

Viewpoint

Is there an optimum level for renewable energy?

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ABSTRACT

Because continued heavy use of fossil fuel will lead to both global climate change and resource depletion of easily accessible fuels, many researchers advocate a rapid transition to renewable energy (RE) sources. In this paper we examine whether RE can provide anywhere near the levels of primary energy forecast by various official organisations in a business-as-usual world. We find that the energy costs of energy will rise in a non-linear manner as total annual primary RE output increases. In addition, increasing levels of RE will lead to increasing levels of ecosystem maintenance energy costs per unit of primary energy output. The result is that there is an *optimum* level of primary energy output, in the sense that the sustainable level of energy available to the economy is maximised at that level. We further argue that this optimum occurs at levels well below the energy consumption forecasts for a few decades hence.

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1. Introduction: the idea of a renewable energy optimum

In a 'business-as-usual' world, such as that assumed in the various scenarios for organisations like the US Energy Information Administration (EIA), the International Energy Agency (IEA), the Organisation of the Petroleum Exporting Countries (OPEC), the World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA), primary energy levels are forecast to be roughly in the range 600–850 EJ in 2030 (EJ=exajoule= 10^{18} J), and 800–1170 EJ in 2050. The IIASA even extends its scenarios out to 2100, with a primary energy range from about 1000–1740 EJ (Energy Information Administration (EIA), 2010; International Energy Agency (IEA), 2010; Organisation of the Petroleum Exporting Countries (OPEC), 2010; Riahi et al. 2007; World Energy Council (WEC), 2007). For comparison, the 2008 global primary energy consumption was 514 EJ, including about 66 EJ (12.9%) from renewable energy (RE) sources (IEA, 2010).

Continued heavy use of fossil fuel will lead to both global climate change and resource depletion of easily accessible fuels. Even nuclear energy is subject to resource depletion, and it also faces a variety of other problems, which limit political acceptance. None of the forecasts just discussed see it playing more than a minor role over the coming decades (Moriarty and Honnery, 2010a). Accordingly, many researchers advocate a rapid transition

to renewable energy (RE) sources. Their analyses imply that RE will have little difficulty in supplying the primary energy levels forecast for the end of this century, since their estimates for RE technical potential are as high as 7500 EJ or more (e.g. de Vries et al., 2007; Hoogwijk and Graus, 2008; Johansson et al., 2004; Resch et al., 2008).

There are precedents for the idea of an *optimum* scale for output. Daly et al. (2007) criticised conventional economists for not recognising that there is an 'optimal scale of the macroeconomy relative to the biosphere'. They asked whether the scale of the global economy is now so large that vital biosphere functions are being compromised. Those working in the 'Ecological Footprint' (EF) paradigm also imply the existence of an optimum scale for human biosphere intervention. Kitzes et al. (2008) argued that in 2002 humanity had an EF of more than 1.2 planet Earths, compared with the 1.0 that is available. In other words we are in overshoot, which will lead to 'the degradation and liquidation of ecological capital.' Kleidon (2006) produced model results which showed that attempts to indefinitely increase humanity's share of the planetary Net Primary Production are ultimately self-defeating in that, past a certain fraction, the absolute level of biomass available for human appropriation falls.

In all three studies, the idea is that there is an optimum level of activity beyond which the ecosystem services freely provided by the natural world are compromised; the optimum number of Earths that can be sustainably used is 1.0; the optimum level of groundwater use might be the level, which can be annually sustained by recharge. We argue in this paper that diversion of Earth's energy flows to satisfy humanity's energy needs is also subject to an upper limit—that there is an optimum level of RE use.

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Kleidon's paper is an attempt to demonstrate this point for biomass use (including all human uses of biomass, not just energy). We argue that it applies to RE generally. It is not enough to show that an optimum value exists for RE; it also has to be shown to have a high probability of occurring in the range of human interest, which, from our earlier discussion, might be anywhere from low levels to as high as 2000 EJ.

We use a global approach, partly for simplicity, but also because for some RE sources, analyses at the regional or national level will give misleading conclusions. For biomass this is because of international trade in agricultural and forestry products. For hydro, 261 river basins straddle international boundaries (Wolf et al., 1999), so that a national optimum could again be misleading.

In summary, we argue that there is an optimum level of primary RE output, in the sense that the sustainable level of energy available to the economy is maximised at that level. We first show that the energy costs of energy will rise in a non-linear manner as total annual primary RE output increases. We then provide evidence that increasing levels of RE will also lead to increasing levels of ecosystem maintenance energy costs per unit of primary energy output. When both these non-linear energy costs are subtracted from primary RE, a maximum value of net sustainable RE occurs. We argue that this optimum RE level probably occurs at a level below the energy forecasts for a few decades hence. Finally, we demonstrate that even this optimum will shrink if climate change continues unabated.

2. Energy costs for energy rise with increased RE output

A vital test for the viability of any proposed energy conversion device, whether RE, fossil or nuclear energy, is that the energy output over its useful life should be greater than the combined energy inputs needed to manufacture, erect, maintain and operate, and finally decommission the equipment. The energy ratio (E_R), as defined here, is the ratio of gross energy output from the device over its operating life divided by the total lifetime energy inputs, with both input and output energy given in primary energy terms. Clearly, if $E_R < 1.0$, the energy project is not viable, regardless of the monetary costs of the energy output. In fact, E_R will need to be much greater than 1.0 if the project is to be viable. One reason for this is the enormous variability in calculated values in the literature for E_R for a given RE source (Moriarty and Honnery, 2007a, 2010a; Honnery and Moriarty, 2011). Net energy is gross output minus input energy. For values of E_R above 10 or so, net energy values are little different from those for gross energy, but for low values of E_R the distinction is crucial.

2.1. Resource quality declines with increasing RE output

For a given RE source, those sites giving the best energy return on input energy are usually built first in any country, as these also tend to yield the cheapest energy. For the world as a whole, this is also approximately true, although in the interests of energy security, some countries tap local lower-quality resources. Such is presently the case for the minor amounts of solar energy produced in Germany. However, Germany is also in the forefront of efforts to develop the solar energy resources of North Africa, and transmit much of the output to Europe.

Resource quality declines can take the form of lower average wind speeds for wind energy, lower average annual insolation levels (and low winter insolation) for solar energy, lower temperature steam for geothermal plants, and increasing depths for Enhanced Geothermal Systems (EGS). For bioenergy plantations, rising output might mean a shift to lower-quality soils, or the

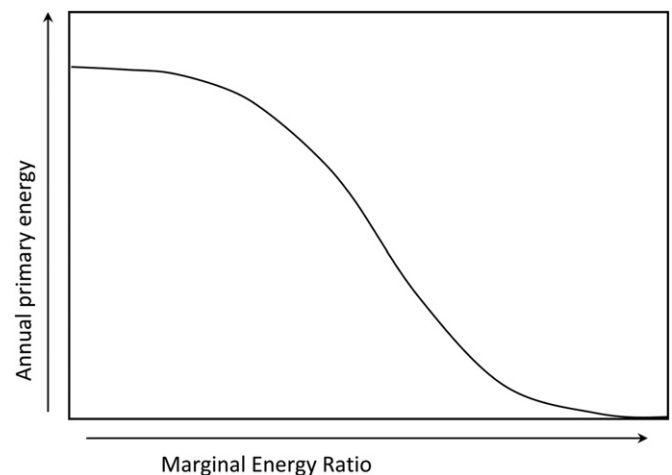


Fig. 1. Schematic graph of annual total primary RE energy vs. marginal energy ratio.

need for irrigation to augment rainfall. For hydropower, 'there are fewer and fewer good dam sites available' (Prichard, 2002). As we have shown elsewhere for wind energy (Moriarty and Honnery, 2010a), the global energy ratio will fall steadily as lower average speed winds are progressively tapped. Similar curves could in principle be constructed for other RE sources, if the relevant data were available. Fig. 1 shows schematically, for RE in general, this trend for primary energy vs. marginal energy ratio (defined as the minimum energy ratio for the given annual primary energy).

There is another way in which resource quality declines with output. Insolation in Germany may be low compared with North Africa, but the energy is produced close to where it is used. Energy from high-insolation North African solar farms, if transmitted to central Europe as in the Desertec proposal (Pearce, 2009), faces transmission distances of up to 5000 km. The capital costs of building such a grid, much of it sub-sea, will be enormous, and total energy losses will also be significant, even for the proposed high-voltage DC systems. The solar farms would need to be located away from the coast to avoid cloudiness (and valuable urban and agricultural land), so supplying fresh water for cleaning mirrors or PV cells could also incur significant input energy costs. The energy costs for water would be even higher if solar thermal energy conversion (STEC) plants are water-cooled (Webber, 2007), which is more efficient than air-cooling. It will also prove necessary to construct roads and other infrastructure for the projects.

2.2. Need for energy conversion and storage rises with RE output

As we have argued in earlier publications (Moriarty and Honnery, 2007b, 2010a), if large amounts of RE energy are needed in the future, the main sources will have to be intermittent—wind, wave, and solar. RE sources that are available on a continuous basis (biomass, hydro, geothermal electricity), can only be ever expected to generate a few tens of EJ globally. (Nevertheless, geothermal energy could produce large amounts of low-grade heat for direct use.) As renewable energy increases well beyond its present low level, the proportion supplied from intermittent sources will inevitably have to rise as well.

As output from intermittent sources begins to dominate total electricity demand, conversion of intermittent electricity to an alternative energy carrier such as hydrogen, and subsequent storage will be increasingly needed, beginning in those grids with few non-fossil alternatives for base-load power. Eventually, intermittent primary electricity will also have to provide for non-electric energy uses, again necessitating conversion to some other

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