ENERGY EFFICIENCY OR LOW-CARBON ENERGY?[1]

An economic assessment of two alternative options for preventing ‘dangerous’ climate change in the light of diminishing returns and economies of scale.

There is much concern about the future effects of anthropogenic climate change. in order to prevent ‘dangerous’ climate change, industrialized countries must reduce their total emissions of CO_2 by at least 60%, and perhaps by as much as 90%, within a few decades. Energy efficiency is often suggested as a solution. I will examine one drawback to this approach, the so called ‘rebound effect’, where increased efficiency leads to an increase in associated economic activity. I shall then investigate environmental impact directly, and develop some simplifying assumptions. Although only 35% of present energy use takes the form of electricity, it is technologically and economically feasible for 60-90% of all energy requirements to use electricity. In our economic model, we therefore assume for simplicity that electricity caters for all energy requirements, and generates all impact (CO_2 emissions).

We consider three alternative strategies for a transformation to low emissions: (1) limiting or reducing national income, (2) increasing energy efficiency, or (3) an investment in low-carbon energy (for arguments sake, nuclear and solar power; which by assumption have no resource constraint when considered together). It is found that options (1) or (2) suffer from diminishing returns: it requires ever more harsh reductions in income, and ever higher capital expenditure on energy efficiency, the greater the required reduction in emissions. For option (3), however, the opposite is true. Investment in non-carbon-generating technology allows economies of scale. For simplicity we model the cost of nuclear to be rapidly declining and then constant past a certain point. This suggests that some government investment is necessary to reduce uncertainty and to realise social gains, but then a well-designed market may be able to take over to realise the lowest cost. Electricity is a convenient form of energy and storage technologies are developing rapidly. In summary, a conceivable electricity requirement of 60-90% of forecast total energy use could be met entirely with nuclear, at little or negative cost relative to the best alternative option for meeting energy needs. Such a plan would reduce CO_2 emissions to a sustainable level, and enhance the country’s long-term strategic and economic position.

Energy efficiency is likely to provide the cheapest options for marginal reductions in greenhouse gas emissions, and therefore are important in *'lower carbon'* scenarios but those options become increasingly expensive, due to 'diminishing returns', an effect associated with the exhaustion of easy options. Alternative, low-carbon energy sources, such as nuclear power, however, become cheaper at larger scale, so long as the technology is not constrained by other factors, and therefore may provide the most promising route to *complete decarbonization* of the energy system.

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Does increased energy efficiency imply reduced use? The rebound effect

One might think that increasing energy efficiency by, say 10%, would lead to a 10% decline in energy use. But this opinion would be false. Efficiency improvements may lead to increases in use that could be so large as to swamp the original gain. This is known as *Jevons Paradox*, from the 19th Century economist, William Stanley Jevons (Jevons 1879). He suggested that improvements in steam engines might lead to greater, rather than less, overall coal use.

There is both a micro and macroeconomic issue of the net effects of efficiency improvements on resource use. is there a '*rebound*' effect (efficiency improvements lead to greater output, and less than proportionate decreases in total fuel use) or even '*backfire*' (efficiency improvements lead to much greater output and therefore *greater* fuel use)? Given the interest in the aggregate effects, i thought the macro perspective was more interesting (and perhaps more difficult).
Technological efficiency in the use of energy is important for a number of reasons, e.g. CO2 emissions. it is important to distinguish between improvements in efficiency that are currently projected (according to ongoing trends i.e. technological change and the continuation of past patterns of government intervention) and *additional* improvements. One framework for clarifying the two is seen in Socolow and Pascala's work on emissions wedges . Socolow and Pascala approximately project 'business as usual' future CO_2 emissions by the continuation of a straight-line increasing trend. Such a trend already includes substantial reductions in the emissions intensity of GDP. These improvements have happened in the past and are likely continue in the future. We need *further* improvements on top of these projections. For example, we may be able to induce benevolent technological change by energy taxation or other methods.

So in addressing the backfire/rebound debate, we need to consider contexts where energy efficiency is discussed:

1. Efficiency in the presence of increased energy taxation, is a mechanism such that abatement costs are much less than would seem at first sight. Rises in energy costs (through increased taxation) lead to reductions in energy use. Energy efficiency is a mechanism for accomplishing this.
2. Efficiency, in the absence of energy taxation, instead is an ‘avoidance’ strategy. The argument might go something like: "Efficiency improvements are the most cost-effective method of cutting emissions. So long as each sector 'does its bit' to improve efficiency, the government need not act. And each sector is doing its bit! Look at these technological efficiency improvements!!!"
3. Mandated efficiency standards are somewhere between these two extremes. if they are relatively cheap to enforce, then they are helpful, so long as the improvements wouldn't have happened anyway. if the improvements are hard to enforce, energy taxation may be a less expensive and more economically efficient method of achieving the same result.

There is a massive economic difference between 1) and 2). in 1), the argument is that we need to reduce emissions so therefore we put up the price of those emissions. in 2) it is argued “we don't put up the price of emissions, since technology will save us.” Argument 2) says we don't need to worry. But this argument is false. Technology is *already factored in* (at current trends anyway). We do need to worry! Especially because of rebound and backfire...

Argument 1) says we should worry, but if we try hard to reduce emissions it won't turn out to be too difficult. Abatement isn't as expensive as we thought it would be. Great! Let's do it!
So if we are evaluating policy we need to be clear which argument we are considering. is it, say, a question about the effect of price increases on energy consumption (microeconomics)? Or is it a question about growth theory (macroeconomics) viz.: what effect does factor productivity have on total consumption of that factor? We could generalise the question regarding improvements in energy efficiency to the general issue as to whether increases in a factor's productivity, lead to overall increases (Backfire hypothesis) or decreases (no Backfire) in that factor's use. There is now a consensus that increases in labour productivity do not reduce employment.

The answer to the question depends on 'which factor?' and 'how granular?'. First consider the factor productivity of a relatively narrow factor (such as, say, burning oil in combustion engines, where the alternative is burning coal in steam engines). In this case, I would say that there is 'backfire'. More efficient oil combustion will sometime pass some threshold where they start to replace steam engines (in say trains). Efficiency improvements in the use of oil lead to greater oil burning. *Backfire*!

Why limiting use is difficult: the open economy rebound effect

There is an (open economy) ‘rebound’ effect if one part of the world (say the OECD) reduces is consumption, whilst the rest is unconstrained. The following diagram illustrates the problem. OECD countries reduce their resource consumption, by a shift in their demand curve. This leads to a reduction in total demand and therefore a reduction in the world price for these resources. However, this reduction in price induces other countries to increase their consumption, partly counteracting the original reduction (a sufficiency ‘rebound’ effect).
The magnitude of the rebound will depend on the elasticities of supply and demand. The rebound effect will be more, with lower elasticity of supply or higher elasticity of demand. For completely inelastic supply, the change in demand will lead entirely to lower prices rather than reduced consumption.

Direct Calculation of Environmental impact

We are interested in total environmental impact, I, where I = P * A * T and
P is population
A is affluence
T is the impact per unit of affluence
Assume for simplification:

- Y = A.P
- Affluence defined as real GDP per person at current prices (Measures a weighted sum of *physical* output but measured in $ terms at current prices)
- Population is fixed and can be ignored
- One unit of impact = One tonne of CO_2 emission
- There is one form of usable energy, electricity, which is a commodity and can be transported without cost or attenuation.
- All emissions are caused by electricity generation.
- Economy is assumed to be closed
- Our impact equation becomes: I = Y*T

it may be useful to consider energy efficiency in different sectors of the economy. We assume that the output of the economy consists of a number of goods (and services), which each require some electricity in their production.
So,

$$I = (S_i O_i / g_i) * b$$

or

$$T = (S_i o_i / g_i) * b$$

Where:

- I Total Emissions
- T Emissions per unit income
- Y Total real output (= income) measured at current prices
- O_i (Physical) Output of good i, $S_i O_i = Y$
- o_i (Physical) Output of good i as a proportion of total output, $o_i = O_i / Y$
- E_i Electricity required to produce good i.
- g_i Efficiency of production of good i (Electricity required per unit of output)
- E Total electricity consumption: $E = S_i O_i . g_i$
- b Emissions intensity of Electricity Production, b = i / E
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However, since we have assumed all energy is used through electricity, we can separate our efficiency strategy from the question of the emissions intensity of electricity.

$$I = E * b$$

To reduce emissions (I), we need to either reduce electricity consumption (E) or the emissions intensity of electricity generation (b). This paper deals with the level of electricity consumption.

$$E = (S_i O_i / g_i)$$

The total emissions are the sum of the outputs of the goods divided by the energy output of those goods. Or, in financial units, total output equals the sum of the value of output of different sectors multiplied by the electricity used per unit of output:

$$E = (S_i V_i * r_i)$$

Where

- P_i Price of good i
- V_i Value of Output of good i, $V_i = P_i * O_i$
- r_i Energy used per unit value $r_i = P_i / g_i$
- o_i (Physical) Output of good i as a proportion of total output, $o_i = O_i / Y$

In order to reduce emissions, there are two possible strategies likely to be effective. We could reduce the importance of those sectors which require a lot of energy. Or we reduce energy needed for those goods which are large portion of the economy.

The problem with rebound/backfire is that autonomous (b) efficiency improvements where it is needed most (in the larger sectors) may lead to growth of energy use in these same areas!!! Aircraft fuel efficiency improvements lead to more flying!!! if efficiency increases in a sector by 10%, but that sector grows by 10%, then the net effect wll be zero. if the sector grows more, then we have a 'backfire' effect. In conclusion, when dealing with a sector (home heating, aviation and personal transportation) the most effective strategy would be to always target efficiency and level of use at the same time. Efficiency could be improved and use capped, for example. This 'double therapy' (even if each of the targets would be modest on their own) may be much more effective than targeting efficiency or use alone. Price increases are effective since they both discourage use and encourage efficiency. Taxation revenues can be recycled so net transfers are zero and internationally competitive sectors are protected. Finally, since most energy use occurs via the 'nexus' of electricity, reducing the emissions intensity of electricity is likely to be very effective at cutting emissions.

In the next section we shall consider the problem from the perspective of neoclassical growth theory. in particular we shall compare energy efficiency and reduced growth with a third possibility, the expansion of nuclear power (or other alternative energy source.

Neoclassical growth theory and environmental impact

The analysis here extends that seen in Nordhaus (1992).
We consider a neo-classical aggregate production function:

$$Y = F (L, R, D, K ; H)$$

Where

- L: Labour
- R: Flow of Natural Resources
- D: Land
- K: Capital
- H; Level of Technology

In particular, we follow Nordhaus in assuming a generalised Cobb-Douglas Production Function:

$$Y = H\,L^{W}R^{L}D^{G}K^{D}$$

Imagine that R represents the flow of extraction of oil.
Energy efficiency measures usually require increased capital. if we increase capital, income rises, but there is no necessary affect on Resource use. if resource use is constrained, it will remain so. if it is not constrained, the diminishing returns on capital increases may put pressure on other factors of production. Perhaps not all capital is the same? Maybe we should also consider energy-saving schemes to be different to other capital: they are different if (as we argue) if there is market failure in this respect.
Consider two separate types of Capital, K_1 and K_2. K_1 and K_2 are thought to be totally separate and not substitutable.
K_2 can be thought of that good that augments the use of Energy directly. Energy resources cannot be used without this.
K_1 is any other capital. Our production function becomes

$$Y = H\,L^{W}(K_2^{e}R)^{L}D^{G}(K_1)^{D'}$$

Then we have

$$Y = H\,L^{W}R^{L}D^{G}K_1^{D'}K_2^{eL}$$

So we see that even under the assumption of some sort of difference between energy-saving capital and other capital, there is no difference in our result. Energy efficiency measures may increase total output; they do not decrease resource use, unless resources are constrained.
Another macroeconomic model as follows:
We assume Labour and Land to be constant. These terms are subsumed into a multiplicative constant, which also includes technological change. instead of R resources we consider only the use of energy resources. All resources must be converted into electricity E before they can be used. We assume for simplicity that electricity generation is the choice between gas (generating CO2 and therefore environmental impact) and nuclear energy (not generating CO2 and therefore without impact). impact is assumed to be proportional to the electricity produced by non-nuclear means (gas).

Our production function is:

$$Y = A\,K^{D}\,E^{s}$$

We assume impact is proportional to non-nuclear energy production.

Conservatively, we assume constant returns to scale for alternative energy (in fact there are likely to be positive returns to scale. However, a large part of these economies of scale and reductions in uncertainty are taken after the first few reactors are built of each type. A simple assumption, therefore, would be that investment has been sufficient to overcome the substantial first-of-series costs and uncertainties and has progressed past a certain point (x=~4GW?), where initial economies of scale have been taken: our analysis relies on a commitment to at least x of a reactor (or for each design of reactors if more than one reactor is chosen).

Hence: Impact = $b(E - aK_n)$
Where K_n is the capital invested in alternative energy generation (K_n>x)

$$E = Y^{1/s} / (A.K^{D/s})$$

impact = $(b/A).Y^{1/s}.K^{-D/s} - a.b.K_n$

Assessment of strategies

We have calculated the total impact as follows:
Impact = $(b/A).Y^{1/s}.K^{-D/s} - a.b.K_n$
We now consider three strategies: reducing output, increasing investment in energy efficiency and similar capital goods, or increasing non-polluting capacity such as nuclear generation:

1. Reduce output at fixed capital: $-d(\text{impact})/dY \,\rvert_{K,\, K_n} = -(1/s)(b/A).Y^{1/s-1}.K^{-D/s}$
2. Increase capital at fixed income: $d(\text{impact})/dK \,\rvert_{Y,\, K_n} = -(D/s)(b/A).Y^{1/s}.K^{-D/s-1}$
3. Increase non-polluting capacity: $d(\text{impact})/dK_n \,\rvert_{Y,\, K} = -a.b$

We have diminishing returns to reducing output (1), since it is guaranteed that $s<1$. Similarly, there are diminishing returns for increasing capital in energy efficiency (strategy 2), since (D and s being positive) $-D/s<1$. Note that in our model, investment in nuclear energy has constant returns to scale. The greater the required reduction in emissions, the more option (3) is to be preferred.

Conclusions

- Reducing output will involve large (human) welfare losses (note, however, that these economic values are not the only values of importance, we should also consider the impact on the environment, independently of human preferences).
- Induced efficiency may well be the most efficient way of decreasing emissions by a small amount in the next few years. But emissions reductions are subject to diminishing returns. Whilst initial increases in energy efficiency are likely to be achievable at low or even negative cost (turning off a light bulb here and there), one has to ask why these improvements have not been made already. Some inefficiency is usual in all theatres of economic life.
- Investment in non-emitting energy production may (or may not: see RAE 2004) be expensive at reducing emissions by a marginal unit. However, investment in technology has constant or increasing returns to scale. it can and should allow a totally carbon-free economy, so long as there are no other binding constraints. Experience with oil suggests that fundamental Uranium resource constraints are not likely to bite, at least not before new technologies (solar/fusion) arrive.