 14%, simulating a situation in which China combines approaching asymptotic exergy efficiency limits with structural stagnation in its maturing economy, and so enters 'efficiency dilution'. The 'declining efficiency gains' scenario shows that, for the same amount of useful work in 2030, a 13% higher primary energy demand would be needed. The implication is therefore that energy demand may be significantly underestimated when national-scale exergy efficiency peaks in the future, if models fail to account properly for second law thermodynamic limits coupled to efficiency dilution effects.

1. Introduction

1.1. Exergy and useful work accounting

China has the largest global share of primary energy consumption and energy related carbon emissions of any country in the world. To inform future global economic and energy policies, much effort is expended on understanding China's historic energy consumption (e.g. (International Energy Agency (IEA) 2012; Letschert et al. 2010; Energy Foundation China 2001)). Similar efforts are placed on predicting future energy demand: using top-down econometric assumptions of primary energy supply, or bottom-up energy efficiency forecasts at the device level (International Energy Agency (IEA) 2010; International Energy Agency (IEA) 2013b; Organisation for Economic Co-operation and Development (OECD) 2012). Given the importance of China to global energy systems, it is important to study energy consumption using a wide variety of tools. Such breadth includes useful work accounting, which takes a broader whole system approach to energy analysis on a second law thermodynamic basis, giving a more complete picture of the useful energy involved at the end (economic transaction) stage.

Exergy is the starting point of the analysis, and can be thought of as 'available energy' (Reistad, 1975). At a whole system level, the 'primary exergy' of all energy carriers (e.g. coal, oil, gas, renewables, food and feed) into the national-economy are calculated. Next this primary exergy is transformed into ready to use 'final energy' (e.g., diesel or electricity) is then used for various end processes (i.e. heat, mechanical work, muscle work and electricity applications). The amount of residual useful energy consumed at this end stage is called 'useful work'. A visualisation of the flow of primary exergy to end useful work is given in Figure 1:

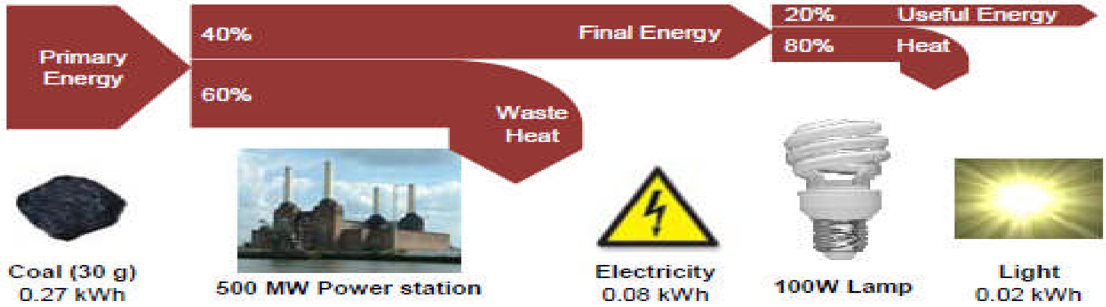

Figure 1: conceptual diagram of exergy to useful energy (useful work), (Courtesy of IST, Lisbon)

1.2. Research framing

Recent work (Brockway et al. 2014) suggests that the US and UK may have reached or be reaching a peak in aggregate exergy efficiency, due to asymptotic efficiency limits arriving at the same time as efficiency dilution. In short: gains from individual technologies are being overtaken by using increasing amounts of less efficient processes, like air-conditioning. This poses the question: could the same be happening in China?' Therefore this paper undertakes a useful work accounting study to China to answer the research question: *what are the drivers of China's energy efficiency and the implications for China's energy supply in 2030?* Three sub-questions were devised:

- *What is China's historical exergy efficiency trend and is it also exhibiting peaking and dilution effects?*
- *What are structural and efficiency drivers behind changes to China's exergy efficiency,*
- *What does this mean for China's future energy efficiency and supply policies?*

The paper proceeds as follows. First, a 1971-2010 exergy efficiency and useful work analysis is undertaken for China, to derive primary exergy, exergy efficiency and consequently end useful work results for this period. Secondly, a Log Mean Divisia Index (LMDI) analysis is undertaken for the period 1971-2010 on the new China and previous US and UK results. Third, the useful work accounting technique is then applied to study differences in forecasts of China's energy demand in 2030 based on two efficiency scenarios. Following this Introduction, Methods and Data are presented in Section 2, Analysis Results are in Section 3, with Conclusions in Section 4.

2. Methods and Data

2.1. Historical analysis (1971-2010)

2.1.1. Overview

Carnahan et al (Carnahan et al. 1975) defined 'useful work' as "the minimum exergy input to achieve that task work transfer". 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} is therefore:

$$\varepsilon_{ij} = \frac{\textit{Useful work,Uij}}{\textit{Primary Exergy,Eij}} = \frac{\textit{The minimum exergy input to achieve that task work transfer}}{\textit{Maximum amount of reversible work done as system reaches equlibrium}} \qquad \textbf{Equation 1}$$

The task-level exergy efficiency data can then be combined with the input exergy data to arrive at estimates of aggregate useful work and national exergy efficiency as shown in Equation 2 and 3. Equation 2 implies that growth in aggregate useful work for an economy is given by the growth in primary exergy input times the increase in national exergy efficiency.

$$\Sigma\, \boldsymbol{Useful\ work} \;=\; \Sigma\, \boldsymbol{E_{ij}}\, \varepsilon_{ij} \qquad \textbf{Equation 2}$$

$$\varepsilon_{tot} \;=\; \frac{\Sigma\, Useful\ work}{\Sigma Primary\ Exergy} \qquad \textbf{Equation 3}$$

Recent work by Serrenho et al (Serrenho et al. 2013; Serrenho et al. 2014) developed useful work accounting on a consistent IEA-based input energy and mapping basis. Brockway et al (Brockway et al. 2014) made further advances to electricity end use and mechanical drive sectors, which has also been used in this study for consistency and comparability. Figure 2 gives an overview of the basic stages:

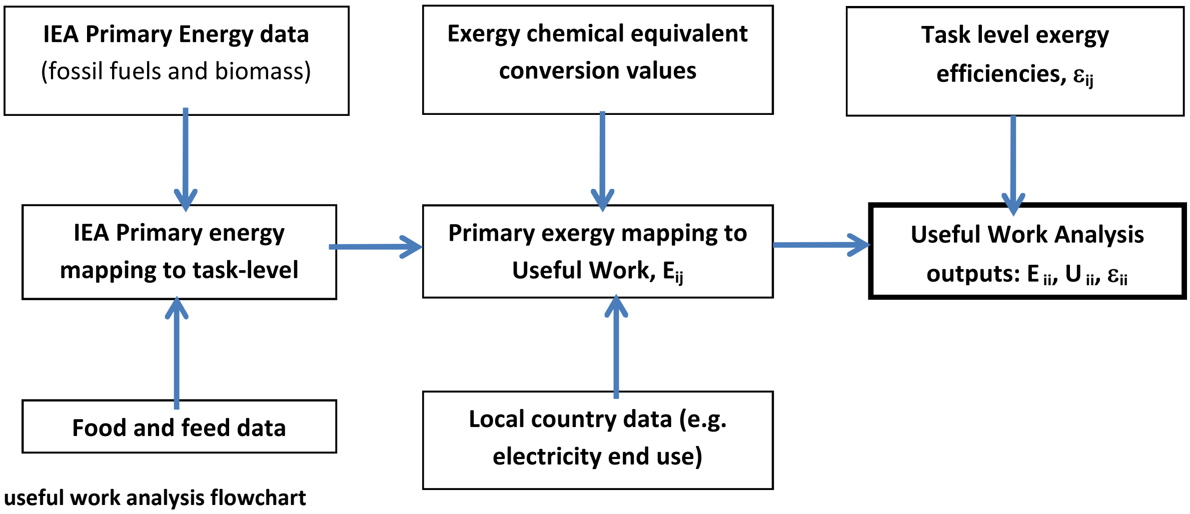

Figure 2: useful work analysis flowchart

2.1.2. Input data

Various primary exergy data sources are used. The IEA energy datasets 1971-2010 (International Energy Agency (IEA) 2013a) for fossil fuel and biomass (combustible renewables) were used. The Total Primary Energy Supply (TPES) values were converted to exergy on a chemical equivalent basis (Szargut et al. 1988), which is around 5% higher than the TPES value. For muscle work, estimates of input food and feed requirements were based on estimated manual labour populations and their food supply (Food and Agricultural Organisation of the United Nations (FAOSTAT) 2013; Wirsenius 2000; Ramaswamy 1994; Krausmann et al. 2007). These inputs were then mapped to task-level end uses (e.g. low temperature heat), in a very similar manner to that described in detail for the UK-US analysis (Brockway et al. 2014).

Exergy conversion calculations are largely based on those used for the previous UK-US analysis (Brockway et al. 2014), supplemented by local Chinese end consumption data for electricity end uses (Amecke et al. 2013; Murata et al. 2008) and transport (Hao et al. 2012; Huo et al. 2012; He et al. 2005; Qunren & Yushi 2001; Wang et al. 2006)and industry (Hasanbeigi et al. 2011; He et al. 2013; Price et al. 2002; Hasanbeigi, Jiang, et al. 2013; Hasanbeigi, Price, et al. 2013)

Lastly, a note on data quality. For input energy data, the IEA data was checked versus the LBNL datasets taken from the Chinese statistical yearbook, and close agreements were found. Nevertheless, an aggregate error remains between national and regional datasets, as described by Guan et al (Guan et al. 2012), where the true primary energy use in China is believed to be ~10% higher. However, as the accounting discrepancy means our national-level datasets underestimate actual primary energy use, coupled to the consistency of such errors, the overall effect is limited for our trends analysis. Regarding task-level efficiencies, whilst our data sources are weaker in many instances than the previous UK-US studies due to data coverage, the overall trends and comparison to UK-US results remain of valid use.

2.1.3. Useful work accounting outputs

Table 1 shows the data outputs: useful work, primary exergy and exergy efficiency at a task-level, which can then be aggregated to a category (e.g. heat, mechanical drive) or national-scale. This data can then be summed (to give overall estimate for main class or country-scale useful work or exergy efficiencies, or used in task-level format as inputs to the LMDI analysis.

Table 1: useful work accounting analysis outputs, (China, 1971)

Main class, i	Task level, j	1971		
		Useful work	Primary exergy	Exergy efficiency
		U_{ij}	E_{ij}	ε_{ij}
		TJ	TJ	%
Heat	LTH	448,189	9,548,743	4.7%
	MTH1	31,076	233,827	13.3%
	MTH2	314,016	2,511,153	12.5%
	HTH	295,187	2,232,430	13.2%
Mechanical Drive	Road	61,681	357,075	17.3%
	Rail	9,973	356,957	2.8%
	Air	0	0	n/a
	Static motors	30,900	118,389	26.1%
	other	28,307	272,351	10.4%
Electricity	lighting	649	78,119	0.8%
	Domestic/commercial - space heating	381	28,347	1.3%
	Domestic - hot water/cooking	580	19,571	3.0%
	Industry - HTH process heating	14,547	184,301	7.9%
	electrolytic end use - industry	10,630	141,770	7.5%
	Communications / electric devices	0	0	n/a
	Refridgeration / air con	3,742	284,157	1.3%
	Domestic - wet/dry motor driven appliances	31	308	10.1%
	Other mechanical drive motors	113,393	737,204	15.4%
Muscle work	Human	25,904	5,431,795	0.5%
	Animals	130,724	5,228,957	2.5%
Total		**1,519,909**	**27,765,455**	**5.5%**

2.1.4. Structural decomposition

Log mean divisia index (LMDI) structural decomposition is a popular technique for analysing drivers of changes in CO_2 emissions (e.g.(Wang et al. 2005; Liu et al. 2007)) and sectoral energy use such as manufacturing (e.g.(Ang 2004; Prasetio & Sorapipatana 2013)). Much of the switch from previous decomposition methods such as Malmquist (e.g. (Zhou et al. 2010; Wei et al. 2007) has been driven by B.W.Ang, who deserves great credit for his efforts in this field (e.g. (Ang et al. 2003; Ang 2005) such that it is now the mainstream decomposition technique (Su & Ang 2012).

Using the LMDI approach, we expand Equation 2 (U = $\Sigma E_{ij}\ \varepsilon_{ij}$) to yield Equation 4, such that it is based on useful work (U) and primary exergy (E) at task-levels, so that the useful work accounting results (as shown in Table 1) are used as input data for the LMDI analysis.

$$\boldsymbol{U} = \sum_{ij} \boldsymbol{U_{ij}} = \sum_{ij} \boldsymbol{E} \frac{\boldsymbol{E_i}}{\boldsymbol{E}} \frac{\boldsymbol{E_{ij}}}{\boldsymbol{E_i}} \frac{\boldsymbol{U_{ij}}}{\boldsymbol{E_{ij}}} \qquad \text{Equation 4}$$

$$D_{tot} = U^T/U^0 = D_{ex}D_{Str}D_{diL}D_{efF} \qquad \text{Equation 5}$$

From equation 4, equation 5 is derived which gives the four drivers as: Input Exergy (D_{ex}); Main class structure (D_{Str}); sub-class (i.e. task) level structural change (D_{dil}); task-level efficiency (D_{eff}). The LMDI analysis then calculates the weight of impact that four drivers have to cause changes in end useful work (U).

2.2. China energy demand scenarios 2010-2030

The 1971-2010 results were used as the basis for investigating future energy demand based on different scenarios of exergy efficiency. Step 1 is to calculate an estimate of useful work in 2030. To do this, overall useful work energy intensity (UW/GDP) is calculated for 1971-2010, using historical GDP data (World Bank 2014), and then extrapolating using a best-fitting curve to 2030. Next using World Bank forecasts of GDP to 2030 (World Bank & The Development Research Center of State Council the People's Republic of China 2012) China's estimated total useful work (to deliver that GDP) in 2030 is determined.

Step 2 splits the total forecast useful work to 2030 into task-level allocations. This is done by balancing projections of previous useful work 1990-2010 from the main analysis against IEA forecasts of forecasts of energy demand to 2030 under a current policies '6 Degrees' warming scenario. (International Energy Agency (IEA) 2014).

Then in Step 3, task-level exergy efficiencies are projected to 2030 under stable (Scenario 1) and declining (Scenario 2) gains assumptions. In these scenarios, a proportion of the 1990-2010 Compound Annual Average Growth Rate (CAAGR) of task-level exergy efficiency is assumed for the period 2010-2030 as given in Table 2:

Table 2: task-level efficiency growth for Scenario 1 and 2

Future decade	% of 1990-2010 task-level CAAGR adopted for given scenarios	
	Scenario 1 (stable efficiency gains)	Scenario 2 (declining efficiency gains)
2010-2020	100%	50%
2020-2030	100%	25%

Lastly in step 4, the same calculation approach is run as for the main 1971-2010 analysis to derive an estimate of the total primary exergy demand for 2010-2030, using Equation 6 below, as based on the projection of total useful work (U) and exergy efficiencies under the two scenarios (ε_1, ε_2), estimates of primary exergy (E_1, E_2) are derived. To convert from primary exergy to energy the chemical exergy conversion ratios are removed, to reveal the TPES projections to 2030 under these two scenarios. The differences tell us about the impact that declining exergy efficiency gains have on primary energy demand versus a continuation of the current 'stable gains' scenario.

$$U = E_1\,\varepsilon_1 = E_2\,\varepsilon_2 \qquad \textbf{Equation 6}$$

3. Results

3.1. 1971-2010 useful work accounting results

3.1.1. China

Figure 3 shows China's end useful work has increased 10 fold since 1971, with the most significant rises in direct heat (particularly for industry) and electricity applications, as given in Figure 4.

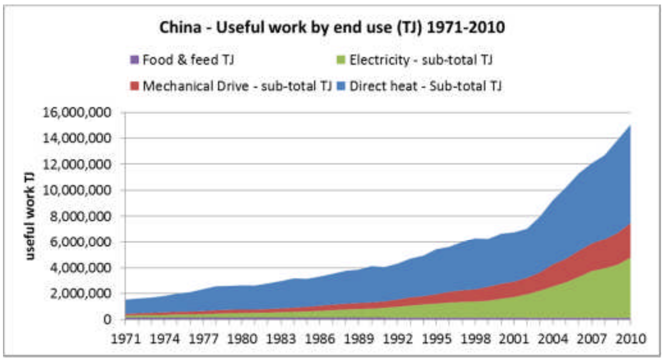

Figure 3: China – useful work by end use 1971-2010

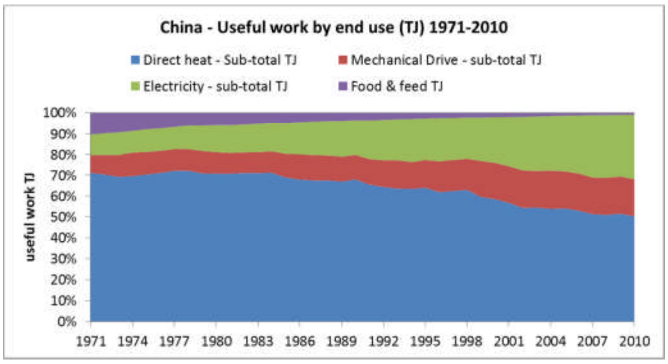

Figure 4: China – useful work by end use 1971-2010

This 10-fold useful work gain has been delivered by a 4-fold growth in primary exergy, as shown in Figure 5. Figure 6 shows the industrialisation of China: muscle work remains around the same value (100,000 TJ) but declines as a proportion of exergy inputs from 30% (1971) to 10% (2010), whilst conversely electricity has grown from 10% to 40% of primary exergy inputs.

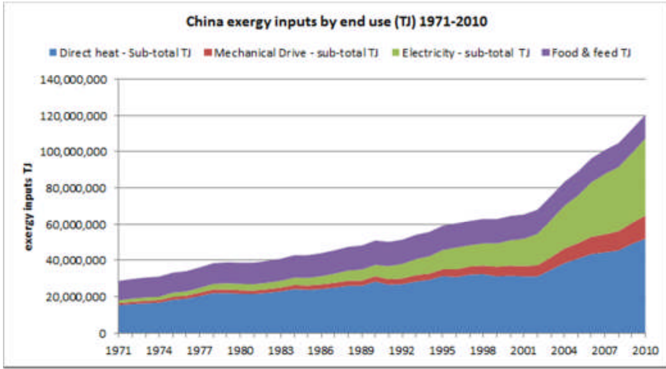

Figure 5: China exergy inputs by end use 1971-2010

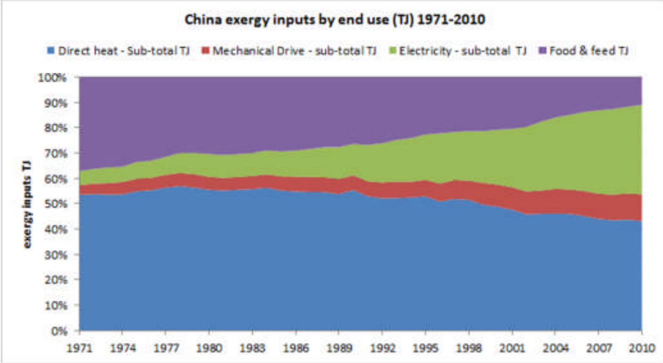

Figure 6: China exergy inputs by end use 1971-2010

The gain in overall exergy efficiency from 5% (1971) to 12% (2010) supplies the remaining 2.5-fold factor in useful work growth, as shown in Figure 7. There are two key drivers pushing the almost linear rise in overall exergy efficiency. The first is the strong efficiency growth is seen in both mechanical drive and heat sectors, which make up over half of total primary exergy inputs. The second is the decline in muscle work, which was a major component in 1971 but now less than 10% of exergy input. Thus the low muscle work efficiency (~2%) has much more impact in 1971 of pulling down overall efficiency than it does by 2010.

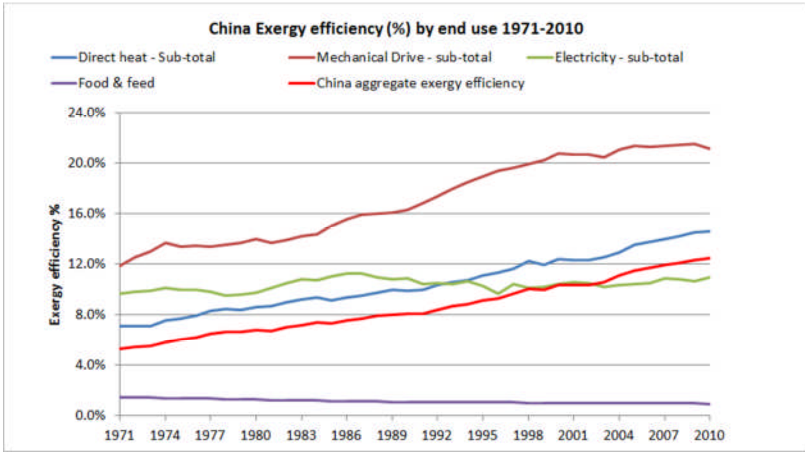

Figure 7: China's exergy efficiency by end use 1971-2010

Figure 6 and Figure 7 also reveal how the 1971-2010 linear growth cannot continue: the structural shift to industry from agriculture is slowing; mechanical drive efficiency has peaked; the diluting shift to electricity use in increasing. This has important implications for future, as is seen now in Figure 8, which shows the contributions to useful work changes in China since 1971. It shows how China's 10-fold growth in useful work 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%. So to service useful work growth, exergy efficiency gains reduce the required rate of increase of primary exergy. Or to put it another way: if China's exergy efficiency had stayed flat, the 10-fold gain in useful work would have required a 10-fold gain in primary exergy.

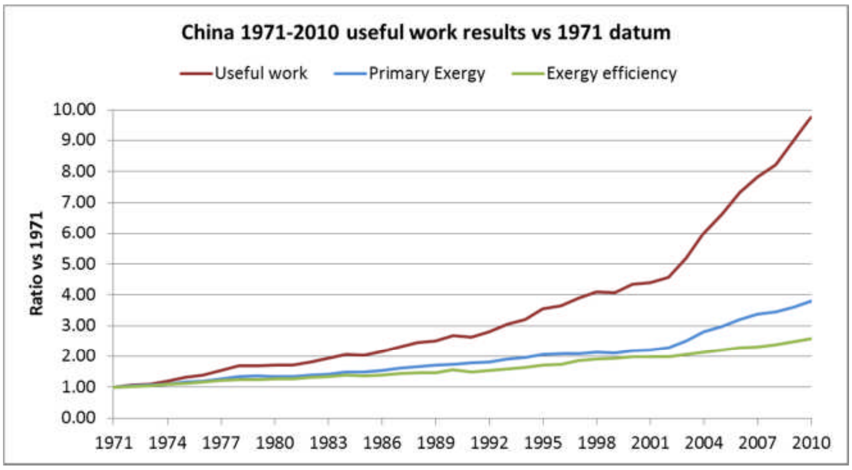

Figure 8: China 1971-2010 useful work results vs 1971 datum

To understand the overall flow of exergy to end useful work, and the exergy losses that occur during the various conversion processes, Sankey diagram of China are in given in Figure 9 for 2010. It shows the domination of fossil fuels in the economy in 2010 and the move to energy intensive end uses, particularly in industry.

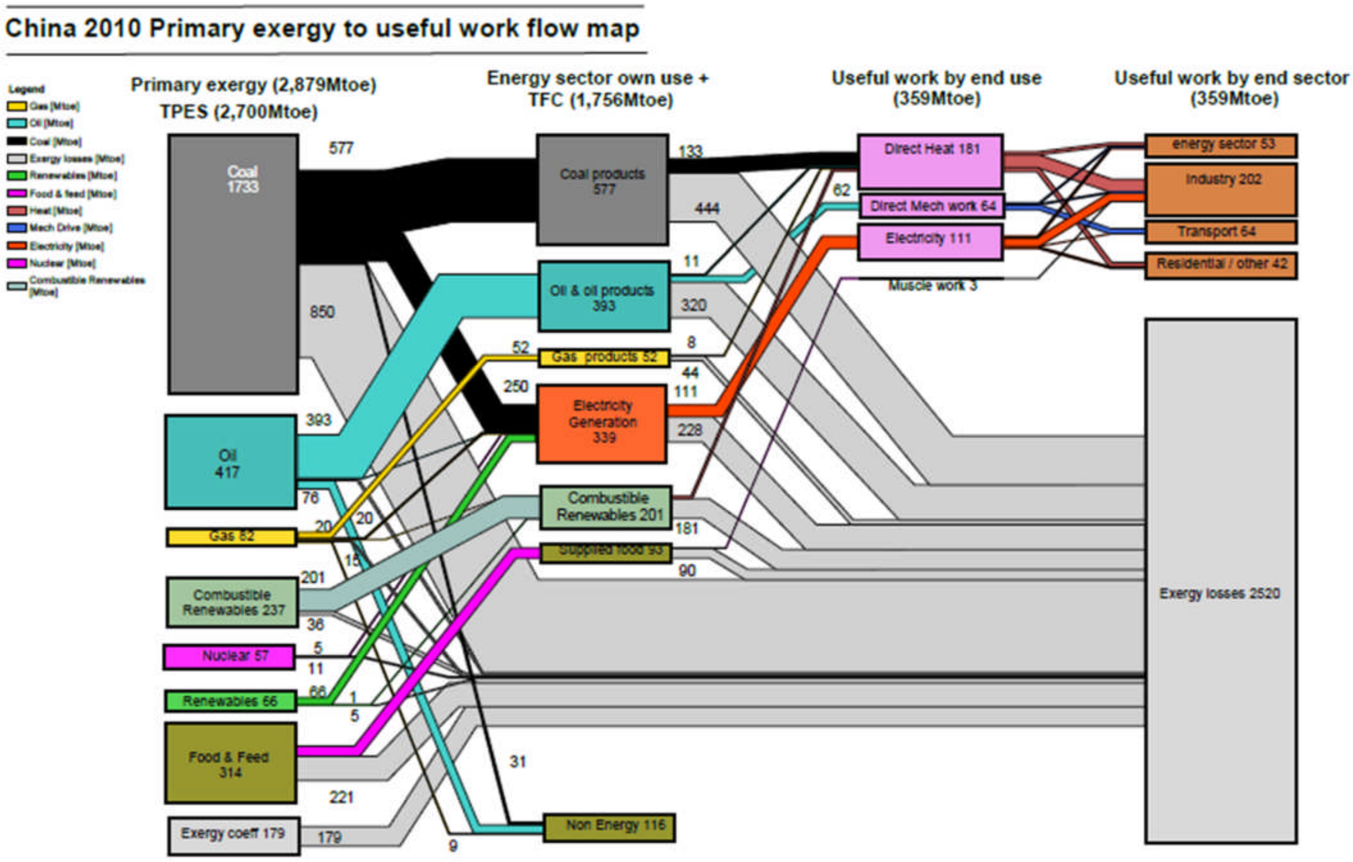

Figure 9: China Sankey Diagram (2010)

3.1.2. Comparison to US-UK useful work and exergy efficiency results

The previous UK-US 1960-2010 results (Brockway et al, 2014) are interesting to contrast at this point. For comparison the same time frame is selected (1971-2010) and the results are displayed in Figure 10, which shows the rising UK efficiency (11% to 15%), the stable US (10% to 11%) and rising China efficiency (6% to 13%). China's exergy efficiency overtakes the US by around 2004.

At first, it is tempting to see China's overtaking the US in aggregate efficiency as technological leapfrogging (e.g. (Goldemberg 1998)). 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 implies structural differences lie at the heart of China's increasing efficiency: i.e. its industrial economy uses more high temperature heat and industrial processes versus the mature economies of US and UK. In turn it also implies as China's economy also matures and its structural composition shifts towards that of the UK and US that this will be a diluting effect on its overall exergy efficiency.

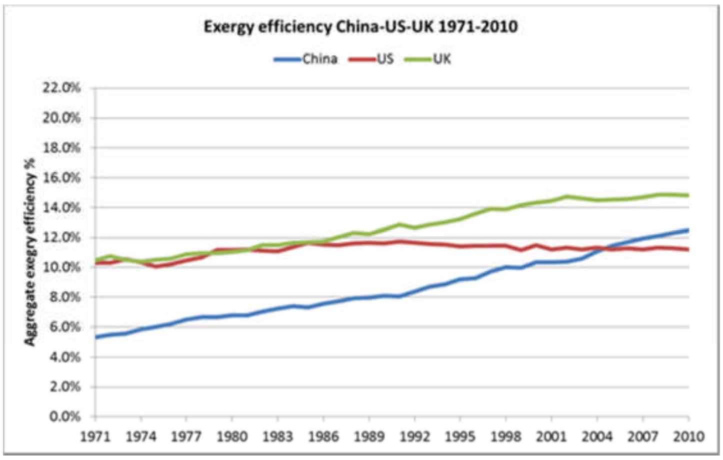

Figure 10: exergy efficiency 1971-2010 for China, US and UK

3.2. LMDI decomposition results

These multiplicative factors are summarised below in Table 3 for the period 1971-2010. In the table, the Dstr (primary class) and Ddil (task-level) factors are multiplied to get an overall structural change factor, which for the UK and US are both below 1.00, meaning overall structural dilution has occurred in both countries, but is offset for the UK by growth in task-level efficiency. This result was not identified explicitly in previous work (Brockway et al. 2014), as this did not use LMDI analysis. China overall structural change factor is well above 1.00 (1.64), meaning structural 'concentration' has occurred as we might expect from its transition from agricultural to industrial powerhouse.

Table 3: summary of LMDI decomposition factors 1971-2010 for China, US, UK

Country	U Useful work	Dex Primary Exergy	Dstr Main sector structural change	Ddil Sub-sector structural change	Deff Task-level efficiency
China	9.80	3.79	1.37	1.20	1.56
US	1.53	1.33	1.03	0.88	1.28
UK	1.42	1.05	1.03	0.87	1.51

Country	U Useful work	Dex Primary Exergy	Dstr*Ddil Overall structural change	Deff Task-level efficiency
China	9.80	3.79	1.64	1.56
US	1.53	1.33	0.91	1.28
UK	1.42	1.05	0.90	1.51

However, Figure 11 suggests whilst there has been no medium term dilution in China (i.e. value below 1.00 for 5 of more consecutive years), the most recent period (since 2004) shows a steady decline in structural concentration towards 1.00. If structural concentration reaches a peak (since it cannot continue indefinitely), then this plot may suggest that efficiency dilution may occur soon, i.e. if that downward trend continues.

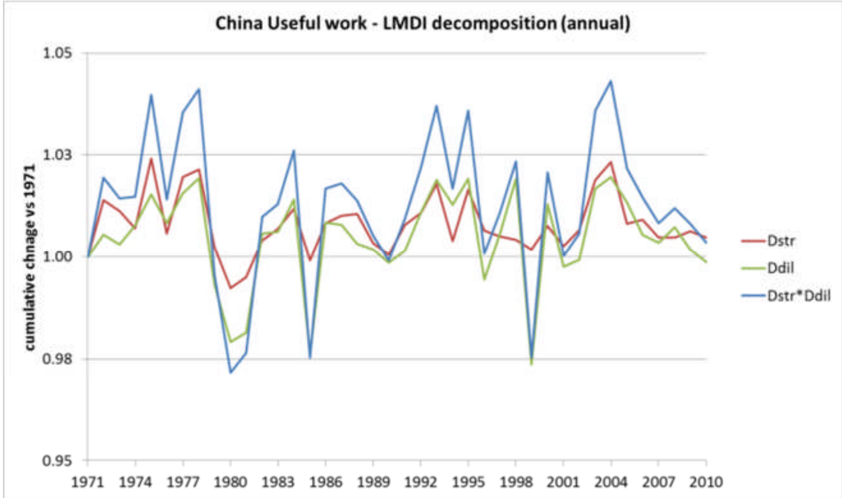

Figure 11: Testing for China efficiency dilution

3.3. Future exergy efficiency: impacts on primary energy projections

3.3.1. Useful work projection to 2030

Percebois (Percebois 1979) wrote that useful energy (useful work) intensity (relative to GDP) was more meaningful than primary energy intensity. This is an interesting observation, as to calculate future primary energy demand in 2030, the first step is to use useful work intensity to estimate total useful work in 2030. Figure 12 shows the useful work intensities based on 2005$US for GDP. It shows a decline in useful work intensity (at constant prices) over time whilst convergence with the UK and US is some way off.

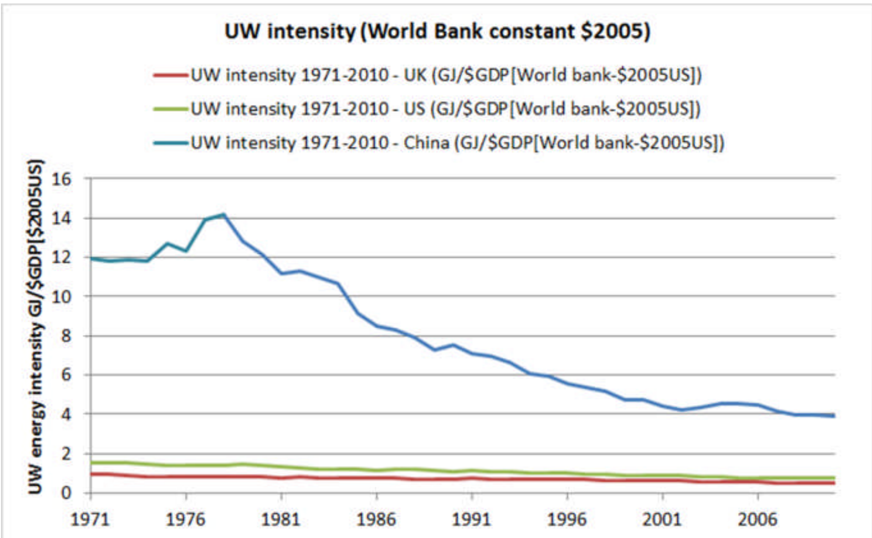

Figure 12: Useful work intensity (UW/GDP [2005$US]))

Next, useful work intensity was projected for China using a best-fitting curve, as shown in Figure 13. The GDP forecast for China to 2030 (World Bank & The Development Research Center of State Council the People's Republic of China 2012) then allows an estimate of required useful work in 2030 to deliver that level of GDP.

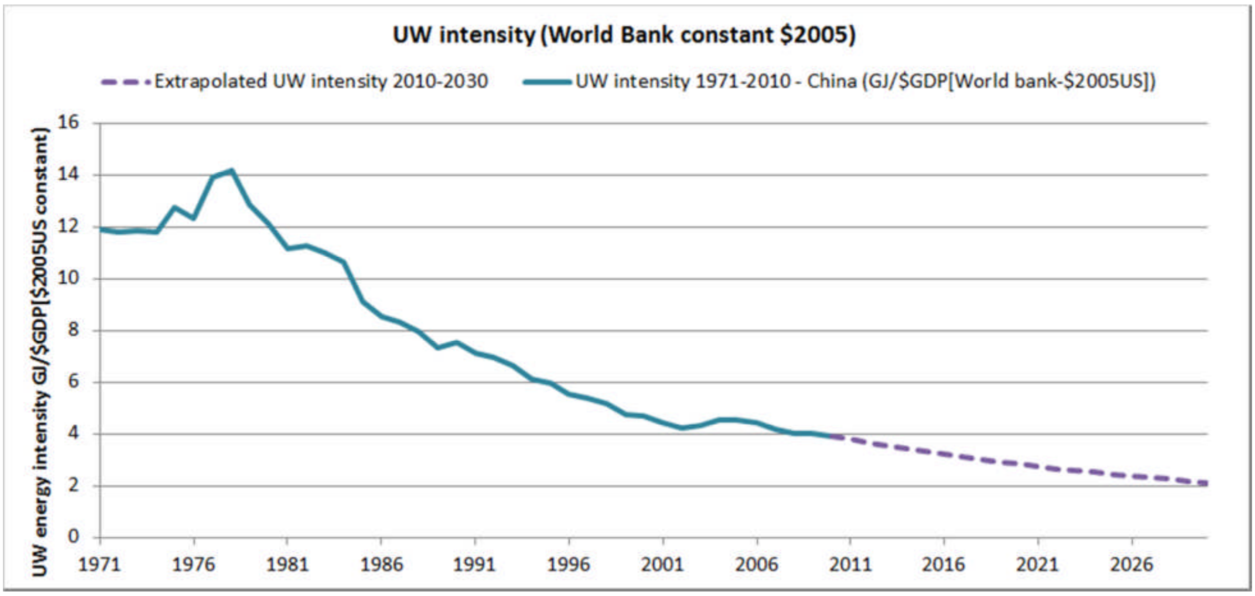

Figure 13: projecting useful work intensity for China 2010-2030

3.3.2. Allocation of task-level useful work

Next, Task-level useful work is projected, based on two strands noted earlier: IEA allocations of final energy in its current trends (6 degrees warming) scenario (International Energy Agency (IEA) 2014), and also the useful work growth in each task-level for 1990-2010 from the main 1971-2010 analysis. The resultant plot in Figure 14 forecasts useful work to nearly double in the next 20 year period. The figure also includes a check from the top-down econometric (UW/GDP) forecast, and shows close agreement with the bottom-up exergy model. On that basis the 2010-2030 model is suitable to calculate primary energy inputs.

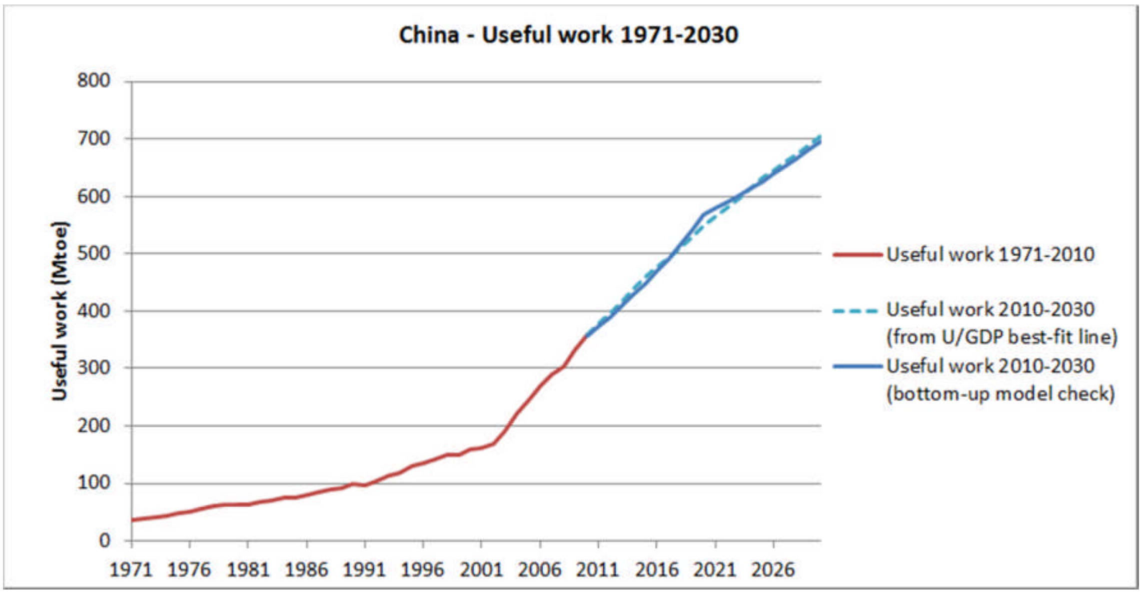

Figure 14: China - useful work projection to 2030

3.3.3. Step 3 - Task-level exergy efficiencies

Next, the task-level exergy efficiencies are projected based on the two scenarios described earlier: stable and declining gains. The results at main class level are shown in Figure 15. They show the effect of the declining gains scenario, which reduce the main class efficiencies to much below where they would be under the constant gains scenario.

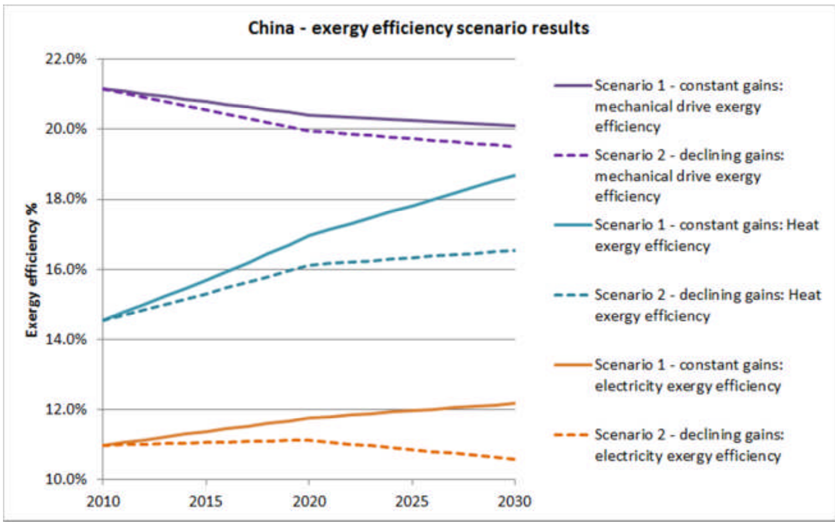

Figure 15: China – exergy efficiency under scenario 1 and 2

3.3.4. Step 4 –Primary end demand in 2030

Finally, the useful work accounting model is run to give estimates of task-level primary exergy requirements. By removing the chemical equivalent ratios, we arrive at final calculation of overall exergy efficiencies and primary energy demand. The results for exergy efficiency are summarised in Table 4 and Figure 16:

Table 4: exergy efficiency scenarios

Scenario		China national-scale exergy efficiency		
		1990	2010	2030
1	**Stable ε gains**	8.1%	12.5%	**15.3%**
2	**Declining ε gains**	8.1%	12.5%	**13.9%**

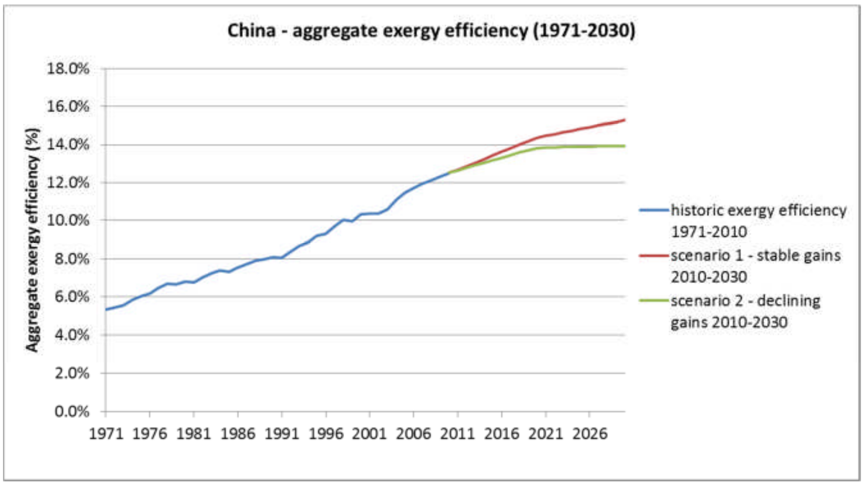

Figure 16: China exergy efficiency scenarios 2010-2030

The results show a rise in Scenario 1 in overall efficiency from 12.5% to 15.3%, based on projections of rates of growth in task-level exergy efficiencies for the period 2010-2030 as for 1990-2010. This is lower than 17.8% (which would occur from a repetition of the 42% gain for the period 1990-2010), due to structural differences between these two 20 year periods. These are both structural shifts (e.g. increasing shift to cars in transport sector) and also absence of structural shifts (i.e. industry boomed 1990-2010 to become the dominant Chinese economic sector so cannot repeat that market share gain). In scenario 2, declining rates of growth in task-level exergy efficiencies mean that overall efficiency levels off to 13.9%, due to declining efficiency gains combined with further structural dilution.

These two efficiency scenarios are then used to project primary energy demand, as shown in Figure 17 . This shows a higher forecast for primary energy under scenario 2, since it has a lower exergy efficiency – as both scenarios deliver the same end useful work.

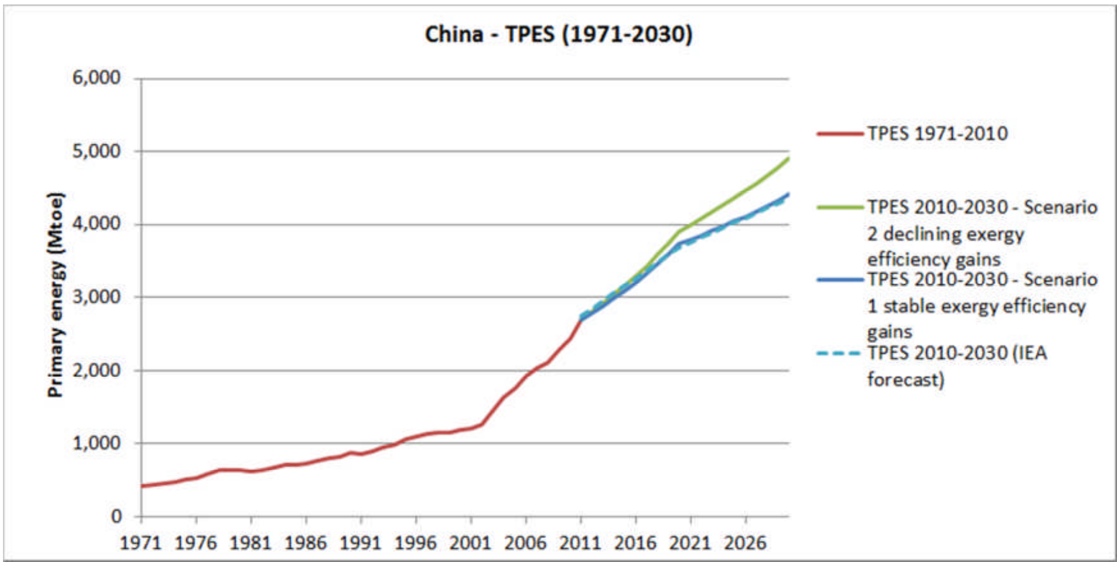

Figure 17 Effect of exergy efficiency on primary energy forecasts

Table 5 summarises the primary energy demand under the different scenarios at 10 year intervals. Scenario 1 (stable ε gains) closely follow the IEA projection values under their 6 degree warming case, though this may be coincidental, since the models are quite different. Nevertheless, it gives some indication that the magnitude of the scenario 1 values are of the correct order. Scenario 2 projects a primary energy demand in 2030 which is 13% higher than that for scenario 1.

Table 5: Primary energy demand forecasts

Scenario		China TPES (Mtoe)			
		2010	2020	2030	% increase vs 2010
-	**IEA TPES forecast (current policies)**	2,255	3,690	4,360	93%
1	**Stable ε gains**	2,255	3,738	4,409	95%
2	**Declining ε gains**	2,255	3,910	4,908	118%

Thus the exergy (i.e. thermodynamic second law) efficiency assumptions of the energy model (in this case scenario 1 versus 2) had a significant impact on projected energy demand. This provides an important note for future energy forecast models, which by working at the energy input level (i.e. primary energy or final energy) won't pick up the dilution effects at the useful work level that exergy analysis does. So it would be worthy of further research to identify how existing models could be adapted to include these effects.

4. Conclusions

We conducted a useful work accounting analysis for China over the period 1971-2030 to answer the research question: *what are the drivers of China's energy efficiency and the implications for China's energy supply in 2030?* We were guided by three sub-questions:

1. *What is China's historical exergy efficiency trend and is it also exhibiting peaking and dilution effects?*
2. *What are structural and efficiency drivers behind changes to China's exergy efficiency,*
3. *What does this mean for China's future energy efficiency and supply policies?*

For the first question, China's exergy efficiency has grown linearly from 5% (1971) to an impressive 12% (2010), which places it between the US (11%) and the UK (15%). However decomposition analysis confirmed this was not technological leapfrogging, but greater use of energy intensive (but more exergy efficient) industrial processes. Whilst we found no evidence of efficiency dilution or peaking in national exergy efficiency for China, the comparative historical evidence suggests dilution may be around the corner. If China accelerates its transition to a mature economy with a growing middle-class, then several efficiency dilution effects will occur: a modal shift to cars will reduce mechanical drive exergy efficiency; a continued shift to residential electricity; and a peaking in the share of HTH and a shift to greater LTH residential heat.

Secondly, the largest driver in the 10-fold rise in China's useful work (1971-2010) was a 4-fold increase in primary exergy. The decomposition analysis found that the 2.5 fold increase in exergy efficiency is split evenly between task-level efficiency gains (1.56) and 'structural concentration' (1.64), e.g. moving from muscle work to mechanical drive.

Third, we set out to find the impact of future energy efficiency scenarios to future energy demand and policy. We found that moving into efficiency dilution - as China continues a transition to an industrialised, urban country – combined with approaching asymptotic efficiency limits - may have profound effects. For energy supply, primary energy (TPES) demand growth may be higher than current projections if models do not properly account for structural dilution at the useful work level. Meanwhile, the focus on micro-efficiency policies may be misplaced if aggregate national scale exergy efficiency stagnates, and may need a rethink, in order to account for efficiency dilution, perhaps by capturing savings before rebound occurs to less efficient processes. In addition, it would mean renewables are needed on-stream faster and larger than currently envisaged, i.e. to 'step in' to fill this carbon reduction wedge.

Overall, the hitherto missing driver of Chinese energy efficiency - approaching second law limits and structural shifts leading to exergy efficiency dilution - could have significant effects on energy supply and efficiency policies, as future primary energy demand may be underestimated by 10-15% by 2030. For mature economies like the US and UK, where total primary energy demand is forecast to be flat, this may mean an increase in primary energy demand versus the more typical flat energy trajectories. Given the importance of future energy demand, further research would be of key benefit, to review existing energy forecast modelling assumptions and how they may be adapted to include second law limits and dilution.

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