Resource acquisition, distribution and end-use efficiencies and the growth of industrial society: Response to reviewer comments and changes to the manuscript.

Response to Prof. Garrett.

1. p. 135 Points 1 to 4 aren't particularly user-friendly because the terminology is novel, especially for an introduction. E.g. "resource distribution networks must inhabit the space occupied by industrial society". Can more enticing language be used?

Perhaps the problem word in this particular example is "inhabit"? We have replaced this with 'fill'. On the four points in general, we accept that there will be a significant degree of novelty for the reader, but this is the point behind using these to introduce the reader to this novelty so that they are given a heads up on what they are about to encounter. Many have commented this is a very useful device because of the novelty of the concepts being introduced. As for rewording them differently, we have attempted to make them as transparent as possible given the reader hasn't yet been introduced to the detailed concepts they pertain to.

2. I find that acronyms can obfuscate more than they clarify, particularly for unfamiliar concepts. Can RADE system be replaced with perhaps "distribution network" or some other language that is descriptive?

Where we mean 'distribution network' explicitly we say this. However, it is important to also name the entire system from resource acquisition through to end use i.e. including the non-distributional components too. Given we need to do this often we find this particular acronym very useful rather than writing it out in full each time and because this gives the system a clear identity. This is the only acronym we introduce. The others (e.g. IEA and ERoEI) are standard in the energy literature.

3. Why use the symbol x for an energetic quantity and y for carbon emissions? The symbol V is used for volume, which is natural, so can some basic thermodynamic quantity be used instead for energy (e.g. G or H)?

Although our work shares many close parallels with e.g. Garrett (2011) where thermodynamics is used to describe the growth of industrial society, our work does not explicitly use this framing and hence we do not feel obliged to adopt the standard from that discipline. Our works owes as much to systems biology or statistics as it does thermodynamics. We believe our symbols are clear and used consistently.

4. p. 138, The distinction between x and x^*, or between primary energy and the points of end use, lies at the core of the paper, but seems somewhat arbitrary. It seems one could view the entirety of civilization as a network, in which case there are primary energy reserves for which the end user is outer-space which basks in civilization's dissipative warmth. Civilization is only the network that dissipates the energy so that it can be radiated to this end-user. Or, if a coal-fired power plant is the primary energy source, should we suppose that the end user is the electric company that builds the transmission lines, or the toaster that consumes the power, or the toast that consumes the toaster heat, or the person who eats the toast, or some component of human body networks in the form of gastrointestinal tubes, veins and nerves, all of which benefit from toast consumption. Absent a truly precise definition, it is hard to see where it all starts and ends in a manner that could precisely be laid out in terms of equations yielding power laws.

We need to draw system boundaries somewhere in order to do the analysis. Our choice is largely dictated for us by how energy use data are presented. Fortunately the choices exercised when compiling primary and final energy use data appear to

relate to boundaries in the system that are not completely arbitrary. Primary energy is the energy harvested by industrial society from the environment and so mark this boundary clearly. Industrial society cannot substantially exercise any control over flows upstream of this boundary. Final energy is more problematic as Prof. Garrett indicates. Here we define it as primary energy less the energy acquisition and distribution costs, less all transport. Although precisely defined, which boundary this relates to is much harder to accurately tie down. We offer an extensive account of our definition of final energy in the text. As stated in the text, final energy is energy arriving in some space where further decisions on relocating energy and materials are irrelevant. By decisions we mean where conscious human agency is being exercised, again as detailed in the text. So yes, the energy keeps flowing and changing state within these spaces, but these flows are not 'directed' by human agents and hence industrial society or, more importantly, the transport losses have become insignificant relative to those encountered upstream of this point. On careful examination we believe the original text goes to some length (three full paragraphs) to attempt to make this as clear as possible and have added an additional paragraph on this in response to Prof. Garrett's next point.

5. Put another way, what element of society is not associated with distribution losses? Through the Second Law, it seems that nodes and networks are indistinguishable since they must all be dissipative.

As discussed above, we are specifically interested in 'directed' distributional losses i.e. ones where human agents exercise control (either explicitly or implicitly) over flows. Therefore, final energy consumption occurs where/when the rate of consumption of energy at some location is significantly greater (e.g. an order of magnitude say) than the flow of useful energy through this location to some other part of the global energy system. We have added the following text to the manuscript to attempt to articulate this and thank Prof. Garrett for pushing us for clarification.

"We define the space associated with unit final energy consumption (referred to as a "control volume" by Dalgaard and Strulik, 2011) as being that where the consumption of useful energy in that space is significantly greater than the transfer of useful energy from that space to other regions of the network. These spaces are complex entities and not easy to identify, again because in a global mean sense they are comprised of broad portfolios of energy uses. That said, examples of such processes might include reading this article on a computer, cooking, constructing or demolishing a building etc."

6. p. 140. My understanding is that food is not a primary energy source in modern society because it's manufacture depends almost entirely on fossil fuels for fertilizer production, crop management, and distribution.

All forms of primary energy depend on other forms of primary energy for their acquisition and distribution.

7. p. 140 and p. 141 "a small fraction"; "relatively small". Please define.

We are unable to provide a meaningful estimate of the fraction of the Grubler wood use that is not burnt for fuel. We have added an estimate (<1%) of the total global primary energy that is attributable to food.

8. p. 140 and p. 141. A variety of assumptions are made here for how to define x and x?. These lead to the very interesting result shown in Figure 1a of a ¾ power scaling law, potentially the most compelling of the paper. To some degree this result must have been

anticipated so it begs the question of the extent to which the value of the scaling law is sensitive to how x and x_* are defined. Can this be explored so that the fit for the value c expresses more than just a statistical uncertainty?

The uncertainties we cite attempt to include the uncertainties in the data sources themselves. With respect to the structural uncertainties arising from the assumptions on the definitions of primary and final energy, there are not many degrees of freedom to explore here. Primary energy is largely a given. As for final energy, the key difference in our definition is the inclusion of transport. We present the IEA final estimates in Figure 1a which do not include transport and have included the regression stats for these data for comparison (0.84 v. 0.75).

9. p. 142. As justification for civilization occupying three dimensions, it might be worth drawing a comparison to the atmosphere, which is also very thin due to gravitational forces, yet is nearly always modeled as a 3D entity.

Clever. We have included this point and thank you for pointing that out.

10. p. 143 Points 1 to 3. Please also see Garrett (2014), which makes similar points.

We accept that Garrett (2014) is covering similar material but couldn’t see that it addresses the specific topics of innovation on distribution mechanisms, dematerialisation and urbanisation and so would prefer to claim uniqueness here, but cite Garrett (2014) elsewhere as it is clearly very relevant to our work.

11. p. 144 It is not obvious to me that $x_* = \Sigma\, x_{*i}$. It seems that this would be true only if there were no interactions between nodes. Countries are purely political boundaries having little to do with exchanges of mass along networks associated with international trade. Where are the interaction terms in the summation?

Clearly nodes interact with each other through e.g. trade. But the IEA data we are describing accounts for this by constructing national inventories. The global energy totals are simply the sum of the country values. That is all we are saying here.

12. Sections 6 to 8 rest upon there being a constant growth rate in primary energy consumption, a result that is based on statistics taken from Grubler (2003). The Grubler statistics indicate that no wind, solar, or water power was used in the 1800s where each were clearly major drivers of the distribution networks that existed at the time. Towns and cities were built to the greatest extent possible along rivers and canals because these offered hydro power for distributing goods and for milling grains. Wind power formed the thrust for the sailing industry which for centuries formed the backbone of international trade. Animal and human power was used to till farms, which in turn relied upon solar energy and photosynthesis for food. How do these omissions affect the result?

This is an interesting point. The Grubler data is a little ambiguous here stating the pre-coal primary energy is comprised of “wood, dung, crop residue, other biomass, etc”. We have expanded the description of the data by including the following statement:

“We note that compiling long-term historic series for virtually any relevant measure of economic activity is challenging due to the paucity of available data the further back one goes. Data on energy use is not exempt from these limitations. For example, the Grübler data we use do not appear to capture the full portfolio of renewables in use in the 1800’s (e.g. wind and water power). However, we also note that the energy data used here still represents one of the best observed metrics of global economic

activity. Also on the specific issue of renewables post 1850, evidence suggests that they were a negligible part of the global energy portfolio during this (O'Connor and Cleveland, 2014, and Fouquet, 2014).”

We have also modified the text introducing the long-run estimate of the energy return rate to underscore the fact that this is attached exclusively to these data. Furthermore, we highlight that Garrett's (2014) analysis of GDP data suggests a more complex picture of an increasing relative growth rate (see below).

13. Consider further that 2.4% per year constitutes a doubling time of 28 years for global energy consumption. Is it really reasonable to presume that 300 years of industrial revolution corresponds to a global jump of a factor of 2000 in energy consumption? What about 2000 years of civilization, covering only the era since Roman times? Was civilization energy consumption really 2.3_10$_{21}$ times smaller in 1 AD? That would imply just 10 nano-Watts available for the world. It seems some further discussion is required on this point. If growth rates changed in the interim, how and why did such changes stop?

We restrict our discussion of growth rates to the 160 years covered by the data. When a ~2.4%/yr growth rate first emerged we do not know. Clearly the Industrial Revolution marked the emergence of novel systemic behaviour and it is erroneous to extrapolate growth rates back prior to this. Any such discussion would be highly speculative.

14 As a point of comparison, an alternative reconstruction of energy consumption over the past 2000 years is provide in the supplementary material of Garrett (2014), pointing to varying rates of growth over time, culminating in an all-time high of about 2.2% per year over the past decade.

We have introduced the following text to contrast our analysis with that in Garrett (2014).

“Using global Gross Domestic Product (GDP) data as a proxy for global energy use, Garrett (2014) suggests that the relative growth rate of global primary energy has increased significantly over this period. However, we note his method of estimating relative growth rate is not comparable to the least squares approach used here, and that he assumes the apparent proportionality observed between primary energy and GDP observed for the last 40 years holds throughout the Industrial Revolution and before.”

Reconciling these differences in future research is a clear priority.

15 p. 147. I don't understand the precise definition of dematerialization. Can an equation be provided?

It is simply falling unit mass of a resource flow. We have expanded the sentence to state this explicitly. The reader is also guided to Ausubel (1989) for a full account of the concept and further evidence for systemic dematerialisation processes. As for an equation, the text links carbon intensity to distribution efficiency quantitatively.

16. Please check the spelling of Ausubel, which is correct in the references but not the text.

Done

17. p. 149. Gas may be lower energy density per unit volume, but it is shipped in compressed form and it is has the highest energy density per unit mass due to

the saturation of hydrogens. If international transport takes the form of shipping, isn't it energy per mass that matters most?

Not necessarily. LNG is bulky (as in unit energy per unit volume), and this appears to add to the transport costs along with the need to keep it cold/compressed.

18. Section 7 Eq. 1 might benefit from further discussion. There are physical reasons to suppose that $x \propto V^{1/3}$ (Garrett, 2014).

We have removed reference to an environment-society interface framing as our framing is one where resources are subsumed by society. We have included a footnote on Garrett (2014) saying:

"Garrett (2014) assumes that environmental resources flow to industrial society across an environment-society interface (surface) and hence speculates that this flow is proportional to $V^{1/3}$ on theoretical grounds."

19. Eq. 7 See also Garrett (2011) where it is expressed as $w = \varepsilon a$.

Garrett (2011) now cited here also.

20. p. 154 The EROEI concept needs to be defined, with references.

This was only added to satisfy an earlier reviewer and adds little given the truncation errors associated with specifying EROEI's are well documented. As a result we have deleted this paragraph.

21. The argument that the growth rate of civilization is constrained by human lifetimes is thought-provoking. It does beg the question of whether it exists for plants and animals since these are also network driven (just look at a tree). Is the growth rate of plants and animals proportional to their lifetimes in a similar fashion? What about cities (e.g. Bettencourt et al. (2007))?

An interesting point. Cities however do not have characteristic lifetimes in the same way. Rather than include further speculation on this (the paper already has a lot!) we feel this falls under further work.

22. p. 159 Measures of GDP may be disputed for on the point of whether they are linked to societal measures of success, but the metric is nonetheless well-defined and well-measured. It is reported quarterly at the national level as the total sum of all financial exchanges. Energy statistics on the other hand are only reported three years after the fact.

Here we will have to disagree. Not only can and are the accuracy of GDP be disputed, because data are collected at the national level their precision is also disputable because values can change depending on judgment alone. This is not the case with primary energy data. Here the key uncertainty is the energy value of the material traded and how much of the physical resource was traded. Beyond that the uncertainties are comparatively low, requiring no exchange rate or inflation adjustment. On the issue of reporting interval, the IEA report three years after the fact after extremely careful and rigorous quality assurance. BP report 1 year after the fact. This has no bearing on the quality of the data other than the amount of time taken for verification.

We thank Prof. Garrett for a really good, thorough review and look forward to ongoing discussions on this area of research.

Response to Anonymous Referee #3

This paper presents an interesting although perhaps provocative view. The authors interpret global economic growth through the perspective of physical network theory. I have some major difficulties with the paper. The authors adopt the conceptual model of a space-filling network that expands over time. They use analogies from biology describing the structure of organisms. However, they don't provide any real argument that this has any relevance to the global economy.

With respect, we believe we do show that the global economy exhibits behaviours that are somewhat analogous to those observed in nature, as expressed through global primary energy use data. It is unequivocal that networks connect resources and points of end use in society and that mass moves through these networks. The question we are exploring is what form these networks take and what implications this has for the growth of society. These networks are most definitely directed. We present evidence to support the theory that they are also near optimal in terms of their distribution efficiency. With regards to their "relevance to the global economy", we think it is beyond argument that the components of the global resource distribution network (i.e. roads, railways, airline routes, shipping routes, cables, pipelines, etc.) are critically important to the global economy, as is energy, and that understanding how mass/energy moves through them will reveal something about how industrial society operates.

Resources are extracted at the point where they exist (influenced by economic and practical constraints which have changed over time) and usage is wherever the largest energy demands happen to be (which in large part depends on historical contingencies and energy availability, and therefore may bear little relationship to modern energy production).

We don't disagree with any of this and it in no way refutes a network view of the expansion of industrial society. However, it is plain wrong to assume we simply describe "modern energy production" as is inferred here. The paper explicitly ties the contemporary energy landscape to the evolution of the global energy system over the last 160 years.

The spaces in between are not necessarily filled, and the economic organisation has not grown larger in any way analogous to a biological organism.

With respect, R3 does not know that. The global economy must be counted as one of the most complex objects in the known universe which is why there is so much debate and uncertainty over its operation.

There is little economic activity in the vast bulk of the oceans, polar and mountainous regions.

At no point do we assume or state that space is filled uniformly and completely. Indeed, we state e.g.:

"If the global RADE network has the dimensions of D = 3, then the scaling observed between x and x* suggests that, at the global scale, the distribution networks that underpin the RADE system are, in aggregate, optimised with respect to energy losses, despite filling a highly irregular three dimensional space."

Building on the biological metaphor; a tree fills space, but there are lots of spaces between the leaves and the roots where the tree isn't present and where photosynthesis and other metabolic processes involving the translocation of mass/energy (carbon, water, other metabolites) does not occur. It is clear from this and following statements that R3 does not understand what is meant by 'space filling' networks in the literature. We have now introduced text on the definition of the unit 'control volume' which addresses this directly.

"We define the space associated with unit final energy consumption (referred to as a "control volume" by Dalgaard and Strulik, 2011) as being that where the consumption of useful energy in that space is significantly greater than the transfer of useful energy from that space to other regions of the network. These spaces are complex entities and not easy to identify, again because in a global mean sense they are comprised of broad portfolios of energy uses. That said, examples of such processes might include reading this article on a computer, cooking, constructing or demolishing a building etc."

Moreover, transport distances are surely bounded by half the circumference of the planet, with an average of half that value.

This is a very simplistic view of the topography of the space in which industrial society operates. What about exploration in the vertical (mines, wells, tall buildings), or space travel, or that paths may need to deviate from the shortest physical distance due to other factors (mountain ranges, ice caps, political or civil unrest….)? More importantly, although the space occupied by the planet is fixed, the potential pathways that can be exploited within this space are infinite. So the opportunity to grow into finer and finer divided space is not bounded simply by the circumference of the planet.

Australia exports large quantities of coal, OPEC exports oil (and has been doing so for many decades). Where is the network expanding physically, recently and in the future?

With respect to the expansion of the network close to points of resource acquisition, the portfolio of energy being extracted globally has always been in a state of flux. New resources are constantly being accessed in increasingly disparate locations to meet growing demand and replace reserves that have been exhausted. To list a few recent examples: oil from tar sands in Canada; fracking for gas and oil in the USA; the production of gas in Qatar for export as LNG; Norwegian oil and gas; the expansion of wind, solar and other renewable energy production the world over. In each of these instances the network has clearly had to expand physically in order to facilitate resource acquisition.

Even with respect to the specific "mature" points of acquisition mentioned by R3 (i.e. OPEC oil and Australian coal) the continued exploitation of these resources entails drilling/mining further into these reserves. To facilitate this, the parts of the distribution network close to these areas of acquisition must therefore physically expand (i.e. deeper mines, new oil wells etc.).

Furthermore, it should also be remembered that the network links points of acquisition to end-use and so has the capacity to expand at both ends. An obvious example of physical network expansion to facilitate end-use would be the extent of growth in China. This growth has required the creation of vast swathes of new network infrastructure, including power grids, rail systems, road networks, shipping lanes, airports, and so on.

There is ample evidence that this process of expansion will continue in the future. In fact we actually find it hard not to think of examples of the network expanding physically as new resources are accessed and new points of end-use are established. See for example BP's Statistical Review of World Energy and Outlook to 2035 for further evidence:

- **http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html**
- **http://www.bp.com/en/global/corporate/about-bp/energy-economics/energy-outlook.html**

More directly, what is the authors' estimate of the relevant length scale and how it has changed? Surely this must be a primary parameter of the analysis, and it might be interesting in its own right.

The average length scale of the network of networks is a parameter in our manuscript (it is given the symbol L) and yes, it is both important and interesting given it increases in all expanding networks. Unfortunately L is not a measured quantity, nor can it be for the global energy system because this system is highly complex, irregular and heterogeneous.

The transport network is nowhere close to space filling.

How does R3 know that? If R3 is referring to roads and railways (i.e. manned terrestrial transport) then these systems collect and distribute resources (including people) in space. Therefore they ARE space filling. If he/she means that there are lots of unfilled spaces then we refer him/her to our reply concerning the tree above.

The ocean is basically empty with a handful of ships

Please see our comment above referring to the "empty space" in the volume of air occupied by a tree. Ships are not networks, but the paths they take from port to port definitely are. As can be seen e.g. here:

(http://en.wikipedia.org/wiki/Ship_transport#/media/File:Shipping_routes_red_black.png)

these are ubiquitous over the oceans. But of course R3 is correct to infer that there is still a very considerable amount of empty space to explore and fill in the oceans with new shipping routes or expansions of current ones in order to link new resources to points of end use. This will only happen if there are resources that are economically attractive to be moved around. We might postulate that future exploitation of the mineral and energy resources on the ocean floor could become important and that at that time resource acquisition and distribution networks might expand in that direction.

the skies are clear

See e.g.:

http://en.wikipedia.org/wiki/Civil_aviation#/media/File:World-airline-routemap-2009.png

and we repeat the same arguments as for the oceans.

, even road networks are far more space than road (this becomes a little dubious when one considers only urban areas, but this is a small part of the energy transport network). Electric cables are not packed into space, and neither are oil and gas pipelines limited by space. I simply don't see why the authors think that the space-filling network theory ought to apply even approximately in this situation.

Clearly R3 has misunderstood what is meant by a 'space filling' network in the literature. It is not the links in the network that fill space (even though they invariably have some space requirement). Networks are said to be space filling if they facilitate the occupation of space in some sense (c.f. the tree). In the present context we refer to roads, railways etc. as space filling because they connect the spaces where resources are to the spaces where they are used.

I think the authors need to work harder on explaining to the readership why this theory might be expected to be relevant.

With respect, R3 is the first of our reviewers and seminar audiences to have misunderstood what is meant by 'space filling' and hence been unable to make the obvious connection between this concept and the familiar understanding of the function of roads, railways, pipelines etc. The problem previous reviewers have with this concept is not that these networks are space filling (they agree that they clearly are), but that we argue that the space being filled appears to be three dimensional. This is why we dedicate an entire section of the manuscript to this issue.

To a good approximation, I would expect the transport distance to simply be the great circle distance between resource extraction and use. Can the authors refute this naive assumption, either by theory or data?

This is an incredibly simplistic view of the ways in which mass moves through industrial society. If one were simply concerned with, say, the movement of coal from Russia, Columbia or the USA to the UK, then, yes, we agree that the great circle distance between ports might give an approximate transport distance. But what about the incredibly fine networks that transport coal from the seam deep underground to the port, and from the port to consumers, including millions of individual households? We believe that we do clearly refute this naïve assumption both empirically and theoretically.

The dimension argument seems implausible and forced. In order for the network theory to apply, I believe it is the case that the expansion in all three dimensions must be at the same (at least, similar) proportional rate. Do the authors think this has happened? What are the quantitative implications, in relation to the horizontal length scale?

If by "rate" you mean velocity, then no, we do not believe this. Firstly, optimal directed network theory does not relate to rates of expansion, it is a static theory. Secondly, the paper dedicates an entire section (4) to the issue of the dimensionality of the space filled by industrial society. With respect, we think, this indicates that R3 has not read section 4 properly. Rather than paste the two pages of text here that addresses this, we point R3 to the discussion in section 4 in answer to the question on this.

So in summary, I do think there might be an interesting story here and I certainly don't want to reject their ideas out of hand, but I do think the authors need to justify the conceptual basis of their analysis rather better than they have done so far.

It is heartening to read that R3 does not wish to reject our ideas out of hand. We accept that more empirical and theoretical developments are required to support this view of the behaviour of industrial society. After all, neoclassical economics has had a little under three hundred years to build its program and it would be wrong to expect an equivalent evidence base to be presented in a single paper. Unfortunately however, many of the comments that R3 has made are naïve or expose a poor understanding of the framework and evidence presented here. Having reviewed the manuscript carefully we believe the text is clear on the issues that R3 raises and do not see the justification for the substantial revision he/she is requesting. Indeed, it is clear from Professor Garrett's review that the concepts and supporting evidence are much more clearly set out than R3 indicates.