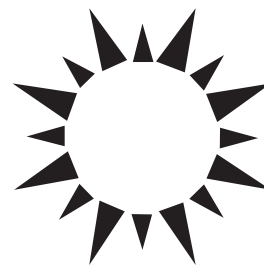


Net Energy Analysis: Concepts and Methods



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Glossary

absolute energy ratio (AER) Energy produced/energy required, including energy from the ground or the sun (dimensionless).

end use Consideration taking into account the efficiency of use of energy produced.

incremental energy ratio (IER) Energy produced/energy required, excluding energy from the ground or the sun (dimensionless).

internal rate of return (IRR) The implied interest rate if energy inputs are considered an investment and energy produced is considered a payoff (units = 1/time).

payback time The time for the accrued energy produced to balance the energy inputs (units = time).

power Energy per unit time.

power curve A graph of power inputs and outputs vs time.

premium fuel An energy type considered especially valuable. For example, oil is usually considered premium relative to coal because it is more flexible in use, less polluting, etc.

Net energy analysis of an energy technology is a comparison of the energy output with the energy needed to supply all inputs—the energy source, materials, and services—to construct, operate, and dispose of the technology.

1. INTRODUCTION AND BACKGROUND

At first glance, net energy analysis (NEA) is a natural, intuitively sensible extension of the idea of energy

cost. Everything requires energy somewhere along the chain of production, including the equipment and services used to find and extract energy. In addition, energy seems to be harder to get with time: efforts to drill, dig, and dam must be in deeper and in more forbidding places for our oil, gas, coal, and hydro-power (offshore for oil and gas, in mountainous terrain for coal, and into the sub-Arctic for hydro-power). This in turn probably implies more energy cost, and shifts the time when this trend will hit the breakeven point. NEA seeks to find out. Some proponents of NEA claim that standard economics will not always indicate this problem (especially if subsidies to energy industries are involved, as they usually are) and that therefore net energy analysis should be carried out largely independent of economic analysis. However, the more common argument is that energy analysis is a supplement to, not a substitute for, economic analysis in decision making.

Net energy concerns peaked in the 1970s and early 1980s following the oil embargo/energy crisis years of 1973 and 1979–1980. Many NEA studies covered oil made from coal or extracted from tar sands and oil shale, geothermal sources, alcohol fuels from grain, biomass plantations, solar electricity from orbiting satellites, and nuclear electricity from ambitious proposed plant-building programs. In 1974, Federal legislation requiring net energy analysis of federally supported energy facilities was enacted. It required that “the potential for production of net energy by the proposed technology at the state of commercial application shall be analyzed and considered in evaluating proposals” [Public Law No. 93-577, Sect. 5(a) (5)]. Since that time, interest in net energy has diminished, but continues sporadically. Adherence to Public Law 93-577 was abandoned early by the U.S. Department of Energy (DOE). In 1982, responding to a criticism from the U.S. General Accounting Office that it was not performing NEAs, DOE said “[it is]

DOE's view that the benefits of [NEA] are not worth the time and effort involved for general application." Net energy analysis is a type of life cycle analysis. The past decade has seen an increase in applications of the latter, but usually these have been applied to consumer products rather than to energy facilities, using toxic and other materials, water, etc., rather than energy, as numeraire.

The DOE had a point; the devil is in the details. NEA is an elusive concept subject to a number of inherent, generic problems that complicate its application. Some of these problems persist, not because they are unstudied, but because they reflect fundamental ambiguities that can be removed only by judgmental decision. The problems include all of those with energy analysis as well as others specific to the "net" question. The difficulty of specifying a system boundary, the question of how to compare energy produced and consumed at different times, and the problem of how to compare energy types of different thermodynamic qualities, density, and ease of storage all make NEA harder to perform and interpret. Some analysts therefore reject net energy analysis but support energy analysis. The latter considers the energy output to be a good or service and attaches no special significance to the fact that it is energy. In this view, it is reasonable and useful to determine how much energy is required to keep a room warm, or to produce a head of lettuce or even a ton of coal, but it is confusing at best and misleading at worst to compare outputs and inputs of a coal mine purely on the basis of energy cost. This fundamental objection attacks the very basis of NEA: NEA assumes that the economic/human life-support system can be separated into the "energy system" and the "rest of the system" and that studying the energy system as a distinct entity is valid. For many applications, this separation, although not perfectly defensible, seems to be acceptable. For others, there are stronger objections.

Little has occurred since 1982 to challenge DOE's dismissive pronouncement, and in this author's opinion NEA has very seldom, if ever, been used as a critical decision criterion. In the Grain Belt, NEA arguments have sometimes been quoted regarding ethanol production from corn, but the sorting out that occurred (with small operators using dry-milled corn shutting down while larger operators using wet milling flourished) can be understood on the basis of the monetary economies of scale, of the role of economic subsidies, and of the details of the flexibility of the two milling processes. In fairness, there is a large debt owed to NEA as a stimulant to proper thinking about resources. Predicting resource avail-

ability on the basis of past trends has been shown to be fallacious by the example of domestic U.S. oil, where increased drilling in "Project Independence" did not reverse the fact that all-time production peak was in 1971. To the extent that prediction by linear extrapolation is an economics technique and that prediction by incorporating the physical aspects of the resource is a net energy analysis technique, NEA deserves credit. But anything can be done poorly, and proper economics should incorporate physical realities. Once that is granted, the question of usefulness lies in the details of NEA.

In advance, it can be anticipated that two specific outcomes of NEA will be least controversial. If the technology appears to be a clear energy loser even after all uncertainties of technique and data are accounted for, the result is useful; the program should be scrapped. Likewise, if the technology appears an unambiguous energy producer, it is likely that NEA can now be deemphasized and the decision to proceed based on other criteria. If the technology is close to the energy breakeven point, NEA seems more appealing. Of course, in this case, a higher degree of accuracy in the result, and hence in the needed data, will be required.

2. QUANTITATIVE ENERGY BALANCE INDICATORS

The statement that an energy technology can be an energy winner or loser implies three assumptions. First, because energy is not created or destroyed (mass-energy in the case of nuclear energy), it would seem that at best an energy (conversion) technology can only break even. NEA usually assumes that the energy in the ground (or coming from the sun) is not to be counted as an input, i.e., is outside the system boundary. This is discussed in detail later. Second, it is usually assumed that high-quality energy (in the thermodynamic sense) is desirable, whereas low-quality energy is not. This would be covered properly if "free energy" were used instead of energy. The common (mal)practice is followed here, i.e., using "energy" actually to mean thermodynamic free energy. Third, it is assumed here that all material and service inputs to an energy facility are expressible in terms of the energy needed to produce them.

Figure 1 shows the basic NEA framework, assuming only one energy type. It is useful to have a normalized indicator of the net energy balance; two are the incremental energy ratio and the absolute

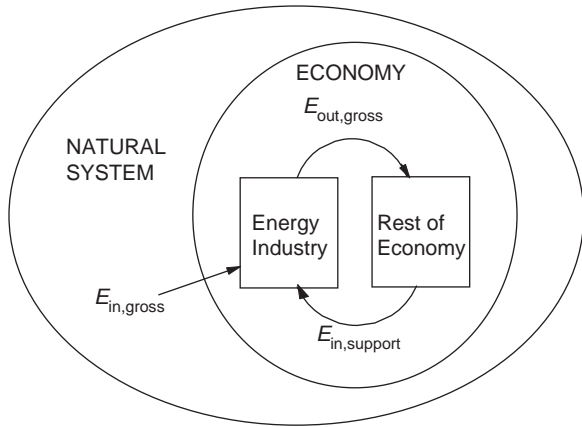


FIGURE 1 Energy flows for net energy analysis.

energy ratio:

$$\text{Incremental energy ratio} = \frac{E_{\text{out,gross}}}{E_{\text{in,support}}}$$

$$\text{Absolute energy ratio} = \frac{E_{\text{out,gross}}}{(E_{\text{in,gross}} + E_{\text{in,support}})}$$

Support energy is that obtained directly from the rest of the economy or used by the economy to provide necessary materials and service inputs. $E_{\text{in,gross}}$ is the energy from the ground or sun, that energy usually referred to as “resource.” $E_{\text{out,gross}}$ is the energy supplied to the rest of the economy. The difference between the two ratios depends on the system boundary. The incremental energy ratio (IER) parallels standard economic practice in that the “cost” of exploiting a resource is the cost of extraction, and includes as inputs only those taken from the rest of the economy. The latter can be thought of as “invested” energy, and the IER is called by some workers “energy return on investment.” An $\text{IER} > 1$ means that we have a net energy producer. The absolute energy ratio (AER) is appropriate to the more global question of the physical efficiency with which a given (say) fossil or renewable energy source can be converted into useful energy. The AER (which never exceeds 1) is useful for determining how much of a given stock of energy resource can be used by the rest of the economy.

Figure 2 illustrates the interplay of the IER and AER. Because of the possibility of energy consumption within the boundary of the energy technology, knowledge of the IER does not uniquely specify the AER, and vice versa. To exhibit how the energy flows vary and cumulate over the facility’s lifetime, we can use a “power curve,” shown in Fig. 3. The power curve tells “everything” (assuming that the system boundary is properly stated, etc.) but is cumbersome. It is desired to have some summary indicator of the whole time path,

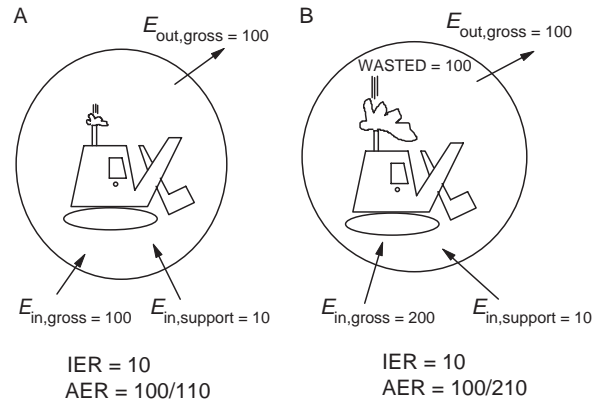


FIGURE 2 Incremental energy ratio (IER) and absolute energy ratio (AER) for two hypothetical coal mines. Both mines have the same IER, but mine B has a lower AER because of energy waste within the system boundary.

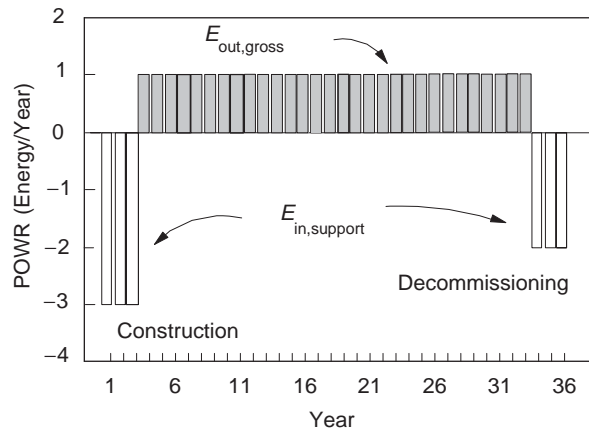


FIGURE 3 Hypothetical power curve for an energy facility through construction, operation, and decommissioning. $\text{IER} = 30 / [(3 \times 3) + (2 \times 3)] = 2$. Payback time = 12 years, but it is not really “simple” because the concept does not apply to a power curve with costs following benefits. $\text{IRR} = 9.1\%/ \text{year}$.

such as (1) the energy ratio (already defined), (2) the energy payback time (the time for the accrued energy produced to balance the energy inputs), and (3) the energy internal rate of return (IRR; the implied interest rate if energy inputs are considered an investment and energy produced is considered a payoff). The formal statement is that the IRR is that value of r for which

$$\frac{\sum_{t=1}^N \frac{E_{\text{out,gross}_t}}{(1+r)^{t-1}}}{\sum_{t=1}^N \frac{E_{\text{in,support}_t}}{(1+r)^{t-1}}} = 1.$$

All three of these indicators have analogues in economics. All require summing energy over many years, and it is necessary to decide how to weigh the present against the future. The IRR by definition

explicitly assumes the standard economic practice of geometric discounting. However, for energy ratio and payback time there is no fixed rule. Most energy analysts do not discount, and that convention will be followed here. Summary indicators will be used for ease of communication but they sacrifice detail and introduce ambiguity. For example, consider simple payback time (i.e., payback time with no discounting), which is defined as that time at which the energy facility has produced as much energy as it has consumed. This definition implicitly assumes a power curve that is negative at first and then becomes, and remains, positive during facility operation. It would be less useful, and even misleading, for more complicated power curves, such as for a facility that requires significant energy inputs late in the lifetime, as for repair, maintenance, or decommissioning (see Fig. 3).

The energy ratio is also subject to difficulties in interpretation. For example, if an electric plant uses some of its own output, should that be added to the

inputs or subtracted from the output? This makes no difference to payback time or to the internal rate of return, but does affect energy ratio. If the power curve is well behaved, i.e., negative at first and then positive over the whole lifetime, then the following statements are equivalent statements of positive net energy production:

- $IER > 1$.
- Simple payback time $<$ facility lifetime.
- Internal rate of return > 0 .

3. CONCEPTUAL AND PROCEDURAL ISSUES

Several of the conceptual and procedural difficulties of NEA are summarized in Table I. It should be noted that there is considerable overlap between issues, and that several also plague economic analysis. Most are

TABLE I
Conceptual and Procedural Difficulties with Net Energy Analysis

Issue	Example	Remedied by careful statement of problem?	Comment
1. Specification of system boundary	Is sunlight "free"?	Yes	Differences of opinion persist among both analysts and users
a. Spatial	Is soil quality maintained in biomass energy production?		
b. Temporal	How much of a passive solar house is functional vs decorative?		
c. Conceptual	Should the energy cost of decommissioning a nuclear plant be included? Should energy costs of labor be included?		
2. End-use consideration	Should NEA of a coal–electric plant be influenced by the efficiency of residential refrigerators? If a car gets better miles per gallon than expected, is the benefit allocatable to the ethanol-from-grain process?	No	An example of the fundamental question of to what extent the energy system is separable from the rest of the economy
3. Opportunity cost	Can energy conservation measures be thought of as producing (saved) energy and then subjected to NEA?	Yes	Difficult-to-set ground rules that are not situation-specific
4. Dynamic problem	Will a rapid buildup of many energy facilities produce net positive energy? The answer can be "no," even if the IER for each facility is > 1	Yes	Raised regarding nuclear and solar energy in the 1970s but shown not to be not significant (rapid buildup did not occur)
5. Existence of more than one kind of energy	Should oil and coal be equally weighted in NEA?	Not completely	Very vexing
6. Average vs. marginal accounting	New oil wells often have a lower IER compared to old wells	Yes	Generic problem
7. Dependence of NEA on economic factors	Energy requirements for steel production depend on price of energy	No	Unavoidable because NEA is based on real technology

problems with energy analysis in general as well as with NEA specifically.

3.1 End-Use Considerations

Should NEA take into account the efficiency of use of $E_{\text{out, gross}}$ to provide an energy service such as cooling a space (e.g., a refrigerator) or moving people (e.g., an automobile)? An example of this problem is the gasohol miles-per-gallon question. It was observed in the late 1970s that cars using gasohol (a mixture of 90% unleaded gasoline and 10% ethanol) got more miles per gallon than would be expected on the basis of the enthalpy of combustion (“energy content”) of the mixture as compared with that of pure gasoline. For the purpose of NEA, this could be viewed as a production of extra energy, i.e., an increase in $E_{\text{out, gross}}$. Should the credit for this increased output be allocated to the ethanol-producing process? If so, the IER increased from 1–1.7 to 1.5–2.4. Or, because the improvement is really due to the existence of the mixture, should it be inadmissible to perform the NEA of ethanol only? And what if the ethanol goes to an end use other than gasohol, for which this issue is moot? Further, this is all dependent on the type of engine. Research provides no definite answer. The user must decide, being attentive to the likelihood that in the event of controversy, different interest groups will tend to select the interpretation that best supports their cases.

3.2 Energy Conservation

NEA can be applied to energy conservation, in which case $E_{\text{out, gross}}$ is the energy saved (“neg-a-watts”), and $E_{\text{in, support}}$ is the energy required to make the insulation, the more efficient motor, etc.

3.3 The Dynamic Problem

This is an age–structure demographic issue, of concern with the rapid buildup of an energy technology. Even though a single facility may have a (lifetime) $\text{IER} > 1$, a program of building many facilities may be a net energy sink for many years. If the program is growing fast enough, the average facility is not even completely built! Concern over this problem was stimulated by exponential program goals for nuclear power plants (in the United States and Great Britain, doubling time = 5 years) and solar heating (United States, doubling time = 3 years). The exponential growth did not occur, and the concern has largely gone away. But it is always a potential problem.

3.4 Energy for Human Labor

There is disagreement on whether to include the energy to support human labor. The two following reasons argue against inclusion:

1. It is difficult to agree on how much of it to include. Is it the energy consequences of a worker’s whole paycheck or just that portion spent for food and lodging?
2. Including labor means that the economy is viewed as producing goods only for government consumption, exports, and capital purchases. Consumption by residences is assumed to be fixed in amount and, especially, in “mix.” Other energy research (for example, energy conservation) exploits the flexibility of personal consumption patterns (to purchase more insulation and less natural gas, for example). This flexibility seems to be preferable.

3.5 Different Energy Types and Premium Fuels

Not all energy types are equally useful. On average, we consider oil and natural gas more useful than coal, and the price reflects this (gasoline retails for about \$10 per million Btu; coal is about \$1.50 per million Btu). Various analysts have accounted for this by giving different weights to different energy types based on criteria such as scarcity or economic price. One example is calculating the IER for “premium” fuels only. Thus, if liquid fuels are defined as premium and an ethanol-from-grain plant can burn coal or crop residues, the IER will be increased over one that burns oil. This explicit introduction of nonenergy criteria again blurs the boundary of NEA.

3.6 Facility Lifetime and Other Sensitivity Issues

In Fig. 3 we see that if the energy facility has a productive life of only 15 years, instead of 30, the IER is reduced to 1, which is the breakeven point. Besides lowered lifetime, lack of reliability could cause diminished output and increased energy inputs for maintenance. Similarly, increased energy costs of decommissioning would reduce the IER; this is a real issue for nuclear power. Of course, the IER could be increased by the opposite of these trends. Explicit treatment of the uncertainty of IER is often performed. An example is an NEA of the proposed solar power satellite (SPS) of the late 1970s. This involved arrays of solar cells in geosynchronous orbit, on which electricity was

converted to microwaves and beamed to terrestrial antennas, for conversion back to electricity. Uncertainties of the lifetime and performance of photovoltaic cells in a space environment, plus relatively high energy requirements for heavy, crystal-grown silicon, which in turn required higher energy costs to place them in orbit, resulted in an IER of 2.1 ± 0.8 for the SPS. The project was not funded, though monetary issues probably dominated net energy questions. Today's solar cells are lighter and more efficient and durable, so that portion of the system would likely be more energetically favorable now.

4. RESULTS AND TRENDS

NEA has changed little since the spate of work in the 1970s and 1980s. A literature search today shows relatively few studies, and these tend to emphasize window coatings to manage solar gain and loss, a continued interest in solid biomass fuels and liquids-

from-biomass, and photovoltaic units. Thus, the data in Table II, showing results for several conventional and unconventional technologies, are dominated by 25-year-old results. Table II indicates that coal tends to have IERs on the order of several 10s. Crude oil and natural gas are on the order of 10. Electricity from a fossil plant is on the order of 3 to 10. Geothermal electricity is of order 4 to 10. For solar technologies, we see that direct combustion of biomass has IERs of 3 to 20, with the energy cost of fertilization a dominant factor at the low end. Biomass liquids have IERs of 1 to 5. One study of ethanol from corn found an IER from 1 to 1.4 for total energy, which increased to 2.3–3.8 when calculated for premium fuel (liquids) only (another study 25 years later similarly found IER = 1.5). Solar space heat has IERs from 2 to 15. The high variation is partly due to climate, partly due to the boundary issue of how much of a solar house is the solar system (especially for passive solar), and partly due to the degree of coverage. The latter is another boundary

TABLE II
Selected Net Energy Results

Technology	Date	IER (unless otherwise stated)	Comment
Coal, U.S. average	1970s	37	
Eastern surface coal	1970s	43	Surface mining tends to have a higher IER compared to deep mining
Crude petroleum delivered to refinery	1970s	7	
Natural gas delivered through gas utility to user	1970s	11	
Coal mine-mouth electric power plant	1977	8	
Solar power satellite	1979	2.1 ± 0.8	Very uncertain; the IER for the photovoltaic cells alone would likely be higher today
Ethanol from corn for gasohol (gasoline:ethanol = 90:10)	1979, 1995	≈ 1.5 to 2.5	Extremely sensitive to issues in Table I
Ceiling insulation as source of saved energy	1970s	136	Best case, previously uninsulated house
Geothermal–electric plant (vapor dominated)	1981	13 ± 4	Geothermal heat is not counted in the IER
Geothermal–electric plant (liquid dominated)	1981	4 ± 1	Geothermal heat is not counted in the IER
Short-rotation (≈ 5 -yr) trees for direct combustion	1980s	10 to 20 if unfertilized; 2 to 4 if fertilized	Unfertilized is likely unsustainable
Short-rotation biomass (trees, ≈ 5 yrs; grass, 1 yr) for direct combustion	1980s	6 if unfertilized; 2 if fertilized	Unfertilized is likely unsustainable
Residential solar space heat	1980s	2–15	Depends on climate and how well insulated the structure is (climate dependent); passive (no moving parts) tends to have higher IER compared to active
Residential solar hot water	1980s	2–5	Climate dependent
Photovoltaic cells	1976	Simple energy payback time ≈ 12 yr	
Photovoltaic cells	2000	Simple energy payback time = 1.1 to 4 yr	Payback time must be compared with device lifetime; this study concludes that the IER ≈ 30 , implying a lifetime of at least 30 + yr

issue. A solar heating system that can supply year-round heat, including that one continuously overcast 5°F week in January, will require more inputs (such as more glass, thermal mass, and storage tanks). This system's IER will be lower than the IER for a system that is not expected to cover the worst periods—for which there is, say, a backup propane furnace that is not considered part of the solar heating system.

A similar comment applies to conservation as an energy source. The $IER > 100$ for ceiling insulation is for the first few inches of insulation in a totally uninsulated house. Putting that same insulation in a house already somewhat insulated would save less energy and give a lower IER. Also, photovoltaic cells have become better net energy producers over time as reliability has increased and material inputs have decreased.

5. CONCLUDING COMMENTS

Interpreting net energy information such as that in Table II almost instantly raises questions of the details and assumptions, which the critical reader must embrace. In spite of these, the concept (and the specter!) of the energy breakeven point and hence exhaustion is compelling enough for continued study. Perhaps the most vivid way to address this is by asking how IERs are changing over time.

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