Energy Payback for Energy Systems Ensembles During Growth

Timothy G. Gutowski, Stanley B. Gershwin and Tonio Bounassisi

***Abstract*—During periods of growth, the energy payback performance of new energy generating technologies deviates substantially from the usual static measures of energy return on investment (*EROI*), and time to breakeven (t_B) for single systems. Here we examine the performance of growing ensembles, develop new measures of dynamic performance, and identify an optimum growth rate (largest value of net energy production) and critical growth rate (rate at which the ensemble generates no new energy). Hence, if ensembles grow too fast they can look like net energy sinks in spite of good (static) single system performance indicators.**

***Keywords*— Energy payback, energy breakeven, energy growth, energy ensemble performance**, EROI.

I. PROBLEM ADDRESSED

The energy payback for new energy systems is commonly measured in terms of time to break even (or payback time) t_B and energy return on investment EROI. New energy technologies are evaluated by these criteria in order to estimate their ability to contribute to our growing energy needs and carbon emissions problems. We will show in this paper that these measures alone are inadequate when characterizing the performance of a series of systems (ensembles) that are built year after year as part of the growing new energy industry. The analysis included here applies to any kind of energy system from nuclear power to soybean diesel. The essence of the problem is that during conditions of growth the early energy investment in manufacturing takes on a new importance. In fact, if growth is too fast, the ensemble will not produce any new energy in spite of positive single system energy indicators. This is particularly important for schemes meant to address climate change. For example, The IPCC recommends reducing CO_2 by 50% to 85% by 2050 compared to 2000 [1]. If new energy systems conceived to produce energy services at reduced GHG emissions, actually look like energy sinks, then they will not contribute to the solution during the period of growth. The problem that faces us is that these new technologies cannot make a substantial contribution to our energy supply without growing. Here in lies the critical dilemma over the next several decades; if they don't grow they can't contribute, and if they grow too fast they can't contribute. It appears to us that the most effective ways to manage this problem would be to implement; 1) policy to manage growth, and, 2) investments in manufacturing technology to reduce manufacturing energy requirements.

Timothy G. Gutowski is a Professor in the Department of Mechanical Engineering at Massachusetts Institute of Technology, Cambridge, MA 02139, USA. (He is the corresponding author. Telephone: 617-253-2034, Fax: 617-253-1556, email: gutowski@mit.edu).

S.B. Gershwin is a Senior Research Scientist in the Department of Mechanical Engineering at Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

T. Bounassisi is an Assistant Professor in the Department of Mechanical Engineering at Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

II. PRIOR WORK

The concept presented here is usually not mentioned by energy analysts. Instead, attention is exclusively focused on "single system" measures such as time to break even and EROI [2]-[8]. However, in a few places we have found a reference to the effects of growth [9]. For example, in one reference it is called "energy cannibalism", [10] in another it is called Energy Internal Rate of Return [11] and in still another reference it is used to assess different energy technologies in India [12].

III. PROJECT UNDERTAKEN

The essence of this project is a mathematical analysis along with a discusson of the performance of various energy systems. These could include nuclear energy, wind power, photovoltaics, and soybean diesel under various technology, location and growth scenarios. Special attention will be focused on PV.

IV. ANALYSIS

We call E_M the energy investment to manufacture the system, and e the annual energy produced (power). Hence the payback time t_B of a single system is E_M/e, and for a system that produces for t_L years (the life time), the Energy Return on Energy Investment (called EROI) is $et_L/E_M = t_L/t_B$. Now, consider the growth of a technology that starts in year *"0"* and builds N_0 new systems that year. The energy cost for this is $E_M N_0$. In year *"1"* these systems produce energy eN_0, and an additional rN_0 systems are built. In later years, *"r"* is the annual growth rate as a fraction of the cumulative number of systems built. This scenario is illustrated in Fig. 1, and Table 1 shows how both manufacturing and capacity grow.

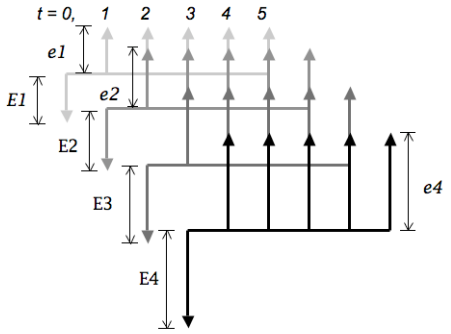

Fig 1. Representation of a growing energy ensemble showing energy invested in manufacturing, E1, E2 etc., and energy produced, e1, e2 etc., after installation. Time proceeds to the right.

TABLE I
CALCULATION OF ENERGY ENSEMBLE PARAMETERS

Year	Mfg. this year	Cum. Mfg.	Cap. Added	Cum. Cap
0	N_o	N_o	0	0
1	rN_o	$(1+r)N_o$	N_o	N_o
2	$r(1+r)N_o$	$(1+r)^2N_o$	rN_o	$(1+r)N_o$
3	$r(1+r)^2N_o$	$(1+r)^3N_o$	$r(1+r)N_o$	$(1+r)^2N_o$
4	$r(1+r)^3N_o$	$(1+r)^4N_o$	$r(1+r)^2N_o$	$(1+r)^3N_o$
..	..			..
..	..			..
..	..			..
..	..			..
n	$r(1+r)^{n-1}N_o$	$(1+r)^nN_o$		$(1+r)^{n-1}N_o$

Note that when talking about the growth of an energy generating technology one usually speaks of capacity. When talking about payback one speaks of actual energy produced. These are not the same, yet here we combine the two topics. In this paper, when we refer to "capacity" we are referring to the actual energy the system is expected to produce under normal conditions. Hence the cumulative energy invested in the manufacturing of the new energy systems after n years is just

$$\varepsilon_M = E_m N_o (1+r)^n \tag{1}$$

On the other hand, the cumulative energy produced is just the sum of column 5 in Table 1 times "e", up to year n, where $0 \le n \le t_L$.

$$\varepsilon_p = \sum_{i=1}^{n} eN_o (1+r)^{i-1} = \frac{eN_o}{r}[(1+r)^n - 1] \tag{2}$$

This gives the total net energy for year n as,

$$\varepsilon_T = -\varepsilon_M + \varepsilon_p = \frac{eN_o}{r}[(1-rt_B)(1+r)^n - 1] \tag{3}$$

Note that the systems listed in column four of Table 1 (labeled "Cap. Added") give the age distribution for systems in the ensemble by year. For example, in year $t_L + 1$, N_o systems will be retired; for $t_L + 2$, rN_o are retired, for $t_L + 3$, $r(1 + r)N_o$ etc. In general we will confine our analysis to the time period $0 \le n \le t_L$.

V. ENSEMBLE PERFORMANCE MEASURES

We are interested in the net energy (equation (3)) and the payback performance of growing energy ensembles. From equations (1) and (2) we can form the new payback measures for ensembles as;

a) the ensemble energy return on investment *or "EsEROI"* as

$$EsEROI = \frac{\varepsilon_p}{\varepsilon_M} = \frac{1}{rt_B}\frac{(1+r)^n - 1}{(1+r)^n} \tag{4}$$

(Generally, this will be evaluated at $n = t_L$). And

b) the ensemble payback time, as the time required to achieve $\varepsilon_T(n_B) = 0$. This is given as

$$n_B = -\frac{\log(1-rt_B)}{\log(1+r)} \tag{5}$$

Now with (3) (4) and (5) we can make the following observations.

A. Zero Growth Rate

At zero growth rate the ensemble measures go to single system values. That is, *as* $r \to 0$, and for $n = t_L$, $\varepsilon_T \to N_o(et_L - E_M)$ and $EsEROI \to EROI$.

B. Optimum Growth Rate

There is an optimum growth rate at which the net energy produced (3) obtains a maximum. For $n = t_L$, and $t_L/t_B = EROI \ge 6$ *and* $t_B \ge 1$ a very good approximation for the optimum growth rate is,

$$r_{opt} = \frac{t_L - 1 + \sqrt{\left[(t_L - 1)^2 - 4t_L t_B\right]}}{2t_L t_B} \tag{6}$$

Note that (6) can be approximated by $r_{opt} = \frac{\alpha}{t_B}$, where $\alpha = \alpha(\frac{t_L}{t_B})$ and ranges between an upper bound at $(\frac{t_L - 1}{t_L})$ and lower bound at $\frac{1}{2}(\frac{t_L - 1}{t_L})$.

C. *EsEROI and n_B*

In general the ensemble energy return on investment is reduced during periods of growth. There are several notable growth rates. Recall that as r → 0, *EsEROI* → *EROI*. That is, the ensemble reduces to a single system.

We define the minimum replacement rate such that at the end of life for the first systems produced i.e. at n = (t_L + *1*) when N_o systems are removed from operation, there are still N_o systems remaining. Stated another way, there are $2N_o$ systems for $n = t_L$. This replacement rate is[1]

$$r = r_r = 2^{1/t_L} - 1 \cong \frac{\ln 2}{t_L} \quad (7)$$

This results in a significant reduction in *EsEROI* at relatively modest growth rates.

$$EsEROI(r = r_r, n = t_L) \cong \frac{EROI}{2\ln 2} = 0.72 EROI$$

At the optimum growth rate it can be shown that

$$EsEROI(r = \frac{\alpha}{t_B}) < \frac{1}{\alpha} \quad (8)$$

In other words, *EsEROI* can be no larger than about 2 and most likely will be less. Compared to what one might expect based on the single system performance parameter of *EROI,* this means the return on investment during growth is actually quite low.

And finally as $r \to \frac{1}{t_B}$, $EsEROI \to 1$ and $n_B \to \infty$.

That is, the net energy produced drops off steeply at higher growth rates, and at the critical growth rate,

$$r_{crit} = \frac{1}{t_B}, \quad (9)$$

the net energy is zero *(ε_T = 0)* and no payback occurs during growth. For $r > r_{crit}$ the ensemble looks like an energy sink, i.e. it uses more energy than it produces.

VI. SINGLE SYSTEM ENERGY PERFORMANCE

The energy performance of new technologies can and often does improve as the technology evolves. Such phenomenon as "learning curves" and "economies of scale" have documented how manufacturing can improve in terms of labor intensity, and cost, as well as energy efficiency [13]. Similarly, device and/or mechanism performance improves, especially when there are incentives to do so. For example, the intense competition and demand for solar-electric conversion has spurred significant improvements in photovoltaic cell and system performance over the last decade. As a result, the single system performance parameters of t_B and EROI have steadily been improving for many of the new energy technologies.

At the same time, the energy performance of many of the new energy technologies is dependent not only on technology, but also on nature. The location and weather conditions can have very significant effects on solar, wind and bio based energy sources. For example, the solar insulation over the 48 contiguous states of the U.S. varies by at least a factor of 3. As a result, a single system that pays back in only one year in southern states may take 3 years or longer in the northern regions. Other effects that are important are how these new systems may perform during use. Some solar installations in the desert for example, become coated with sand and dust requiring regular washings in order to maintain their performance. Likewise, wind power systems have been susceptible to overloading which can result in blade and gear box failures, which in turn can lead to significant down times.

Many of these effects can be addressed by technology improvements but these in turn could also affect the energy performance parameters. For example, replacement components and maintenance energy costs should be added to the manufacturing energy costs. In this regard, one of the potentially largest missing components to the usual energy evaluation of new energy systems is storage. In actuality the quality of the energy services delivered by the various new technologies under consideration is vastly different. A particular case in point is that solar and wind technologies are non dispatchable and intermittent, while bio based fuels are in theory both dispatchable and continuous (land use issues aside). Hence the current methods of characterizing wind and solar are incomplete, especially if they are to be compared with fossil fuels and biofuels. As a result, when including storage, we can expect the single system parameters (now with larger system boundaries) for wind and solar to decline i.e. t_B will be longer and EROI will be lower. Current estimates for single system energy payback metrics can be found in [14, 15, 16].

[1] Note that there are many other possible definitions of replacement rate but they all lead to the same general conclusion.

VII. PV CASE STUDY

The system ensemble sensitivity to growth can be illustrated with a couple of hypothetical, but realistic examples.

1. t_B = 1.5 years; t_L = 25 years; EROI = 16.7; r = 20%

   This gives, n_B = 2 years and EsEROI (t_L) = 3.3

2. t_B = 3 years; t_L = 25 years; EROI = 8.3; r = 30%

   This gives, n_B = 8.8 years and EsEROI (t_L) = 1.1

3. t_B = 3 years; t_L = 25 years; EROI = 8.3; r = 35%

   This gives, $n_B = \infty$, EsEROI(t_L) < 1 and $\varepsilon_T(t_L)<0$.

In other words, in the first example the breakeven time is pushed out from the expected 1.5 years to 2 years and the return after 25 years is a significantly smaller fraction of the invested energy than expected (i.e. 3.3 instead of 16.7). For poorer performing systems (t_B = 3 years) and higher growth (30 to 35%) we see a very serious reduction in performance compared to what one might expect from the single system performance parameters. In fact for example 3, the whole ensemble produces no new energy over the 25 year period of growth examined here, and looks essentially as an energy sink.

VIII. BEHAVIOR FOR TIMES GREATER THAN T_L

For times greater than t_L, old systems will be sequentially retired, subtracting from the net energy given by (3). For large growth rates this reduction may not be noticeable, but at small growth rates this reduction can be substantial. For example, as previously mentioned at the replacement rate and time $n = t_L + 1$, the number of energy producing systems is halved.

For any arbitrary growth rate the normalized reduction in cumulative capacity at the retirement year $t_L + 1$ is given by,

$$1 - \frac{1}{(1+r)^{t_L}} \tag{10}$$

More generally, we can write the expression for cumulative net energy for the time period $t_L + 1 \le n \le 2t_L$ as

$$\varepsilon_T = eN_o \frac{(1+r)^n}{r}[(1-rt_B) - \frac{r}{(1+r)^n} - \frac{r}{(1+r)^{t_L+1}}] \tag{11}$$

IX. CLOSING COMMENTS

The obvious way out of the potential growth dilemma is to improve system performance and to manage growth. System performance can be improved by improving both the system production performance as well as the manufacturing efficiency. We believe that in some cases there may actually be more potential in the later, particularly for PV.

Of all the parameters introduced here, perhaps the most important is the critical growth rate, $r_{crit} = 1/t_B$. We close by giving an estimate of these current values. Here we rely heavily on the results given in [16] (which generally agree with [14]). We believe these values are closer to how systems are actually functioning today. Assuming t_L = 25 years for all four technologies we get: biodiesel 10%, Nuclear 24%, PV 32% and Wind 80%. Matching these values with the rates needed to address carbon emissions and greenhouse gas targets suggests that nuclear and wind appear better for the medium short term and PV is better suited for longer term. We believe that biodiesel would be a niche market because of land use issues and should grow only at modest rates. For the very short term we believe that ***energy efficiency*** in buildings and transportation, along with suitable incentives to prevent the rebound effect constitute the best options [13]. Of course, as technology changes these observations could change too. And we hasten to point out that there is more to this issue than just *EsEROI* and n_B.

REFERENCES

[1] B. Metz, O. Davidson, P. Bosch, R. Dave, L. Meyer (Editors), "Climate Change 2007: Mitigation of Climate Change". Working Group III Contributions to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, p 229 2007.

[2] John A.Turner, "A realizable renewable energy future", *Science,* 285**,** 687 ,1999.

[3] J. Hill, E. Nelson, D. Tilman, S. Polasky and D. Tiffany, "Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels", *PNAS*, vol. 103, No. 30, July 25, 2006, pp.11206-11210.

[4] A. Pradhan, D.S. Shrestha, J. Van Gerpen, and J. Duffield, "The energy balance of soybean oil biodiesel production: A review of past studies", *Transactions of the ASABE*, Vol. 5, No. 1, 2008, 185-194.

[5] V. Fthenakis, Hyung Chul Kim and E.A. Alsema, "Emissions from photovoltaic life cycles", *Environmental Science & Technology*, accepted January 2008.

[6] V. Fthenakis, J. E. Mason, K. Zweibel, "The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US", *Energy Policy*, 37, 2009, p.387.

[7] V. Fthenakis, and E.A. Alsema, "Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004-early 2005 status",

Progress in Photovoltaics: Research and Applications, No. 14, John Wiley & Sons, Ltd., 2006, pp. 275-280.

[8] E.A. Alsema, M.J.de Wild-Scholten and V.M. Fthenakis, "Environmental impacts of PV electricity generation – A critical comparison of energy supply options", presented at the 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, September 4-8, 2006.

[9] A. Black, "PV energy payback Vs PV input energy due to market growth", presented at Solar World Congress to the Solar Energy Society, Orlando, Florida, August 2005.

[10] J. Pearce, *Energy Policy and Energy Cannibalism*, http://me.queensu.ca/people/pearce/research/index.php accessed Oct 9, 2009.

[11] Tom Konrad, EROI and EIRR URL http://cleanenergywonk.com/2009/11/16/managing-the-peak-fossil-fuel-transition%C2%A0/ accessed 11/23/09.

[12] J. Mathur, N. K. Bansal, and H.-Joseph Wagner, "Dynamic energy analysis to assess maximum growth rates in developing power generation capacity: case study of India", *Energy Policy*, 32, 2004, 281-287.

[13] J. Dahmus, and T. Gutowski, "Can efficiency improvements reduce resource consumption?" J. *Industrial Ecology*, to appear 2010.

[14] V. Smil, *Energy in Nature and Society*, MIT Press, 2008.

[15] The World Watch Institute, *Vital Signs*, 2007-2008, 2007.

[16] Ida Kubiszewski and C. Cleveland, "Energy return on investment (EROI) for wind energy", The Encyclopedia of Earth, last updated June 18, 2008. URL http://www.eoearth.org/article/Energy_return_on_investment_%28EROI%29_for_wind_energy