Low Carbon and Economic Growth – Key Challenges

Institute for
Integrated Economic Research

LOW CARBON
AND ECONOMIC GROWTH

This report is part of a group of documents focused on the compatibility of carbon emission reductions and economic growth with a specific emphasis on the situation of emerging economies.

Our research arrives at the conclusion that growth in the industrial age is tightly linked to the availability of cheap and highly versatile energy sources. A shift to a different paradigm will likely reduce the potential to grow for most economies, but particularly for aspiring industrial societies (like China). The report is structured as follows:

- Executive summary
- Core report with alternative (energy-focused) macroeconomic models
- Topical Q&A supplements on a number of key issues related to low carbon
- 2-4 page country summaries on a number of emerging economies

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Introduction

This report questions one of the key underlying assumptions of most plans to reduce carbon emissions: that it is possible to grow or maintain economic output while at the same time reducing the anthropogenic production of greenhouse gases.[1] In this document, we will demonstrate our findings that the generally desired developmental path to urbanization and industrialization is very unlikely unless it can be based on large quantities of low-cost and high-quality energy. This contradicts the current push for greenhouse gas reductions, as the only (seemingly) unlimited energy sources with the right properties are fossil fuels like coal, natural gas and (until recent price increases) oil. These fossil fuels have been at the core of economic development and growth, but only as long as they were not burdened with the cost of their externalities: pollution, climate change, and depletion. In comparison, renewable sources are either not scalable or geographically limited (such as hydropower[2] and geothermal[3]), are cost-prohibitive[4], or produce only lower quality energy[5], a reality we don't expect to change anytime soon. In a future where fossil fuels are no longer available at low cost, either due to extraction limits or because they include the cost of externalities (such as a carbon tax or sequestration efforts), we cannot envisage how the current growth model of advanced economies can continue, let alone support emerging economies to reach a comparable level.

Given this likely inability to grow in a carbon-neutral way, we suggest a very different development path for the future which would allow improvements in the quality of life, health, and wealth for a large portion of the population: the introduction of simple, mostly non-industrial renewable and sustainable technologies. If done properly, we expect that the rural poor – the majority of the population in developing nations, and 70% of those living on less than $1.25 per day[6], can benefit from significant life and wealth improvements, while greenhouse gas emissions stay the same or even shrink. The lives of billions of people living in dense urban centres could also be positively affected by some of these approaches, but because their incomes and therefore their well-being are linked to industrial processes, it appears that meaningful growth will be more difficult to achieve in large urban areas without increased fossil energy consumption and thus carbon emission growth.

In this report, we introduce the concepts and data supporting this point of view, and suggest a few areas where improvements seem possible. This report is divided into three parts:

- Review and refocusing of relevant macroeconomic theory
- Introduction to high linkage between energy (cost) and wealth
- Low-carbon development potential, with a focus on emerging economies

[1] Economic output here refers to the commonly used measurement of Gross Domestic Product,.

[2] Hydropower development is limited in OECD countries and limited by precipitation. EIA (2010).International Energy Outlook Electricity. Available from http://www.eia.doe.gov/oiaf/ieo/electricity.html Accessed January 31, 2011.

[3] See "Barriers". IEA (2010). Renewable Energy Essentials: Geothermal. Available from http://www.iea.org/papers/2010/Geothermal_Essentials.pdf Accessed January 31, 2011.

[4] See both 2005 and 2010 versions of IEA/NEA: Projected Costs of Generating Electricity. http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2207

[5] For example, solar hot water heaters have brief payback periods, are relatively inexpensive to install, but only provide lower quality heat energy.

[6] UN-IFAD (2011).Rural Poverty Report 2011.http://www.ifad.org/rpr2011/report/e/print_rpr2011.pdf Accessed January 31, 2011.

1. A different macroeconomic theory

1.1. The main macroeconomic view

Most macroeconomic planning models operate under the assumption that "economic growth", i.e. adding more real (inflation-corrected) output every year can continue indefinitely[7]. This might be interrupted by recessions and other distortions, but those do not alter the long-term trend. This view remains largely unchallenged with the exception of some small groups of resource-based and ecological economists, but their views are not typically included in political or financial decision-making processes.

In most theories, a number of key factors are said to drive economic progress (and growth):

- Labour productivity gains[8]
- Substitution (inputs and technologies)[9]
- Technology progress[10]
- Population growth (labour availability)[11]

Our analysis generally supports the view that these key components are useful in describing past growth. However, while the ingredients of traditional models are in line with our findings, our approach sees them only as derivatives of a broader resource- and energy-based view. In this paper we aim to demonstrate how most of the above key parameters were actually driven by resource and energy availability, and not just the result of human progress, as they are typically explained. The implications of these differences on economic systems are significant.

Our economic success over the past 200 years has been remarkable, providing steady growth in most societies, despite a rapidly growing human population. Not only were there six times more humans in the year 2000 compared to 1820, but equally impressively, per capita GDP has increased nine times during the same period (Figure 1).

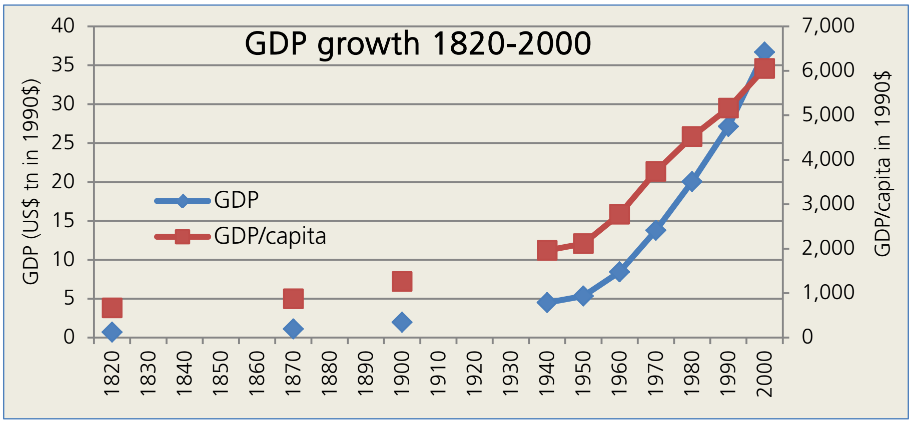

Figure 1 - GDP and GDP/capita in 1990 International Geary-Khamis dollars[12]

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[7] E.g. models presented in the following macroeconomic theory texts: Hubbard and O'Brien (2009). Macroeconomics; McConnell, Brue, and Flynn (2008) Macroeconomics: Principles, Problems, and Policies. Mankiw (2010).Macroeconomics.

8 Solow, R.M. (1957). Technical Change and the Aggregate Production Function. The Review of Economics and Statistics 39(3):312-320

[9] Solow, Robert (1974). The economics of resources or the resources of economics. Am. Econ. Rev. 1–14.

[10] Stiglitz, J.E., (1979). A Neoclassical Analysis of the Economics of Natural Resources. In: Smith, V. Kerry (Ed.), Scarcity and Growth Reconsidered. RFF and Johns Hopkins Press, Baltimore, MD

[11] Galor, O. and D. N. Weil. 2000. Population, technology and growth: From Malthusian regime to the demographic transition. American Economic Review 90(4): 806-828.

[12] Angus Maddisson. The World Economy: Historical Statistics. OECD.Data available from http://www.ggdc.net/maddison/Historical_Statistics/horizontal-file_02-2010.xls Accessed February 2, 2011.

1.2. An alternative view

Below, we will explore these aspects further, analysing in detail what drove economic growth in the 19th and 20th century. This ultimately leads to a significantly altered macroeconomic view, with the following characteristics:

- Improved (labour) productivity became possible due to a substitution away from human labour to fossil energy use, with relatively unfavourable exchange patterns, i.e. to complete the same task using technology, much more energy was required compared to the original task performed by a human[13];
- Technology thus does not act as an independent driver but rather as an enabler of higher and more efficient energy consumption for purposes desired by humans[14];
- Globalization (mostly in the past 20 years) further acted as a strong driver of optimised resource and energy allocation with benefits for all involved participants;[15]

Traditional economics, while referring to productivity and technology, does not encompass a view that is based on resource or energy consumption. Instead, it explains productivity gains and economic growth using a technology model that is driven by "endless" human ingenuity. This is also the case for better specified endogenous growth models, which focus on modelling a separate R&D sector and economic incentives that drive technological developments, to explaining the process of human ingenuity.[16] The validity of such models in a period of abundance of resources and availability of low cost energy is not questioned. However, their applicability to a situation where cheap fossil fuels are no longer available is put into doubt by this report. From our point of view, technology historically served much more as an "access enabler" to higher fossil energy consumption.

On a similar note, globalization, the exchange of key contributors across the world, largely has not been introduced into most macroeconomic models, despite the fact that it has substantially altered and expanded the economic potential of the world.

Below, we will review these drivers from an energy- and resource-based perspective, construct a more relevant and – so we think – realistic economic picture, and then outline the implications that flow from it.

1.3. It is all about energy

Looking into well documented and acknowledged resource limits leads to a better understanding of the role energy plays in economic systems: numerous papers have analysed increasing water shortages on a global scale[17]. With ground reservoirs draining, glaciers shrinking and more and more rivers being polluted, water availability has become an issue in many places, particularly related to potable or irrigation water. But a closer analysis confirms that there isn't really a water shortage on a global scale. Water covers more than 70% of the Earth's surface. The average annual global precipitation equivalent to 95-115 cm – is more than enough, on average. However, rain has variable distribution with most precipitation falling between 30 degrees latitude north and south[18]. So essentially, something more funda-

[13]Cleveland et al. (1984). Energy and the U.S. economy: A biophysical perspective. Science 225: 890-897.
Hall et al. (1986). Energy and Resource Quality: The Ecology of the Economic Process. Wiley Interscience. New York.
Hall et al. (2003).Hydrocarbons and the evolution of human culture. Nature 426: 318-322.
[14] Kaufmann, R. K. (1992). A biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change. Ecological Economics 6: 35-56.
[15] See section 2.10 on globalization below.

[16] Sorensen & Whitta-Jacobsen (2005). Introducing Advanced Macroeconomics: Growth & Business Cycles. Berkshire: McGraw-Hill.

[17] For example see: UNEP (2008). Vital Water Graphics - An Overview of the State of the World's Fresh and Marine Waters. 2nd Edition. UNEP, Nairobi, Kenya.; UNEP (2007). Global Environmental Outlook 4. UNEP, Nairobi, Kenya.; Li Jiao (2010).
[18]Chahine, M.T. (1992). The hydrological cycle and its influence on climate. Nature 359:373 – 380.

mental is lacking in those places where fresh water is scarce: the ability to bring water to its desired point of use and/or to purify and/or desalinate water to make it useable. The key enabler for this is energy. Specifically, low-cost energy that is affordable by the regions affected. This is no issue for (resource-)rich oil exporters in the Middle East which are able to bear the cost of desalination plants, but poses insurmountable hurdles to poor regions with draining groundwater reservoirs.

Very much the same dynamic holds true for practically every resource society considers to be scarce. Typically, what we have consumed doesn't disappear but is still available on this planet, but often in concentrations where recycling isn't economical.

Even oceans contain almost every precious metal on this planet, yet in very low concentrations. With sufficient effort, we could extract gold, silver, uranium and many other elements from the sea. However, the energy required is too large compared to other sources where much less energy is needed to extract materials from higher grade ores.[19] Thus, we do not attempt to filter minerals from oceans.

Equally, pollution or the unsustainable use of environmental services can be seen as a lack of effort spent (=energy used) in repairing damage done to the environment. With sufficient low-cost energy, many of today's problems were inexistent.

Ultimately, each metabolism or process which creates structure – i.e. "something meaningful" – by transforming higher entropy to lower, whether it is biological, chemical or mechanical, requires an energy transformation to take place[20]. Plants do not grow without sunlight, cars don't run without fuel, computers don't operate without electricity, and humans don't live without food (=energy), nor does any other species.

It is thus difficult, if not impossible, to name any activity that is priced by markets - no matter how virtual it might be[21] - that does not require energy. This raises the question of how exactly the two are related?

1.4. Biophysical or ecological views

Anchoring economic output with the resources that enable them has become part of two sub-divisions of more recent economic science, biophysical and ecological economics. Both have – outside their relatively small group of adherents – failed to

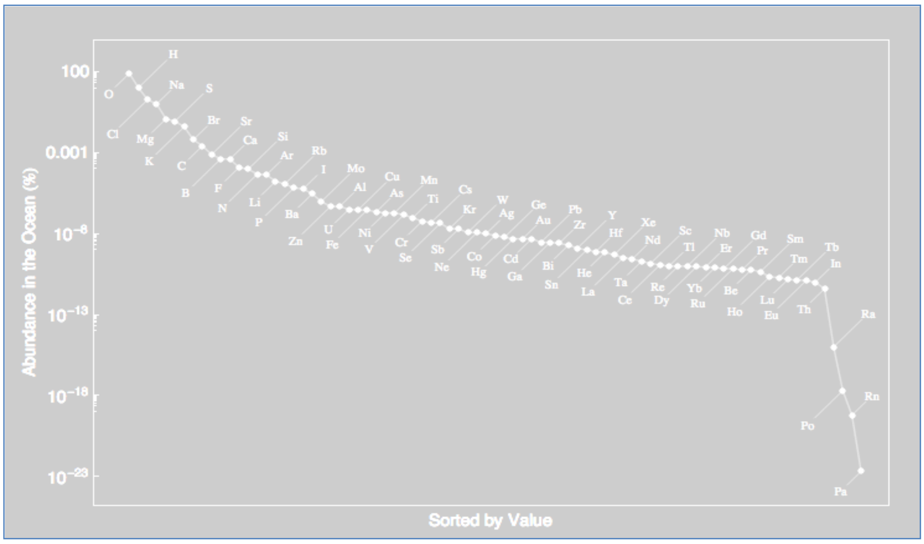

Figure 2 - Abundance of elements in the ocean (Data from Wolfram Research/ Mathematica, Accessed January 13, 2011)

[19] Bardi U. (2010). Extracting Minerals from Seawater: An Energy Analysis. Sustainability 2(4): 980 – 992.

[20] Georgescu-Roegen, N. (1975). Energy and Economic Myths. Southern Economic Journal, 41,3:347-381. http://www.jstor.org/pss/1056148
Odum, H. T. (2007). Environment, power, and society for the twenty-first century: The hierarchy of energy. New York: Columbia University

[21] The Internet accounted for 0.8% of all electricity use in 2005 and consumption is rapidly growing with the increase in streaming of internet video content. Koomey, J. G. (2007). Estimating total power consumption by servers in the U.S. and the world, Lawrence Berkeley National Lab http://hightech.lbl.gov/documents/DATA_CENTERS/svrpwrusecompletefinal.pdf Accessed January 31, 2011.

gain significant traction, and their findings have not found their way into mainstream economic decision-making. The main reason behind this omission might be that they do not matter as long as natural resources and energy remain largely unconstrained input variables into economic processes.

Biophysical economists' views suggest a relatively strict connection between economic output and energy and natural resource inputs. Many of those theories emerged during and after the oil crisis of 1973/4, following the concepts presented in "Limits to Growth"[22]. During that time, energy prices increased rapidly within months, and many advanced economies went into recession. Resource experts, non-traditional economists, and population scientists began to explore the risks imposed by constrained resources amid quickly growing populations. Ecologists and the newly formed subdivision of biophysical economists studied the historically very strong link between energy consumption and GDP growth and criticised traditional economics for failing to include energy as an important component of economic models and a key driver of growth[23].

However, traditional economists maintained their position that higher energy prices would lead to lower energy consumption and to a discontinuation of the correlating trend because higher prices for energy sources would simply encourage shifts away from energy by means of substitution, without affecting the overall growth pattern.

These views were seemingly confirmed, when after the mid-1970s, the relatively strict long-term correlation between primary energy use and economic output weakened, and advanced economies around the world required less additional energy to grow their output (see Figure 3 for the United States).

Other aspects of biophysical theories did not get tested as new oil resources and improved technologies enabled a continued growth of energy and resource consumption at low prices once again, beginning in the 1980s and continuing into the early 2000s, supporting traditional perspectives[25].

This new evidence was answered by biophysical economists with a multitude of explanations, ranging from a shift away from energy-intensive goods to products of lower intensity and services, to a replacement of lower-quality fuels with electricity and the introduction of nuclear power, but it never truly gained traction again until very recently with the rise of energy and commodity prices

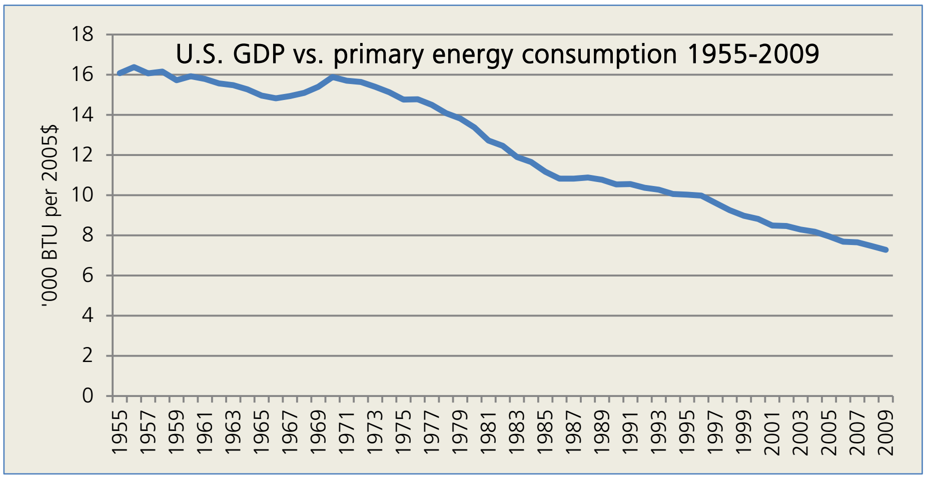

Figure 3 - US Primary energy consumption vs. GDP 1955 – 2009[24]

[22]Meadows, D. H. et.al., (1972). The limits to growth: A report for the Club of Rome's project on the predicament of mankind. New York: Universe Books

[23] Kümmel, Reiner. "The Impact of Energy on Industrial Growth" (1982). Energy – The International Journal 7:189-203.

Energy information administration (EIA)[24]

[25] The giant oil field "The Forties" (and others) were discovered in the North Sea in 1970 and began production in 1975. Oil prices fell by 2/3s from the $90 range in 1980-1981 to $28 by 1986 (2011 US$), due to a glut of oil on the market.

which began around 2005 and culminated in 2008 with oil and natural gas prices up to seven times their historical average, resulting in record price levels of food and non-food commodities. After a brief period of relief due to the economic crisis, many commodity prices are up again to those levels of 2008, bringing the issue back to the table.

1.5. Energy and GDP - a stronger connection than expected

Based on a worldwide analysis, we conclude that at the global scale the correlation between energy input and economic output is stronger than even biophysical economists have anticipated in their recent work, as soon as the object of research no longer is a single economy, but rather the entire world.

Figure 4 shows two important correlations. First, despite a weakening trend after the mid-1970s, higher economic output still seems to be linked to primary energy inputs, with the two being highly correlated (r^2=0.92 from 1980 to 2006). Second, if instead one compares useful energy that can directly be applied to desired processes, the correlation becomes even stronger. For example, global GDP and electricity consumption from 1980 to 2008 show a very strong correlation (r^2 = 0.97), and the same is true for transportation fuels.

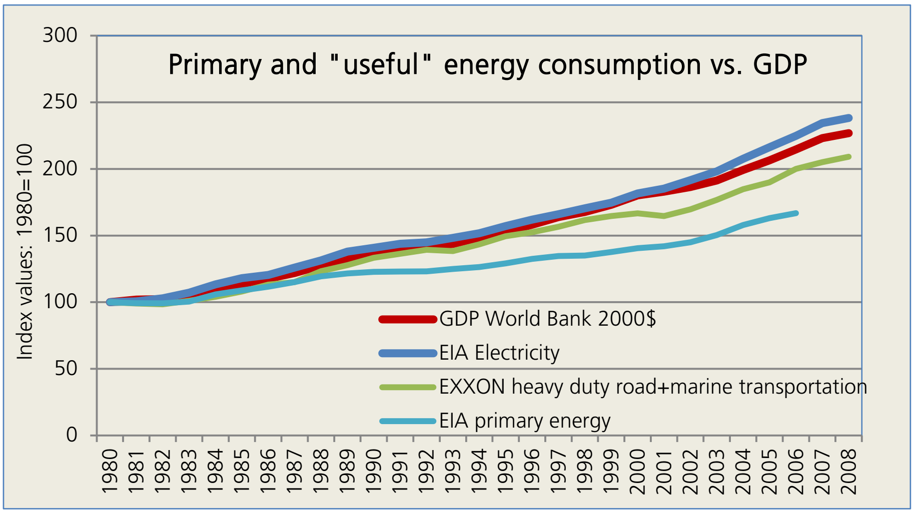

Figure 4 - Global GDP vs. various energy consumption indices (1980 = 100)[26]

When looking at this data, two aspects got overlooked. Firstly, traditional economics ignored that advanced economies were going through a continuing process of "de-industrialization", with most of the heavy manufacturing being relocated to emerging economies, first and foremost China. This has created an illusion of disconnect between economic growth and energy input – essentially the illusion that OECD economies are becoming more energy efficient.[27] If one includes energy transfers embedded in imports of raw materials and finished goods, no economy in the world demonstrates a disconnect between energy and GDP.

Second, biophysical economists downplayed the fact that there is indeed second order technology development taking place, which is geared at lower primary inputs into processes, or energy efficiency. This can be attributed to energy saving measures which reduce primary energy use, such as the introduction of more efficient technologies in many areas, the substitution of fuels[28], and improved energy conversion technologies at the primary conversion level[29], for example, in electricity generation (Figure 5).

[26] GDP :http://databank.worldbank.org; Primary Energy and Electricity: EIA. International Energy Statistics
http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm; Road and Marine Transport:
http://www.exxonmobil.com/corporate/files/news_pub_eo_2009.pdf

[27] Guan, Peters, Weber, Hubacek (2009). "Journey to world top emitter – an analysis of the driving forces of China's recent CO2 emissions surge." Geophysical Research Letters.36, L04709.

[28] See note 13.

[29] See section 1.13

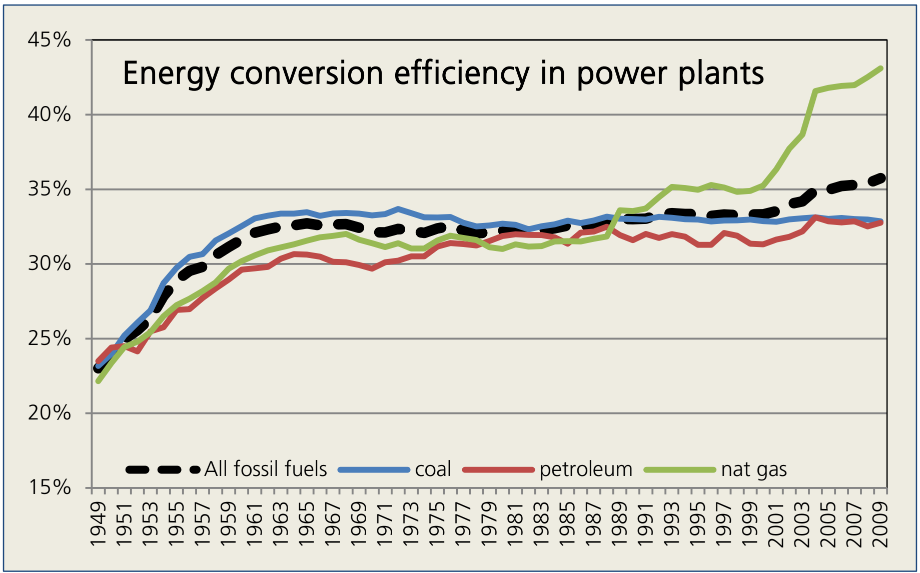

Figure 5 - Average efficiency (%) by fuel type for fossil fuels in electricity production in the United States[30]

The efficiency of power plants has improved from about 24% in the 1950s to an average of 33% today, with the highest efficiency plants reaching 47% (coal) and 50+% (natural gas), returning more net available energy to societies from the same input quantities[31]. To separate the effects of substitution and biased technical change a number of authors have used end use energy consumption corrected for primary energy efficiency gains. Their results show that capital and energy services are complimentary and no substitution over time takes place.[32] Based on these results, we would argue that there has never been any disconnect between energy consumption and economic output on a global level.

So while some efficiency-related improvements can be observed over time, the evidence suggests that energy does remain the key driver behind all processes and transformations taking place in an economy. In this light, it seems fair to conclude that energy is not a dependent variable of growth, but instead a prerequisite for economic development.

To summarize these findings, the following statements about energy hold up against scrutiny:

- Each economic transaction requires an energy conversion;
- Each additional transaction (i.e. growth of economic activity) requires an additional energy conversion
- The economy/energy connection may be weakened by energy efficiency improvements or by substitution of processes or outputs, but never be broken.

With this background, we will further investigate the dynamics of the industrial age observed to the present day by applying an energy-based view to existing macroeconomic concepts.

1.6. An energy-based explanation of productivity gains

Traditional economics argues that economic growth can only take place if total factor productivity or total factor inputs increase[33] by an increase in human or capital input, or – more importantly – if the return on investments of capital or labour increase.

Productivity gains are regarded as the most dominant driver of the industrial age by far. Between 1870 and 1979, labour productivity across entire economies grew by a factor of 10 (Canada, U.S., Italy) or even 20 (Sweden,

[30]Derived from EIA (2011). Electric Power Annual . available from www.eia.gov/cneaf/ electricity/ epa/epa_sum.html , accessed Feb 2,2011, EIA numbers show larger global improvements for coal: www.iea.org/ciab/ papers/power_generation_from_coal.pdf
[31] Beer, J. High Efficiency Electric Power Generation; The Environmental Role. MI. Available from http://web.mit.edu/MITEI/docs/reports/beer-combustion.pdf Accessed Feb 2, 2011.

[32] Kander, Astrid, Schon, Lennart (2007). "The energy-capital relation – Sweden 1870 – 2000." Structural Change and Economic Dynamics. 18, p. 291-305. Ayres, Robert, Warr, Benjamin (2009). The Economic Growth Engine: How Energy and Work Drive Material Prosperity. United Kingdom: Edwar Elgar Publishing Limited

[33]See section 1.1

Japan) – see Table 1.[34]. For individual industries, the improvement was even higher[35]. The most substantial productivity improvements have been observed in information technology.[36]

Country	GDP/work-hour
Australia	498%
U.K.	685%
Switzerland	930%
Netherlands	1010%
Canada	1150%
United States	1180%
Germany	1610%
Norway	1660%
France	1690%
Finland	1810%
Sweden	2160%
Japan	2580%

Table 1 - Total productivity growth 1870 to 1979 (inflation-corrected)[37]

Increases in agricultural productivity further demonstrate how "efficient" human labour has become. For the largest part of human history, more than 90% of the population was occupied in farming. Even in 1900, 41% of the U.S. workforce was employed in agriculture, a number that continues to decline to this date[38] (Figure 6). Today, in most Western economies, between 1.5% and 3% of the workforce are associated with farming occupations[39].

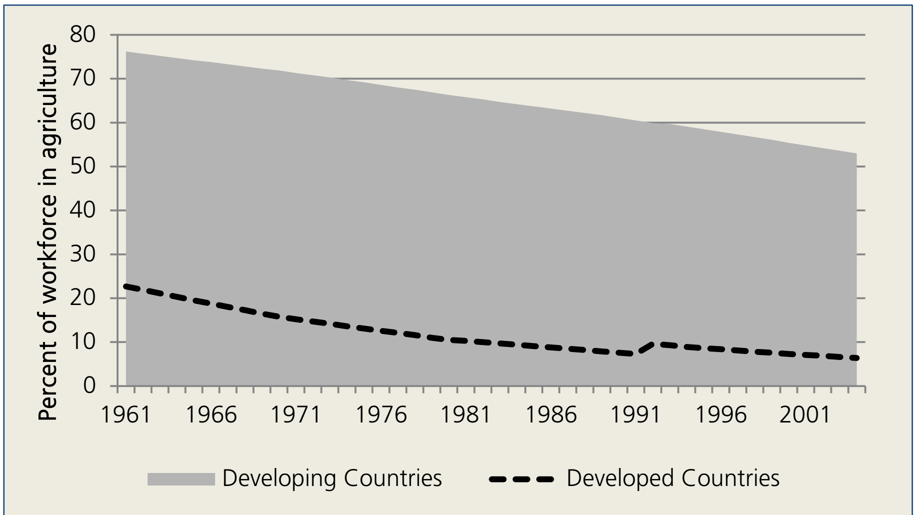

Figure 6 - Per cent of total workforce in agriculture 1961 - 2004[40]

It is important to note that typical productivity numbers derived from monetary output value only tell part of the story; the true measure of the replacement of human labour becomes visible when looking at units of output. Over the past two centuries, quantitative output in all agricultural productivity has grown significantly. Yet because these gains also led to lower prices of those goods, value based productivity numbers don't present the true picture. When looking at output growth per labour hour, the true dimension of this change technology brought about becomes visible. For wheat, yield per labour hour in the United States grew by a factor of 50 since 1800, and by a factor of 105 for corn (Figure 7).

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[34]Baumol, W. J. (1986). Productivity Growth, Convergence, and Welfare: What the Long-Run Data Show. The American Economic Review, 76,5:1072-1085. (source of productivity table) Maddison, A. (1982). Phases of Capitalist Development, New York: Oxford University Press. (data for table)
[35]Bureau of Labor Statistics.Industry productivity indexes. December 19, 2005. Available from ftp://ftp.bls.gov/pub/special.requests/opt/dipts/iprsicdata.txt Accessed Feb 2, 2011.
[36]Bureau of Labor and Statistics.U.S. Department of Labor.Superseded Historical SIC Industry Labor Productivity and Costs Indexes. Available from ftp://ftp.bls.gov/pub/special.requests/opt/dipts/iprsicdata.txt Accessed February 2, 2011.
[37]Baumol, W. J. (1986). Productivity Growth, Convergence, and Welfare: What the Long-Run Data Show. The American Economic Review, 76,5:1072-1085.
[38]Dimitri, C, et al. (2005). The 20th Century Transformation of U.S. Agriculture and Farm Policy.USDA – Economic Research Service.Available from http://www.ers.usda.gov/publications/eib3/eib3.htm Accessed February 1, 2011.
[39]Earthtrends searchable database results: 2011. Agriculture and Food -- Labor: Agricultural labor force as a percent of total labor force. http://earthtrends.wri.org/searchable_db/index.php?action=select_countries&theme =8&variable_ID=205
[40] See note 39

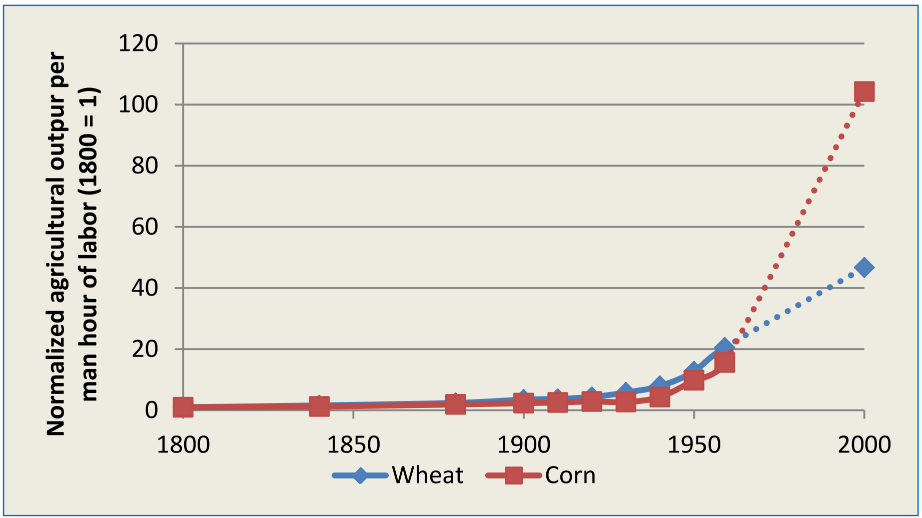


Figure 7 - Normalized agricultural output per man hour of human labour in the United States (1800 = 1)[41]

Commonly, human ingenuity (technology progress) is seen as the main driver behind this shift away from physical labour, an in one way this is absolutely true – without machinery and newly engineered approaches, these productivity gains would have never happened. However, there is another, albeit hidden, aspect that underpins technology. It is obvious when we compare the shift from walking to using a vehicle, and inherent to all aspects of human activity that gets replaced with mechanical processes: **energy applied by human or animal muscle is replaced with energy used by machinery.**

Of the 2,100 to 4,000 calories that the average human adult consumes daily, 45-70% of daily total energy expenditure (varying with lifestyle and age) is dedicated to basal metabolism, of which a large percentage (approx. 40%) is dedicated to power our complex brain[42]. Approximately 10% of our energy is dedicated to ingesting and digesting food. The remaining 20-45% is dedicated to physical labour, the most variable and second largest component of daily energy expenditure[43].

When human labour is replaced by machinery, the complexity of such replacement is often significant. A good example is transportation. Driving a car replaces walking with the use of a highly complex system providing faster motion, the ease of traveling larger distances and the ability to take cargo along.

When comparing a walk to using a car, it becomes fairly obvious that moving 1 ton of steel to transport one person from point A to point B consumes significantly more energy than what it takes in the form of muscular energy. When expending 1 kWh, a human can walk for approximately 20 miles on regular terrain. With one litre of petrol, which contains about 9.7 kWh of raw energy, a typical car is able to travel about 6 miles, so with 1 kWh in the form of petrol, a car moves only 0.6 miles. For many commutes, where only one person is using the car, this represents an efficiency reduction by a factor of 33, not yet including the energy embedded in the car, in the roads, parking garages, traffic management systems, fuel production and transportation, and all other aspects required to keep a car-based transportation system going.

[41] 1800-1960: Data from Rasmussen (1962), year 2000: Data from Pimentel (2008). Rasmussen, WD. (1962). The Impact of Technological Change on American Agriculture, 1862-1962. The Journal of Economic History 22 (December): 578-591 Pimentel, D and Pimentel, M. (2008) Food, energy and society (Third edition). Boca Raton: CRC Press.

[42] RaichleME, and Gusnard DA (2002). Appraising the brain's energy budget. PNAS 99,16:10237-10239.

[43] Food and Agricultural Organization of the United Nations (FAO) (2001).Human energy requirements. Report of a Joint FAO/WHO/UNU Expert Consultation. Rome, 17–24 October 2001. Available from ftp://ftp.fao.org/docrep/fao/007/y5686e/y5686e00.pdf Accessed February 1, 2011.

However, there are further differences between the two approaches. A car can only be used for very few things, mainly transporting people and goods, while the ability to walk and run is only one of many abilities of the human body. So by adding cars and their use as a replacement for walking, human systems have added one highly complex system for just one purpose – transportation.

For almost all activities where the shift from humans to machinery takes place, very energy-efficient and versatile human labour was and is replaced by relatively energy-inefficient mechanical labour. These shifts require complex tools, buildings and designed processes with many more steps than would be required by a human. In all transactions we have reviewed, this trade of machine labour for human time comes with a net loss in energy productivity and even more so when embedded energy in buildings and machinery, and supporting processes is included.

This shift is demonstrated conceptually in Figure 8. With each step of mechanization and automation, human effort (time and energy required) is reduced, and other energy inputs (operating fuels and energy stored in buildings and machinery) is increased, at a much higher rate. Due to the energy-inefficiency of this trade, labour productivity gains were exchanged for energy productivity losses.

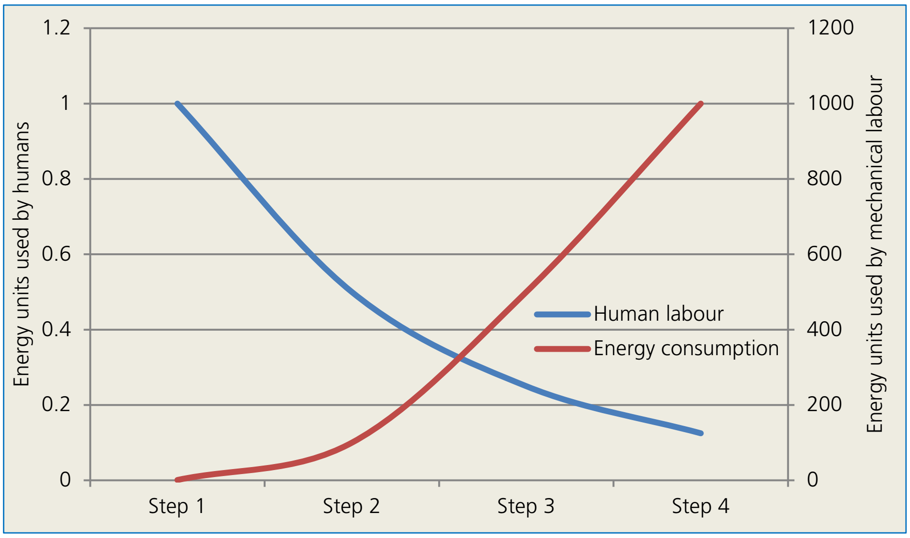


Figure 8 - Energy unit replacement for steps of mechanization

The benefits of this shift are large, because very costly human time is freed up and replaced by a much less energy-efficient mechanical process. As throughout the 19th and 20th century, energy and natural resources became cheaper and more abundantly available, their substitution for human labour has been highly beneficial. Better exploration, more efficient extraction technologies and new reservoirs and mines led to lower and lower effort going into sourcing and extracting the key ingredients of human economic activity.

Below, we provide two examples for this type of shift; the move from milking cows using human labour towards highly industrialized milking technologies, and the shift from walking to using a car.

Milking Cows: Hand-milking requires approximately 110 hours of labour per cow per year, or approximately 20 minutes per day[44]. Other than human labour and solar energy flows required to grow feedstock, there is no other energy required. No equipment is needed in this simplest of milking systems, other than a stool and bucket.

The introduction of the first mechanical milkers reduced the human labour required to milk cows to 51-80 hours per cow per year, or 9-15 minutes per day[45].

[44]Wilcox, W.W. and Rauchenstein, E. (1948). The Effect of Size of Herd on Milk Production Costs
Journal of Farm Economics 30, 4: 713-723
Available from
http://www.jstor.org/stable/1232787?seq=5
Accessed February 1, 2011.
[45] See note 44.

Current milk parlour technology has reduced daily work per cow to 3-6 minutes. This most common parlour system requires energy inputs of 250 to 400 kWh of electricity per cow per year[47]. Further energy inputs are required in the production and maintenance of the milking system. The cost of these systems ranges from $9,000 to $10,000 per stall, with an associated building cost of $6,000 to $8,000[48].

The latest in dairy farming technology is an Automatic Milking System (AMS). These "gates", through which cows have to pass on their way to their fodder, further minimize human labour inputs to milking, reducing human labour to 2 minutes per cow per day. On the downside, they are more expensive, and have higher energy costs in their production and maintenance. Electricity use per cow increases to 400-600 kWh per year. AMS cost significantly more than traditional parlour stalls (from $ 60,000 to $175,000), and require an additional $10,000 in structural investments to buildings[49]. Both traditional parlour systems and AMS have a similar 10-year expected lifespan.

	Hand Milking	Parlour Milking	Automated Milking
Labour required per cow/year	110 hours	27 hours	12 hours
Energy Use of Human(including handling and maintenance)	~8.25 kWh/cow/yr	~2 kWh/cow/yr	~ 0.9 kWh
Energy Use of the System	0	250-400 kWh/cow/yr	400-600 kWh/cow/yr
Embedded energy of the system[a]	Minimal	~840 kWh/cow/yr[b,c]	~2,400 kWh/cow/yr[b,c]
Total non-human energy	N/A	~1,090 to 1,240 kWh/cow/yr	~2,800 to 3,000 kWh/cow/yr
Replacement ratio of machine to human labour	N/A	~174 to 198:1	~381 to 408:1
[a] assumed 17.5 MJ/$ (4.86 kWh/$) for industrially manufactured goods based on Table 10 (page 41) and other sources[46], [b] 10 year lifespan[47],[c] based on suggestions by Rotz et al 2003			

Table 2 - Comparison of machine labour to human labour for two milking technologies[51]

Table 2 shows that in order to milk the same number of cows the amount of human labour (time and thus energy) was reduced and replaced with significantly larger quantities of mechanical labour, between 174 and 198 times for a milking parlour, and around 400 times more for an automated system[50], something only feasible in high-income countries.

Although the energy cost in joules of this shift was higher, it provided cheaper costs in terms of required labour investments and monetary costs, which has paved the way for wage increases, price reductions for milk, and higher profits for farmers, or some combination of the three.

[46] Hall, CAS, Balogh, SB, Murphy, DJ. 2009. What is the minimum EROI that a sustainable society must have? Energies 2(1), 25-47.
[47] Rotz, C.A. Coiner, C.U., Soder, K.J. (2003). Automatic Milking Systems, Farm Size, and Milk Production. Journal of Dairy Science, 86,12:4167-4177. Available from http://fnicsearch.nal.usda.gov/bitstream/10113/13062/1/IND43619763.pdf Accessed February 1, 2011.
[48] 2003 nominal USD.

[49] See note 47.

[50] These views are simplified, as energy quality and primary energy are not included. For most economies, electricity is based on approximately 2.5 times higher inputs in primary energy. Since we only present the concept, a further breakdown seems not warranted, particularly because it would be different for each country, dependent on their generation mix for electricity
[51] Assumed 120 cows, and 12 milking stations for parlour and automated milking systems.

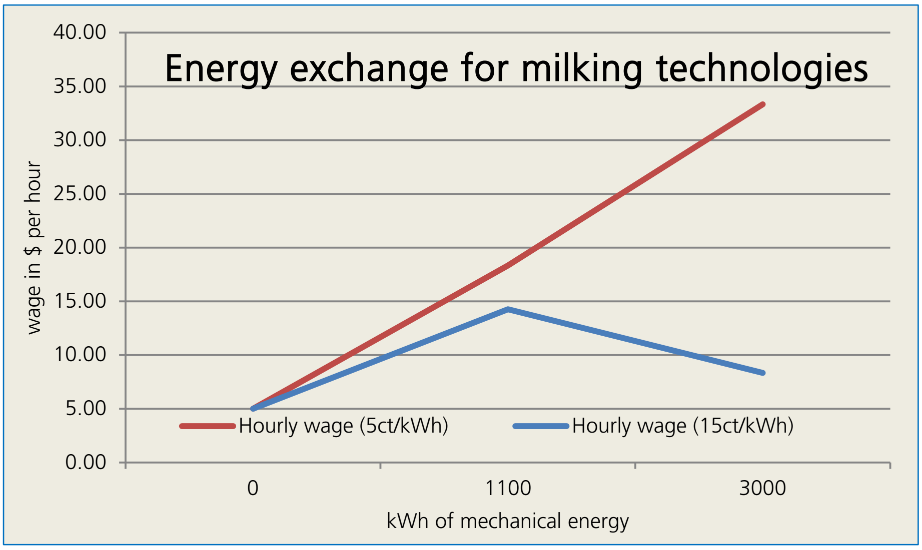


Figure 9 – Effect of increased mechanical energy use on wages in milking

Figure 9 demonstrates the effect on wages, assuming that farmer profits and milk prices stay the same. Starting out with an hourly salary of $5 for a farm hand who milks by hand, the increasing use of low-cost mechanical energy reduces time (and increases productivity by common measures). If we assume an average energy price of 5 US$ cents/kWh (in direct and indirect energy use), this leads to a wage increase to $18 for the most advanced parlour milking stand and almost $33 for the fully automated solution.

Should average energy input cost rise to 15 cents, the aggregate increase is softened for the parlour version (leading to a wage reduction to $14), while the most advanced solution no longer makes sense, as it pushes hourly wages down to $8, close to the original wage for manual milking. Obviously, this can be compensated by higher prices for milk or by lowering farm profits, but this would in turn withdraw more purchasing power from other parts of society.

Using cars: Another easy-to-understand example for this trade-off is human transportation: automobiles provide humans with much higher speed, larger ranges and more comfort when moving between points. Below, we compare the energy use between walking and travel in a car (occupied by one person, the standard when commuting).

When walking on flat ground, a human expends about 50 watt-hours (0.05 kWh) of energy per mile[52]. For this example, we have assumed a model vehicle that averages 25 mpg, 10,500 miles per year and 150,000 lifetime miles. Gasoline contains 36.6 kWh of energy per gallon, requiring fuel of 1.464 kWh/mi travelled. At 100 GJ (27,777 kWh) of embodied energy per mid-size vehicle, over a 150,000 miles lifetime, this equals another 0.185 kWh/mi. Also the embedded energy of the automobile was calculated at 0.14 kWh/mi based on Schafer et al. (2006)[52]. Considering the energy cost to extract the oil, refine it, and deliver it to a fueling station, we find an energy cost of 0.26 kWh/mi. Together, fuel production and delivery, vehicle energy, and travel by automobile require 37 units of non-human energy for each unit of human labour that is replaced. But this is only a part of the total energy requirements, because cars require paved pathways, traffic management systems and infrastructure to build and maintain cars, and many other contributions.

We draw the boundary for automobile travel narrowly with building the roadway, its operations and repair. The energy costs of construction and maintenance for various roads, including bypass energy costs, have been calculated in the 2010 ECRPD project of Intelligent Europe[53].

[52] Schafer et al. 2006. Future Fuel Cell and Internal Combustion Engine automobile technologies: A 25 year life cycle and fleet impact assessment. Energy. v. 31. p 2064-2087
[53] Intelligent Energy Europe, 2010, Energy Conservation in Road Pavement, Design, Maintenance and Utilisation. [online]. Accessed: July 02, 2010. Available at: http://www.roadtechnology.se/ecrpd.eu/index.asp?mainID=50

We have converted the values assuming a lifetime of 20 years between repaving, and an average 365,000 trips per year, per mile based on US numbers[54].

	Walking	Automobile
Average speed	3.0 – 4.0 mph	35 mph
Energy Use of Human	0.05 kWh/mi	Minimal
Energy use by mode of transport	Minimal	1.464 kWh/mi
Energy in fuel production and delivery	N/A	0.26 kWh/mi
Energy embedded in automobile	N/A	0.14 kWh/mi
Total non-human energy (vehicle only)	N/A	1.86 kWh/mi
Replacement ratio of machine to human labour (vehicle only)	N/A	37:1
Energy for road maintenance/operation	N/A	0.21 kWh/mi/trip[55]
Embedded energy in roadway	N/A	0.56 kWh/mi/trip[56]
Total non-human energy	N/A	2.63 kWh/mi
Replacement ratio of machine to human labour (including infrastructure)	N/A	53:1

Table 3 - Replacement of human labour with machine labour for car use per mile

Including this embodied and maintenance energy (surface coating, cleaning, repair), an additional 0.67 kWh of non-human energy is required for each mile travelled. Finally, the operation costs of the road – mainly lighting energy costs – are added estimated in Simonsen and Walnun (2011)[57]. The car and road construction and operation energy together result in a grand total of 2.28 kWh/mi replacing 0.05 kWh of human labour per walked mile. We thus calculate the replacement ratio to be 53:1 for non-human to human energy from car and road alone (Table 3). This notably doesn't include many other direct and indirect costs of cars, like land use, buildings and externalities.

These two illustrative examples demonstrate what technology change primarily brought about: a significant reduction of human effort, but at the cost of much higher overall energy consumption. As long as mechanical energy came at such a low cost, this proved beneficial for humans.

1.7. Human labour and fossil fuel costs compared

Below, we examine this trend more generally: a strong healthy human can deliver about 1 kWh of energy per day, on average probably closer to 600 W[58]. To calculate a rough estimate of human labour costs in dollars per kWh, we use GNI-per-capita (World Bank Atlas Method) and assume 0.6 kWh per day of output from human labour, on 255 working days per year. For the U.S. with a per capita GNI of $47,580 in 2008 (World Bank Atlas Method), the average price for one kWh of human labour is approximately $311. Globally, average GNI per capita of $8,691 equals to approximately $57 per 1 kWh of human labour[59]. Compared to that, the same amount of energy in oil at $20/barrel (the long-term inflation-corrected average) cost us 1.2 cents/kwh (today, at $90, it is 5.3 cents/kWh), and an equal amount of energy from coal comes to 0.7 cents.

Table 4 shows how different the price of energy is for many sources on a primary energy content basis.

[54] 765 tons/mi x 2.9 GJ/ton = 2219 GJ/mi. x 277.8 kWh/GJ = 505,500 kWh/mi (30 year lifetime)
[55] 2008: e.g. $148 million for 570 miles of Thruway in NY = $260,000/mi/yr. x 3.8 kWh/$ = ~1,000,000 kWh/mi/yr. 208 million trips (passenger and commercial) on Thruway each year – an Average of 365,000 trips per mi.
[56] 765 tons/mi x 2.9 GJ/ton = 2219 GJ/mi. x 277.8 kWh/GJ = 505,500 kWh/mi. Divided over a 30 year lifetime, an average of 365,000 trips per mile per year.

[57] Simonsen, M., Walnun, H.J., 2011. Energy Chain Analysis of Passenger Car Transport. Energies. V. 4. p. 324-351

[58] Average human power output is 0.1 HP, or 75W x 8 hours = 0.6 kWh. Giampietro, M and Pimentel D. (1990). Assessment of the energetics of human labor, Agriculture, Ecosystems & Environment, Volume 32:257-272.
[59] World Bank 2011.World Development Indicators. Available from http://data.worldbank.org/data-catalog/world-development-indicators?cid=GPD_WDI Accessed February 2, 2011.

Human labour and fossil fuel costs compared

	Cost per kWh	Multiple of U.S. human	Multiple of avg. human
Average humans (United States)	$311	1	0
Average humans (globally)	$57	6	1
Average humans (Bangladesh)	$3.39	91	17
Low cost PV (current), without grid	$0.30	1,033	187
Gasoline at $6 per U.S. gallon	$0.16	1,890	341
Future CSP (projection), no grid	$0.15	2,067	373
Gasoline at $4 per U.S. gallon	$0.109	2,844	514
Natural gas electricity (no grid) at 8$ per Mcf	$0.090	3,444	622
Oil at $150 per barrel	$0.088	3,523	636
New large nuclear (no grid)	$0.080	3,875	700
Onshore wind (no grid and balancing)	$0.080	3,875	700
Electricity from natural gas at 4$ per Mcf	$0.060	5,167	933
Electricity from new coal plant (no grid)	$0.060	5,167	933
Gasoline at $2 per U.S. gallon	$0.055	5,636	1,018
Oil at $75 per barrel	$0.044	7,045	1,273
Electricity from old coal plant (no grid)	$0.020	15,500	2,800
Natural gas at 4$ per Mcf	$0.014	22,143	4,000
Oil at $20 per barrel	$0.012	25,833	4,667
Coal at $2.50 per MBTU	$0.008	38,750	7,000

Table 4 - Cost per kWh for human labour, for different energy inputs

The benefits of trading human labour for fossil fuel energy directly relates to the ratio of energy cost to human labour cost and becomes jeopardized as soon as energy and resource cost increase (e.g. the effort for their retrieval, handling, disposal, and compensation of externalities). Given the high leverage of energy in the replacement process described above, the growing costs of inputs into those systems have highly adverse effects on the benefits experienced by humans. They invariably lead to a reversal of labour and capital productivity, i.e. either the goods produced become more expensive vs. the labour of the buyer, salaries have to decrease, or profits will shrink. Many industries with a high sensitivity to energy cost already show this symptom, for example in trucking and other transportation services, where wages and profits have shrunk significantly during the past years[60].

With the arrival of higher energy cost at the level of farm goods and petrol pumps, this effect spills into everybody's lives.

This vulnerability has been underrecognised in most economic theories. Energy cost increases of a factor of two can greatly reduce the benefits humans derive from a process; and in some cases can even eliminate the overall feasibility of that process altogether, as was demonstrated for the milking example (see Figure 9).

We further demonstrate the concept of those replacements in Figure 10 below. Most replacements of human labour follow the milking example, where marginal benefits decrease for each mechanisation step, i.e. to phase out a little more human labour, even more mechanical energy is required. In the example below, one human hour (assumed with a net output of 0.075 kWh) is originally priced at $3.00 kWh, and is replaced with mechanical energy at various prices. All the benefits from this exchange are returned to the working human, i.e. prices of goods or profits remain unchanged.

[60] Fuel costs as a percentage of total operating costs for all major airlines worldwide increased from 13.6% in 2001 to 32.3% in 2008. The proportion of labour costs in 2001 was 28%. By 2008 this decreased to 20%. Source: IATA (2010). Economic Briefing: Airline fuel and labour cost share. http://www.iata.org/whatwedo/Documents/economics/Airline_Labour_Cost_Share_Feb2010.pdf

Human energy (kWh)	Mechanical energy (kWh)	Replacement ratio	Hourly wage dependent on various prices for mechanical energy			
			5 cent	10 cent	15 cent	20 cent
0.0750	0	0	$3.00	$3.00	$3.00	$3.00
0.0375	1	27	$5.90	$5.80	$5.70	$5.60
0.0188	2	36	$11.60	$11.20	$10.80	$10.40
0.0094	4	61	$22.40	$20.80	$19.20	$17.60
0.0047	8	114	$41.60	$35.20	$28.80	$22.40
0.0023	16	220	$70.40	$44.80	$19.20	negative
0.0012	32	433	$89.60	negative	negative	negative
0.0006	64	860	negative	negative	negative	negative

Table 5 – Replacement benefit of human with mechanical labour

In the model, an initial step replaces half the human hours (30 minutes or 0.0375 kWh) with 1 kWh of mechanical energy, for each further reduction of human effort by 50% we assume a doubling of energy inputs, following the typical pattern of decreasing marginal returns[61]. This is an arbitrary choice, but very much in line with the empirical examples described above.

As table 5 shows, energy costs of 5 cents support a rise of the human hourly wage to around 90$ (at a replacement ratio of 433 mechanical energy units per original human energy unit).

Once the maximum benefit is reached, further replacing increasingly smaller amounts of human labour with more mechanical energy no longer add economic value, because the marginal cost of additional energy consumption grows faster than the savings from even less manual work.

When energy prices double, peak benefits are already reached at $45 and a replacement ratio of 220. A tripling in energy prices reduces the benefit to a maximum of $30. This negative effect can be partially offset by energy efficiency gains, higher prices for goods or by drawing out the life-span of equipment and buildings, but in the long run, the net effect on wages becomes significant.

It is important to note that this does not apply so much to consumer energy uses such as space heating or lighting, as they come at the end of a chain where benefits have been reaped throughout the provision of energy services in an economy, but is relevant for activities where the mechanism shown above has generated productivity gains. This is the case in almost all tangible parts of our economies, for example, in mining, materials enhancement, manufacturing and transportation, but equally in many service industries.

The conclusion from the above model is that the benefits of industrialization (productivity gains on labour and capital) almost always came at the cost of a reduction in energy efficiency. They are quickly reduced once energy prices rise, as the trade-off (a large amount of low-cost energy vs. small amounts of human labour) starts to work against humans.

Ceteris paribus the following applies: if average energy prices double, human wages will be cut in half. This happens unless prices of goods can grow, but that is unlikely when these constraints are imposed on societies, as energy price rises in that case are self-limiting. The growing cost share of energy inputs in all economic processes, which in our example represents an enduring growing effort required to produce energy, implies that a much larger share of societal wealth needs to be redistributed from wages to the procurement of energy.

[61] This is not to argue that at times, breakthrough technologies lead to significant energy reductions, which change parameters of providing a service altogether, for example by using wireless instead of wired technology for telephony. However, these examples are rare, and for most industrial processes, each replacement of human energy by mechanical inputs typically led to higher overall energy consumption.

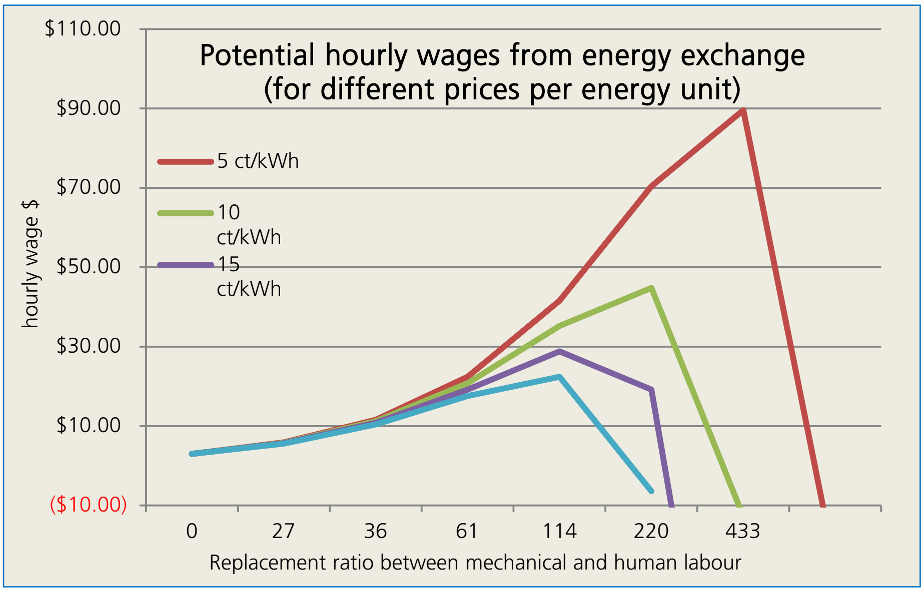


Figure 10 - Theoretical benefits to human workers by substituting low cost energy for human labour

Increased energy efficiency can partially mitigate this. However, as we will further describe below, efficiency gains in many process chains are typically in the 10-30% range. This is not nearly enough to offset the productivity losses from higher input costs, which do not only come in the form of higher energy bills, but equally in the form of higher prices for other raw materials, machinery, and other infrastructure that has to be built with more expensive inputs.

One example where this currently becomes most relevant is food, where a combination of input price growth (which is mostly directly or indirectly – from energy-intensive fertilizers - energy-based for food production[62]), shortages and speculation has created an untenable situation for many people in emerging economies.

1.8. The role of technology

A key explanation of macroeconomic theory is that human ingenuity drives the development of new and better technology, making processes more and more efficient – in a way that they require less and less human labour and become cheaper (also increasing capital productivity). As discussed above, this is true in the sense that these improvements reduce the requirement for human labour in producing a specified unit of a good, but – in most cases – at the cost of significantly higher overall energy consumption for infrastructure, operations and management of a new, more technologically advanced and sophisticated process.

Thus, technology definitely played an important role in this continuous improvement of economic conditions, but not in the way portrayed by traditional economists. We believe a more accurate view is one where technology is seen as a contributor to human wealth in four different ways:

- First-order technology change: as an enabler replacing human labour with mechanical labour to accomplish the same objective, usually by trading low quantities of human energy against large quantities of non-human (mostly fossil fuel based) energy;
- Second-order technology change: as an enabler of "new, previously impossible" energy and matter conversions, which create a product or service that is seen as relevant to human societies, making more energy meaningfully available to society;
- Third-order technology change: as a means of accelerating resource throughput: i.e. identifying, extracting and enhancing more natural resources and energy at a cost level affordable to societies;
- Fourth-order technology change: by improving energy/conversion efficiency itself, e.g. improving the process of converting energy and raw materials into desired goods, or low quality energy

[62]Henderson J. (2008). Are energy prices threatening the farm boom? Iowa State University Extension.Data from USDA and Commodity Research Bureau.AgDM Newsletter November, 2008

inputs into high quality outputs.

As the energy consumption and GDP per capita data depicted in Figure 4 demonstrates, human societies have succeeded in all four areas, but energy efficiency hasn't been their major success. Global energy consumption has kept growing during the past decades in line with output, albeit at a slightly slower pace when compared to the period before the oil crisis in 1973/4. Europe, which had imposed significant energy taxes after the crisis in the 1970s, played an important role in this move, as it triggered innovation in many areas, ranging from building technologies to transportation, but most successfully in energy-intensive industrial processes, like steel, aluminium or fertilizer production, and energy generation.

1.9. The overall trend for energy and resource cost

The future of fossil fuels, particularly of oil, but also many other resources including water and minerals, appears problematic. The issue is not the point when oil will run out, but rather whether sufficient supply can be forthcoming to meet growing demand at acceptable prices. Debate continues over proven reserves of oil and whether the peak in production has arrived already or not. Many experts agree that we probably have used about 40-50% of recoverable oil[63].Unfortunately, we will be able to put this argument to rest only in hindsight. But what is more important is the fact that - no matter how much additional oil we can still explore - the effort to retrieve future barrels will be much larger relative to the past. Currently, there continue to be fewer barrels found for every barrel produced. From 2000-2009, only one barrel was discovered for every 2 barrels produced[64]. Since 2000, more than half of new oil discoveries have been in off-shore areas, with some in very deep water[65]. When compared to current and previously producing wells, these off-shore deep wells are many times more complex. The Gulf of Mexico oil spill in 2010 provided solid evidence of the increased costs – both direct and indirect – of trying to exploit harder-to-reach oil deposits.

Less "easy oil" means that we have to drill in hostile environments deep under the surface of oceans, or resort to oil shale as feedstock. But we also see that ore grades of other resources are falling. The ore grade of copper has declined from 1.9% in 1950 to 0.79% in 2009. With this decline, more than double the amount of rock needs to be moved to extract the same amount of copper relative to several decades ago.[66] We also see that the depletion of groundwater sources translates to getting drinking water from desalination plants or fossil (non-renewable) aquifers far away, at higher effort (=energy costs).[67]

This decline in easily extractable resources and the increased effort to retrieve them is much more important than the exact year when peak production of a particular resource will occur. As more and more energy is required to obtain the same output of a resource, there is less net energy available to society. When production cannot match increasing demand, the cost of these fuels and materials increases.

1.10. What energy efficiency accomplishes

Fourth-order improvements in technology have been a key effort of the past decades. During the past 40 years, significant progress was made in a number of processes, ranging from power generation to fertilizer production and aluminium smelting (Table 6). When looking at current

[63]Deffeyes, K (2005). Beyond oil: The view from Hubbert's Peak. New York: Farrar, Straus and Giroux.
Campbell, CJ (2006). The Rimini Protocol an oil depletion protocol: Heading off economic chaos and political conflict during the second half of the age of oil. Energy Policy 34 (August 2006): 1319-1325.
Campbell, C.J. & J.H. Laherrere (1998).The end of cheap oil. Sci. Am. 278: 78–83.
[64]IEA (2010). World Energy Outlook
[65] See note 59.

[66] Arellano JPM (2009). Megatrends in the Copper Industry. Chili: Codelco & Gerst MD(2008). Revisiting the Cumulative Grade-Tonnage Relationship for Major Copper Ore Types. Economic Geology 103: 615-628.
[67] Karagiannis & Soldatos (2007). Water desalination cost literature: review and assessment. Desalination. 223: 448 - 456

efficiencies, they are slowly but steadily approaching their theoretical physical maximums, which makes each next improvement step more difficult and more costly to achieve[68].

Industrial Process	1950/1960 Efficiency	Current Efficiency		Theoretical Maximum Efficiency
		Average	Maximum	
Electricity Generation from Coal	~25% [a]	33% [a]	47% [b]	68.7% (Carnot Maximum)
Ammonia Production [c]	~35% (~60 GJ/t)	51% (41.6 GJ/t)	75.7% (28 GJ/t)	Theoretical minimum 21.2 GJ/t
Aluminium smelting	~39% [d] (23 kWh/kg)	60% [e] (15 kWh/kg)	69% [f] (13 kWh/kg)	Theoretical minimum: 9 kWh/kg Industry goal: 11 kWh/kg by 2020

[a] Calculated from: EIA. (2010). Annual Energy Review. Table 8.2a and 8.4a
[b] Beer, J.M. (2007). High efficiency electric power generation: The environmental role, Progress in Energy and Combustion Science, 33, 2:107-134.
[c] International Energy Agency. (2007). Tracking Industrial Energy Efficiency and CO2 Emissions in support of the G8 Plan of Action. http://www.iea.org/textbase/nppdf/free/2007/tracking_emissions.pdf
[d] Das, et al. (2004). Energy Implications of the Changing World of Aluminium Metal Supply. JOM 56,8:14-17
e Smil, V. (2008). Energy in nature and society: General energetics of complex systems. Cambridge, Mass: MIT Press.
[f] Alcoa. (2011). About us – Aluminium smelting. Available from http://www.alcoa.com/global/en/about_alcoa/pdf/Smeltingpaper.pdf Accessed Feb 1, 2011.
[g] Choate, WT and Green, JAS. (2003). U.S. Energy Requirements for aluminium Production: Historical Perspective, Theoretical Limits and New Opportunities. BCS/U.S. DOE.

Table 6 - Selected industrial processes and their historical, current, and theoretical maximum efficiencies.

When looking at the remaining potential energy savings in the key processes of industrial societies (for example, nitrogen fertilizer production, steel manufacturing, concrete production, etc.), the room for improvement from cradle-to-grave efficiency gains is relatively small when compared to the dynamics of growing cost and effort in energy generation and resource retrieval. Thus, despite technology constantly progressing, quantum leaps in some of the main building blocks (energy and commodities) of human society are unlikely, making our fight against higher prices a difficult one.

1.11. Globalization – a quest for lower energy cost

The ubiquitous shift away from manual to mechanical labour has created a situation where humans are no longer the limiting factor in many processes, as consistently high unemployment rates in many still growing economies indicate. However, those with the highest skills remain rare, as do those with the lowest labour cost.

This can be observed when looking at the production locations for textiles and leather gear. Since there continues to be no meaningful automation approaches for sewing and stitching fabrics together, this is still largely done by hand. During the past 20 years, the 'Made in' labels of textiles provide an impressive documentation of the quest for lower and lower cost labour. By now, almost all low- to medium-cost textiles are manufactured in Asia, first and foremost in China, where 26% of total value of the global textile trade comes from and much more in volume – estimates go up to 70%.[69]

This shift towards low-cost labour is only one aspect of globalization; equally important is a shift towards

[68] Due to laws of thermodynamics or time constraints (would require an infinitely long processing time) these theoretical physical maximums will never be reached.

[69] WTO (2008), volume are estimates of industry experts

lower cost energy. China, now the world's largest manufacturing country, is a very good example for understanding these dynamics. In 2009, China produced between 30 and 40% of global output of many industrial goods (Table 7), while the country's GDP only amounted to 8.6% of the global total. This also explains the country's comparatively high energy intensity (14.2 MJ/$GDP in 2000 constant US$) - a consequence of taking over many energy- and labour-intensive tasks from around the world – supporting a de-industrialization in countries with higher energy and labour cost and their seemingly energy-efficient economies, driven by the hunt for the lowest manufacturing cost.

Three economic factors make China an attractive place for global manufacturing. Firstly, a large, relatively skilled and motivated workforce available at low cost, secondly, a vast base of raw materials and energy (coal), and thirdly, a strong and determined government actively managing the country's positioning as a manufacturing powerhouse, providing stable conditions for investments.

	Self-sufficiency		Energy Intensity	Global Share (2009)			
	Primary Energy (2008) [a]	Food Calories [b]	MJ/$ (2008) [a,c]	GDP [c]	Steel Production [d]	Aluminium Production [e]	Fertilizer Production [e]
United States	77%	119%	9.2	24%	5.7%	4.6%	5.9%
China	93%	90-95%	14.2	8.6%	44.3%	34.6%	32.5%
UK	75%	74%	5.7	3.7%	0.7%	1.4%	<0.5%

[a] EIA (2010). International Energy Statistics – Total Energy, [b] Multiple sources [c] World Bank (2011). World Development Indicators for 2008 (in 2000 constant US$). [d] World Steel Association (2011). Statistics Archive.http://www.worldsteel.org/index.php?action=stats_search&keuze=steel&country=all&from=2010&to=2010
[e] USGS (2011). Mineral Commodities Summaries 2011. http://minerals.er.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf

Table 7 - Self-sufficiency, energy intensity, and global share of GDP and manufacturing for selected processes for the US, China, and the UK

Emerging economies (especially China) thus offer an environment of lower labour cost combined with low-cost energy (industrial electricity prices are in the range of 3-4 cents/kWh in China[70] vs. 6-11 cents in most other advanced economies)[71]. This creates an additional benefit by improving the human labour and capital productivity of advanced economies, as even more expensive labour and energy gets substituted by lower priced replacements. This is a continuation of expanding previous productivity gains beyond the simple replacement of human labour with energy, but now the replacement is with even lower cost inputs, without a change in quantity.

There are, however, a number of long-term risks associated with this strategy, particularly because it will slowly shift China's workforce expectations higher. Unfortunately, there can be no "next step" in off-shoring, as no other resource pools for labour and energy exist that can come close to matching the abilities of China. Should labour and energy cost rise significantly, China will lose its competitive edge over other economies (or domestic production in advanced economies), reducing its share of global outputs, and at the same time reversing part of the productivity

[70] Industrial Countries' Power Cost Comparison. Translated from Taiwan BBC News. http://www.aspigroup.com/news/PowerCost020706.pdf
[71] IEA Statistics (2009).Energy Prices and Taxes.4th Quarter 2009.

gains advanced economies experienced from outsourcing to China[72].

1.12. Conceptual Summary

After looking at empirical data, we introduce some theoretical concepts. Below, we use a simplification to conceptualize the ideas introduced in the previous paragraphs, describing human and non-human efforts throughout various steps of industrialization. This theoretical model is focused on the limited view of a specific person involved in the manufacturing of one unit of a good. The dynamics take place on three levels:

- Direct labour productivity, e.g. the labour (energy/time) units required directly from humans throughout the production of one unit of the desired good. The values are conceptual, however, there are no major human economic activities where the overall principle does not resemble the one presented here, the only difference lies in the order of magnitude of labour energy replacement with non-human energy
- Energy productivity – energy required to produce one unit of a desired good, irrespective of its origin (human labour, other energy sources)
- Cost, measured not in monetary terms, but in an "original labour value unit", which describes how many units of the human's own original time is required to receive one unit of the original good. This is an important distinction as it is independent of inflation or other monetary aspects.

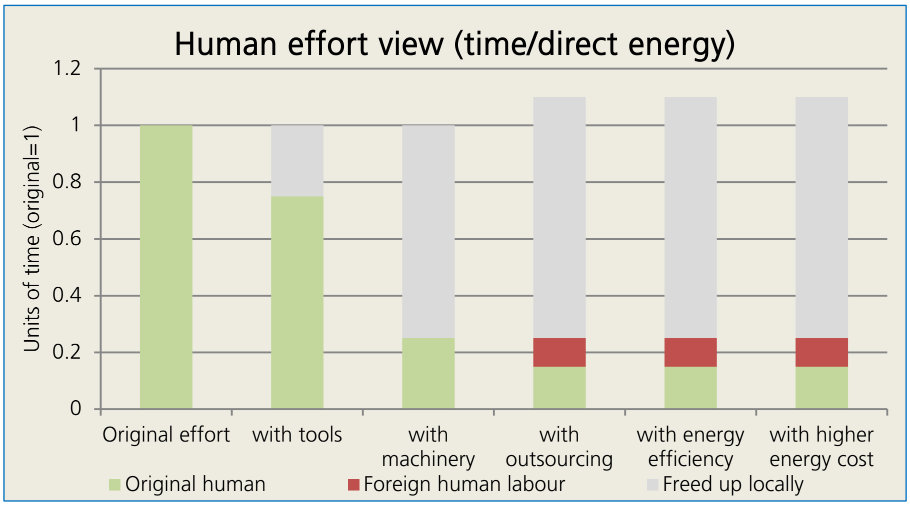


Figure 11 - Direct labour productivity growth per unit of output (theoretical)

As soon as technology advances set in, large productivity gains take place (Figure 11). Human time (and energy) investments significantly go down as mechanical labour is introduced. Offshoring further reduces domestic labour use. Ultimately, the "original" person is leveraging other energy sources, which frees up time for other activities, for more production of the same good, for new inventions, more leisure time, etc. In short – this enables all the benefits humans have experienced throughout history from those shifts.

Secondly, the energy efficiency view (Figure 12) looks at the energy perspective of the same transaction. With the transfer from the original "human only" to a tool- (or animal-labour)-supported approach to industrial efforts, total energy input almost always grows by orders of magnitudes, often 2 or even 3 (1,000%, up to 10,000%[73]) per unit produced. Outsourcing to foreign locations grows energy consumption further, as transportation is added. When energy efficiency measures or new and better technologies are introduced, this reduces energy consumption, but rarely by orders of magnitude. It is more likely these improvements are in the range of 10-30[74]% of the original energy consum-

[72] At a small scale, outsourcing to Vietnam, and other South East Asian nations has been increasing due to more favourable tax laws for foreign corporations and rising labour costs in China, but this is not a scalable approach given the size difference of populations: China: 1.3 billion, Vietnam 87 million, Thailand 67 million, Cambodia 15 million.

[73] See section 1.6

[74] See section 1.10

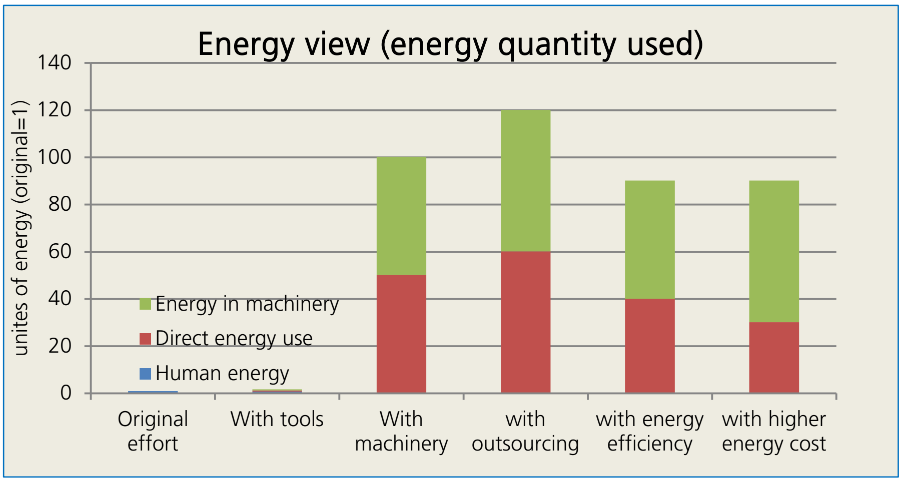


Figure 12 - Energy consumption in a process after structural changes, energy efficiency and increased energy costs

ption. In many cases, this is accompanied by a shift from consumption throughout the process to upfront (energy) investment and more complex and demanding technology[75]. Europe's introduction of energy taxation was a key driver of this shift away from consumption to upfront use. This becomes particularly attractive if the upfront energy comes at a much lower price[76].

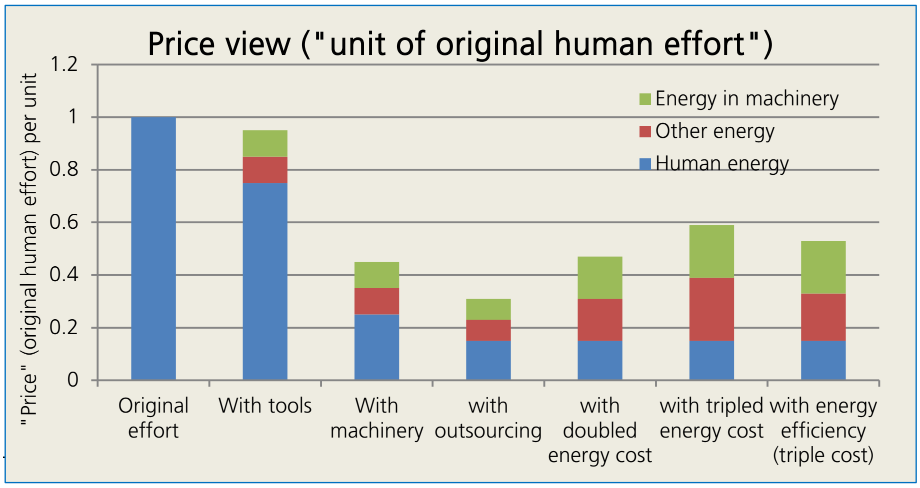
Lastly, the aspect of replacing human labour with technology is related to cost, which in this context answers the question: how much of the original human's own effort is required to pay the entire cost?[77]

Despite an orders of magnitude difference in energy consumption, the reduced involvement of the most expensive energy source – humans – significantly lowers the price per unit. This benefit can be (and was) used in many ways: to grow wages in human societies, lower the price of a product, or raise profits for investors.

Globalization introduced yet another factor, because it added even cheaper energy into the mix (relatively abundant and with fewer environmental controls) and replaced the still required human effort with hours at lower cost from emerging economies.

This final combination created the highest benefit for the "originator", as the largest possible percentage of effort was shifted to the place of lowest energy and labour cost, while all labour that could be meaningfully replaced was substituted with mechanical energy.

Figure 13 - Price view of productivity shifts (theoretical)



[75]: A good example are cars: here, European fuel taxes have driven significant efficiency improvements (mpg) of cars, but often at the cost of complex and energy-consuming technology and materials in the vehicles themselves. For example, the use of aluminium, a highly energy-intensive material, increased significantly over the past decades, to reduce weight and improve mileage.

[76] If energy going into a product is provided at 4ct/kWh (China industrial electricity), reducing consumption of end-user electricity sold at 20ct/kWh, the benefit of even a net energy loss could be financially attractive.

[77] We purposefully stay away from financial currencies, as they are of limited importance.

At the point where substituted inputs (mechanical energy and off-shored labour) become more expensive, the benefits of those shifts slowly reverse for the original beneficiaries. This lowers labour productivity as measured by traditional economic models.

Figure 14 demonstrates the summarized effect of labour and energy productivity increases for an equivalent output quantity. The main step is the one towards industrialization, often involving multiple sub-steps, followed by outsourcing, and energy efficiency improvements. As soon as energy cost rises, cost curves rise along with it, and for most processes, no technology change can make this undone. In the graph this looks harmless, but it effectively means doubling or tripling prices.

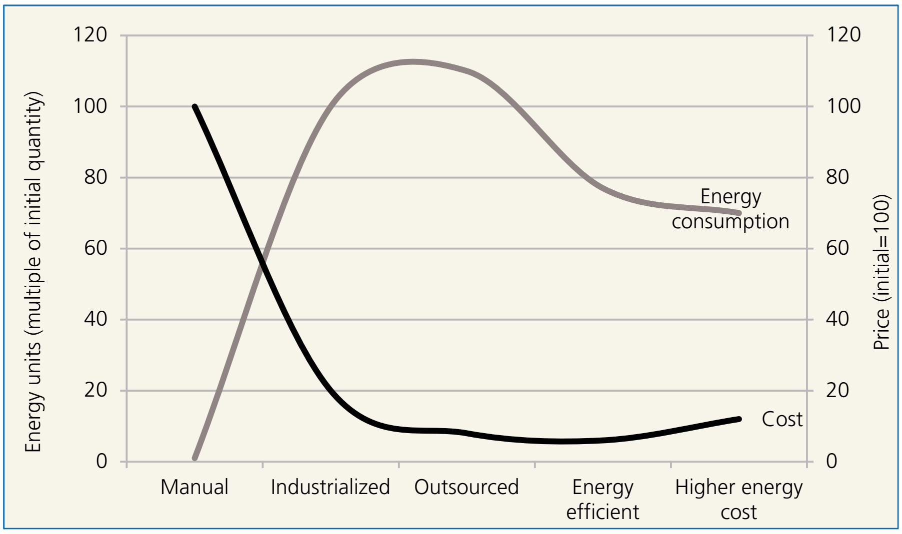


Figure 14 - Energy and cost for industrialized processes over multiple phases (theoretical)

1.13. The effects of growing energy cost on productivity

More recently, as increased effort to extract resources and energy has led to growing costs, the previously established trend breaks down. With doubling or tripling energy cost – a scenario that isn't far away from reality[78] - many industrial processes become unviable, unless a low-price substitute for increasingly expensive fuels becomes available. There the fundamental notion that energy is only poorly substitutable for capital through biased technical change is of large importance. Otherwise, as assumed in traditional economics, energy could easily be substituted for capital and labour inputs through a general equilibrium adjustment, easily offsetting any energy cost increase. However, there is an increasing body of literature – as discussed in section 1.5 – that supports our perspective in that capital and energy substitution is fairly limited and can only take place over long periods of time, if ever. In absence of substitutes an energy price increase leads to reduced energy consumption and a reduction of overall global output.

For each economy or segment of an economy, the levels of meaningful substitution between human and mechanical energy can be determined if the rate of substitution between human labour and mechanical labour is known. On an aggregate level, if we assume an average rate of substitution of approximately 1:100 for most industrial processes, i.e. one human energy unit is typically replaced by 100 mechanical energy units (including energy embedded in infrastructure), we can examine the effects of current or future energy prices to determine whether industrialization efforts remain viable. If the cost ratio between human labour and mechanical labour falls below that threshold, a process is no longer economically feasible for this particular economy (or a subset of the economy performing those tasks).

[78] Oil prices currently (January 2010) are at about 4 times their historic average

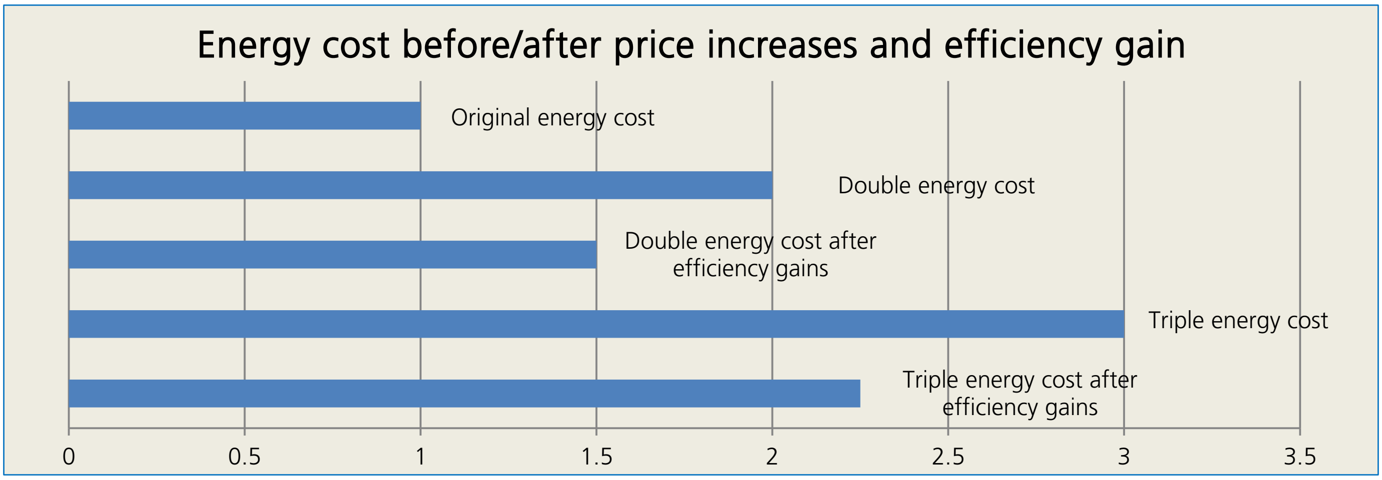


Figure 15 - Effect of rising prices after efficiency gains of 25%

One example: Indonesia has a cost of approximately $12 per human generated kWh (UK: $299, world average: $56). Using the approximated substitution ratio of 100:1 for mechanical versus human labour as our guide, any energy source with a price above 12 cents/kWh (representing gasoline at $4/gallon) becomes limiting, as it is no longer able to provide productivity improvements, and therefore economic benefits to the country. This explains why higher energy costs will become inhibitors of industrialization trajectories and present planning hurdles that are difficult or nearly impossible to overcome.

At the least, this effect leads to a reversal of past gains by either reducing wages, raising prices of goods, or destroying profit margins of companies and investors. This isn't immediate, as buffers do exist. These include the ability to extend the depreciation period for infrastructure or reduce maintenance, by optimizing inputs, including energy efficiency improvements of processes. However, in the long term it is highly unlikely that those efficiency gains can offset an energy price increase of 100 or 200% (see Figure 15).

As soon as the pace of energy price increase outpaces the rate of efficiency gain – and this point has long been reached in most supply chains – it leads to a de-facto de-industrialization of societies. As long as large suppliers of low-cost inputs are available (China, India, etc.), negative effects are not significant. Once those manufacturing "hotspots" also become subject to higher energy costs, the entire value-chain loses its advantage over much less industrialized efforts.

2. Consequences for low-carbon efforts

The dynamics described in chapter 1 have significant consequences for carbon mitigation efforts, irrespective of them being focused on renewable energy technologies, on carbon capture and sequestration, or on approaches to save energy. At this point in time, it is difficult to see a way of globally reducing carbon emissions by decreasing inexpensive fossil fuel consumption while sustaining economic growth or even stability. An integrated view on this topic leads to the conclusion that the two objectives might be largely incompatible. We will further analyse this below, using the example of China and other emerging economies, and expanding on the potential for fossil fuel mitigation technologies to become cost-neutral.

We are aware of the fact that this finding contradicts many existing models. In order to understand the reason for these differences, we have completed a thorough review of a number of often-used models, which can be found in Appendix A of this report.

2.1. Energy cost requirements in industrial processes

In the models presented we explained how industrialization became successful – by replacing human labour with significant quantities of non-human (mostly fossil) energy, a dynamic which can only be partly reverted by technology advances. The largest recent factor in this process has been China, which was the single biggest contributor to fossil fuel consumption in the last ten years. Increased coal, oil, and natural gas inputs were used to rapidly increase industrial capacity, while at the same time keeping labour cost low[79]. Today, most primary energy inputs into basic manufacturing processes come at a cost between 1 and 4 US$ cents per kWh of available process energy. In order to arrive at the same benefits in the future, economies would need the same cost levels (in inflation corrected terms) to build and maintain their infrastructure (industrial, but equally transportation-related). At the top end of this scale, the global benchmark for large-scale industrial electricity is approximately 4 dollar cents per kWh.

If energy cost grows significantly, the feasibility of many processes is challenged, and the overall benefits to societies decrease. Table 8 shows the feasibility of processes at a price of 4 cents/kWh for a number of economies, assuming an exchange ratio between human and mechanical labour of 1:100, e.g. one human energy unit is replaced with an average of 100 mechanical energy units. The colours show the feasibility depending on different prices of electricity (total cost for generation, distribution and management). The approach uses an average mechanical to human replacement ratio of 100:1 for electricity found in many processes we analysed. In this case, as soon as 1kWh of human labour becomes cheaper than 100 kWh of electricity, substitution no longer makes economic sense (denoted in red). In reality, we assume that much higher ratios are required to release sufficient labour capacity to enable a self-sustained industrialization process. This upper threshold was defined at 300:1, as this condition begins to significantly reduce benefits (dark green above 300:1, gradient from light green-yellow-light red between 300:1 to 100:1).

[79] The Chinese economy contributed 92% to the growth in global coal consumption, 12% to the growth in global natural gas consumption, and 54% to the growth in global oil consumption between 2000 and 2009.

Table 8 demonstrates that with higher energy costs a continuation of industrialization is only feasible for countries with high labour cost, whereas the number of economies that undergo negative benefits increases as electricity (or other energy) cost grows. It is important to say that the above analysis looks at the average cost in an entire economy, if the focus is on low-income labour – the one typically replaced in manufacturing – effects become even more pronounced. For example, if applying the U.S. federal minimum wage of US$ 7.25 per hour, and assuming an 8 hour day, a kWh in the U.S. would be priced at 58$. At this level, human low-cost labour becomes unattractive to replace by mechanical energy much earlier even in advanced economies.

At this point in time, no scalable low-carbon alternatives exist to provide electric power at a lower rate than the coal-based electricity available in China and some other low-energy cost economies. Figure 16 shows the current price expectations for a number of energy generation technologies. Here, it is important to say that not only the cost of generation matters, but equally the cost required to mitigate variability and availability issues.

Country	$/kWh of human labour	Exchange ratio for various prices for electricity ($/kWh)			
		0.04	0.08	0.12	0.16
United States	310.99	10,366	5,183	3,455	2,592
United Kingdom	299.08	9,969	4,985	3,323	2,492
Mexico	65.37	2,724	1,362	908	681
World Average	56.80	2,367	1,183	789	592
Brazil	48.63	2,026	1,013	675	507
South Africa	38.37	1,599	799	533	400
China	19.93	831	415	277	208
Indonesia	12.28	512	256	171	128
Guyana	9.48	395	198	132	99
Nigeria	7.65	319	159	106	80
Ghana	7.52	313	157	104	78
Sudan	7.32	305	152	102	76
India	7.07	294	147	98	74
Zambia	6.27	261	131	87	65
Pakistan	6.15	256	128	85	64
Vietnam	5.62	234	117	78	59
Kenya	4.77	199	99	66	50
Cambodia	3.98	166	83	55	41
Bangladesh	3.40	142	71	47	35
Tanzania	3.00	125	63	42	31
Uganda	2.75	115	57	38	29
Rwanda	2.68	112	56	37	28
Nepal	2.62	109	55	36	27
Mozambique	2.48	103	52	34	26
Ethiopia	1.83	76	38	25	19
Malawi	1.70	71	35	24	18
Liberia	1.12	47	23	16	12
Congo, Dem. Rep.	0.98	41	20	14	10

Table 8 - Ratio of energy inputs (human vs. mechanical labour) for various economies, feasibility of human-for-mechanical labour exchanges at a 1:100 ratio

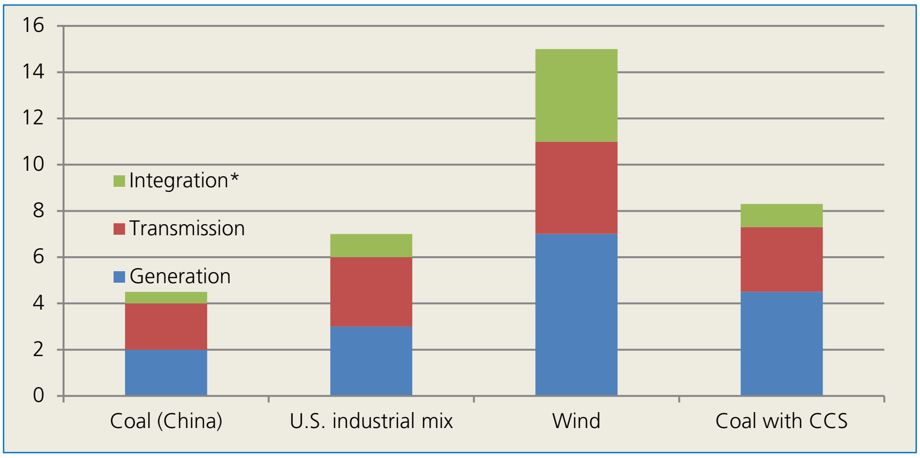


Figure 16 - Delivery cost for stable electricity from various sources[80]

In order to make renewable sources bearable in an industrial society without the need to outsource to places where energy costs remains low, their costs would have to be brought down to a comparable level. If this cannot be accomplished, the current economic growth trajectory cannot be continued on a global scale.

One of the main challenges is the fact that a significant portion of the differences in the energy intensity of various countries is related to the type of contribution they make to a globally interlinked system. For those which have successfully moved towards high-tech or service based economies, their energy intensity is below the global average, whereas those which have become the manufacturing or resource powerhouses show significantly above-average intensities, e.g. they produce less output per unit of energy when compared to other countries (Figure 17).

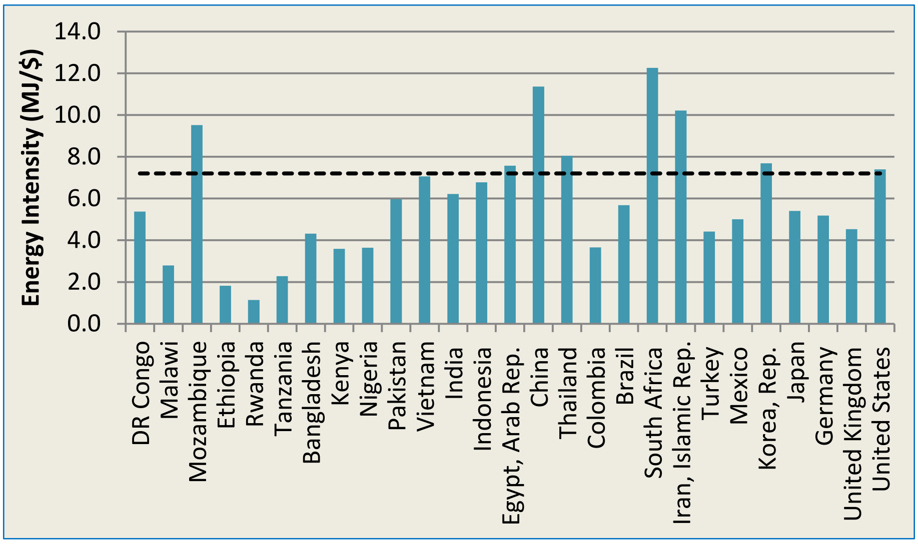


Figure 17 - Energy intensity in MJ/$ for various countries (MJ/ $ - PPP)[81]

Instead of seeing this as documentation of developed countries' success in using less energy for the same amount of economic output, it is rather proof of their ability to outsource most of their heavy industrial activities to the second group.

Unfortunately, when economies aspire to industrialise, the average energy intensity per unit of GDP is the highest at the point of industrialization, which turns this into an almost insurmountable hurdle as long as energy prices are too high.

Figure 18 shows the effects of higher energy prices for various activities in an economy. While subsistence farming approaches are – as long as they are not heavily dependent on fertilizers and fuels – relatively unaffected by higher input cost, industrial societies (including mechanized farming) are most severely

[80] IEA/NEA (2010).Projected Costs of Generating Electricity. Paris, France. OECD.
EIA (2009). Levelized Cost of New Generation Resources, 2016.http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html
*Kunz H, Hagens NJ, Balogh SB (2010). Net Energy and Variability. In review.

[81] GDP data: World Bank – WDI, Primary Energy data: EIA International Energy Statistics.

affected. Once societies become more consumer and service sector driven (like most advanced economies), they are less susceptible to direct energy price increases, but instead indirectly under pressure from growing cost of imports (or devaluation of their currency).

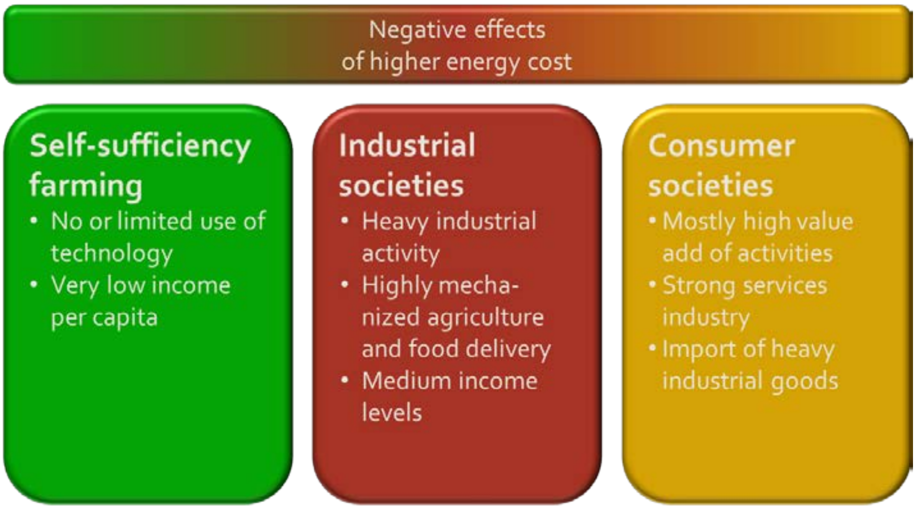


Figure 18 - Implications of higher energy cost by type of society

2.2. China - the main source of low cost energy

Industrial energy in China is currently delivered at very low prices, which is also true for electricity, where large industrial customers operate with final cost of approximately 3-4 ct per kWh[82]. With that price, the country offers the lowest cost industrial energy available at a significant scale. Compared to another low-cost energy supplier, Norway, where a favourable geological and meteorological situation supports a generation strategy that is based up to 100% on hydropower, China produces 75% of its electricity from coal, 16% from hydro, 6% from natural gas and 2% using nuclear (2009)[83]. Other alternative energy technologies do not play a major role. Wind power, for example, had a share of around 1%, despite impressive relative growth rates.

The cost of large scale industrial energy in other economies often ranges between 6-9 ct/kWh[84], more than twice that of China . Already this price has led to a reduction of standard industrial production in most advanced economies over the past decades, shifting their focus to higher value industrial goods (like Germany and Japan), or almost completely de-industrializing (like Britain). A telling example for the importance of low-cost energy (as well as low trade and commodity prices) is the smelting of Aluminium – where countries like Norway are becoming producers despite their lack of resources of the raw material Bauxite[85].

China's focus on coal is not likely to end anytime soon, despite publicity about renewable energies. Total coal capacity (operated with a load factor of approximately 50%) is forecast by the Chinese government to grow by another 350 GW until the year 2020[86], bringing total coal based power output to approximately 4,300 billion kWh. At the same time, the country is pushing other energy sources, such as nuclear, hydropower, and wind. For wind, the most ambitious estimate is to raise installed capacity from 42 (2010) to 230[87]

[82] See note 63

[83]EIA. 2011. Country Analysis Briefs – China. http://www.eia.doe.gov/emeu/cabs/China/Electricity.html Accessed Feb 9, 2011.
[84] See note 64.

[85] USGS: Norway, despite having 0% of the world's aluminium reserves and a very peripheral position in Europe, has become the 7th largest producer of aluminium with 2.5% of the world's production capacity.
[86]EIA. 2011. Country Analysis Briefs – China. http://www.eia.doe.gov/emeu/cabs/China/Electricity.html Accessed Feb 9, 2011.
[87] Lower and upper range: China Daily (2009). China's wind-power boom to outpace nuclear by 2020. April 20, 2009. Available from http://www.chinadaily.com.cn/bizchina/2009-04/20/content_7695970.htm and Shi Jiangtao (2011). Clean Power not always green power. Available from http://topics.scmp.com/news/china-news-watch/article/Clean-power-not-always-green-power
Renewable Energy World (2010).China's Wind Power Forecast at 230 GW by 2020.http://www.renewableenergyworld.com/r

(2020) GW. Currently, wind provides 1.1% of China's electricity supply.[88] In the most ambitious scenario and assuming a capacity factor of 20% (today, China's wind plants operate at only 15% due to significant issues with their grid integration), China would produce about 400 billion kWh from wind. Electricity consumption in 2010 amounted to 4190 billion kWh.[89]

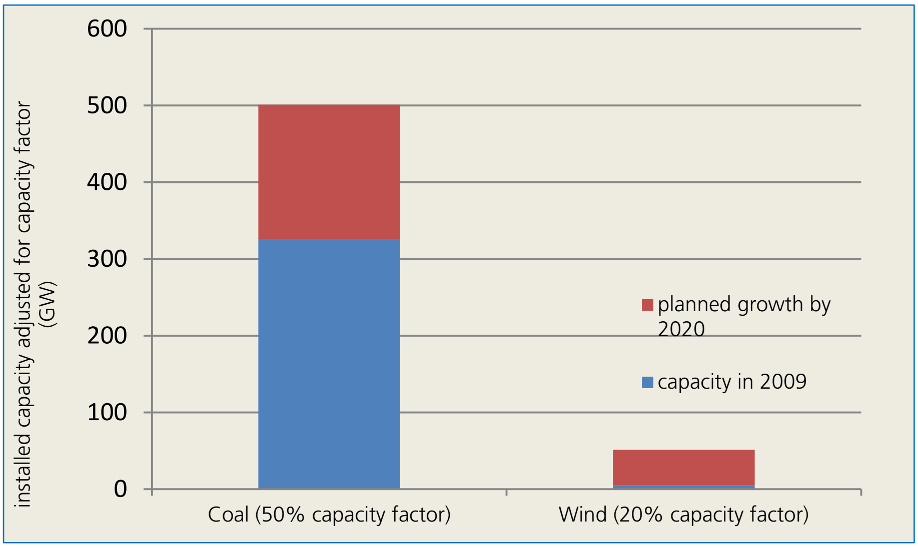


Figure 19 - Load factor adjusted coal and wind capacity for China 2009 and 2020

Figure 19 demonstrates the reality of Chinese planning. The push for massive increases in wind capacity becomes marginalised, relative to the magnitude of the expansion in carbon-based generation capacity. If the expansion is successful at the planned rate, wind power will have a share of approximately 5% in China's electricity mix by 2020. This does not affect the country's energy and carbon output significantly, nor does it affect the cost-advantage over other economies. The other renewable sources are not likely to change this picture within the time frame to 2020, as under the 12th five-year plan (2011-2015) fossil fuel additions to electricity capacity are planned to be equal to renewable energy and nuclear power sources.[90] An exception would be if the investment by China and others in renewable power led to a significant reduction in their price, which could create the potential to increase the share of renewable energy much faster than currently planned, a development that will be addressed in section 3.3 below.

In order to understand the Chinese position in the carbon discussion, it is important to analyse the possible consequences of various developments from international low-carbon negotiations. We see three scenarios that could develop:

- Global carbon limits are introduced that apply equally to all countries. In this case, China will be forced to withdraw from its expansion of coal power generation at the planned rate and replace this approach with cleaner technologies, or alternatively introduce carbon capturing and storage (CCS). In all these cases, a near doubling of the cost for Chinese electricity[91] will be the consequence, which leads to a reduction of the country's competitive advantage in international manufacturing. Second, this invariably would lead to increased

ea/news/article/2010/10/chinas-wind-power-forecast-at-230-gw-by-2020

[88] Hou Yujie (2011). Electricity consumption hits 4192.3 bln kWh. Xinhua. Available at http://news.fnchn.com/Electricity_consumption_hits_101473.aspx

[89] See note 88.

[90] Zhang Zhengfu (2011). China adopts 5 year blueprint , aiming for fairer, greener growth. Available at: http://news.xinhuanet.com/english2010/china/2011-03/14/c_13777814.htm

[91] If the least expensive option, CCS is chosen - Hamilton, Herzog, Parsons, Cost and U.S. public policy for new coal power plants with carbon capture and sequestration, Energy Procedia, Volume 1, Issue 1, Greenhouse Gas Control Technologies 9, Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), 16-20 November 2008, Washington DC, USA, February 2009, Pages 4487-4494

cost for the goods exported to advanced economies, reducing the purchasing power of those economies, which in turn will lead to less consumption of Chinese goods.

- The introduction of global emission standards without limits for emerging economies like China would lead to a further shift towards Chinese low-cost energy, while advanced economies would reduce their energy consumption along with growing energy prices. It would further enable China to benefit from the heavy investment into the manufacturing of renewable energy technologies, as it becomes a major supplier of those technologies being mass-deployed (like for wind and solar generation). Ironically, this strategy reduces the cost of those technologies, as they will be manufactured with lower cost labour "dirty" (carbon-intensive) energy.
- The most likely route, which doesn't lead to binding global standards, would continue the status quo, with some countries voluntarily engaging in lower carbon strategies, and thus pushing more work in China's direction, but not to the extent of the second scenario.

One vital aspect of China's competitiveness is the long-term sustainability of low energy prices; something that is presently incompatible with large shares of renewable energy generation or with carbon mitigation efforts. Since China provides both low-cost energy and low(er) cost labour, this increases the affordability of goods for advanced economies which import Chinese products. But this is only the case as long as China can produce at the current cost structure. As soon as it becomes affected by significantly higher prices, the country – and the world along with it – will be negatively affected. In the case of China, "Low Carbon" immediately translates to "lower global industrial output".

2.3. Why renewable energy likely will remain too expensive

China's current price for low-cost energy sets the benchmark for a future change in energy pricing. For electricity, there is only one renewable energy source which is competitive in this range – large hydropower that benefits from natural (or easily dammed) reservoirs. Unfortunately, many developed countries have already exhausted their potential for meaningful and cost-effective hydropower[92], which in most locations is only seasonal and cannot be used as a base for an industrial society alone[93]. Other renewable sources currently produce electricity at significantly higher cost and/or with less favourable properties of the energy delivered.

During the past 20-30 years, alternative generation technologies have become cheaper, along with a continuously growing installed base (Figure 20). In particular, photovoltaic solar panels cost (per kWpeak) shrank 40% between 1998 and 2009, and a further reduction of $1.00 to $1.20/W installed (US) by 2010 (estimated)[94]. The most rapid reduction took place in recent years as Chinese production has increased. Today, approximately 50% of all photovoltaic panels are produced there[95].

This fact that China has taken over a significant portion of panel manufacturing confirms a mechanism described in 1.11. Shifting the production away from advanced economies reaps the same benefits described in our productivity model – replacing expensive and relatively clean inputs from advanced economies with cheaper and "dirtier" inputs from emerging countries.

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[92]IEA (2002).Renewables Information 2002. Available from http://www.oecd-ilibrary.org/energy/renewables-information-2002_9789264099531-en

[93] Norway with its relatively steady flow of hydro is the rare exception, most hydropower nations in more moderate climates have a high seasonality, which makes hydropower-only grids unstable

[94]LBL (2010).Tracking the Sun III The Installed Cost of Photovoltaics in the U.S. from 1998-2009.http://eetd.lbl.gov/ea/emp/reports/lbnl-4121e.pdf

[95]Mints, P (2010).Solar PV market analysis.http://www.renewableenergyworld.com/rea/news/article/2010/07/solar-pv-market-analysis
Translated from German: Durand, D (2010).German manufacturers lose massive market share. http://www.wiwo.de/unternehmen-maerkte/deutsche-hersteller-verlieren-massiv-marktanteile-445926/

The price reductions in this case are not technology-driven, but due to this shift. China plans to take a similar role in wind-turbine manufacturing, which likely will support a reversal from the current resource-cost-driven trend to higher cost for newly installed capacity (Figure 21).

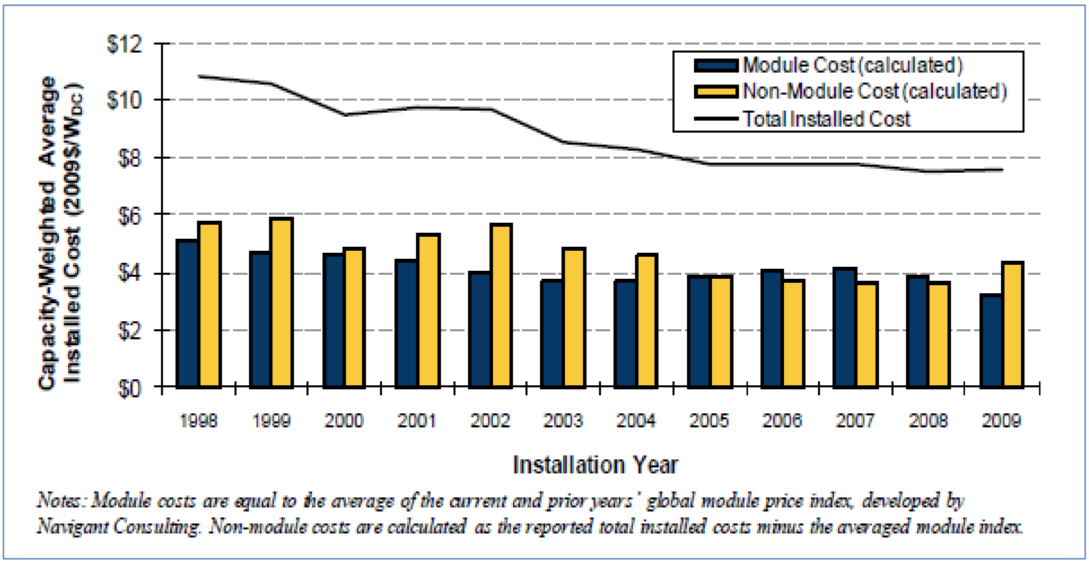

Figure 20 - Cost trend of solar power in the United States[97]

Irrespective of the potential for installed costs of wind power to decline as soon as China is able to apply its lower cost labour and energy base, the overall trend for newly installed capacity in the wind and solar electricity sector is no longer a clear one. Cost improvements from economies of scale in manufacturing and better technology – for example a reduction in silicon wafer thickness – has been offset by growing input prices for almost all raw materials and energy inputs, of which at least a partial share is permanent due to higher effort required to obtain these inputs. The continuation of this trend would contradict the expectation of many industry experts: that in the long run, with rising cost of fossil fuels, renewable energy sources will

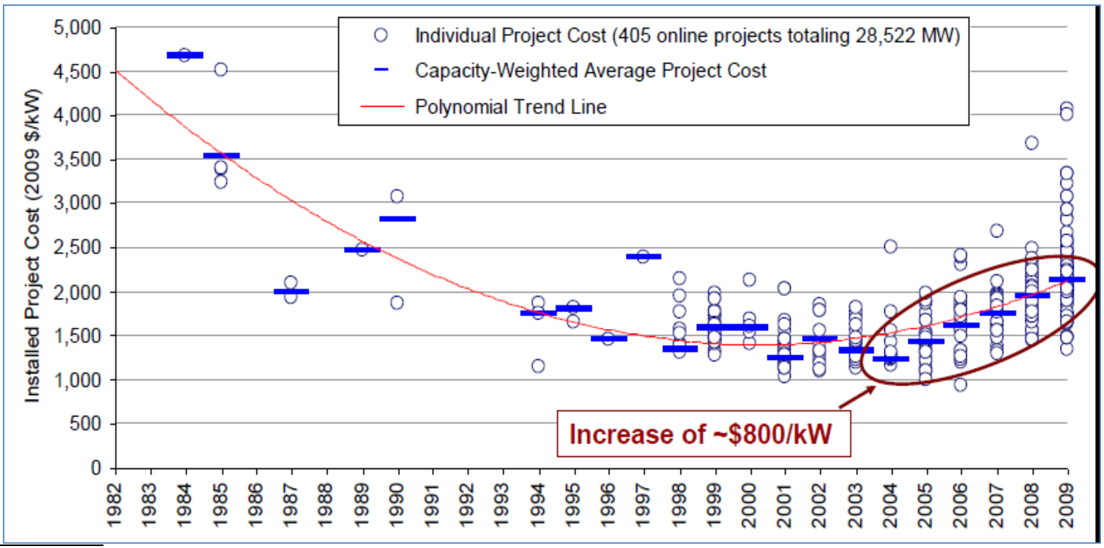

Figure 21 - Wind power installed cost and trend: 1982 - 2009[96]

[96]Wiser, et al. (2009).2009 Wind Technologies Market Report. http://eetd.lbl.gov/ea/emp/reports/lbnl-3716e.pdf

[97] Barbose et.al. (2010), Tracking the Sun III, The installed cost of photovoltaics in the U.S. from 1998-2009, Berkeley Lab, Berkeley

suddenly become competitive. We don't consider this likely. As described above, almost all renewable energy technologies are at the end of a chain which almost exclusively contains fossil fuel inputs that cost only a fraction when compared to the final output cost of those renewable technologies. Input energy, mostly in the form of electricity, but equally natural gas and diesel, is required in mining and refining raw materials, and in fabricating, transporting and installing the technologies (Figure 22). As soon as the cost of fossil fuels rise, this will lead to higher cost for renewable technology and thus a higher price for their energy outputs. So unless new and currently unproved technologies come into play – an overall rise of energy cost is to be expected both in the non-renewable and renewable sector.

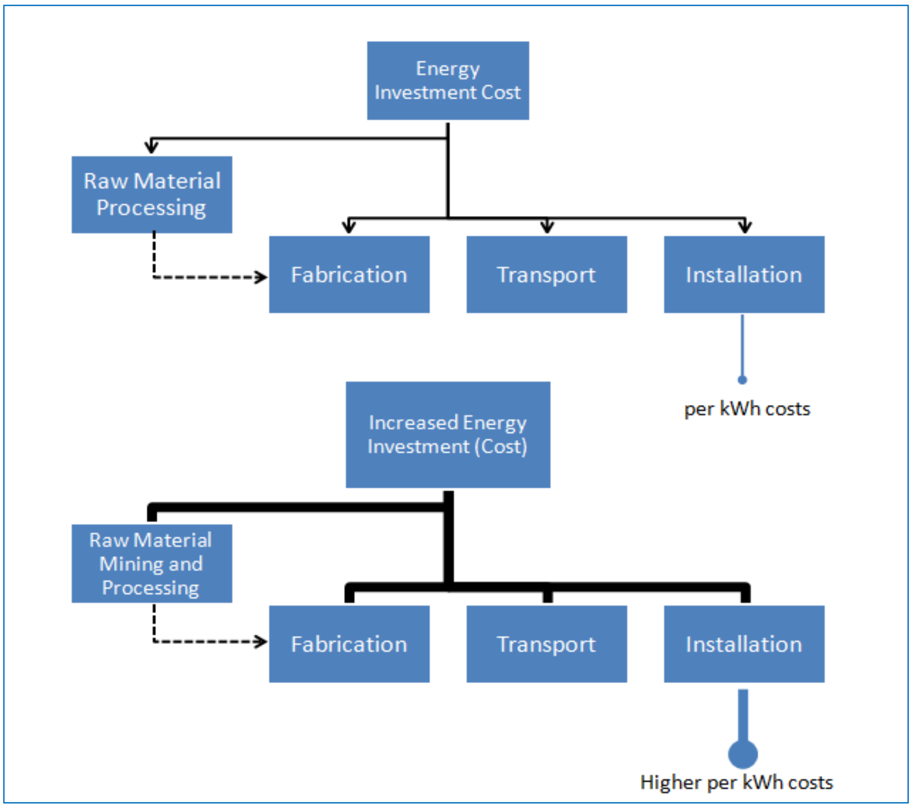

Figure 22 - Influence of higher energy cost on renewable electricity generation

2.4. Why fossil fuels are cheaper

The key reason why fossil fuels – as long as their extraction isn't overly complex – are almost always cheaper than renewable technologies can be explained when looking at the underlying process. Mostly, renewable sources are at a clear disadvantage when compared to fossil fuels from a strict perspective of obtaining a joule of useful energy. One example: liquid fuels from crude oil and from biomass both are based of solar flows that were converted by plants and other primary producers into biomass. In both cases, their chemical properties and physical attributes need to be changed to provide useful fuel with appropriate densities. In order to convert biomass to a meaningful combustion fuel, water and oxygen need to be reduced, and molecules with higher volumetric energy density created. While fossil fuels were condensed and enriched by geological forces (heat and pressure) and converted into highly energy-rich and versatile molecules, the biomass currently grown comes in a relatively unattractive form, contains moisture and has a low energy density. In order to turn it into comparably powerful fuels, significant efforts need to be undertaken, efforts which themselves require energy and technology inputs and thus reduce overall net benefit (EROI) of the final fuel.[98] Figure 23

[98] There are two major approaches for determining the net benefit of an investment in energy procurement: EROI is the ratio of energy out over energy in, or, energy extracted to energy invested. Net energy assessments, though the methodology may vary, subtract the energy investments needed to produce a fuel from a given resource, or calculate the gross production needed to net a given amount of fuel. The equation is [(EROI – 1)/EROI) × 100]. For example, for oil, if the EROI is 10:1, 90 net barrels of oil would be available from every 100 barrels pumped (10 percent, or in this case, 10 barrels, would need

shows this difference conceptually for liquid fuels, which mainly lies in the time horizon of when useful augmentation takes place.

The same is true for electricity. While the combustion of fossil fuels with high energy density (coal, natural gas) can be easily transported to a power plant near consumers, and burnt at the time of demand, renewable sources deliver in much less favourable ways and – before being useful – need to be transported and/or stored to match demand, with significantly higher effort. There are exceptions to this rule, for example in geologically favourable locations where large scale hydropower and geothermal power is possible, but those are not scalable and available everywhere[99]. More detail on the subject of delivering stable energy is supplied in appendix B.

Important: this does not include externalities of energy use, but rather the cost that is paid today by consumers of fossil energy[100].

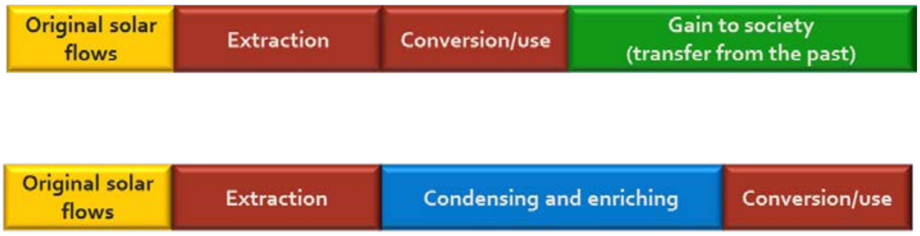

Figure 23 -Comparing fossil fuel energy to biomass

A large number of climate change related studies show a different perspective, where the costs of fossil fuels rise over time, while renewable energy costs decrease as technical progress continues.[101] By combining these expectations with an assumed large decrease in energy intensity over time, these studies demonstrate that the global economy can switch to a major share of low-carbon energy sources by 2050.[102] We find the assumptions behind these results unsupported (please also see appendix A for a close review of some key studies). As discussed in section 1.5, the extrapolation of past efficiency improvements observed in advanced economies, is not based on a global assessment because it does not take into account the shifts of energy intensive activities to emerging economies.

Our worries about overly optimistic assumptions regarding the ability to reduce CO_2 and energy intensity while continuing economic growth are mirrored in a recent report by the New Economics Foundation[103]. The authors observe that over the past decades, industries requiring large energy inputs and generating correspondingly huge amounts of carbon emissions have been mostly outsourced to developing nations, creating the illusion of decarbonisation in developed regions. The report concludes that this move towards high-end service economies can, of course, not be replicated globally – the physical goods that are to be consumed have to be produced somewhere. As the report states, over five billion tonnes of CO_2 were embodied in the international trade of goods and services in 2001, the vast

to be invested to get the next 100 barrels out of the ground). For ethanol, this equates to 13 barrels of net fuel production for each 100 barrels produced. The remaining 87 barrels worth of energy would need to be re-invested to get the next 100 barrels of ethanol production.

[99] Iceland, Philippines, Norway, Switzerland, Canada East, etc.

[100] Thus, this view does not include currently unpaid environmental damage, potential future negative implications from global warming, and other externalities, since current economic systems operate without those. If we were to include the cost of those externalities in the cost of fossil fuels, their new total cost would be equally prohibitive to many industrial processes.

[101] IPCC (2008). Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment report of the Ingergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

[102] Ecofys, WWF, (2010). "The Energy Report: A fully sustainable and renewable global energy system is possible by 2050". Utrecht: Ecofys Group. Available at: http://www.ecofys.com/com/publications/The-Energy-Report-Ecofys.htm. European Climate Forum (2009). "Roadmap 2050: A Practical Guide to A Prosperous, Low Carbon Europe" Potsdam: European Climate Forum. Available at: http://www.roadmap2050.eu

103 Simms A, Johnson V, Chowla P (2010). "Growth isn't Possible". New economics foundation.

majority flowing from developing to developed nations. This amount is greater than the total annual emissions from all EU25 nations combined, but is not accounted for in regional assessments of CO_2 and energy intensity. The authors label this a form of "carbon laundering".

Even worse, this externalization process actually considerably increases global emissions. Taking a closer look at the UK and China, the report points out that 555 million tonnes of CO_2 were embodied in trade from the latter to the former in 2004. While this reduces the UK's apparent emissions by 11%, it actually increases the country's real emissions by 19% because of less efficient industrial processes in China compared to the UK. In addition, the shipping of goods itself creates another 10 million tonnes of CO2. Globally, the UK may be responsible for six to eight times the amount of carbon emissions that are officially accounted for.

The authors go on to point out that historically, annual improvements of CO_2 and energy intensity have never been enough to offset emissions increases caused by economic growth – not even in developed nations that are heavily outsourcing their energy use and carbon discharge. Thus, in absolute terms, CO_2 output has always risen. In addition, global CO_2 intensity has actually increased by 0.33% annually between 2000 and 2007 due to an increasing use of coal (mostly in China). As the report observes, coal use can be expected to rise even further due to increasingly severe constraints on other fossil sources of energy, mainly oil and natural gas. Please note that this does not only relate to production rates in absolute terms, but also to the quality of the resources that can still be exploited – declining EROIs (net energy gains) directly translate into rising energy intensity. On top of this, as discussed before, the potential for further technological improvements of CO_2 and energy intensity is very limited for mature industrial processes which have mostly been operating near their practically achievable optima for decades.

2.5. Specific issues for emerging economies

The above issues are relevant to all economies. However, some emerging countries are under heavier pressure because these are already pursuing an industrialization strategy to increase economic growth. They may also be further affected by higher energy cost and/or a shift to renewable technologies in two further ways:

- Their labour cost is significantly lower, e.g. the replacement between human labour and mechanical labour becomes unattractive much earlier than in advanced economies, unless they manufacture for others – with the consequence that they reap only marginal benefits from becoming industrialized (e.g. China)
- Their financial interest rates are high. This not only stands in the way of investments into industrialization efforts, but equally when trying to introduce renewable technologies. One of their key properties is that most of the investment is due upfront, whereas fossil fuel technologies incur a larger share of the cost during operations. This is less challenging for a low-interest environment, but can destroy the economics of renewable investment where risks and thus interest rates are significantly higher (See Box 1).

Box 1: Influence of interest rates on wind power cost

Example: a wind turbine costs 1500$ per MW of nameplate capacity and produces at a capacity factor of 25% for 20 years, produces one kWh at a cost of 8.2 cents/kWh, with 2% maintenance cost per annum and an interest rate of 5%. If the interest rate to be paid rises to 10%, one kWh suddenly costs 11.4 cents, at 15% interest, each kWh has a price of 15 cents.

Thus, in a situation with growing fossil fuel costs it becomes very difficult to industrialize a country, or maintain an industrial infrastructure. This is even more the case with renewable technologies as long as these remain at far higher cost levels then fossil fuels.

Figure 24 shows the consequences of the above analysis and the feasibility of using renewable sources (mostly from solar flows). While intelligent use of technology (relatively low-tech) can indeed enhance quality of life and wealth for the poorest groups and countries, industrial activity (including industrial farming) is fully dependent on a favourable ratio between the cost of human labour and energy inputs. For more advanced societies, this effect is somewhat relaxed, as they import most energy-intensive goods from locations with low-cost energy and thus are less susceptible to the downsides of higher energy cost[104].

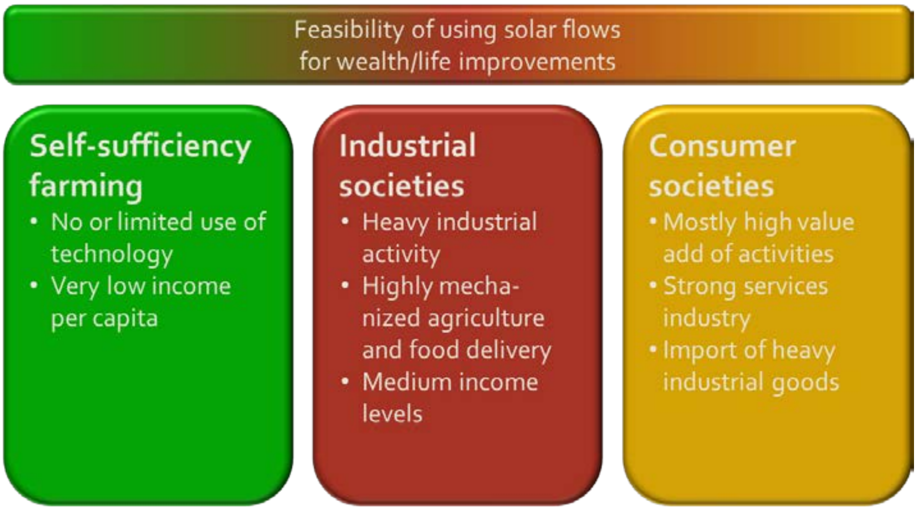

Figure 24 - Feasibility of using solar flows for wealth and life improvements

2.6. Conclusions

While this report doesn't question the need for reducing carbon and other greenhouse gas emissions, it seriously questions the generally accepted notion that this is possible without disrupting the current industrialisation based growth paradigm. It therefore questions the idea that emerging economies could develop an industrial society without using carbon-intensive fuels.

One key driver of the past 250 years of human development has been to find new and innovative ways to use more low-cost energy. Despite a continuous push for energy efficiency, we find that so far efficiency gains have by far not been able to offset the effect of doubling or tripling input prices for energy and raw materials into human processes. If this cost trend continues, this will lead to lower economic output.

The only way to avoid this is one of inconsequence: if advanced economies aspire to accomplish low-carbon targets while outsourcing their energy-intensive industrial processes to places without such standards. It seems obvious that this would not benefit an objective of reduced greenhouse gas emissions.

Thus, the most likely trajectory for all economies wanting to reduce their carbon emissions – and not just export them – will ultimately be to lower economic output. For emerging economies it likely means to stop trying to industrialize and urbanize, but instead to improve lives of rural populations who still lead lives with a low carbon footprint. The next chapter will look at some of the implications related to this suggestion.

[104] Some of those countries actually offer proof to our theory. In Germany, for example, a number of energy-intensive industries are exempt from energy taxes and subsidies for renewable energy

3. Low carbon in emerging economies

Based on the above findings, it is important to analyse the potential of certain countries to continue (or even begin) a desired growth path. Below, we will look at various types of economies from the perspective of their potential to grow while limiting or reducing carbon emissions. We do not include a review of carbon compensation approaches (such as REDD), but focus on core economic activities.

3.1. Types of economies

If countries are managed under the assumption that they have to sustainably provide for themselves with mostly balanced trade and current accounts, they either have to be independent or capable of setting up exchange with other economies to complement their bundle of services to the population not provided internally. Thus, it is feasible to establish a low-energy and low-carbon economy which is mostly focused on services (like for example the U.K. or Switzerland), but as demonstrated above that requires another country to pick up the gap, as even those economies still require energy, building materials, food and other commodities or processed goods. The same is true for emerging countries: whatever part of the entire value chain they do not provide internally has to be imported. If the cost of those imports increases due to higher input cost at their origin, without a concurrent increase in exports, it will reduce the purchasing power and thus the wealth of the importer.

When trying to understand low-carbon potential, this actuality must be kept in mind. As long as other locations offer energy services and other inputs at a lower cost, one economy can become less polluting, at the cost of their pollution being shifted elsewhere.

In the analysis of low carbon potential below we distinguish between a number of key properties of countries which have a significant influence on their possible future trajectory, both concerning their ability to develop and grow, but equally related to their ability to reduce carbon dioxide emissions. The qualifications are often not exclusive, as countries might show the properties of more than one category:

- Resource Suppliers: These countries export significant quantities of minerals, ores, energy or other primary inputs into industrial processes. They do not necessarily run a trade surplus, as they sometimes lack the ability to process the resources extracted, and thus receive only limited benefits from them. Depending on the ownership structure, those countries derive part of their economic output from the margins between cost and market price of extracted goods. Typically, a significant majority of resource extraction efforts are fossil fuel based and can only marginally be changed due to the sensitivity of all supply chains to higher input cost.
- Manufacturers: In this case, a country provides significant share of their workforce to process goods for export, mostly based on low-cost labour or low-cost energy (like China). Switching to less polluting fuels would increase the cost of energy inputs and thus reduce their competitiveness
- Consumers/Recipients: These countries are the poorest, as they neither produce nor supply to the global economy in significant quantities, but rather have a domestic economy with additional inputs from international aid and/or remittances of ex-patriates. Those countries typically run trade deficits and significant current account deficits. On the other hand, they may have the

highest potential for lower carbon emissions from improving their own capabilities based on renewable technologies.

3.2. Sector-specific energy use and carbon-intensity

When discussing the implications of lower carbon emissions and higher energy cost on manufacturing processes (see sections 2.1 and 2.2), the fact that almost all industrial processes replace small quantities of manual labour with significantly larger amounts of mechanical labour makes those processes particularly susceptible to higher energy costs. The same is true for extraction and primary energy generation processes – the higher the input cost for labour and energy into that particular process, the lower the benefits from selling those natural resources or resulting products at market prices, which are typically driven by forces outside the control of one individual country.

Figure 25 demonstrates this situation for aluminium production. If only the input cost for electricity changes from the lowest available price ($0.03 per kWh) to the median price for industrial electricity ($0.08/kWh), the margin of the producer is heavily affected, reducing the benefits. This is only looking at direct energy use in the electrolytic process; indirect energy cost will further affect the other components.

In this context, it is important to understand the ability of various sectors to respond to higher energy cost. Table 9 provides an overview of sector-specific energy use. From the data, it becomes clear that Industrial and related economic activities such as mining and manufacturing are the most energy-intensive (per $ of produced GDP). For most countries, the energy intensity of these sectors is double or triple as large as in the transport, residential, or service related sectors. The discrepancy becomes even more apparent when looking at the weighted average of countries. Industrial and mining sectors show at least five times larger energy intensities when compared to the service sector. The only exceptions are countries which have not developed in any industrial manner at all, such as Tanzania, Nepal, and Ethiopia. In these countries very few energy intensive activities take place. Because of this, the energy intensity values are comparable across the two sectors.

This observation is in agreement with the data in Figure 24, which places the highest hurdle for replacing low-cost fuels with more expensive ones in countries dependent on industrial processes. As one might expect, the carbon intensity differences among nations and economic sectors are very similar to those for energy intensity. Table 9 gives the sector-specific carbon-intensity values for many of the researched countries The weighted average for carbon intensity is nearly six times larger for industrial related sectors then for service related sectors (1.57 vs. 0.28 tons CO_2/$). Once again, only countries which are still at a subsistence level show similar carbon intensities across the industrial and service related sectors, simply

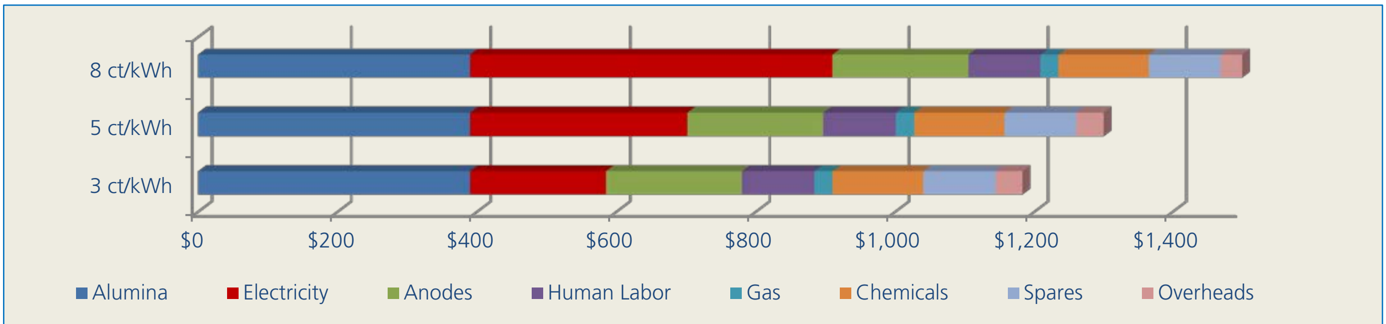

Figure 25 - Aluminium production cost for various electricity price points[105]

[105] Metal trader, 02/2009

Energy Intensity in MJ/2005$ GDP PPP Carbon Intensity in t CO_2 /2005$ GDP PPP	Overall value		Mining, Utility, Industry, Manufacturing, Construction Sectors		Other Sectors	
	Energy	CO_2	Energy	CO_2	Energy	CO_2
United States	6.7	0.51	19.1	1.54	3.6	0.25
United Kingdom	4.3	0.30	11.4	0.85	2.8	0.18
China	11.5	1.07	19.7	1.89	11.6	0.98
Indonesia	7.2	0.59	10.4	0.86	4.1	0.33
South Africa	13.2	1.43	33.4	3.83	3.5	0.28
Nigeria	4.7	0.53	4.7	0.66	4.6	0.43
Brazil	4.3	0.35	9.3	0.80	2.5	0.19
Vietnam	6.8	0.58	10.2	0.90	4.5	0.37
Mozambique	11.0	1.20	14.1	1.63	10.1	1.07
Ethiopia	12.7	1.36	8.9	0.80	13.3	1.44
Tanzania	5.6	0.55	6.7	0.61	5.2	0.53
Kenya	4.7	0.49	10.4	1.21	3.3	0.32
India	7.6	0.77	20.2	2.15	2.6	0.22
Pakistan	6.4	0.44	15.0	1.00	3.2	0.24
Bangladesh	5.5	0.56	11.9	1.34	3.0	0.25
Zambia	5.7	0.58	6.9	0.69	5.1	0.53
Ghana	11.3	1.25	14.4	1.83	10.0	1.01
Nepal	4.2	0.43	3.1	0.31	4.5	0.45
Cambodia	4.6	0.42	4.7	0.36	4.6	0.44
Sudan	3.7	0.33	4.5	0.42	3.2	0.29

Table 9 - Overview of sector-specific energy use and carbon intensity for countries of interest[106,107]

because there is so little industrialization present in these nations.

We summarize the output of our energy intensity calculations in Table 10, including areas of potential mitigation, and associated hurdles per sector. Countries in the “middle” of the development spectrum, i.e. those which have evolved away from subsistence-related activities, but haven’t matured to be mostly focused on services, are most susceptible to higher energy cost and less capable of migrating away from fossil fuels.

3.3. Finding feasible applications

To best understand the ways in which energy applications and technology can be applied most feasibly in emerging economies, the factor of exchange between human labour and energy in processes becomes the crucial element. At low per capita income levels, the feasibility of replacing human labour with mechanical processes is limited to those processes or technologies that offer significant societal benefits at a low exchange ratio, i.e. where relatively little mechanical energy is needed to replace human labour. In this respect, the following aspects matter:

- Direct ratio of energy application between human labour and its

[106] Own Calculations based on 1) International Energy Agency (2010). “Energy Statistics of Non-OECD Countries 2010 Edition” Paris: IEA Publications, 2) Wood fuel production data [internet]. Forestat, Rome: FAO; Wood Fuel – accessed February 26, 2011 . Available from http://faostat.fao.org/site/626/default.aspx#ancor, 3) Gross Domestic Product PPP Data [internet]. World Economic Outlook Database, IMF: Washington; GDP based on PPP valuation of country in current prices U.S. Dollars – accessed February 20, 2011 – Available from http://www.imf.org/external/ns/cs.aspx?id=28, 4) GDP sector breakdown [internet]. National Accounts Main Aggregates Database, New York: UN; GDP and its breakdown at constant 2005 prices in US Dollars – accessed February 20,2011 – Available from http://unstats.un.org/unsd/snaama/dnlList.asp.

[107] IIER Calculations based on 1) International Energy Agency (2010). “Energy Statistics of Non-OECD Countries 2010 Edition” Paris: IEA Publications, 2) Wood fuel production data [internet]. Forestat, Rome: FAO; Wood Fuel – accessed February 26, 2011 . Available from http://faostat.fao.org/site/626/default.aspx#ancor, 3) Gross Domestic Product PPP Data [internet]. World Economic Outlook Database, IMF: Washington; GDP based on PPP valuation of country in current prices U.S. Dollars – accessed February 20, 2011 – Available from http://www.imf.org/external/ns/cs.aspx?id=28, 4) GDP sector breakdown [internet]. National Accounts Main Aggregates Database, New York: UN; GDP and its breakdown at constant 2005 prices in US Dollars – accessed February 20,2011 – Available from http://unstats.un.org/unsd/snaama/dnlList.asp, 5) Cement and Gas Flaring emissions data [internet]. Fossil-Fuel CO2 Emissions, Tennessee: CDIAC; Preliminary 2008-09 Global & National Estimates by Extrapolation – accessed February 22, 2011. Available from http://cdiac.ornl.gov/trends/emis/meth_reg.html

replacement with mechanical labour (accounting for total energy in infrastructure and consumption)
- Cost of inputs into infrastructure and consumption
- Flexibility in energy use, e.g. share of upfront investment vs. operating inputs, and the ability to store and use energy upon demand
- (Societal) discount rate for investments, determining the feasibility and risk of investment

For each economy, we believe we have demonstrated that only exchanges where the equation:

[cost of mechanical energy]
x [ratio of replacement]
< [cost of human labour]

holds true, will make sense. Since human labour costs remain low due to an abundance of available workers, we must focus on the left side of the equation. For this equation to hold then, a nation must have either a source of high quality mechanical energy available at very low prices (i.e. early industrialization in China fuelled by inexpensive coal and some hydropower), or have select technologies that possess a lower ratio of mechanical energy replacement for each unit of human labour.

The size of the advantage required is also dependent on the split between upfront investment and operational cost, e.g. the smaller the fixed (upfront) investment and the larger the flexible cost of use, the larger the advantage (see example below in Box 2). Further, local risk (expressed in societal discount rates which also are reflected in financial discount rates) is relevant, as it further discourages upfront investment.

The same applies for machinery, tractors, generators, and transportation equipment. Their use does not become attractive until they provide a benefit that frees up more value in the form of human labour than it consumes in cost for the replacement equipment and energy.

For most of the countries in question, standard industrial processes are much less feasible, or only feasible at very low energy input cost, as their replacement rates often exceed 100 times the human energy initially required for a task. The higher energy cost becomes, the fewer benefits to society arise from such an exchange (see Table 8). At very high energy prices, most economic advantages are lost. Due to this, renewable sources of energy – or fossil fuels burdened with carbon taxes or the cost of sequestration, no longer offer the benefits required for industrialization, and, unless there are unforeseen technological breakthroughs, are unlikely to do so in the foreseeable future.

Box 2: Mobile phones

Example: the use of mobile phones by rural societies in very poor countries. The brief use of a (often shared) phone replaces long distances of walking or messenger use, eliminates insecurity and speeds up processes significantly. Thus, even though the cost of labour may be very low, humans are limited by speed and transportation infrastructure. The value of being able to instantaneously transfer information is much higher than that which takes hours or days to arrive.

Also, the upfront investment for final users is relatively small when compared to fixed line phone networks, and handsets are often subsidized. Because the investment is often made by foreign companies operating at their rates of capital cost, this option is even more attractive.

	Relative energy intensity	Energy units MJ per $/output	CO_2 mitigation potential	Hurdles	Comments
Subsistence farming	Low	3 – 6	High	Low available capital to invest in new technologies. Little financing available.	High share of human and partially animal labour
Industrial agriculture	High – large input	15 - 25	Medium to low	Yield dependent on application of fossil fuel derived fertilizers/ pesticides, as well as biotech engineering	Fuel for operating tractors and combines typically a small portion of annual energy costs
Mining	High	20 - 40	Low	As resource quality declines, more material must be extracted at higher cost to achieve a constant level of output	
(Manual) manufacturing	High	7 - 12	Low	This "manual" sector (for example in textiles or manual food processing) is less affected by higher energy prices	If energy cost rises on a global scale, less
Industrial manufacturing	High	15 - 20	Low	Large embodied energy and capital investment required. Requires steady supply of electricity/energy for production	Incompatible with variable production from renewable sources of electricity without modulation or back up
Construction	High	15 - 20	Low	With large embodied energy content in building materials and high susceptibility to interest rate rises, this sector is at risk from rising resource cost	
Transportation	Moderate to high	8 – 15	Medium	Investment in electrification of transportation systems (car, rail, e.g.) requires large scale energy intense infrastructure investments	
Services	Relatively low	2 – 6	High	In many cases requires goods and materials produced at low energy and labour costs.	Only feasible to focus on services when countries can outsource industrial activities

Table 10 – Energy intensity, carbon mitigation potential and potential hurdles for various economic sectors

The key challenge becomes to identify those technologies and processes where an energy investment and subsequent investment in fuel consumption can replace human labour with mechanical labour, at the lowest replacement energy ratio possible. Using this method of analysis, one would be able to determine more accurately which aspects are feasible with high- cost (and effort) renewable energies, allowing societies to benefit from lifestyle and wealth improvements without adding carbon emissions.

3.4. The special role of electricity

Electricity and oil availability seem to be two key drivers of industrial success. Above, we demonstrated that the correlation between electricity consumption and economic output is extremely high, which – in our view – relates to the fact that almost all key economic processes today require stable electric power at some point – for example, all processes that are microprocessor-driven cannot function without electricity. However, there is one very important difference between the two[108] in most processes. Electricity is a flow of energy, whereas oil is a 'stock' and thus more easily stored. In order for a proper functioning of the electrical grid, production and demand must be maintained in perfect balance (less than a 1-2% margin of error).

Within a modern economy, stable electricity is a key contributor to smooth operation of almost all advanced processes, yet it is very complex to accomplish. We have developed a metric for electricity availability, the Electricity Availability Index (EAI). It is calculated by multiplying the percentage of a country's population with access to electricity and the percentage of hours in a year that there is uninterrupted electrical service. Figure 26 plots the EAI compared against GDP/capita (purchasing power parity adjusted) for 99 countries. It shows that stable electricity is key to producing economic activity significantly above 10,000 US$ per capita (PPP). The fact that no country with electricity availability below 98% exceeds a per capita GDP of US$ 20,000 suggests that electricity seems to be the prerequisite for high output, and not the inverse. One of the most important takeaways is that the value of steadily available electricity at all times seems to far exceed the value of situations that experience regular blackouts, irrespective of the total amount of energy available.

Of all the developing countries researched for this project, only three (China, Brazil, and Vietnam) have managed to accomplish the objective of a mostly stable electricity grid. All other countries rank low or very low regarding their EAI. (Median = 35%, average = 41%). With the introduction of certain renewable technologies[109], the objective of having reliably available electricity becomes even more challenging, even for advanced economies. Please see appendix B for a more detailed analysis and explanation of this issue.

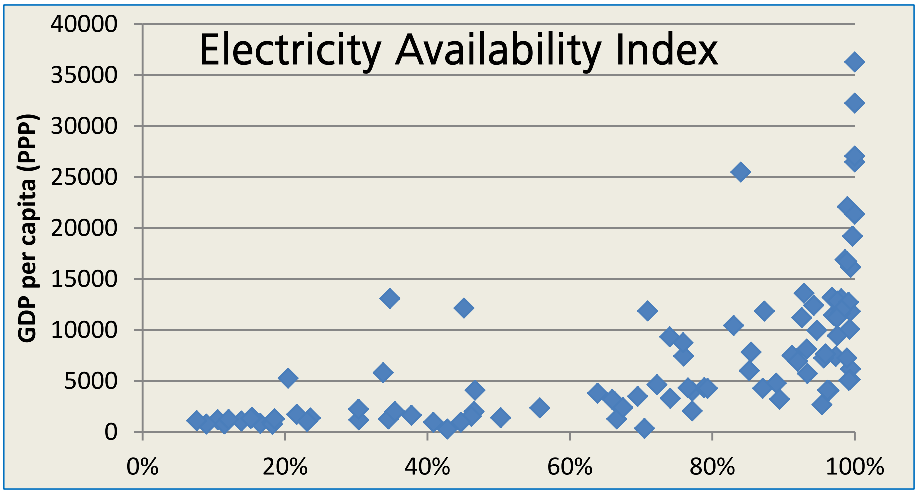

Figure 26 - IIER Electricity Availability Index vs. GDP/Capita (PPP) for 99 Countries[110]

Electricity can be available in multiple ways, with different properties.

- Patchy local electricity: in this situation, local sources are available sporadically or intermittently, from either generators or renewables. These sources don't offer high quality power and typically are only able of powering

[108] Or any other combustible fuels like wood, coal, natural gas etc.

[109] All stochastically available renewables, mainly solar and wind, are posing challenges for their grid integration which might – at larger penetration rates – even challenge most advanced societies (see appendix)

[110] European Bank for Reconstruction and Development. Business Environment and Enterprise Performance Survey (BEEPS): http://www.ebrd.com/pages/research/economics/data/beeps.shtml; IEA World Energy Outlook. The Electricity Access Database: http://www.worldenergyoutlook.org/database_electricity10/electricity_database_web_2010.htm; Enterprise Surveys. Infrastructure: http://www.enterprisesurveys.org/ExploreTopics/?topicid=8 Accessed March 30, 2011.

simple devices not susceptible to frequency or voltage shifts. This includes lighting, or chargers for mobile devices such as laptops or phones. Often, the power in this case is expensive, but only used in small quantities for high-value applications. No major processes are directly dependent on it.

- Stable local power: a small grid, a hydropower plant, or a well-managed fossil fuel driven system powering a house, a compound, an industrial complex or even a small town is able to establish reliable "islands" in environments without overall electricity availability. In many developing countries, some parts of large cities are very much following that approach, or some industrial compounds with their own power generation capabilities
- Stable regional/national grids: a grid system providing electricity to larger regions in a stable and robust fashion. Except for significant parts of China, none of the countries analysed in this paper is even close to accomplishing stable grid situations, which puts further restrictions on the ability to develop industrial societies and even more so to establish service industries

With energy prices increasing quickly, and renewable technologies often adding burdens to electricity grids, we see a rather low likelihood of additional regional or national electrification projects to advance much further in most economies analysed. However, local pockets of stable electricity may be established, and even more so a more widespread availability of small-scale electricity, which might provide the ability to power important applications.

Given this general problem of implementing stable power grids, which seems unlikely to be overcome, our suggestions put low emphasis on technologies requiring grids and favour those without this requirement, delivering patchy or local services.

3.5. Low-carbon technologies

When taking the above into account, it seems advised to identify potential low-tech solutions that can help reduce a country's carbon footprint while improving the lives of its citizens. Based on our country analysis, the agricultural sectors in many – even middle-income – countries offer a possible avenue for such technologies. In each situation, the local context is of the utmost importance, and the success of a solution in one region does not guarantee success in another.

The aim of the technologies is to improve the quality of life for a significant number of people. A two-step process is suggested to determine whether or not a particular technology has the potential to improve quality of life. First, it is required to assess individual technologies on a qualitative basis, including indicators such as derived direct and indirect labour-hour benefits, input cost, energy use flexibility (share of upfront investment vs. operating inputs), and extent to which materials are locally sourced. Second, we consider the potential ability of these technologies to have a tangible impact on relevant categories of the Human Development Index (HDI) and Multidimensional Poverty Index (MPI), which are generally accepted and widely used measures of wellbeing.

The HDI is a single statistic, calculated by UNDP, which serves as a frame of reference for both social and economic development and is a broad aggregate of national level statistics. The MPI assesses poverty at the household level, and is calculated as the product of the percentage of people who are poor and the average intensity of deprivation. "Health", "living standards," and "education" are the three dimensions common to both[111]. The health dimension in the MPI has two indicators: nutrition and child mortality. The living standards dimension of the MPI includes six indicators: cooking fuel quality, quality of sanitation facilities, water quality, electricity availability, home floor quality, and assets. Living standards in the HDI, on the other hand are measured by gross national income per capita. Education has not

[111] UNDP 2010. MDI and HDI. Available from http://hdr.undp.org/en/statistics/mpi/ and http://hdr.undp.org/en/statistics/hdi/ Accessed March 18, 2011.

been taken into account here, as it lies outside of the scope of this report. We do not discount its importance in developing local skills required for low carbon development.

To summarize, the approach is to look at a broader level of improvements in the quality of life than just a direct rise in income, by means of qualitative indicators and criteria of standardized indices. This aligns well with the fact that many technologies give benefits outside or beyond raising income, via saved labour hours, an increase in assets, or both. For example, a good quality housing floor serves to have a fixed asset that cannot be stolen or claimed by family or neighbours in times of need, and also saves labour time as it is easier to maintain a clean and hygienic environment. Our goal here is not to recalculate potential HDI or MPI improvements based on the implementation of these technologies, but rather to use them as a guideline to structure our preliminary research.

3.6. Criteria for low-carbon technologies

For the selection and assessment of potential low-carbon development technologies (appendix C) the following ten criteria have been applied:

1. The payback period of input energy should be small relative to the overall benefit. This implies small energy inputs for both construction/initial implementation and operation and function;
2. As far as possible, they should be driven mostly by solar and other natural flows. The use of easily-assembled technologies such as water wheels and windmills is preferred over advanced technologies such as solar panels and wind turbines which require high-tech manufacturing capabilities;
3. They should not compete with important societal requirements (such as food security, physical and mental health, and environmental protection), but rather support them;
4. The support/benefit afforded by any low-carbon solution must be in the form of direct improvements in the societal requirements outlined above, or by additional income or labour-hour savings;
5. Low-carbon solutions relying on key technologies from outside the target country should require minimal or no support from abroad;
6. Greater than 90% of a technology's components should be sourced within the country of use;
7. Solutions and technologies should not be dependent on stable electrical grids, as many of the countries selected for this study are deficient in such infrastructure;
8. The implementation of technologies should be flexible in that advanced skill levels to manufacture or operate are unnecessary. Operations that are not limited to just one source of fuel or natural resource are favoured;
9. Successful technologies should have relatively small upfront investment, while a significant share of effort during use is preferred, and have a short monetary payback period;
10. Total costs need to be affordable, meaning that the direct ratio of replacement between human and mechanical labour is low – ideally 20-50 units (or less) of fuel supplanting 1 unit of human labour.

3.7. Need for of an in-depth technology analysis

Appendix C shows a small selection of examples of possibly suitable technologies. To make this development path work, well tested methods need to be developed that are tailored to the specific targeted country. The starting point lies in the assessment of local demand together with local representatives to identify specific problems and needs, as well as any other region specific hurdles that need to be overcome for successful implementation. Based on such an assessment a list of technologies can be identified, which combine low-carbon profiles and clear benefits for emerging economies. It seems important that this effort is brought underway soon.

Appendix A – Review of Low-Carbon Literature

The findings presented in this report strongly contradict the general opinion that it is possible to continue an economic growth path and still reduce greenhouse gas emissions from fossil fuel combustion. All the evidence outlined in this document suggests that "Green Growth" is an oxymoron, and that only one of the two is possible on a global scale – growth or reduction in greenhouse gases. We have outlined our evidence, but still want to put some effort into highlighting the specifics of why our findings differ so fundamentally from other people's opinion.

Important: We always refer to "economic growth" using Gross Domestic Product, where growth is measured as "more economic output in real monetary terms". We do not dispute that alternative paths exist to improve happiness and wellbeing in a "greener" world, but so far, all expectations when it comes to political decision-making are geared towards higher output. A large number of papers and studies suggest that exactly this is possible – to grow economies while reducing carbon emissions. Below, we analyse a few key publications that make such a claim, and explain why we think that they are not correct on this subject. The selected publications discussed are representative of most studies in the field, as the same line of argumentation is used throughout, and only the depth of study and economies analysed differ.

Overall, there are three types of sources we examined:

- studies suggesting that a future with large shares of renewable energy sources is feasible both technically and economically (e.g a number of reports making the case for renewable energy introduction strategies in Germany (published by BWI), the U.K. (DECC), the U.S. (NREL), and equally, the new IPCC special report on renewables;
- integrated assessment models that analyse overall economic impact of massive GHG reductions (e.g. ADAGE, WIAGEM, NEMS, RICE, Nordhaus, et.al.);
- papers describing long-term reductions in carbon-dioxide emissions and energy intensity of advanced economies as mainly technology-driven, seeing the potential for the same kind of development on a global scale;

A-1 Renewable energy scenarios

Unfortunately, any closer analysis of reports about the theoretical potential of renewable energy contradict our findings in two ways. First of all, they don't assess the property of energy produced (comparing the cost for a kWh of energy at the power plant irrelevant of the ability to control this output, for example for wind power). From our perspective, uncontrollable outputs (wind, solar) that require transportation or storage need to be discounted, which would raise prices significantly[112]. Please see appendix B for more detail.

Further, such analyses often claim that some renewable energy technologies are competitive, by comparing highly taxed consumer electricity prices in OECD countries with costs of renewable energy sources that have been financially backed by feed-in tariffs. The recent IPCC Special Report on Renewable Energy Sources (SSREN) is a notable example.[113]

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[112] Discounting is required because if demand and supply are not in sync, efforts are required to match them, either by storing output, by transporting it over large distances, or by shifting demand. All these efforts require additional energy and incur losses or cost

[113] IPCC (2011). Special Report Renewable Energy Sources (SRREN): Summary for Policy

The OECD countries consumer price with renewable energy cost comparison ignores the low price required to enable industrialization as described in section 2.1, the price borne by industry. The small segment of high cost electricity consumption at the consumer end in OECD countries only becomes affordable by benefits accrued across the economy from the production process. OECD countries consumer electricity prices are much too high to bear for developing countries, and will likely remain too high, and they are much too high for any industrial production. In addition to this apples to oranges comparison, the average of past cost declines is simply extrapolated instead of extrapolating only the portions caused by R&D efforts and economies of scale. A large portion of past cost declines are due to decreases in input cost, including the shift to locations offering lower cost labour and energy, which cannot be repeated (for example for solar panels).. Further, we observe slowly increasing extraction cost, where for many inputs the historic declining cost trend has already reversed. This is true for labour due to higher cost of living, but equally for energy sources (oil, coal, natural gas) and key metals. Here, unexploited surface mining areas are located in remote and politically less stable regions, while resources in many existing locations need to be mined deeper, increasing operating and infrastructure costs. In the longer term a permanent increase in cost is also to be expected from a continued decline in ore grades.

A-2 Low carbon economy models

Analyses that conclude that only a few per cent of GDP would be necessary to stabilise carbon emissions by 2050 do not necessarily conflict with our conclusions, as these mainly rely on carbon mitigation outside of burning fossil fuels. For example, the Stern Review on the Economics of Climate Change, which concludes that between 1% and 3.5% of GDP is required to stabilise carbon emissions, attributes the largest share of this cost burden to mitigating fossil fuel consumption, which according to the study results in less than 25% of the total emission reductions by 2050. The biggest share of emission reductions comes from a combination of deforestation, reforestation, changing land-management and agricultural practices, reducing gas-flaring, and altering industrial processes.[114] The key challenge however lies in the fact that almost all models expect growth as an underlying assumption.

Over the past decades, several hundred computational models dealing with the economics of climate change and climate change mitigation have been published (for an overview, see Metz et al. 2007[115]). While a detailed review of each single model is well beyond the scope of this paper, a discussion of some of the most common basic assumptions shared between models is highly relevant in order to assess the validity of mainstream views on the relation of economic growth, energy availability and CO2 emissions.

One of the most critical issues here is CO_2 intensity, the amount of CO_2 emissions generated by each unit of energy consumed. Most models that we are aware of assume that CO_2 intensity will decrease over the coming decades, either extrapolating past trends or referring to (mostly unspecified) expected technological progress. Describing the influential RICE model, Nordhaus & Yang[116] write: “Uncontrolled emissions are a slowly declining fraction of gross output - a relationship which is consistent with the observed 'decarbonisation' in most countries over this century that is also predicted by more detailed energy models”. In the same vein, the IPCC report (Metz et al. 2007, section

Makers. [online]. Available at: http://srren.ipcc-wg3.de/report. Accessed May 24, 2011.

[114] Stern, Nicholas (2008). The Economics of Climate Change: The Stern Review. Cambridge: Cambridge University Press.

[115] Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) (2007). “Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change”. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[116] Nordhaus, William D & Yang, Zili (1996). “A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies”. The American Economic Review 86(4):741-765.

3.4.1.1) observes that " The majority of scenarios in the literature portray a similar and persistent decarbonisation trend as observed in the past. In particular, the medians of the scenario sets indicate energy decarbonisation rates of about 0.9% (pre-2001 literature median) and 0.6% (post-2001 median) per year, which is a significantly more rapid decrease compared to the historical rates of about 0.3% per year. Decarbonisation of GDP is also more rapid (about 2.5% per year for both pre- and post-2001 literature medians) compared with the historical rates of about 1.2% per year. [...] This means that towards the end of the century these more extreme decarbonisation scenarios foresee net carbon removal from the atmosphere, e.g. through carbon capture and storage in conjunction with large amounts of biomass energy.". Crucially, the IPCCs overall assessment here is that "Such developments represent a radical paradigm shift compared to the current and more short-term energy systems, implying significant and radical technological changes." (ibid).

In sum, two points are critical regarding model assumptions about carbon and energy intensity: firstly, the extrapolation (or even supposed intensification) of past carbon emission reduction trends to the future, disregarding the fact that these trends have already been observed to be subsiding (Metz et al. 2007, section 3.2.1.5) and are at least partly due to regional externalization of energy-intensive industrial production that cannot be repeated on a global level. Here we refer once again to the study provided by the New Economics Foundation on net carbon transfers between emerging and advanced economies, which concluded that the externalization of carbon actually led to higher carbon emissions for the same economic output[117]. The size of this effect is significant, approximately 20% of global emissions occurred in the production of a good in one country that was consumed in a different country.[118] In case of the UK for instance, carbon emissions would have been 11% higher in 2004 if the goods imported from China would have been produced on UK soil.[119] In absolute terms, CO_2 output has always risen in line with GDP at an individual country level, as soon as these transfers are accounted for. In addition, global CO_2 intensity has actually increased by 0.33% annually between 2000 and 2007 due to an increasing use of coal, mostly in China, which contributed with a 77% share of the global increase). This is consistent with 2010 data, where global carbon emissions stood at an all-time high, as reported by the IEA. It strongly supports our position, stating: "The challenge of improving and maintaining quality of life for people in all countries while limiting CO2 emissions has never been greater. While the IEA estimates that 40% of global emissions came from OECD countries in 2010, these countries only accounted for 25% of emissions growth compared to 2009. Non-OECD countries – led by China and India – saw much stronger increases in emissions as their economic growth accelerated"[120].

A-3 Efficiency extrapolations

Assumptions about technological progress are not only critical with regard to projected changes in carbon intensity, but also with regard to projected economic growth. In most models, regional output is modelled in terms of a Cobb-Douglas type production function that essentially has the form Y=ALK, with Y being output, L being labour, K being capital and A being total factor productivity. Crucially, labour corresponds to population while factor productivity is mostly equated with technological progress (not taking into account exchanges of inputs with similar

117 Simms A, Johnson V, Chowla P (2010). "Growth isn't Possible". New economics foundation.
Atkinson, et al. (2011). "Trade in 'virtual carbon': Empirical results and implication for policy". Global Environmental Change 21:563-574.

119 Li, Y., Hewitt, C.N. (2008). "The effect of trade between China and the UK on national and global carbon dioxide emissions". Energy Policy 36: 1907-1914.

120 IEA 2011, accessed on June 2, 2011: http://www.iea.org/index_info.asp?id=1959

properties, but different price), both variables being exogenously introduced into the models. Since both factor productivity and population are generally projected to increase, this introduces an inherent "growth bias", i.e. an increase in economic output that is essentially cost-free since it does not result from interactions within the model, but results from an a priori choice of parameters.

This is particularly relevant for the regionally disaggregated RICE model by Nordhaus (Nordhaus & Yang 1996) which assumes a partial convergence of incomes between subregions: "The major uncertainty in the economic projections is long-run levels of per capita output in the different regions. These projections are based on the assumption of partial convergence of per capita incomes. That is, we assume that the relative differences in regions' per capita incomes decline over time but do not disappear. The extent of convergence is a controversial issue, but to the extent that differences in per capita incomes are primarily based on differences in the extent of adoption of available technologies, productivity differences should largely disappear over the long run." In consequence, Nordhaus notes that "One interesting feature of this approach is that it gives considerably higher estimates of output and emissions than do the conventional global models [...]" (ibid).

Again, assumptions about future technological progress are critical here. As the IPCC report succinctly puts it, "technological development, however and under whatever policy it unfolds, is a (if not the) critical factor determining the long-term costs and benefits of mitigation." (Metz et al. 2007, section 11.5.2). Also note that in regionally disaggregated models like RICE, there is an even stronger growth bias for developing nations as these are exogenously assumed to approximate the labour productivity levels of developed economies – under these assumptions, it is no surprise that economic growth persists even under relatively rigid CO_2 curtailment policies. This is not a result of the modelling process, but a feature that was built into the models. We do not think that this reflects reality, particularly for developing countries where such a convergence has not been found in statistical analyses and remains a highly contested view.[121]

A-4 Conclusion

In all the studies analysed so far, we cannot find sufficient evidence that contradicts and falsifies our position. This strongly supports our case that the theories put forward in this report should be further reviewed and tested. If they are proved to be mostly correct, meaning that economic growth is not compatible with lowering carbon dioxide emissions from fossil fuel consumption, this should have significant consequences for policymaking, both in advanced and emerging economies. We think that this aspect deserves much closer inspection as it implies a fundamental difference in how feasible many low carbon efforts will be.

[121] Cepni, E., (2010). "Does convergence matter if it takes 100 years? Different scenarios of convergence". Futures. 41:882-894.

Appendix B – Electrical Grid Review

As electricity grids are themselves complex supply chains, establishing them in a stable fashion is typically beyond reach for emerging economies. The lack of a stable electrical grid precludes these nations from using a large number of more complex industrial applications and service industries, and limits manufacturing to more manual or simple mechanical tasks. It seems important to understand why this is the case, and why this creates an almost insurmountable hurdle for development in the way these countries typically aspire to – towards industrialization and globalization. This hurdle becomes even higher as soon as renewable technologies, mainly wind and solar power, are considered. In this appendix, we want to highlight the issues behind those problems.

B-1 How a grid works

In order to understand the requirements for grid stability, we introduce a few relevant aspects. Electric grids have a very low tolerance for discrepancies between supply and demand at any given time, as well as for other distortions in delivery[122]. Typically, grids are organized in regions, within which further sub-regions are used for management purposes. Europe, for example, is divided into 5 major synchronization areas, of which four are now managed by an integrated grid operating organization (ENTSO-E). Synchronization areas include the IPS/UPS (not part of ENTSO-E, covering Eastern Europe, Russia and other North-East Asian countries), Nordel (Finland, Sweden, Norway and East Denmark), UCTE (23 European countries and West Denmark), and ATSOI/UKTSOA (United Kingdom and Ireland). The North American grid is subdivided similarly, with 3 major interconnections and 8 regional reliability councils.

In order to secure a stable and faultless supply of electricity, stability in high voltage, frequency (50 Hz in Europe, 60 Hz in the North America) and synchronisation (between multiple parts of the network) are the key parameters continuously monitored and managed by grid operators. Typically, electricity frequency is synchronised across one entire grid area. As in most other regions, the major European grid region (ENTSO-E Continental Europe) defines frequency as the key indicator for over- or undersupply. Normal operations are assumed within a range of 49.2 and 50.8 Hz (1.6% tolerance) as defined in existing service guidelines[123]. This range corresponds to the immediate frequency drop or rise related to the sudden loss of approximately 3GW of generation[124] (causing a drop) or a similar increase in load (causing a rise). This so-called "reference incident" (for UCTE) represents about 0.5% of the total generation capacity (630 GWe), which is equivalent to 0.8% of the peak load (390 GW) observed in the UTCE synchronous area[125].

The primary grid control, which balances generation-demand-mismatches within the first seconds and minutes, is dimensioned on the basis of the worst-case assumption that 1% of deviation between supply and demand initially translates to an intole-

[122] Electric Power Research Institute (EPRI). 2009. EPRI Power Systems Dynamics Tutorial. EPRI, Palo Alto, CA. 1016042. http://my.epri.com/portal/server.pt?Abstract_id=000000000001016042 Accessed July 12, 2010.

[123] European Network of Transmission System Operators for Electricity (ENTSO-E). 2009. Operations Handbook Policy 1 – Load Frequency Control.

[124] For comparison – the largest power plants (mostly nuclear) have a capacity of slightly above 1GW

[125] Ibid.

rable deviation of 1 Hz in a 50 Hz grid. This frequency deviation is set as the critical threshold below which predefined grid areas are disconnected in order to stabilize the network, leading to local blackouts. To put this into context: At any given time, input into a grid has to match output with an accuracy of >99%.

In most industrialised societies, electricity demand follows relatively stable and predictable patterns, which differ according to season, day of week and time of day. Typically, demand is highest during workdays, particularly from late morning to the early evening, with a peak either around the middle of the day or between 4-6 p.m. The large majority of demand is driven by activities tied to a specific day and time of day, such as industrial uses, machine and computer operations, food preparation and the operation of some household appliances, lighting, and air conditioning. Some activities – typically a relatively small part of demand - are slightly less time-constrained, including the operations of some household appliances, and heating or cooling in systems with storage, and perhaps in the future, charging electric vehicles.

These changes in demand determine a grid's load factor – e.g. the ratio between lowest and highest load over a period. Typical grids that cover a mix of residential, commercial and industrial consumers usually see a load factor between 1.5 and 2.5, e.g. the highest daytime consumption is 1.5 to 2.5 times higher than the lowest use typically experienced during the night or on weekends. To meet those demand patterns, electricity supplies typically consist of multiple sources, of which each has a specific profile suitable for different needs.

Base load – defined as the long-term minimum demand expected in a region – is usually provided by technologies with relatively low cost, high reliability and limited ability to modulate output. This includes nuclear power plants[126], lignite coal plants and hydroelectric water mills in rivers. Those plants typically have to operate continuously at relatively stable loads, as otherwise their efficiency is reduced significantly, leading to higher cost per unit of output. Also, re-starting those power plants is relatively time-consuming and inefficient. In most countries, base load capacity is capable of covering approximately 100% of low demand.

Intermediate or cyclical load – the foreseeable portion of variety in loads over a day is provided by load-following sources that can modulate to higher or lower output levels – or almost entirely be turned off and on within a relatively short time. However, these sources usually require some lead time to grow or reduce, for example some coal power plants. Further, gas power is used for a significant portion of cyclical load.

Peak load – usually required within very short periods of time for a few hours a day – can be provided only from sources that can be turned on and off within minutes, this typically includes gas and small oil power plants as well as stored hydropower. Peak capacity can be provided by spinning reserve plants (e.g. running plants that can increase capacity quickly) or by non-spinning sources, which can be turned on within minutes.

Beyond technology limitations, one key factor in the eligibility of a technology for the use in peak, cyclical and base load mode is the cost share between investment and fuel cost. The higher the fuel cost share (e.g. natural gas or oil operated power plants), the more suitable a technology becomes to support peak power; the higher the investment share, the more operational hours are required to arrive at an acceptable average price per kWh (e.g. nuclear power).

[126] In France, with an unusually high share of nuclear power, the modulation of nuclear power plants takes place only by season, and not to any significant degree on an hour-to-hour or day-to-day basis. While it is technically possible to run newer generation reactors in load-following mode, there is little economic incentive to do so, and this trend appears likely to continue into the future (Pouret et al. 2009). Pouret, L., Buttery, N. and Nuttall, W.J., 2009. Is Nuclear Power Flexible? Nuclear Future 5(6), pp.333-341.

In general, energy supply technologies offer very different value to societies depending on how controllable they are. The importance of variability depends on the type of energy demand system. Storage-based energy sources such as oil, natural gas, or coal, (and to some extent hydropower), which are not subject to meaningful degradation, allow suppliers to maintain flows according to demand. They thus provide greater value and lower risk on the supply side. The ability of technologies to reduce production during times of oversupply is less relevant for grid operability, but the dissipation of unusable excess output comes at the cost of destroying otherwise usable electricity, thus influencing electricity cost per net available kWh.

Flow-based energy sources, such as run-of-river hydropower, solar power and wind energy, don't allow for supply-side control without additional investments and storage losses. To a certain extent, the same is true for energy conversion technologies that produce flows from stocks, but require long lead times to switch on or off once they are operational. For example, nuclear power plants and some coal based power plants incur significant efficiency reductions when changing their load. Flows occur mostly independent of demand or prices. Deferral of supply of flow based energy is possible only with storage technologies, which typically involve a significant conversion or entropy loss, and additional upfront investment.

On the other hand, in electricity production systems, most stock-based conversion technologies (e.g. nuclear, coal, oil and gas generators) produce steady flows. In these situations, inflexibility of supply can be managed. Flow-based inputs with low (and mostly only short-time horizon) predictability like solar and wind power deliver output stochastically as a function of weather conditions. Once the infrastructure for these technologies has been installed (e.g. a photovoltaic panel, a wind turbine or a solar thermal concentrator) it can produce anything from 0% to 100% of nameplate capacity, completely independent of demand. This does not necessarily translate to complete (short term) unpredictability, as weather forecasts are able to provide some limited planning input; however, the overall delivery pattern is fully stochastic.

Similar patterns exist when energy is used. Gas, coal or oil based fuels can be stored at a high energy density for significant periods of non-use with only limited (for natural gas) or no losses (for oil and coal), and then used as needed. Electricity however, once produced, does not have that feature – it is expensive to store and storage always incurs losses. Electric power not used or stored at the time of its production is no longer usable even a few seconds later.

B-2 Stable output technologies

Run-of-river hydropower delivers steady outputs that are not typically easy to alter. This is largely also the case for nuclear and most coal power plants that convert stocks into flows and cannot be modulated easily. Their outputs vary little and are predictable for extended periods of time when considered in aggregate (i.e. while one power plant might fail, the aggregate supply of multiple plants using one technology typically delivers stable returns to a grid system). However, these technologies cannot transition their output either up or down in a timeframe short enough to meet daily demand fluctuations. These output changes are typically associated with energetic (and thus financial) losses. In situations where they supply electricity grids (as opposed to individual industrial facilities), these technologies are not flexible enough to follow all the peaks and lows demanded by society and therefore are of lower overall value. If they are only used against the portion of demand that is stable, their contribution becomes 100% valuable and highly predictable in aggregate.

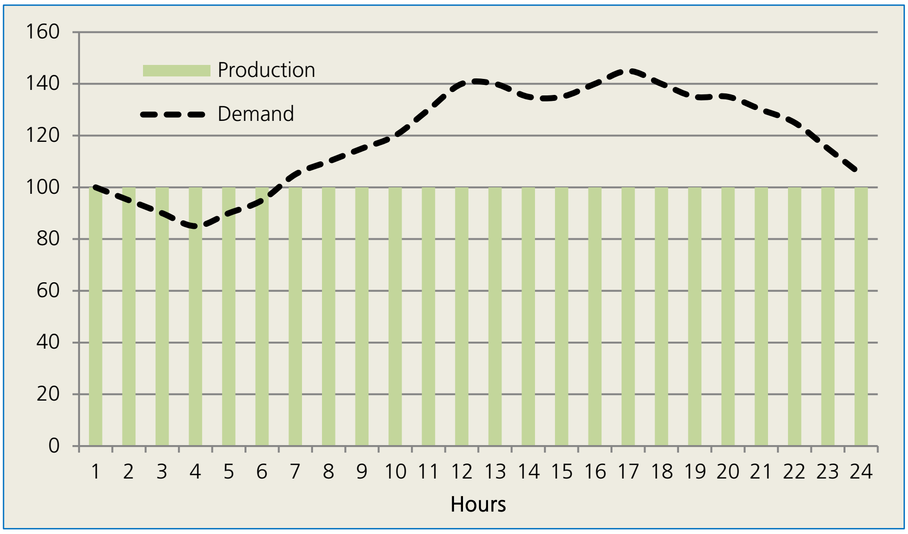

Figure B-1 - Hypothetical electricity demand cure plotted against a steady source of electricity

We use a hypothetical example depicted in Figure B1, consistent with most demand curves for electricity for advanced economies of a day of operations of steady output sources in a network with a large proportion of stable outputs, for example France with a high share of nuclear power:

B-3 Flexible technologies

Most stock-based technologies, like gas- or oil-fired power plants, or stored hydropower, can be modulated in a way that directly follows demand patterns as they emerge. As such, they bear no demand shortfall risk. However, in some cases, as these fuel types are the most valuable, they produce at relatively high costs (particularly for oil-based generation, but similarly for natural gas).

The example in Figure B-2 illustrates an electricity grid composed of a stable base of steady output technologies (such as nuclear, coal or any combination thereof), supplemented with flexible generation capacity (such as stored hydropower or natural gas).

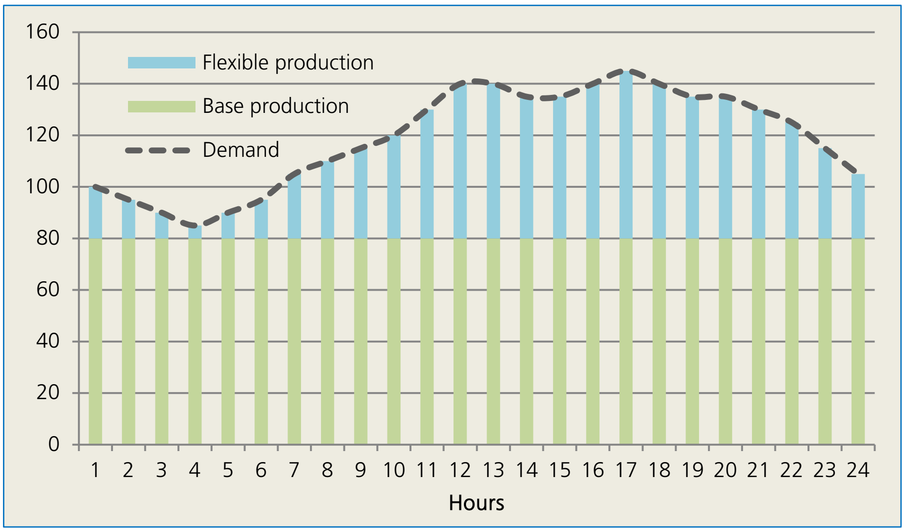

Figure B-2 - Electricity demand curve plotted against base load power generation coupled with flexible generation capacity

Together, these technologies are able to perfectly match human demand.

B-4 Stochastic technologies

Stochastic flow-based power generation techniques often show no or very limited correlation with demand, and deliver their energy outputs based on mostly independent variables like sunshine or wind. These may partly coincide with demand, as with solar power, which is produced during day-time high demand phases, however users have no control over this phenomenon and (depending on weather) output may appear or disappear almost completely across large areas within short periods of time.

The example highlighted in Figure B-3, shows a week of average wind power production and aggregate demand for Denmark from the summer of 2009. In this region, one of the best environments globally for wind power generation, wind supplies approximately 25% of total annual electricity demand. On an hourly basis, however, this coverage varies from 0% to 120% of total demand, across all hours of a typical year[127].

It is apparent from the above examples that two energy sources that have the exact same net energy output provide different values to society, once their different delivery patterns are considered. Sources that are fully manageable or contribute steadily to on-going demand are preferable to those supplying their outputs mostly uncorrelated to demand, when all other parameters are equal.

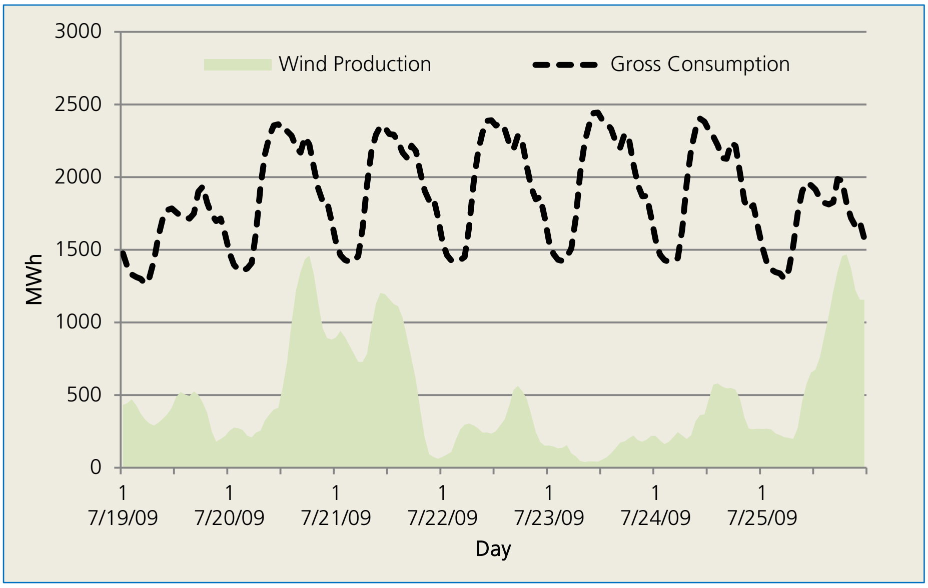

Figure B-3 - Aggregate electricity demand in Denmark (West) vs. total hourly wind production

As noted above, the current electrical grid in developed nations is powered mainly by stock-based forms of energy, but there are plans to increase the amount of solar and wind energy generating capacity in many of these nations (see Figure B-4). This is likely to pose greater challenges than foreseen by current plans, as a number of our own model calculations show. Electrical generation in developing nations varies greatly. Some nations (especially in West Africa, e.g.) rely on hydropower systems fed by intermittent periods of rain. During the dry seasons, these plants must reduce output, and grid stability cannot be maintained. Other countries rely mainly on diesel-powered electrical generation, either on a small scale (in rural areas) or on a large scale (Cambodia, Somalia, Liberia, e.g.). While these are stock-based systems, they operate on the available flow of fuel to that nation – which may be interrupted due to supply chain break downs, or at times of high prices electricity generation may no longer be economically feasible.

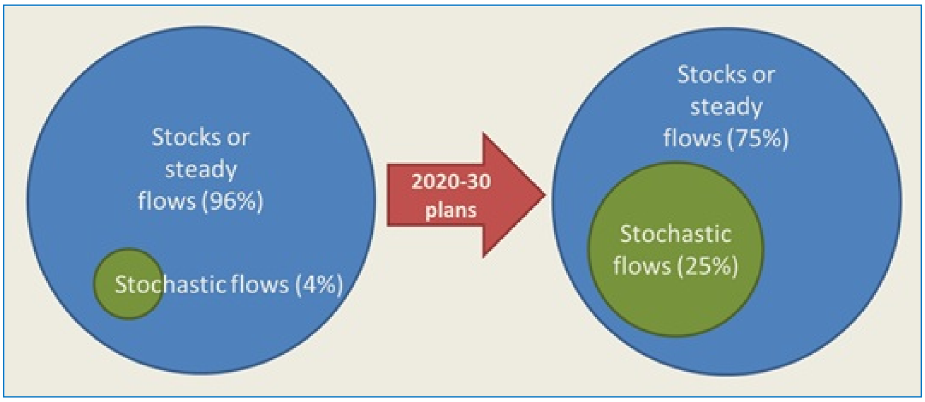

Figure B-4: Current and projected future proportions of stock or steady flow electricity generation vs. stochastic generation (solar and wind power).

Some of the more developed nations in our research project, Pakistan,

[127] Danish Electricity Market Data [Internet]. Fredericia, Denmark: Energinet; c2010 – accessed November 24, 2010. Available from http://www.energinet.dk/EN/El/The-wholesale-market/Download-of-market-data/Sider/default.aspx

India, and Indonesia have underdeveloped electrical grids that lack the capacity and/or flexibility to deal with a highly variable and increasing electrical demand. The results are frequent blackouts, brownouts, and unstable frequency and/or voltage.

Renewable sources of electricity generation produce highly variable output, not just on an hour to hour basis, but have seasonal fluctuations as well. Adding variable production to unstable electrical grids, without sufficient and flexible back-up generation capabilities[128] could quickly overwhelm the system and lead to mismatched supply and demand (i.e. blackouts).

At a smaller, more local scale, distributed solar or wind generation installation is more viable than tying into the electrical grid. However, these systems require expensive and frequently replaced battery systems to provide power at night, or during lulls in the wind, which is why they are only feasible at a small scale for applications with the highest value.

[128] Usually natural gas plants or hydropower

Appendix C – Low Carbon Technology Examples

Below, we provide an initial – and very patchy – list of potential technologies where we assume that they are able to provide substantial benefits for emerging economies, without adding to their carbon output. They follow the key 10 criteria defined our main report (please see 3.6) and cover a number of categories.

C-3 Agricultural Environments

It is our understanding that the largest potential for low-carbon technologies remain with the agricultural sector in most developing economies, as this is an area where improved technologies can actually improve well-being, health, and even GDP without significantly raising carbon emission, or even with reduced carbon-dioxide outputs.

The key issues affecting poorer societies can be improved addressing the following issues:

- Availability of water for crop growth (steady, non-depletive irrigation)
- Reliable availability of safe potable water
- Food production in a non-soil-depleting way
- Improvement of cycling of nutrients and resources without the build-up of toxins
- Sanitation and other disease prevention mechanisms
- Availability of clean cooking fuels
- Availability of transportation and tractor biofuels that does not compete with food production

A number of key technologies seem to be qualified to support those objectives

- Small-scale water-retention systems
- Low-tech drinking water supply
- Low-fertilizer approaches
- Cycling of human and animal waste for energy and nutrients
- Cooking biogas production from animal and human remains
- Non-competing marginal plants for simple fuel oil production
- Small-scale solar power for patchy high-value electricity use

C-4 Small towns and labour-intensive manufacturing

The second largest potential for development of countries without increasing fossil fuel inputs lies with small scale labour intensive production of construction materials, basic goods, renewable fuels, and improved waste management and cycling. Specialization of labour with some (renewable) energy inputs in a village and small towns could create higher efficiency and hence larger incomes and better living standards in a low-carbon way, while at the same time reducing the need for imports. The key issues that might be resolved are the following:

- Availability of decentralized small scale renewable electricity
- Sustainable production of constant renewable fuel supplies for transport and manufacturing
- Improvement of transport infrastructure
- Increase in resilience of towns from weather events
- Better living conditions
- Cycling of nutrients and resources

A number of key technologies seem to be qualified to support those objectives

- Production of biogas from human and agricultural residues, including manure and crop residues, which replace the need for firewood
- Decentralized power generation approaches (risk: foreign technology imports required) to replace diesel/gasoline driven generators
- Manufacturing of more efficient heating stoves
- Labour productive means to produce bricks and tiles for housing and infrastructure

- Manufacturing of tools that increase labour productivity
- Improved sanitation systems with cycling

C-5 Industrial activities based on fossil fuel inputs

As discussed extensively, in industrial activities fossil fuels are a pre-requisite given their cheap cost and stable input as a fuel stock. The potential to decarbonise here is limited as in most areas other fuels are too expensive, not available in a stable manner, or both. Also efficiency improvements are often only incremental, and hence mostly not affordable for an emerging country at the bottom end to introduce. Nevertheless where renewable energy and efficiency improvements are available some steps towards decarbonisation can be made. The key issues that might be resolved are the following:

- Retrofit of human and animal labour
- Supplements from renewable technologies acting as "range extenders" for fossil fuels
- Improved cycling of waste

C-6 Technology examples

Below, we introduce a number of potentially suitable technologies. They have not been fully reviewed, but should provide some indications as to what approaches might still be possible at low or no carbon level.

A. Treadle pump irrigation

Irrigation can turn otherwise non-arable land into arable land. An example is Pakistan where the irrigation network and groundwater have been utilized to turn a highly arid country into one where agriculture forms the backbone of the economy. Malawi shows considerable irrigation potential, but currently suffers from drought, food shortages, and subsequently poverty and food insecurity. Treadle pumps have been identified as good low-cost sources of irrigation water. They have been shown to increase farmer incomes and employment, leading to various material gains. The issue of investment and spare parts, however, remains.

B. Low-cost drip irrigation systems:

These systems can extend growing seasons and improve efficiency of water use. However, they are reliant on some plastic or rubber tubing. (systems can be made from recycled or repurposed materials like sterilized IV drips).

C. Boiling water treatment of seeds

Banana and plantain form an important part of human diets in the world's humid tropics. Global production stands at approximately 140 tonnes. However, as with any crop, pest management is important. Banana and plantain fall prey to weevils and several species of nematodes. If sucker planting material is infected, the pests propagate quickly, resulting in significant losses. Simply boiling peeled and paired suckers for 20-30 seconds effectively removes the threat of these pests. The practice is simple, but must be done carefully and precisely; timing is very important. This method of pest control does not require any specific technology. The expense incurred for the use of heating (wood, fossil fuel) is minimal as the planting material need only be boiled once prior to cultivation. Boiling is only required again for fresh planting material.

E. Home composting

Compost serves multiple purposes, including waste management and cultivation. There are numerous methods to produce compost, but the basic scientific principles are much the same. Open pit composting does not require external energy sources or electricity. However, a degree of manual labour can be expected for pit digging and turning the compost. However, the use of purchasing or manufacturing composting bins carries some cost. The open pit method is widely practiced in rural areas, while urban composters prefer using bins.

F. Integrated soil fertility

Providing crops with balanced nutrition is essential to achieve high yields. The problem with modern fertilizer is the notion that "more-is-better." Integrated soil fertility is highly labour-intensive, but requires no fossil fuel or electrical input. The process relies on known methods of yield maximization, including the use of organic fertilizer and precise timing of fertilizer and water application. It must be noted, however, that using organic material means lower nutrient content, and thus, large quantities for each application. This implies fossil fuel use for transportation. Due to labour intensity or the need for fossil fuel inputs, the process is not economical unless the crop produced is of high value.

G. Sheet metal corn shellers:

The harvest of corn is by many farmers conducted through shelling the cobs by hand, which is a very labour intensive process that costs several hundred labour hours a year for a large harvest. The simplest technology to increase efficiency is a corn sheller made from a sheet of metal that can be produced from a hammer, pliers and a cutting tool. In small villages these can be manufactured for local farmers, to generate income for the local manufacturers, and optimize labour productivity at the farming level.

H. Humanure composting

Human excrements can be turned from a health hazard and environmental pollution into a source of nutrients for soils in agriculture by composting them. The process of "humanure" composting is from the outset similar to other composting methods, except that special care needs to be taken to ensure sufficient heat generation for a number of days to kill any pathogens, in order to improve local waste management and limit the further spread of diseases and worms.

I. Limited applications for biofuels

In some fertile areas, biofuel crops, especially oil seed crops such as Jatropha and Pongamia, can have positive returns on energy investment for the creation of biodiesel fuels or use as a fuel in so-called Straight Vegetable Oil (SVO) modified diesel engines – particularly if produced with low-tech extraction approaches. These SVO engines require some modification and a small amount of petro-diesel to operate. In small scales these fuels are relatively expensive (i.e. labour-intensive) to produce, and non-competitive with petro diesel, but may be more competitive in developing nations given the high costs associated with imported diesel. Biofuels also have non-transportation uses such as lighting or cooking as a kerosene replacement. There are a number of criteria of which the most important is that it remains non-competing with food production.

J. Charcoal from field wastes

The largest share of crop residues from agriculture are burnt for heating and cooking purposes in developing countries. The practice is both environmentally problematic as it adds to depletion of soils, and a health hazard due to the smoke that is released in its combustion. There are a number of methods to increase combustion efficiency of the residue, so that both less is required and less smoke is released. One of the simplest designs is to prepare small charcoal briquettes from the residue using a metal barrel in which the residue material is carbonized, subsequently binding the material using local materials such as cassava pulp, and pressing it into a briquette that is drying for a number of days. The process is very simple but requires a number of skills, due to which it is best approached through specialized labour.

K. Biogas/bio-digesters

The local production of biogas for heating and cooking purposes from agricultural waste can be profitable for small scale farmers with a number of hectares. The applicability of a biogas producing digester is diverse as feed-in can come from crop residues, animal manure, or other organic waste. Simple designs are based on holes in the ground that contain the organic slurry, on top of which a wooden frame with weights is placed to generate sufficient pressure to hold the gas. More intricate sturdy designs are available on the market at a minimum cost of 350 dollars which often needs technology from abroad. The cost of these is usually too high to be born without financial support schemes, despite them saving time in terms of fuel-wood gathering. To prevent competition with food the local context needs to be taken into account.

L. Simple high-efficiency clay stoves

The burning of wood in open fires is inefficient as little heat is retained, and many hours are spent gathering the wood. In places where proper clay soil is available, stoves can be built by hand using a pan as a mould, to reduce the amount of combusted material required.

M. Rice husk and other residues use in stoves and electricity production

Husk Power Stations is an off-grid electricity company based in the poorest state of India, Bihar. It transforms rice husks into electricity in an eco-friendly way, all the while keeping the costs low enough for the poor people to afford. This system could burn 50 kilograms of rice husk per hour and produce 32 kilowatts of power. The costs were lower than what the families had been spending on kerosene lamps. In order to further decrease costs so that energy could be supplied to all, the company removed everything unimportant that increased manufacturing or maintenance costs.

N. Improved latrine designs

In village and slum areas, where materials are available to construct improved latrines these are the best approach to deal with human excrements in a hygienic manner. Their design can be standardized to scale up implementation, such as in the case of a two-pit latrine design implemented in countries such as India and Nepal. It is based on two pits with a concrete platform on top that is practical to clean, and a ventilation pipe. One pit is closed when it is full for composting that can be emptied safely after one year, while the other pit is in use. A combination with biogas production is equally feasible.

O. Runoff rainwater harvesting

This method is particularly useful for drought-affected regions, but does require some investment for the construction of brick and cement tanks. The process simply requires observing the gradient of land and the direction of rainwater runoff flow. Rainwater that would otherwise be wasted (or at least require fossil or electrical energy to pump out of the ground) is redirected and stored for later use.

P. Brick and tile production

The production of housing in developing countries is often done using wood, inefficient brick producing kilns, or sun dried bricks of poor quality. The best low tech approach is to use hand press technology to create stabilised bricks or tiles. Local high quality subsoil is excavated and mixed with available materials for durability, pressed together using a manual hand press, and dried by the sun. The key factor is soil quality preferably with clay content and little to no gravel, in combination with the availability of stabilisers such as cement or lime. The more industrialised approach is to improve the efficiency of used kilns for large quantity brick production from a level of 3+ MJ per kg of fired brick to 1.4 MJ per kg or lower using vertical shaft Kilns. The efficiency of the process in terms of energy consumption can be increased by adding cow dung to the mixture as it operates as an internal fuel. This also reduces breakage and increases plasticity.[129]

Q. Mining and Extraction

The largest cost of mineral extraction is for transport and milling to remove unwanted rocks as a first step in mineral separation. In overtly manual operations the quantity which can be obtained per unit of time is low as milling speed is limited by human or animal labour. Small scale hydropower provides more stable energy input, and constant electricity supply is the best option for high speed throughput. The choice of mill is of high importance in reducing energy costs, but this is often limited due to the characteristics of extracted rocks for which special mill requirements are needed. These differ for each deposit due to differences in mineral and rock composition.

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[129] Theo Schilderman (2002). "Sustainable Small Scale Brick Production: A Question of Energy" United Kingdom: Practical Action

R. Pneumatic/hydraulic processes

The basis of industrialization lies in mechanizing processes to increase the speed at which they can be conducted. The prerequisite for this is the availability of electricity. However, when using direct water or wind power from mills, this hurdle can be overcome and significant quantities of easily available energy services can be redirected for semi-industrial uses.

Table C-1 - Overview of low-carbon technologies and their potential ability to meet low-tech development criteria

Potential Technology / Indicator	1. Low fossil fuel inputs needed	2. Driven by solar and abundant natural flows	3. No competition with important societal requirements	4. Improved labour efficiency or income increase	5. Low external support required	6. Locally sourced inputs	7. Does not require stable electricity grid	8. Flexibility in implementation	9. Low upfront investment and short monetary payback period	10. Low ratio of replacement between human and mechanical labour
Treadle pump irrigation	++	++	++	+	+	o	++	o	o	tbd
Low cost drip irrigation systems	+	+	++	++	+	o	++	+	o	tbd
Boiling water treatment of banana and plantain	+	+	-	++	++	++	+	+	+	tbd
Home composting knowledge	++	++	+	+	++	++	++	+	+	tbd
Integrated soil fertility	++	++	++	++	++	++	++	--	++	tbd
Donkey plough	++	-	+	++	++	o	o	-	-	tbd
Small scale biofuels from waste	-	o	o	++	-	--	+	o	-	tbd
Biomass digesters	+	+	o	+	o	++	+	o	-	tbd
No tillage planting methods	+	+	o	o	++	++	++	--	+	tbd
Sheet metal corn sheller	+	++	++	++	+	o	++	+	++	tbd
Charcoal production via field waste/vegetable binder	+	+	--	o	++	+	++	+	+	tbd
Clay stoves designs	o	++	+	+	++	++	++	o	++	tbd
Rice husk and residue stoves	+	++	+	+	+	o	++	-	o	tbd
Humanure composting	++	++	o	+	++	++	++	++	+	tbd
Two pit latrines	+	++	++	o	+	+	++	+	+	tbd
Runoff rainwater harvesting		++	++	+	++	++	++	++	++	tbd
Low tech micro-hydro	o	++	+	+	-	+	+	-	-	tbd
Brick and tile presses	-	o	++	+	o	o	++	o	-	tbd
Efficient brick kiln	o	-	o	+	+	o	+	o	o	tbd
Pneumatic/hydraulic processes	+	++	++	++	+	++	++	-	-	tbd
Legend: -- (very poor) - (poor) o (moderate) + (good) ++ (excellent)										

About IIER

The Institute for Integrated Economic Research is a non-profit organisation based in Switzerland and the U.S. We focus on independent, unbiased analysis of macroeconomic systems.

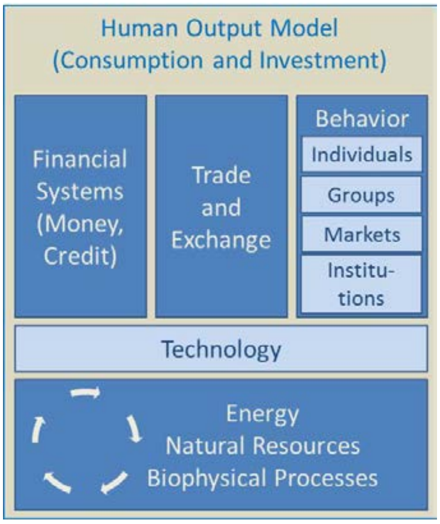
1. Background of IIER

IIER was established in 2007 based on the recognition that traditional macroeconomic modelling and planning does not sufficiently depict the reality of human economic systems, and that conventional approaches used to predict and plan the future are falling dangerously short of describing real conditions.

This view was confirmed during the economic crisis of 2008/9, which convinced us to formally establish IIER as a research institution focused on understanding the future from an economic systems perspective, and on providing knowledge to scientific and policy-making institutions on an open-source basis. The key objective is to enable better decision-making for a future which – in our view – will be challenging. Below, we introduce a few key topics of research.

2. Macroeconomic Modelling

At the core of our work is what we call the "IIER Human Output Model", which describes the key components of global economic output. It is much more inclusive than all other macroeconomic models we are aware of, and as such has stronger explanatory and predictive power. It uses resource and energy availability as the foundation for all economic transactions and sees technology as a means of making those resources available to humans, with finance, trade and human behaviour acting as key enablers and/or inhibitors.



3. Energy Delivery Systems

Another important component of our research is the analysis of energy delivery systems, trying to understand as to how future energy availability can be secured when fossil fuel use is reduced or burdened with carbon or other environmental taxes. This includes a detailed study of individual technologies, their cost, scalability potential, etc., but also the modelling of complex systems (like power grids), with the aim of understanding the influences technology shifts will have.

4. Credit Market Research

Further research efforts are devoted towards understanding the global financial system, which we believe is poorly described both with respect to internal dynamics and how that system actually interacts with the "real world". From our research we believe that financial systems currently pose the highest risk to societies, bearing a potential for disruptive events of even greater severity than the financial crisis in 2008.

5. Trade and Exchange

Understanding the role of trade and the ability of "globalisation" to shift resources to the place of their best possible use is also poorly understood and integrated in current economic views, both concerning the benefits of trade but also the potential risks resulting from highly interdependent global supply chains.

6. Behavioural Science

The study of human behaviour and the "imperfection" of our decision-making play an important role in our research. Here we try to understand the implications of changes in actions and perceptions of humans and their consequences for economies. Counter to most systemic models in economics, perception changes have always been the strongest drivers of "tidal shifts" in world history, as they are able to either enforce or mitigate underlying fundamental realities.

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