OPTIMIZING GREENHOUSE GAS MITIGATION STRATEGIES TO SUPPRESS ENERGY CANNIBALISM

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Abstract

Energy cannibalism refers to an effect where rapid growth of an entire energy producing (or conserving) technology industry creates a need for energy that uses (or cannibalizes) the energy of existing power plants or devices. For the deployment of renewable energy and energy efficiency technologies to grow while remaining net greenhouse gas emission mitigators, they must grow at a rate slower than the inverse of their energy payback time. This constraint exposes a current market failure that significantly undervalues the physical reality of embodied energy in products or processes deployed to mitigate GHG emissions and indicates potential solutions.

1. Introduction

The scientific majority consensus on climate change articulated by the Intergovernmental Panel on Climate Change (IPCC) is that human civilization's combustion of fossil fuels for energy and the concomitant greenhouse gas (GHG) emissions has resulted in global climate destabilization [1]. If our civilization maintains our current trajectory towards continued climate destabilization, the earth will reach a tipping point from which it will not recover [2,3]. This potential catastrophe exists because climate change in the long term is likely to exceed the capacity of natural, managed and human systems to adapt [1]. In order to avoid this rather grim fate for the earth it is widely recognized that our current technological society must rapidly develop sources of renewable energy and radically improve energy efficiency [4-7]. This has created a call for an aggressive strategy to prevent serious harm to the global environment and the long-term viability of the human experiment by deploying vast quantities of sustainable renewable energy [3,7,8]. Similarly aggregating small reductions in GHG emissions by utilizing energy efficiency technologies can also have a substantial positive global impact [3,5,9-11]. Unfortunately, neither the enormous scale of the current fossil fuel energy system nor the necessary growth rate of either energy efficiency technologies or renewable energy technologies is well understood with the boundary conditions set by the net energy produced during growth of an industry. This technical limitation is best described as an “energy cannibalism” [12,13], which refers to an effect where rapid growth of an entire energy producing (or energy conserving) industry creates a need for energy that cannibalizes the energy of existing GHG emission mitigating power plants (or energy efficiency technology manufacturing plants).

In this paper: i) a generalized process will be derived for determining the energy cannibalism for a given energy technology, ii) the limits on the growth rate set by energy cannibalism will be discussed in the context of climate stabilization, iii) complications to future projects of net emissions will be outlined, iv) the scale of the energy problem will be quantified and the necessary growth rates will be generalized for GHG emission mitigating energy technology (ET – for both renewable energy producing and energy conserving technologies). Finally, the impact the concept of energy cannibalism will have on the economics of climate change mitigation will be discussed. Conclusions and recommendations are made from the analysis to assist decision makers in optimizing deployment of technologies on large scales to reduce GHG emissions to safe stable levels.

2. Energy cannibalization due to rapid growth

2.1 Energy payback time and GHG emission conservation payback time

Due to the contamination of the current energy mix with fossil fuel combustion, all current technologies are dependent to some degree on fossil fuel energy and thus also contribute to GHG emissions. In order for an ET to have a net negative impact on GHG emissions of the energy supply, first it must produce enough emission-less energy or conserve enough energy to offset the emissions that it is responsible for, and then it must continue to produce energy or conserve energy to offset emissions from existing or potential fossil fuel plants. Many technologies are candidates for meeting these requirements such as renewable sources of energy (wind power, solar power, microhydro, etc.) and energy conserving technologies (e.g. solid state lighting, insulation, Energy Star appliances, etc.). These requirements, however, can become challenging in view of rapid growth because the construction of additional ET production plants to enable the rapid growth rate, creates emissions that cannibalize the GHG mitigation potential of all the ET plants viewed as a group.

To illustrate this point it is helpful to view all ET plants of a given type as a single aggregate plant or ensemble and look at the ensemble's ability to mitigate emissions as it grows [13]. This ability is first dependent on the energy payback time (t_{EP}) of the plant, or the amount of time it takes for a given device to produce (or conserve) as much energy as it took to construct. For a generic energy producing technology (or energy conserving technology), an installed total capacity, C_T (in GW), produces (or conserves):

$$E_T = tC_T = t\sum_{n=1}^{N} C_n \qquad (1)$$

of energy per year, where t is the time the plant is running at capacity in hours in a year, C_n is the capacity of an individual ET and N is the total number of ETs.

If we assume that in the same year the industry of that technology grows at a rate, r, it will produce an additional capacity of rC_T. It should be made clear here that the analysis is based on a standard unit of time – a year. The amount of energy that the industry produces (or conserves) is obtained by multiplying by the time and is thus rC_Tt. In order to keep the derivation transparent, it is assumed that the additional capacity does not produce (or conserve) its energy, rC_Tt, in that year but only in subsequent years. The time that the GHG emission reduction technology takes to pay for itself in terms of energy it needs over its life cycle, or the t_{EP}, is given by embodied energy invested (over the entire life cycle), E_E, divided by energy produced (or energy saved), $E_{P/S}$. Thus t_{EP}, as measured in years, is:

$$t_{EP} = \frac{E_E}{E_{P/S}} \tag{2}$$

An identical analysis can be completed for GHG emissions. If a given ET causes GHG emissions during its manufacture and use, it must operate for a finite amount of time to achieve climate forcing neutrality.

2.2 Energy cannibalism

The energy needed for the growth of the entire ET ensemble is given by the cannibalistic energy, E_{Can}:

$$E_{Can} = \frac{E_E}{E_{P/S}} rC_T t \tag{3}$$

Regardless if the technology is an energy producer or conserver, the technology ensemble will *not* produce any net energy if the cannibalistic energy is equivalent to the total energy produced. So by setting equation (1) equal to (3) and simplifies to set equation (2) equal to the inverse of the growth rate:

$$\frac{E_E}{E_{P/S}} = \frac{1}{r} = t_{EP} \tag{4}$$

Equation 4 shows that the growth rate of an ET industry may not exceed the reciprocal of the energy payback time to have a positive net energy. For example, if the energy payback time is 4 years and the capacity growth of either an ET ensemble is 25%, no net energy is produced and no GHG emissions are offset. This is because the same analysis is also true for GHG emissions. The embodied GHG emitted in order to provide for the ET divided by the emissions offset every year must be equal to one over the growth rate of the ET simply to break even. This cannibalism of energy for new ETs has a profound effect on their ability to assist in the mitigation of GHG emissions.

It should also be noted here that the energy payback times for a given ET are dependent on the exact deployment. For example, a wind generator will have a much faster t_{EP} and thus allow for a higher growth rate if deployed in a region with high average wind speeds, while the same generator deployed in a less attractive location will have a lower t_{EP}. Similarly, a high efficiency solid-state lighting system will have a faster payback if it is installed in a location that demands constant use (e.g. an enclosed stairway or in emergency exit signs) versus a system installed in a building that has relatively infrequent use such as an entertainment complex or church.

3. Energy cannibalism sets the speed limit for growth

The restrictions of energy cannibalism are not limited to complex 'hi-tech' devices; even mundane technologies such as home insulation have a maximum climate neutral growth rate. The r limit set by energy cannibalism for insulation, as for many ETs, not only varies widely because it is highly geographically dependent (e.g. weather, local energy sources, and human behavior), but also has largely not been determined. Some alternative energy technologies, such as solar photovoltaic cells, have considerable literature dedicated to life cycle analyses (LCAs) and embodied GHG emissions, but the majority of energy conserving or producing technologies have not been scrutinized as thoroughly. To combat GHG emissions on an appropriate mass scale, full LCAs and t_{EP} s must be calculated for all candidate technologies. For leaders to make informed, intelligent decisions about which ETs to deploy on a large scale this data is imperative.

This work becomes increasingly important as civilization approaches the tipping point in climate stabilization. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that atmospheric CO_2 concentration will need to be reduced from its current 385 ppm to at most 350 ppm [2]. This CO_2 concentration is determined by a limit of 1°C global warming (relative to 2000, 1.7°C relative to pre-industrial time), aiming to avoid practically irreversible ice sheet and species loss [14]. This 1°C limit, with nominal climate sensitivity of ¾°C per W/m^2 and plausible control of other GHGs [15], implies maximum CO_2 concentration of approximately 450 ppm [14], which must not be crossed before stabilizing at a lower concentration. This physical limit to global CO_2 concentration places enormous boundary conditions on the ability to deploy any ETs on a scale necessary to reduce fossil fuel use and drive the CO_2 concentration below 350 ppm. Given the current trend of increased energy use for economic development, additional GHG emissions necessary for the massive growth of ETs to offset fossil fuels may not be tolerable. This boundary condition is a very complex moving target, however, because of the inherent instability of energy prices in the current market system. Recent increases in energy costs and particularly the cost of gasoline had remarkable effects on both demand destruction, but also the entire economy. Similarly demand destruction, whether by economic hardship, lack of available credit, or efficiency improvements, decreases energy costs and below a certain threshold can increase energy use.

Thus, to prevent additional climate forcing while mass deploying ETs on the global scale the condition of equation (4) for the aggregated for all ETs must be met. This effectively sets a limit on growth of the entire body of ETs while ensuring that the net energy remains positive. This limit in the growth rate of non-GHG emitting energy sources also sets the limit for the time to which the anthropogenic climate forcing can be stabilized without radically shifting human economies. Considerable further work is needed to quantify this limit by calculating t_{EP} s of all potential ETs to determine the optimal mix of technologies for driving down CO_2 concentration below 350 ppm. This appreciable work needs to be developed quickly on a global scale as each passing year makes the problem of replacing fossil fuels before reaching the 450ppm absolute limit of CO_2 concentration that much more challenging.

4. Complications in quantifying the effects of energy cannibalism

The cannibalization effect, however, is more complicated than the simple yet vast results above would indicate. There are both positive and negative effects.

First, with each ET plant constructed, the embodied GHG emissions of the next plant will be reduced because the fraction of non-fossil fuel based energy has increased. As the embodied GHG emissions is decreased and the effective growth rate can be increased. It is also likely that sources of energy that have lower mass CO_2-eq. per unit energy rates than fossil fuels will be deployed at an expanding rate as economies of scale drive down cost as production increases (e.g. solar photovoltaic cells) [16]. This will speed the decrease in the embodied GHG emissions for any type of ET ensemble. Similarly for each ET device deployed that conserves energy the total amount of energy needed is reduced, which reduces the necessary r to meet a climate neutral energy state at a specific point in time. In addition, as the total demand is reduced the least efficient conventional plants are taken off line. This further decreases the embodied energy of future ETs. Thus the growth rate needed for stabilization of the earth's climate can be decreased with a suitable deployment of ETs.

Second, as we deplete the dwindling supplies of fossil fuels the embodied energy and emissions to extract and use these sources increases. We must drill deeper, uncover more earth, and explore increasingly less hospitable territories to capture declining supplies of both fuels used to form ETs and materials used to make ETs. For example, Cleveland and Costanza studied the energy return on energy invested (EROI) of natural gas production in Louisiana through early production, peak, and into decline [17]. They found that the EROI decline rate of a resource as it is dwindling is both linear and remarkably steep. The EROI plunged from maximum to minimum in only the last 25% of the energy extracted [17]. As the EROI decreases for fossil fuel energy used to supply ETs, the energy payback time of the ETs increase, and the embodied energy and emissions both increase. This is also the case if nuclear energy is used to provide the embodied energy of ETs because as more nuclear energy is utilized the high grade ores are depleted and less concentrated ore, which demands greater embodied energy to process is required [12]. The further we deplete the given resource the worse the effect. Thus the limit of the growth rate of ETs needed for stabilization of the earth's climate would be decreased. In an age where the production of the supplies of particular fossil fuels are reaching their peak in an ever growing list of regions and the global peak in oil extraction appears near, this concept becomes increasingly relevant to energy payback calculations. Full vetting of this concept along with the beneficial effect discussed previously, will need to be completed in the future as all ET candidates are identified and full LCAs are completed for each geographical location.

5. Necessary renewable energy rates of expansion

5.1 Replacing existing fossil fuel energy infrastructure

The total final energy consumption for 2006 was 8,150 millions tons of oil equivalent, of which fossil fuels made up about 79% [18]. Fortunately, the entire energy infrastructure does not need to be replaced. To stall climate change, current global GHG emissions must be cut by about 60% [15]. Thus, if the non-GHG emitting energy were to be supplied by any of the sustainable sources of energy (e.g. solar, wind, small hydro, geothermal, etc.) or a combination, an additional 3,863 millions tons of oil equivalent of ETs would need to be produced per year from these sources to meet *today's* energy needs while preventing additional climate change. Currently, renewable energy represents 18% of global energy consumption, but the relatively constrained supplies of traditional biomass and large hydropower make up about 16% [18]. New sources of renewable energy such as small hydro, modern biomass, wind, solar, geothermal, and biofuels provide only 2.4% (196 million tons of oil equivalent). Thus to reach 3,863 millions tons of oil equivalent of ETs by 2050 and the aggregate of the renewable ETs will need to grow by more than 7% annually. In light of the recent increases in production of these technologies (e.g. solar photovoltaic at 50% per year [18]) simply obtaining that level of growth is not the primary constraint even though the magnitude of the quantities themselves are substantial.

5.2 Rate of energy demand increase

The construction of this much ET infrastructure is a formidable challenge, but the GHG emission induced climate challenge is being significantly complicated by rapid increases in energy needs as developing countries elevate themselves out of poverty and the wealthy throughout the world continue to increase the consumption of remaining fossil fuel supplies at an astonishing rate. The United Nations forecasts the global population will reach 8.5 billion by 2050 [19] with 80% of this increased population expected to reside in energy-intensive urbanized areas. This increase and shift in demographics is expected to lead to rapid growth in global energy demand. The need for a new non-fossil fuel-based energy source is evident from comparing the standard of living, which is dependent on energy, in the most developed countries and developing countries. Although the population of the developing world is five times that of developed nations, they consume less than 40% of the world's energy supply [20]. Therefore, the climate challenge is being significantly complicated with the developing world's continuing transition into a standard of living similar to those in the industrialized nations that require more energy consumption.

Growth rate limits can be obtained if renewable energy alone is considered as a means to protect the planet by reducing fossil fuel-related greenhouse gas emissions. First to cover the non-acceptable current fossil fuel production of energy as discussed in section 5.1, 7% growth is needed for the next 40 years in renewable energy sources. Thus the energy payback time is limited to about 13 years by the energy neutral growth rate. This rate is dictated by energy cannibalism for the replacement of existing unacceptable fossil fuel infrastructure. Next, growth in energy demand must be considered. The World Energy Council projects that in a high growth world in which economic growth and energy consumption steadily increases, the global primary energy consumption could reach 24.8 Gigatons oil equivalent (Gtoe) by 2050 [20]. It should be noted here that these projections may be high due to the current global economic recession and lack of confidence in a debt based economy, but they are the best available source of estimations. Thus the range of growth rate limits and energy payback times can be set by no growth case and this maximum expected growth. For the high growth case, this enormous increase in energy demand represents a major challenge to current energy infrastructure. Not only must the magnitude of the energy demands be met, but they must be met in a way which will avoid further CO_2 forcing of the climate system by overcoming the energy cannibalization effect. In this far more challenging case of both limiting fossil fuel combustion to 40% of the present, while allowing for growth in energy use to 24.8 Gtoe, renewable energy sources must increase by more than a factor of 100 by 2050. To do this, renewable energy sources will need to increase by 12% per year for the next 40 years. Energy cannibalism thus demands that the growth of the renewable energy sector be limited in aggregate to payback times of about 8 years. For many of the ETs under consideration this is not primarily a problem. For example, solar photovoltaic cells generally have payback times under 5 years with most less than 2 years [21]. However, the balance of systems, or the way in which the solar photovoltaic cells are deployed, e.g. a high canopy system consisting of a large quantity of steel can increase the payback time substantially.

6. Discussion

As the world focuses on methods to reduce fossil fuel combustion and the concomitant global climate destabilization, policy is often driven by concern over the economic costs for a given reduction in greenhouse gas emissions. As the climate system approaches a tipping point, such economic considerations must come behind physical laws. There are many examples of ETs that perform well from a net energy perspective, but fail to provide an attractive return on economic investments. High efficiency window retrofits, for example, have t_{EP} of less than a year for many regions, but have economic paybacks measuring in years or even decades. Similarly, methods to reduce GHG emissions economically (as with highly subsidized nuclear power) may not make sense in high growth conditions needed (and lower ore grades are used) to supplant fossil fuels when energy cannibalism is considered) [12]. These results indicate a need for a move towards of a global “energy economy” - an economy based on a real physical value of energy rather than on a subjective valuation of worth, in order to make informed decisions to ensure a stable climate for all nations and the biosphere. This can be accomplished using a number of mechanisms such as carbon credits [22], carbon trading [23], output-based allocations [24], carbon taxes [25], a shift to an energy-based economic system, and other methods discussed elsewhere including this conference. Regardless of the system used, the economic costs of energy need to be better aligned with the physical reality of energy. This challenges the market economy to adapt to fix the current market failure, which has driven investments in inefficient and polluting technologies for decades.

7. Conclusions

This paper has furthered preliminary work, which has shown that the GHG emission neutral growth rate of both energy conserving technologies and renewable energy technologies are constrained by the effects of energy cannibalism. To grow at the 7-12% rates needed to stabilize the climate under energy demand increases, while remaining net GHG emission reducers, all ETs must grow at a rate slower than the inverse of their payback time (in aggregate <8 years). To have the information needed to overcome this effect, first full LCAs need to be developed for all ETs so that the technologies with the fastest energy payback times can be deployed first in the appropriate regions. In addition, every effort should be made to increase the efficiency, and thus energy produced (or conserved) of all candidate ETs by improving material choices, manufacturing techniques, and reducing embodied energy of transportation by encouraging regional/local manufacture. It is imperative that decision makers begin to focus on the real energy payback times and growth rates to combat global climate destabilization rather than rely on simple economics, which is often independent of physical reality. ETs that overcome energy cannibalism by becoming energy breeders, which produce many time their embodied energies, must be supported by policy to deploy them in mass quantities within the next 40 years to stave off the worst of climate destabilization.

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