Ominous portent of the omitted variable: the urgent need to understand energy's role in productivity growth

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Abstract

The consequences of a global economic recovery that does not reduce carbon dependency are profoundly concerning, yet some economic recovery agendas have unsettling overtones of 'business-as-usual'. In Australia, for example, restoring 'productivity growth' is firmly on the agenda. 'Productivity growth' is commonly understood to mean either higher labour productivity – an increase in value-added (or GDP) per hours worked by labour – or an increase in 'total factor productivity', otherwise described as technological change. Either way, as ecological economists have shown, the remarkable pace of technological change and the impressive increases in labour productivity achieved over the last century have markedly raised the level of material and energy throughput into the economy – yet it is this 'resource productivity' that must be improved in order to achieve 'green mileage' and greater sustainability.

The question arises then: can an economy pursue a recovery based on increases in labour productivity, total factor productivity and resource productivity simultaneously? The fact that the question is not being asked in policy circles appears to be because natural resources, and energy in particular, are often omitted altogether from the aggregate production functions used to measure productivity increases, creating somewhat of a 'blind spot'. Even if energy is included as a factor of production, methodology consistent with the assumptions of the neoclassical theory underpinning conventional productivity measurement undervalues it by weighting it at its GDP 'factor cost share'.

Drawing on ecological economics research, this paper puts the case as to why energy should be included as a factor of production; why weighting energy by its 'factor cost share' when it is included, is wrong; how this commits a type of 'water versus diamonds' valuation error; and why this matters so much at this point in time.

Introduction

Restoring productivity growth is firmly on the agenda in Australia. The Prime Minister, Kevin Rudd, has recently described 'productivity growth' as a 'building block of the future' that will enable Australia to 'carve more out of global growth'.[1] A reference to the House of Representatives in August 2009 is requesting a Parliamentary Inquiry to examine the 'factors responsible for Australia's current lower rate of productivity growth' and to find 'key levers' which will assist in returning the Australian economy to a trajectory of robust growth in productivity'.[2] An inquiry seems appropriate. Even after an enormous literature comprising more than 50 years of theoretical and empirical research, there is still significant ambiguity as to the meaning of 'total factor productivity' among leading researchers in the field, as Lipsey and Carlaw (2004) demonstrate.[3]

There appears to be greater agreement, or at least uniformity of practice, in the techniques used to measure productivity empirically. Many of these approaches have residual neoclassical elements. One of these elements, the practice of weighting factors of production by 'factor cost shares' in GDP has drawn criticism from an ecological economics literature. A steady growth in this literature over the last 20 years or so, appears to have culminated, to date, in the extensive research of Ayers and Warr (2009).[4] There are important implications and a warning in the insights of the ecological economists as regards productivity growth.

The paper is in four sections. Following this introduction, the first part attempts to present, in lay terms, the neoclassical underpinnings to the conventional measurement of total factor and labour productivity, giving the rationale for weighting factors of

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[1] Australian Prime Minister, Kevin Rudd, Speech to the AI Group Annual National Dinner, 18 August 2009.

[2] Parliament of Australia, House of Representatives, Standing Committee on Economics, *Inquiry into raising the level of productivity growth in the Australian Economy,* http://www.aph.gov.au/house/committee/economics/Productivity/tor.htm

[3] R. Lipsey and K. Carlaw, 'Total factor productivity and the measurement of technological change', *Canadian Journal of Economics*, 37(4), 1118–1150, 2004.

[4] R.U. Ayres and B. Warr, *The Economic Growth Engine*, Edward Elgar, Cheltenham, 2009.

production by their cost shares in GDP. The second part of the paper provides the ecological economists' critique of this practice, and part three describes the methods and results of their research. The fourth part of the paper draws out some implications of this analysis, noting the important warning it contains, and the need for further research into the consistency of productivity goals.

A. The theoretical underpinnings to standard productivity measurement

Robert Solow's studies of 1956 and 1957 contributed the theoretical foundations for measuring productivity.[5] The approach assumes that the entire economy can be thought of as having a single production function, as would an individual firm. The single sector aggregate production function combines the factors of production labour (L), and capital (K), together with a technology (A) to produce economic value added, or GDP (Y). Commonly, the production function is specified in Cobb-Douglas form:[6]

$$Y = A_t K_t^{\alpha} L_t^{\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The subscript t designates time, and A_t is 'total factor productivity' or technical change over the period of time. A_t is exogenous to the model – meaning that it causes output to grow *independently* of changes in K or L – and it is assumed to grow at a constant rate. The parameters α and β are constants and may be understood broadly as embodying the technology with which K and L combine to produce output in an economy. The parameters α and β also measure the output elasticities of the factors of production, K and L. For example, if α is 0.3, then a 1 per cent increase in capital, K, in the economy will lead to a 0.3 per cent increase in GDP (Y).

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[5] Robert M. Solow, 'A contribution to the theory of economic growth', *Quarterly Journal of Economics*, 70, 65–94, 1956; Solow, 'Technical change and the aggregate production function' *Review of Economics and Statistics*, 39, 312–320, 1957.

[6] Many studies do now use more sophisticated and more flexible functional specifications, such as constant elasticity of substitution (CES) or translog functions. From the point of view of appreciating the shortcomings, as they apply to the role of energy, the Cobb Douglas function is illustrative of the 'factor share problem' applying to all formulations.

Taking logarithms and differentiating (1) with respect to time, t, gives:

$$\frac{\partial \ln Y}{\partial t} = \frac{\partial \ln A}{\partial t} + \alpha \frac{\partial \ln K}{\partial t} + \beta \frac{\partial \ln L}{\partial t} \ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Equation (2) can be expressed in the form of rates of change as:

$$r_y = r_A + \alpha r_K + \beta r_L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where r is the (time) rate of change of the corresponding variable.

This can be rearranged as:

$$r_A = r_y - \alpha r_K - \beta r_L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4).$$

Equation (4) shows that increases in total factor productivity, A, over a certain time, can be calculated as a residual, so long as one knows by how much Y, K and L have increased over the same period, and if we also know what values to assign for α and β. Since the question of the values assigned to α and β is at the centre of the difficulties with the neoclassical approach, it is worth explaining in detail how they are derived.

In the economy depicted by the Cobb Douglas production function of (1), it is assumed that both the product and factor markets are perfectly competitive, so that factor prices for K and L (the rent for capital and the wage for labour) will be equal to their marginal productivities.[7]

The marginal products of the two factors will be the first differential of the production function (1):

$$\frac{\partial Y}{\partial K} = A\alpha K^{\alpha-1} L^{\beta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

and

$$\frac{\partial Y}{\partial L} = A\beta K^{\alpha} L^{\beta-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

[7] In an idealised competitive economy, competition between firms ensures that workers will be paid just as much but no more than the value that their labour adds to the firm's production.

The total payments made to capital and labour — that is, the cost share of capital and labour — will therefore be equal to the marginal products of each factor multiplied by the amount of each input used.

The cost share of capital $= \frac{\partial Y}{\partial K} K$

$$= (A\alpha K^{\alpha-1} L^{\beta}) K = \alpha A K^{\alpha} L^{\beta}$$

$$= \alpha Y$$

By a similar method, the cost share of labour $= \beta Y$

In a perfectly competitive economy, the payments to factors of production in the two factor economy assumed in the model, will exhaust the value added. That is, the factor cost share of capital plus the factor cost share of labour sums to the total value added in the economy (Y):

$$\alpha Y + \beta Y = Y \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The values of α and β may therefore be estimated as 'factor cost shares' of total output. Empirically, the cost share of capital in GDP tends to be estimated at around 23–30 per cent, whilst labour's share of total cost is 65–70 per cent. These factor cost shares are multiplied by the measured increases in K and L, respectively, and the residual between the sum of these and Y is total factor productivity, as indicated in (4).

When Robert Solow first used this approach in 1957, hoping to explain economic growth in the United States over the period 1909 to 1949, he was surprised to find that the measured and weighted increases in capital and labour over the period could only explain 10 per cent of the observed growth in the United States economy. The remaining 90 per cent Solow attributed to 'technical change', which therefore had to have some explanation outside the model Solow was working with. The technical

change variable subsequently became 'total factor productivity'. It is also often called the 'Solow residual'.

For many decades after Solow's research, economists devised and tested models that might throw some light on the Solow residual.[8] For example, the literature now suggests that adjusting for labour quality (where the hours worked by people with higher skills are given a higher weighting) can explain more of the productivity gains. The reasoning is that the changing composition and skills of the labour force are an important factor in growth.[9] Other factors suggested in a large literature include years of education, life expectancy as a proxy for health, micro-economic reform, political stability, democracy, and the like. Many of the variables tested are collinear with output growth, and it is therefore difficult to 'sort out' statistically, their individual explanatory power.

As well as the empirical research investigating Solow's residual, new theories of growth known as 'endogenous growth' models have been proposed. In an effort to explain more of the growth process from within the theory itself, these theories have suggested feedback systems involving L and K. For example, 'learning by doing' and 'learning by investing' is thought to encourage further investment and also to expand the stock of knowledge. This knowledge then becomes a public good encouraging further investment, and so on.

The endogenous growth models have a more realistic picture of the economy. It seems, however, that finding appropriate proxies to test the models, to see if they can explain growth historically, or between different countries, has been relatively

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[8] For excellent surveys of the research undertaken see (chronologically): M. Ishaq Nadiri, 'Some approaches to the theory and measurement of total factor productivity: A survey', *Journal of Economic Literature*, December, 84(4), 1137–77, 1970; R. Nelson, 'Research on productivity growth and productivity differences: Dead ends and new departures', *Journal of Economic Literature*, September, XIX, 1029–1064, 1981; and Lipsey and Carlaw, pp.1118–1150.

[9] See, for example, C. Groth, M. Gutierrez-Domenech and S. Srinivasan, *Measuring total factor productivity for the United Kingdom*, Bank of England Quarterly Bulletin, Spring, 2004.

unsuccessful.[10] Moreover, only rarely do either of the model groups discussed above, exogenous or endogenous, include natural resources or energy as a third factor of production.

B. The ecological economics critique of the theory underpinning productivity measurement

The problem with conventional productivity measurement centres on the fact that natural resources, particularly energy, are rarely given explicit treatment as factors of production. Further, even in instances where energy is included as a third factor of production, it is weighted by its factor cost share – that is, the share of energy costs in value added – in the same way that α and β are used as cost share weights for K and L in a two factor production function, as illustrated in Part A.

The objections to weighting energy by its factor share can be explained in a series of propositions. First, in contrast to the neoclassical view of production as a *substitution* process, goods and services are actually produced in a *transformation* process that uses energy, labour and machines (capital) services to transform raw materials into products and services. Secondly, this means that in production functions in all firms and all sectors across the economy, the factors of production are more often that not *complements* rather than substitutes, at least in the short run. Energy, as used in one form or another to provide power, is an *essential* component of all production technologies. If a factor is essential, it cannot be assumed, as the neoclassical theory does, that other factors will substitute for it.[11] Thirdly, it follows then, that to assess the importance of production by its cost share — when it is usually by far the cheaper factor of production (its cost share is around 5 per cent compared to around 25–30 for

[10] D. Pearce 'Technology, environment and sustainable development: what role for technology policy? In OECD *Technology policy and the environment*, OECD Paris, 19, 2002 and Ayres and Warr, p.11.

[11] Machines need fuel to operate. Humans could provide muscle power to 'substitute for' energy, as they have done in the past, but that would not substitute perfectly for fossil fuel in any production process, and in any case, food must provide the energy.

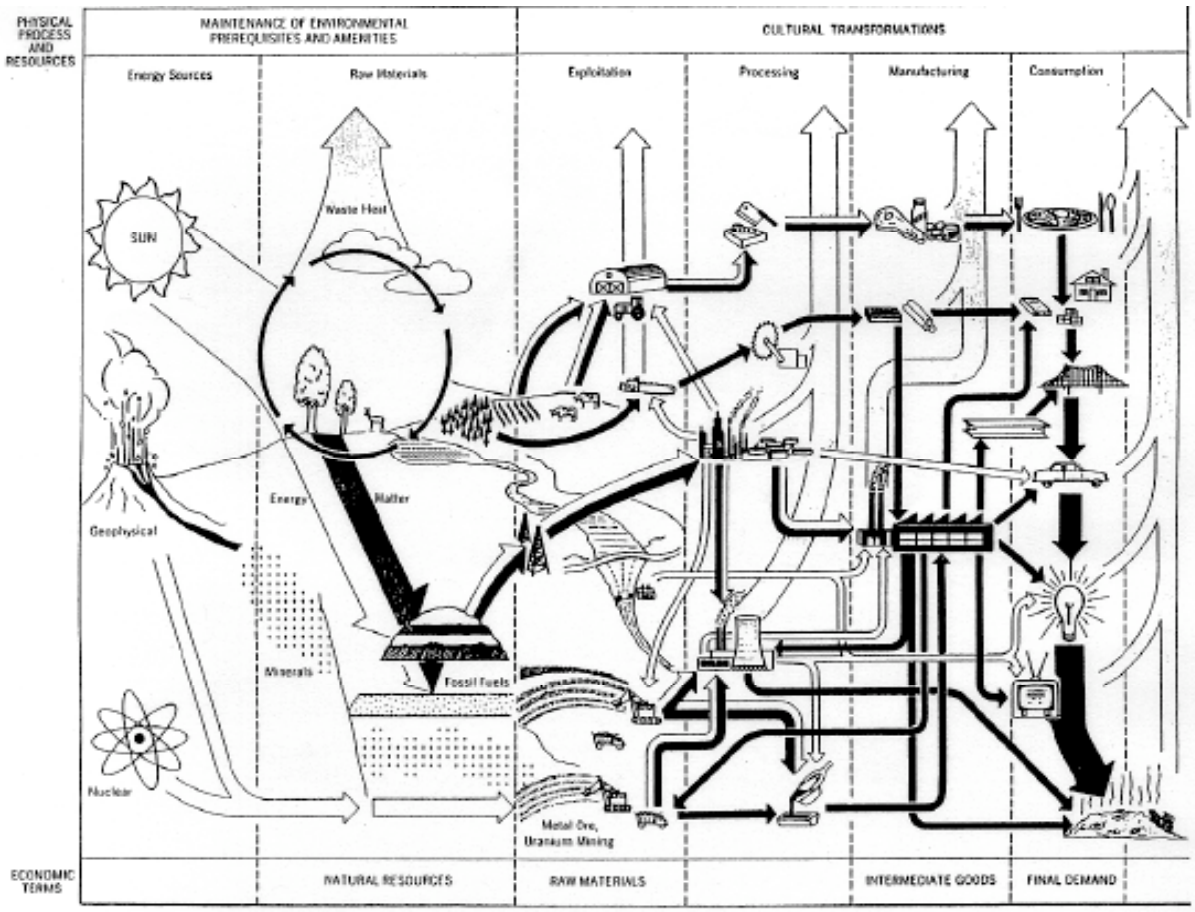
capital and 65–70 per cent for labour) — is to miss the fact that it is an essential factor. Weighting energy by its cost share commits an error similar to thinking that water is valueless in the well known 'water versus diamonds' paradox of first year text books. This is discussed further below.

Production as a transformation process

The Cobb-Douglas production function described in part A assumes that there is plenty of scope for K and L (and E, if energy is included as a third factor of production) to substitute perfectly for each other in a production process, without affecting production levels. The Cobb-Douglas function does limit substitutability at the extremes, but only after large amounts of one factor have almost replaced the other. To ecological economists, by contrast, a production function describes a transformation process: a technical recipe for transforming energy, materials, labour and capital into goods or a service. Some substitution may be possible between sources of energy (e.g. electricity for gas) and some substitution is certainly possible between labour and capital (at least in the longer run), but the relationship between energy on the one hand, and labour and capital on the other, is one of *complementarity* rather than substitutability. The implications of recognising that energy (power) is a complement, and therefore essential in production processes, are quite profound.

The importance of energy in the economy can be seen more clearly when the economy itself is viewed, not as an abstract circular flow in perpetual motion, but as a multi-sector chain of linked stages in which energy powers the transformation that takes place at each stage. Figure 1 illustrates this 'life cycle' perspective. It shows the flow of energy (in the unfilled arrows) in various processes of resource extraction, reduction, refining, manufacturing and transporting finished goods, final consumption and waste disposal.

Figure 1: Energy in the economy



Source: Hall, C. and Klitgard, K. (2006:13). The picture shows a biophysical model of the economy and the role of energy in it. Energy (from the sun) sustains natural ecosystems and then energy (mostly fossil fuel in developed countries) is used in the various processes from raw material extraction, intermediate and final good production, transportation, and final consumption of goods and services to waste disposal. The filled arrows are materials, and the open arrows, energy.[12]

Value is added by energy, capital and labour, as Ayres (2008:18) describes:

> Each stage has physical inputs and physical outputs that pass to the next stage. At each stage of processing, value is added and useful information is embodied in the products, while low value, high entropy, low information wastes are separated and disposed of. Global entropy increases at every step, of course, but the value-added process tends to reduce the entropy of useful products, while increasing the entropy of the wastes. An adequate description of the economic system, viewed in this way, must include all materials and energy flows, and information flows, as well as money

[12] C. Hall and K. Klitgaard, 'The need for a new biophysical paradigm in economics for the second half of the age of oil', *International Journal of Transdisciplinary Research,* 1(1), 13, 2006.

flows. These flows and conversion processes between them, are governed by the first and second laws of thermodynamics, as well as by monetary accounting balances.[13]

The error in using factor costs shares: 'diamonds versus water' paradox

Despite the many points at which energy is necessary to power processes in the economy, it remains true that, relative to other factors of production, it has a lower cost. Like valuing water at its market price, valuing energy at its cost share of GDP is to miss how essential it is in the economy.

When energy is only a small share of GDP, it is easy to think it unimportant. Doing without a small share of GDP would be no great sacrifice since such a large percentage of the goods and services that contribute to GDP would remain – or so it might seem. Whilst this may be true of many of the goods and services that comprise GDP, it is certainly not true of energy, as it is not true of water.

Just as with water, the low price of energy reflects its abundance as the gift of millions of years of nature's processes, assisted in recent decades by sophisticated technologies. The price of both water and energy reflects their value in exchange for their next use — their *marginal* utility or marginal use value. It does not reflect the *total* use value of either resource — as the diamonds versus water paradox of elementary textbooks pointed out.[14]

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[13] R.U. Ayres, 'Sustainability economics: where do we stand?' *Ecological Economics*, 67(2), 298, 2008.

[14] See, for example, Daly, H. (2000) 'When smart people make dumb mistakes', *Ecological Economics,* 34(1), 1–3, reprinted in *Ecological Economics and Sustainable Development*, *Selected Essays of Herman Daly*, Edward Elgar, Cheltenham, 2007. Daly advances a similar line of argument with respect to the early climate change analyses of Nobel Prize winners Thomas Schelling and Williams Nordhaus. Both authors claimed that climate change impacts would be small because food (thought at that time to be the only sector affected by climate change) comprises only a small share of GDP. The illusion seems to be similar: an assumption that anything that comprises a small share of GDP will not be missed, if suddenly inavailable. If food did become scarce however, its share of GDP would rise significantly, because it is essential to life. The same cannot be said of, say, a sudden shortage of flat screen TVs.

Perhaps a confusion of marginal and total utility with respect to energy is the reason the 'blind spot' persists in conventional measurement of productivity. The point is important because if it is thought, as conventional measurement implies, that only a small share of our increases in standard of living is explained by energy, then the converse also becomes true. That is, it would be thought that only small reductions in standards of living would accompany an event that made energy scarce.

C. The role of energy in productivity growth

The German team of Reiner Kuemmel, Dietmar Lindenberger, Wolfgang Eichorn and their other research partners over the years, appear to be amongst the first to investigate the role of energy in productivity gains. Initially researching the German economy, and using a production function based on physical inputs, hours of labour and capital, Kuemmel, Lindenberger and Eichorn (1998) reach the conclusion that changes in energy inputs are the crucial factor influencing value-added (or GDP) over time. [15] The research team estimate that energy contributes 50 per cent to value-added in the German industrial sector, while human labour contributed only 5 per cent and capital 45 per cent. Estimates of a similar magnitude were made in an analysis of the industrial sectors of the US and Japan. Using these figures as the weights for the energy, labour and capital factors of production, the production function used by Kuemmel *et al* (1998) reproduced the empirical data on value-added 'astonishing well'.[16]

Groscurth (1998: 239) makes the interesting observation that such results indicate that much of the financial reward of applying 'cheap and powerful' energy in production systems has actually been transferred to the labour force. He suggests that this transfer

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[15] This research reported here is translated and reported by H. Groscurth, 'Elements of a policy for more labor and more environmental protection', *Ecological Economics*, 27, 237–242, 1998. See also R. Kuemmel, J. Henn, and D. Lindenberger, 'Capital, labor, energy and creativity: modelling innovation diffusion', *Structural Change and Economic Dynamics*, 13, 415–433, 2002; and R. Kuemmel, D. Lindenberger, W. Eichhorn, 'The productive power of energy and economic evolution', *Indian Journal of Applied Economics*, 8, 231–262, 2000 (Special Issue in Honour of Paul A. Samuelson, July–September 2000).

[16] Groscurth, p.239.

mechanism has developed historically over a long period and has been successful in its time, but it is no longer appropriate. By keeping energy cheap, Groscurth argues, there is a continuous incentive to exploit nature, thereby damaging life-supporting capacities. It also keeps the factor labour very expensive, and this increases pressure to substitute it with capital (and energy), creating unemployment.

Hall *et al* (2001) and Hall and Klitgard (2006) commend the biophysical perspective of an economy that Kuemmel and his team take. They argue that this perspective highlights the way that evolving forms of energy and the technology using it, have increased standards of living (goods and services produced) over time. For example, food was produced in hunter-gatherer societies using 'the energy of each individual's muscular activities and the force concentrating technologies of spear points and blades'.[17] Energy from human and animal muscles, wood, elevated-water, and then coal were used as societies grew. Then, at the beginning of the twentieth century, the discovery of oil (and its derivatives), with its even greater energy intensity and transportability, transformed the economic landscape on a scale economic hitherto unimaginable. This transformation was especially due, of course, to one special technological evolution of energy and capital: that being oil combined with the internal combustion engine. As Hall *et al* say, 'huge armies of energy slaves (now) create our wealth'.[18]

Another research program over many years by Ayres and Warr (reported in Ayres and Warr, 2009) has built on that of Kuemmel and associates, and produced similar conclusions. Arguing that, as far as technical change is concerned, economists have had a tendency to 'persistent avoidance of specifics', Ayres and Warr seek to understand the nature of technological barriers and breakthroughs in specific economic sectors.[19] They observe that the capability of virtually every technology utilised in industrial society tends to be limited by the properties of the materials used.

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[17] Hall and Klitgaard, p.13.
[18] C.A.S. Hall, D. Lindenberger, R. Kuemmel, T. Kroeger and W. Eichhorn, 'The need to re-integrate the natural sciences with economics', *BioScience*, 51(6), 667, 2001.
[19] Ayres and Warr, p.51.

Breakthroughs occur when new materials are found that extend the capability of the existing ones. Importantly, the increased functionality almost always entails more complicated processing involving more powerful forms of energy and stronger materials. In searching for a proxy for technological progress therefore, Ayers and Warr (2009) focus the continual upgrading of capabilities enabled by energy. They identify what they term 'exergy conversion efficiency' as a surrogate for technological progress. This term is perhaps more easily understood as 'improvements in the useful work done' by energy throughout all the stages of the economy indicated in Figure 1, including that used for consumption purposes such a space heating and cooling. Since 'useful work' is central to the Ayers and Warr analytical framework, however, that term itself needs further clarification.

Ayers and Warr use the terms 'work' and 'useful work' as physicists understand these terms, rather than as do economists. Energy is useful to humans because it does work, in a thermodynamic sense, in supplying goods and services. 'Power' in physics is defined as 'work performed per unit of time' and the term 'work' itself is understood most readily as mechanical work, or 'horsepower'. Strictly, this is how 'work' used to be conceived in the 18th century when the notion was specifically defined in terms of the distance a horse pulls a plough over a time period, or in terms of a pump raising an amount of water against a force of gravity. In fact, since that time, other types of work have been identified, namely, thermal work, chemical work and electrical work.

If 'work' is understood broadly in this sense, then 'useful work' refines the concept to focus on the fuel producing the work. Specifically, 'useful work' indicates the extent to which a given fuel source is able to achieve the work required (be it mechanical, thermal, chemical or electrical) without incurring losses (such as transmission or frictional losses) along the way. Humans, for example, need the fuel source 'food' to provide calories to perform mechanical work. If, say, 3000 calories are consumed per day, some 1500 or so of these are needed for chewing and digesting food, circulating blood, breathing and other metabolic needs. Then apparently, muscles convert energy

into work at only about 15 per cent efficiency.[20]On the whole therefore, food, converted to mechanical work by the human body is a relatively inefficient way of producing work. By comparison, as described by Ayres and Warr, hydropower, uses gravity to produce electricity, and electricity is a form of energy that can be converted to mechanical work (or chemical work) with much less loss incurred along the way. It is, according to Ayres and Warr, almost 'pure useful work'. [21]The comparison is complicated, however, by the fact that electricity can then be combined with appliances that will then have varying rates of efficiency in producing useful work. Summing up, Ayres and Warr suggest that examining the progression in fuel sources used over a period of time, and more specifically the improvements that have occurred in our ability to convert these fuels into useful work, will provide us with a proxy for technological change. This then, is the 'exergy conversion efficiency'. Significantly, it is a proxy that is empirically measurable.

After performing a somewhat daunting set of calculations converting forms of energy in use in the economy by the 'average conversion efficiency' of each, to indicate the work done, Ayres and Warr introduce a three factor production function with 'useful work', U, as the third factor. The form of the production function (a 'LINEX') is borrowed from Kuemmel and colleagues, and contains factors which are complements in some respects, and substitutes in others respects.[22] The results of empirical testing suggest that useful work, U, can explain almost all of the productivity gains over the 20th century for the US, Japan and the UK.[23] Ayres (2008:307) concludes that:

> One can now be quite certain that exergy (as delivered in useful work) is indeed a third factor of production, in agreement with intuition, if not with some earlier authors. In fact, the calculated elasticity of energy as useful work is up to ten times higher than those earlier estimates based on the factor share assumption.

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[20] Ayres and Warr, p. 89.

[21] Further detail and explanation on all this is found on Ayres and Warr, pp.89-98.

[22] The specific properties of the production function are summarised in Ayres, pp.300–301.

[23] See Ayres and Warr, pp.197–212; and B. Warr, H. Schandl, and R.U. Ayres, 'Long term trends in resource exergy consumption and useful work supply in the United Kingdom, 1900 to 2000', *Ecological Economics*, 68, 126–140, 2008.

Whilst the calculated output elasticities of energy were at least ten times those indicated by the use of factor shares, those of labour, especially unskilled labour, were much less than the 70 per cent or so indicated by factor shares. The results suggested that pure unskilled labour, in the absence of machines and sources of power, is almost unproductive at the margin: 'One more unskilled worker, without tools and mechanical or electrical power, adds almost nothing to economic output'.[24] Unskilled labour must be being paid therefore, not from its own productivity since that is low, but from the productivity of energy. This is the transfer mechanism mentioned earlier by Groscurth (1998:239) whereby labour receives the rewards generated by energy.

D. Conclusions and policy implications

Preceding sections of this paper have argued that the standard practice of measuring productivity by weighting energy according to its factor cost share underplays the role increasingly potent forms of energy have played contributing to the high labour and total factor productivity growth of the last century. Building on the work of earlier researchers, Ayres and Warr (2009) have shown, for example, that the amount of useful work done (in a thermodynamic sense) by energy in the United States, Japan and United Kingdom economies, is actually a good proxy for technological change occurring in those countries over the last century. It appears that energy contributes to growth at least 10 times more than a factor cost share would indicate, whilst unskilled labour contributes almost zero.

If it is true that past increases in productivity in developed countries have been underpinned by capabilities enabled by energy, most of which are fossil fuel based, the question arises as to the likelihood of further productivity gains of this same order of magnitude in a future that switches much more towards sustainable (or low carbon) sources of power? At least in the foreseeable future, fuels using carbon geo-sequestration or renewables having an EROI (energy return to energy invested) to

[24] Ayres and Warr, p.216.

rival that of carbon-emitting fossil fuels, such as would enable sustained further increases in useful work, are not on the horizon.

Ayres and Warr (2009: 297) warn that slower global growth seems a likely outcome:

> The most important implication of the new theory, up to now, is that future economic growth is not guaranteed because the efficiency gains that have driven growth in the past may not continue. Economic growth depends on producing continuously greater quantities of useful work. This depends, in turn, upon finding lower-cost sources of exergy [useful work done by energy] inputs or more efficient ways of converting higher cost inputs into low-cost work outputs. In a world where the cheapest sources of exergy seem to be approaching exhaustion, the key to continued growth must be to accelerate the development of lower-cost alternative technologies, and policies, that increase conversion efficiency.
>
> Meanwhile, if the rate of technological advance fails to compensate for the combination of approaching resource (notably cheap oil) exhaustion and policies needed to cut back on carbon dioxide emissions, we have to anticipate the possibility that economic growth will slow down or even turn negative. Global depression in the coming decades seems to us to be a serious risk.[25]

It appears that this warning, and the analysis underpinning it, is not reaching policy or media circles. Acting on a scale, and at a pace, that seems unprecedented in recent history, the threat of recession in Australia seems to have galvanised politicians into something of a frenzy. The impression is created that this rare and 'one-off' event can be averted with clever measures, after which we may relax and return to where we left off. But the energy productivity research suggests the distinct possibility of longer term slowing in growth — raising the question: shouldn't we be planning for this possibility now? What sectors and businesses are likely to be most affected? How will this affect our ability to fund climate change adaptation and withstand its drought, bushfire and other impacts? It seems extremely unwise, both from a political and a practical perspective, to continue a 'blind faith' that growth will return to previous

[25] Ayers and Warr, p.297.

levels for a sustained period, especially if serious efforts are also being made to reduce carbon emissions and 'dematerialise'. Moreover, if productivity is to be 'the building block of the future' for Australia, as current policy states, then accompanying policies to promote energy efficiency would seem urgent. That is to say, surely it would be wise for the major investment programs that are to achieve the productivity goal to be integrated as much as possible with a second 'plank' of the program, namely new policies promoting energy efficiency. Since ultimately, sustainability requires a switch to low carbon energy sources, an all out effort to 'let a thousand flowers bloom' with respect to renewable energy research and development seems urgent, as well. Only with sustainable forms of energy having EROI's close to those obtained from energy in the past, does maintenance of rates of productivity growth rates seems possible.

Some other, perhaps more prosaic implications of a better understanding of the role of energy in productivity growth are:

- It is well known that past labour productivity increases have been achieved with very high increases in material throughput.[26] Little seems to be known about the relationship between labour productivity and material, or (as more commonly described) resource, productivity, however. Surprisingly, the issue appears to have received little attention from any school of economic thought. David Pearce (2002) noted the possibility that labour and resource productivity could be negatively related – improvements in resource productivity, also termed dematerialisation, being a priority for those advocating sustainability. Pearce observed therefore that there may be a concern that pursuing resource productivity as a goal of policy will harm the 'traditional' goal of raising labour productivity.[27] If there is such a concern, Pearce argued that one could respond with the suggestion that raising resource productivity would have

[26] In a series of exponentially rising graphs, Ayres and Warr illustrate in detail the enormous increases in industrial metabolism – the flow of materials through the economy as extraction, production, consumption and disposal take place – over the 20th century in the USA. The components of industrial metabolism examined are fossil fuels, metals, construction materials, inorganic and organic compounds and biomass. See Ayres and Warr, pp. 69–87.

[27] Pearce, p.22.

favourable effects on human capital by avoiding a loss of amenity and natural capital that may otherwise affect human health. In this way, labour productivity may actually be assisted. It seems important at the very least, to review the compatibility of productivity goals.

- The argument above is one aspect of the broader point that pursuit of increased labour productivity – increases in GDP per unit of labour employed – ignores the problems inherent in the measure of GDP itself. In other words, a policy goal of increasing labour productivity will fail to ensure well-being in areas ignored by GDP generally. These include leisure time, health status, income equality, gender equality, personal liberty, political freedom and so on[28]. Most importantly, perhaps from an ecological economics point of view, it will ignore deterioration in ecosystems and pollution, as it has done in the past.
- If it is true, as the energy research reported in section C of the paper discovered, that the marginal productivity of unskilled labour is almost zero, then labour will undoubtedly be the factor that is first to be laid off in a prolonged slow down. Political 'will' cannot force businesses to hire people or to retain unproductive labour. Investment programs designed to re-skill labour are therefore well founded on these grounds. The same research also suggests that it would be wise, because unskilled labour has low productivity, to use the revenues from tradeable permits, to lower the fixed costs of hiring labour.

- The research also reinforces the 'natural capitalism' vision of Hawken, Lovins and Lovins (1998) and their ideal of a 'service and flow' economy. However difficult it might be to implement, this calls for a shift from an economy where consumers always purchase new goods to one where the services of goods are still received, but retailers *lease* the goods. Air conditioners are not sold outright to consumers but are leased and maintained by air conditioning firms – the latter now having an incentive to find the cheapest way of providing the service. Carpet services are not sold, but leased, so again, a search for economies and less toxicity is in the interest of the carpet-service seller. This is

[28] See, for example, Hamilton, C. 2003, *Growth Fetish*, Allen and Unwin, Sydney, Chapter 2, pp 22-6.

a fundamental change in the relationship between consumers and sellers, but it is one that achieves higher resource productivity.

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