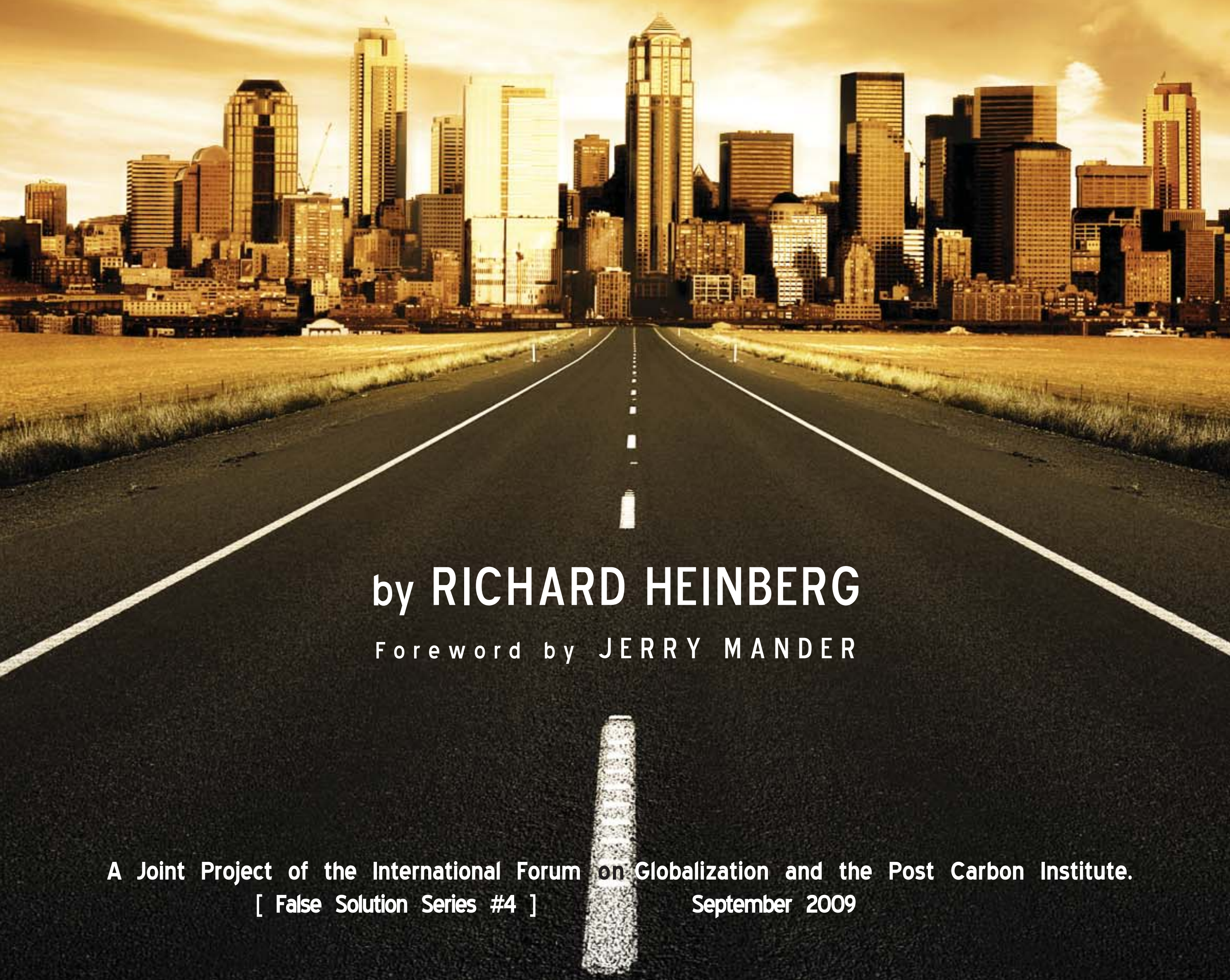
[THE CONSERVATION IMPERATIVE]

SEARCHING FOR A MIRACLE

"NET ENERGY" LIMITS & THE FATE OF INDUSTRIAL SOCIETY



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'Net Energy' Limits & the Fate of Industrial Society

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Tokyo. Powered by imported oil and gas, combined with nuclear and coal. Japan is world's 3rd largest importer of oil and gas (after U.S. and China) and 4th largest user of energy (after U.S., China, Russia.) Fierce competition among industrial nations for remaining supplies, especially from Africa, South America, and the middle East, creates a precarious geopolitical situation. Japan may turn in future to more nuclear.

ISTOCK

As fossil fuels' supply dwindles and becomes more costly and polluting, renewed attention is on nuclear, and a theoretical "4th generation" of safer technology. But, as with proposed "clean coal" technology, "new nuclear" remains in the realm of scientific imagination, with high odds against it, and terrible downside potential. Problems of safe production, transport, waste disposal, ballooning costs, and limits of uranium supply are not nearly resolved. And nuclear's "net energy" ratio—the amount of energy produced vs. the amount expended to produce it—is low, putting it squarely into the category of "false solution."

FOREWORD: WHICH WAY OUT?

by Jerry Mander

International Forum on Globalization

This landmark report by Richard Heinberg is #4 in the False Solutions series published since 2006 by the International Forum on Globalization.

Prior reports include "The False Promise of Biofuels," by IFG board member Jack Santa Barbara, which was first to predict what was confirmed a year later in dire studies from the Organization of Economic Cooperation and Development (OECD) and the United Nations—that the mad rush toward biofuels, especially corn ethanol, well underway by 2006, would cause more global environmental, agricultural and hunger problems, than it could ever begin to solve.

Despite this, U.S. policy continues to favor subsidizing industrial biofuels.

A second publication in the series, produced in partnership with the Institute for Policy Studies, was "The Manifesto on Global Economic Transitions"—a collective effort among 50 IFG Board and Associate Members. It is essentially a draft roadmap for the mandatory transformation of industrial society in recognition of limits imposed by planetary carrying capacities.

The third report, "The Rise and Predictable Fall of Globalized Industrial Agriculture," was written by former IFG executive director, Debbie Barker. That report shredded the expensively advertised notions that industrial agriculture systems are the best way "to feed a hungry world." The opposite is actually the case. The publication exposed and amplified a myriad of little-recognized connections of industrial farming to advancing hunger, global migrations, and climate change, among many other deadly effects. All of these publications are now in wide distribution.

The report which follows here, "Searching for a Miracle: 'Net Energy' Limits, & the Fate of Industrial Society," by our longtime friend and colleague Richard Heinberg, an associate member of IFG and senior fellow of the Post Carbon Institute, is the first to use the newly emerging techniques of "life cycle technology assessment," and in particular "net energy" analyses, for in-depth comparisons among all presently dominant and newly touted "alternative" energy schemes. These include all the major renewable systems currently being advocated. For the first time we are able to fully realize the degree to which our future societal options are far more limited than we thought.

With fossil fuels fast disappearing, and their continuing supplies becoming ever more problematic and expensive, hopes have turned to renewable sources that we ask to save "our way of life" at more or less its current level. Alas, as we will see, the "net energy" gain from all alternative systems—that is, the amount of energy produced, compared with the amount of energy (as well as money and materials) that must be invested in building and operating them—is far too small to begin to sustain industrial society at its present levels. This is very grim news, and demands vast, rapid adjustments by all parties, from governments to industries and even environmental organizations, that thus far are not clearly in the offing. There are, however, viable pathways forward, most importantly and urgently the need for a wide-ranging push for conservation; it is only a question of realism, flexibility, *dedication, and more than a little humility. Our beloved "way of life" must be reconsidered and more viable alternatives supported.*

THE WRONG TREE

We observe daily the tragic, futile official processes that continue to unfold among national governments, as well as global political and financial institutions, as they give lip service to mitigating climate change and the multiple advancing related global environmental catastrophes. Those crises include not only climate disruption, and looming global fossil fuels shortages, but other profound depletions of key resources—fresh water, arable soils, ocean life, wood, crucial minerals, biodiversity, and breathable air, etc. All these crises are results of the same sets of values and operating systems, and all are nearing points of extreme urgency.

Even our once great hopes that world governments would rally to achieve positive collective outcomes in some arenas; for example, at the United Nations climate change talks in Copenhagen, as well as other venues, are proving sadly fatuous. But certain things are ever-more clear: Global institutions, national governments, and even many environmental and social activists are barking up the wrong trees. Individually and as groups, they have not faced the full gravity and meaning of the global energy (and resource) conundrums. They continue to operate in most ways out of the same set of assumptions that we've all had for the past century—that fundamental systemic changes will not be required; that our complex of problems can be cured by human innovation, ingenuity, and technical efficiency, together with a few smart changes in our choices of energy systems.

Most of all, the prevailing institutions continue to believe in the primacy and efficacy of economic growth as the key indicator of systemic well-being, even in light of ever-diminishing resources. It will not be necessary, according to this dogma, to come to grips with the reality that ever-expanding economic growth is actually an absurdity in a finite system, preposterous on its face, and will soon be over even if activists do nothing to oppose it. Neither does the mainstream recognize that economic systems, notably capitalism, that *require* such endless growth for their own viability may themselves be doomed in the not very long run. In fact, they are already showing clear signs of collapse. As to any need for substantial changes in personal lifestyles, or to control and *limit* material consumption habits? Quite the opposite is being pushed—increased car sales, expanded "housing starts," and increased industrial production remain the focused goals of our economy, even under Mr. Obama, and are still celebrated when/if they occur, without thought of environmental consequences. No alterations in conceptual frameworks are encouraged to appreciate the now highly visible limits of nature, which is both root source of all planetary benefits, and inevitable toxic sink for our excessive habits.

In this optimistic though self-deluding dominant vision, there is also dedicated avoidance of the need for any meaningful *redistribution* of the planet's increasingly scarce remaining natural resources toward more equitable arrangements among nations and peoples—to at least slightly mitigate centuries of colonial and corporate plunder of the Third World. And on the similarly ignored question of the continued viability of a small planet that may soon need to support 8-10 billion people? Some actually say it's a *good* thing. We should think of these billions as new consumers who may help enliven economic growth, so goes that argument. But only if we find a few more planets nearby, perhaps in a parallel universe somewhere, bursting with oil, gas, water, minerals, wood, rich agricultural lands, and a virginal atmosphere.

The scale of denial is breathtaking. For as Heinberg's analysis makes depressingly clear, *there will be NO combination of alternative energy solutions that might enable the long term continuation of economic growth, or of industrial societies in their present form and scale.* Ultimately the solutions we desperately seek will not come from ever-greater technical genius and innovation. Far better and potentially more successful pathways can only come from a sharp turn to goals, values, and practices that emphasize conservation of material and energy resources, localization of most economic frameworks, and gradual population reduction to stay within the carrying capacities of the planet.

THE PARTY'S OVER

The central purpose of all of our *False Solution* documents, including this one, is to assert that this whole set of assumptions upon which our institutions have hung their collective hats, is tragically inaccurate, and only serves to delay, at a crucial moment, a major reckoning that must be understood immediately.

We are emphatically *not* against innovations and efficiencies where they can be helpful. But we are against the grand delusion that they can solve all problems, and we are against the tendency to ignore overarching inherent systemic limits that apply to energy supply, materials supply, and the Earth itself. For example, the grandest techno-utopian predictions at large today, such as "clean coal," via carbon sequestration, and "clean nuclear," via a new "safe 4th generation of reactor design," have already been revealed as little more than the wild fantasies of energy industries, as they peddle talking points to politicians to whom, on other days, they also supply with campaign cash. There is no persuasive evidence that clean coal, still in the realm of science fiction, will *ever* be achieved. Most likely it will occupy the same pantheon of technological fantasy as nuclear fusion, not to say human teleportation. In any case, the entire argument for clean coal, however absurd, still ignores what happens to the places from where it comes. Visit Appalachia sometime—now virtually desertified from mountain top removal, and its rivers poisoned to get at that soon-to-be "clean" coal. Clean nuclear offers similar anomalies—no currently contemplated solution for waste disposal is anywhere near practical—even if uranium supplies were not running out nearly as quickly as oil. To speak of nuclear as "clean" or "safe" is a clear sign of panic while, vampire-like, it's permitted to again rise from its grave.

Okay, we know that some technological "progress" is useful, especially among renewable energy alternatives. Systemic transformations toward a highly touted new complex mix of "renewable" energy systems such as wind, solar, hydro, biomass, wave and several others, will certainly be positive, and together they could make meaningful contributions, free of many of the negative environmental impacts that fossil fuels have brought.

But, as this report exquisitely explains, as beneficial as those shifts may be, they will inevitably fall far short. *They will never reach the scale or capacity to substitute for a fossil fuel system that, because of its (temporary) abundance and cheapness, has addicted industrial nations to a 20th century production and consumption spree that landed us, and the whole world, into this dire situation.* As Richard Heinberg has so eloquently said before, and used as the title of one his very important books, "the party's over."

So, those limitless supplies turned out not to be limitless, or cheap, (or any longer efficient), and we are left with only one real option: to face the need for a thorough systemic transformation of our entire society to one that emphasizes *less* consumption of material resources and energy (conservation), less globalization (shipping resources and products back and forth wastefully across oceans and continents), and *more* localization which has inherent efficiencies and savings from the mere fact of local production and use, and far less processing and shipping. Such changes must be combined with achieving lower population in all global sectors, and the fostering of an evolution of personal, institutional and national values that recognize (even celebrate) the ultimate limits of the earth's carrying capacities, presently being dramatically exceeded. None of that vision has infected the Copenhagen processes, nor those of the U.S. Congress, nor debates in national parliaments; anything short of that is just a self-protective, self-interested smoke screen, or, sheer denial of the realities at hand.

THE NET ENERGY FACTOR

Richard Heinberg's report makes its case by a methodical examination and *comparison* of many of the most important features inherent to the key energy systems of our time. His detailed summaries include "life cycle assessments" of the currently dominant systems such as oil, gas, coal, and nuclear—the very systems which built industrial society, and brought us to this grave historical moment. These systems are now each suffering advancing supply shortages and increased costs, making their future application dubious. Heinberg then explores and compares all the alternative systems now being hotly promoted, like wind, solar, hydro, geothermal, biomass and biofuels, incineration, wave energy and others. He delineates ten aspects of each system, including everything from direct monetary cost (*can we afford it?*), as well as "scalability" (*will its benefits apply at a meaningful volume?*). He also includes environmental impacts in the formula; the location of the resources; their reliability (*the wind doesn't blow all the time and the sun doesn't shine*); density—how compact is the source per unit?; transportability, etc.

Most important is the tenth standard that Heinberg lists—and the bulk of this document is devoted to it: "net energy," or, the Energy Returned on Energy Invested (EROEI). Heinberg explores this revolutionary analytic terrain thoroughly, basing his reportage on the groundbreaking research of leading scientists, notably including Charles Hall of Syracuse University, who has been the pioneer explorer of the full import of "net energy" to the future of industrialism and economic growth.

What is revealed from this process is that the once great advantages of fossil fuel systems, which in their heyday were able to produce enormous quantities of cheap energy *outputs* with relatively little investment of energy *inputs* or dollar investments—Heinberg puts the EROEI ratio at about 100:1—can no longer approach that level. And, of course, they continue to ravage the planet. Meanwhile, the highly promising alternative energy systems, which in most respects are surely far cleaner than fossil fuels, cannot yield net energy ratios that are anywhere near what was possible with fossil fuels. In other words, they require for their operation a significant volume of energy *inputs* that bring their energy *outputs* to a very modest level. Too modest, actually, to be considered a sufficient substitute for the disappearing fossil fuels. In fact, as Heinberg notes, there is no combination of alternative renewables that can compete with the glory days of fossil fuels, now ending. So, what does this portend for modern society? Industrialism? Economic growth? Our current standards of living? All prior assumptions are off the table. Which way now? Systemic change will be mandatory.

Of course, there is a huge segment of the grassroots activist world that already instinctively understood all this some time ago, and has not waited for governments, separately or in collaboration with others, to do the right thing. The world is now bursting with examples on every continent of enthusiastic efforts to transform communities into locally viable and sustainable economic systems. We see a virtual renaissance of local food systems, thus replacing the supplies of the industrial agriculture machine that often ships from across thousands of miles of land or ocean. And this burgeoning movement is directly supported by a parallel movement toward re-ruralization. We also see extraordinary efforts to limit the power of global corporations operating in local contexts. There is a growing effort by communities to assert control over their own local commons; to resist privatization of public services; and to return to local production values in manufacturing and energy systems so that conservation is placed ahead of consumption. A myriad other efforts also seek to affirm local sovereignty.

Among the most exciting expressions of these tendencies has been the birth and spread of an international "Transition Towns" movement. Originally launched a few years ago in southwest England, it has helped stimulate literally thousands of similar efforts in local communities, including hundreds in the U.S. All are trying to go back to the drawing board to convert all operating systems toward active conservation efforts that minimize material and energy flow-through, protecting scarce resources, while moving toward energy and production systems that are cognizant of and reactive to an entirely alternative set of values.

So far, this is not yet threatening to the larger machines of industrialism and growth, nor to the primacy of corporate power, but time is definitely on the side of such movements. It behooves us all to align ourselves with them. In this case, it is mandatory that we build and take action at the local grassroots level, while also demanding change from our governing institutions, locally, nationally and internationally. But in any case, as the document you are about to read helps make exquisitely clear, the status quo will not survive.

GIGIE CRUZ/GAIA

One hidden underbelly of a global economy, dependent on growth and consumption; this roadway runs through miles of trash and waste fields outside Manila. Similar landscapes of waste and pollution are found today in every modern country with one of the world's largest just outside New York.

ISTOCK

Some nations want to expand off-shore drilling, despite threats of spills to oceans, beaches, reefs, and sealife. Increased hurricane dangers from climate change make safety of these platforms ever-more doubtful, and raise chances of future Katrina-like collapses. Meanwhile, oil production also suffers overall declining rates of "net energy" and is far less viable than in its heyday. (See chapter three.)

One

OVERVIEW

THIS REPORT IS INTENDED as a non-technical examination of a basic question: *Can any combination of known energy sources successfully supply society's energy needs at least up to the year 2100?* In the end, we are left with the disturbing conclusion that *all* known energy sources are subject to strict limits of one kind or another. Conventional energy sources such as oil, gas, coal, and nuclear are either at or nearing the limits of their ability to grow in annual supply, and will dwindle as the decades proceed—but in any case they are unacceptably hazardous to the environment. And contrary to the hopes of many, there is no clear practical scenario by which we can replace the energy from today's conventional sources with sufficient energy from *alternative* sources to sustain industrial society at its present scale of operations. To achieve such a transition would require *(1)* a vast financial investment beyond society's practical abilities, *(2)* a very long time—too long in practical terms—for build-out, and *(3)* significant sacrifices in terms of energy quality and reliability.

Perhaps the most significant limit to future energy supplies is the "net energy" factor—the requirement that energy systems yield more energy than is invested in their construction and operation. There is a strong likelihood that future energy systems, both conventional and alternative, will have higher energy input costs than those that powered industrial societies during the last century. We will come back to this point repeatedly.

The report explores some of the presently proposed energy transition scenarios, showing why, up to this time, most are overly optimistic, as they do not address all of the relevant limiting factors to the expansion of alternative energy sources. Finally, it shows why energy conservation (using less energy, and also less resource materials) combined with humane, gradual population decline must become primary strategies for achieving sustainability.

* * *

The world's current energy regime is unsustainable. This is the recent, explicit conclusion of the International Energy Agency[1], and it is also the substance of a wide and growing public consensus ranging across the political spectrum. One broad segment of this consensus is concerned about the climate and the other environmental impacts of society's reliance on fossil fuels. The other is mainly troubled by questions regarding the security of future supplies of these fuels—which, as they deplete, are increasingly concentrated in only a few countries.

To say that our current energy regime is unsustainable means that it cannot continue and must therefore be replaced with something else. However, replacing the energy infrastructure of modern industrial societies will be no trivial matter. Decades have been spent building the current oil-coal-gas infrastructure, and trillions of dollars invested. Moreover, if the transition from current energy sources to alternatives is wrongly managed, the consequences could be severe: there is an undeniable connection between per-capita levels of energy consumption and economic well-being.[2] A failure to supply sufficient energy, or energy of sufficient quality, could undermine the future welfare of humanity, while a failure to quickly make the transition away from fossil fuels could imperil the Earth's vital ecosystems.

Nonetheless, it remains a commonly held assumption that alternative energy sources capable of substituting for conventional fossil fuels are readily available—whether fossil (tar sands or oil shale), nuclear, or a long list of renewables—and ready to come on-line in a bigger way. All that is necessary, according to this view, is to invest sufficiently in them, and life will go on essentially as it is.

But is this really the case? Each energy source has highly specific characteristics. In fact, it has been the characteristics of our present energy sources (principally oil, coal, and natural gas) that have enabled the building of a modern society with high mobility, large population, and high economic growth rates. Can alternative energy sources perpetuate this kind of society? Alas, we think not.

While it is possible to point to innumerable successful alternative energy production installations within modern societies (ranging from small home-scale photovoltaic systems to large "farms" of three-megawatt wind turbines), it is not possible to point to more than a very few examples of an entire modern industrial nation obtaining the bulk of its energy from sources other than oil, coal, and natural gas. One such rare example is Sweden, which gets most of its energy from nuclear and hydropower. Another is Iceland, which benefits from unusually large domestic geothermal resources, not found in most other countries. Even in these two cases, the situation is more complex than it appears. The construction of the infrastructure for these power plants mostly relied on fossil fuels for the mining of the ores and raw materials, materials processing, transportation, manufacturing of components, the mining of uranium, construction energy, and so on. Thus for most of the world, a meaningful energy transition is still more theory than reality.

But if current primary energy sources are unsustainable, this implies a daunting problem. The transition to alternative sources *must* occur, or the world will lack sufficient energy to maintain basic services for its 6.8 billion people (and counting).

Thus it is vitally important that energy alternatives be evaluated thoroughly according to relevant criteria, and that a staged plan be formulated and funded for a systemic societal transition away from oil, coal, and natural gas and toward the alternative energy sources deemed most fully capable of supplying the kind of economic benefits we have been accustomed to from conventional fossil fuels.

By now, it is possible to assemble a bookshelf filled with reports from nonprofit environmental organizations and books from energy analysts, dating from the early 1970s to the present, all attempting to illuminate alternative energy transition pathways for the United States and the world as a whole. These plans and proposals vary in breadth and quality, and especially in their success at clearly identifying the factors that are limiting specific alternative energy sources from being able to adequately replace conventional fossil fuels.

It is a central purpose of this document to systematically review key limiting factors that are often left out of such analyses. We will begin that process in the next section. Following that, we will go further into depth on one key criterion: *net energy*, or *energy returned on energy invested* (EROEI). This measure focuses on the key question: All things considered, how much more energy does a system produce than is required to develop and operate that system? What is the ratio of energy *in* versus energy *out*? Some energy "sources" can be shown to produce little or no *net* energy. Others are only minimally positive.

Unfortunately, as we shall see in more detail below, research on EROEI continues to suffer from lack of standard measurement practices, and its use and implications remain widely misunderstood. Nevertheless, for the purposes of large-scale and long-range planning, net energy may be the most vital criterion for evaluating energy sources, as it so clearly reveals the tradeoffs involved in any shift to new energy sources.

This report is not intended to serve as a final authoritative, comprehensive analysis of available energy options, nor as a plan for a nation-wide or global transition from fossil fuels to alternatives. While such analyses and plans are needed, they will require institutional resources and ongoing reassessment to be of value. The goal here is simply to identify and explain the primary criteria that should be used in such analyses and plans, with special emphasis on *net energy,* and to offer a cursory evaluation of currently available energy sources, using those criteria. This will provide a general, preliminary sense of whether alternative sources are up to the job of replacing fossil fuels; and if they are not, we can begin to explore what might be the fall-back strategy of governments and the other responsible institutions of modern society.

As we will see, the fundamental disturbing conclusion of the report is that there is little likelihood that either conventional fossil fuels or alternative energy sources can reliably be counted on to provide the amount and quality of energy that will be needed to sustain economic growth—or even current levels of economic activity—during the remainder of the current century.

This preliminary conclusion in turn suggests that a sensible transition energy plan will have to emphasize energy conservation above all. It also raises questions about the sustainability of growth *per se*, both in terms of human population numbers and economic activity.

MALCOLM LINTON/LIAISON

As in South America, Africa's oil resources are a target for corporate giants like Shell. Indigenous communities are invaded by massive infrastructures in their forests and waters, bringing oil spills, forced removals, and military actions. In the Niger delta, where this warning sign turns away people from docks, nearly full-scale war has broken out between resisting indigenous groups, such as the Ogoni people, and global oil companies, seeking control of traditional lands.

GLOSSARY OF TERMS

CCS: Carbon Capture and Storage. When applied to coal, this still somewhat hypothetical set of technologies is often referred to as "clean coal." Many energy experts doubt that CCS can be deployed on a significant scale.

Carbon Dioxide, or CO_2: A colorless, odorless, incombustible gas, that is formed during respiration, combustion, and organic decomposition. Carbon dioxide is a minor natural constituent of Earth's atmosphere, but its abundance has increased substantially (from 280 parts per million to 387 ppm) since the beginning of the Industrial Revolution due to the burning of fossil fuels. CO_2 traps heat in Earth's atmosphere; as the concentration of the gas increases, the planet's temperature rises.

DDGS: Distillers Dried Grains with Solubles. A byproduct of producing ethanol from corn, DDGS is typically used as livestock feed.

Efficiency: The ratio between the useful *output* of an energy *conversion* machine and the *input*, in energy terms. When the useful output of conversion increases relative to input, the machine is considered more energy efficient. Typically *efficiency* applies to machines that use energy to do work (like cars or household electrical devices), or that convert energy from one form to another (like coal-burning power plants that make electricity). *Efficiency* differs from *EROEI* (see below), which typically describes the ratio between the broader energy inputs and outputs of an energy *production* system, such as a coalmine, a wind farm, or an operating oilfield. The distinction can be confusing, because sometimes both *efficiency* and *EROEI* can be applied to different aspects of the same energy system. For example, *efficiency* is used to describe the input/output of a photovoltaic solar panel (in terms of how much of the energy of sunlight is converted to electricity), while *EROEI* describes how much useful energy the panel will produce as compared to the amount of energy required to build and maintain it.

EGS: Enhanced Geothermal System. This refers to a fledgling technology that employs equipment developed by the oil and gas industry to pipe water deep below the surface, where the natural heat of Earth's crust turns it to steam that can turn a turbine.

EIA: Energy Information Administration, a branch of the U.S. Department of Energy.
Electricity: Energy made available by the flow of electric charge through a conductor.

Embodied energy: the available energy that was used in the work of making a product. This includes the activities needed to acquire natural resources, the energy used manufacturing and in making equipment and in other supporting functions—i.e., direct energy plus indirect energy.

Energy: The capacity of a physical system to do work, measured in joules or ergs. (See expanded definition, next page.)

Energy carrier: A substance (such as hydrogen) or phenomenon (such as electric current) that can be used to produce mechanical work or heat or to operate chemical or physical processes. In practical terms, this refers to a means of conveying energy from ultimate source to practical application. Our national system of electricity generating plants and power lines serves this function: it converts energy from coal, natural gas, uranium, flowing water, wind, or sunlight into a common carrier (electricity) that can be made widely available to accomplish a wide array of tasks.

EROEI: "Energy Returned on Energy Invested," also known as EROI (energy return on investment), is the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource. Not to be confused with *efficiency* (see above).

Feed-in tariff: An incentive structure to encourage the adoption of renewable energy through government legislation. Regional or national electricity utilities become obligated to buy renewable electricity (from renewable sources such as solar photovoltaics, wind power, biomass, hydropower, and geothermal power) at constant, above-market rates set by the government.

Food energy: The amount of chemically stored energy present in food, usually measured in kilocalories (often written simply as "calories"). All animals require a minimum periodic intake of food energy—as well as water and an array of specific nutrients (vitamins and minerals).

GHG: Greenhouse gases.

Horsepower: A unit of power originally intended to measure and compare the output of steam engines with the power output of draft horses. The definition of a horsepower unit varies in different applications (e.g., for rating boilers or electric motors); however, the most common definition, applying primarily to electric motors, is: a unit of power equal to 746 watts. Where units of horsepower are used for marketing consumer products, measurement methods are often designed by advertisers to maximize the magnitude of the number, even if it doesn't reflect the realistic capacity of the product to do work under normal conditions.

IEA: International Energy Agency. Headquartered in Paris, the IEA was created by the OECD nations after the oil shock of 1973 to monitor world energy supplies.

IGCC: Integrated Gasification Combined Cycle, an advanced type of coal power plant in which coal is brought together with water and air under high heat and pressure to produce a gas—synthesis gas (syngas), composed primarily of hydrogen and carbon monoxide — along with solid waste. It then removes impurities from the syngas before it is combusted.

IPCC: Intergovernmental Panel on Climate Change, a scientific body tasked to evaluate the risk of climate change caused by human activity. The panel was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). The IPCC shared the 2007 Nobel Peace Prize with Al Gore.

Joule: A unit of electrical energy equal to the work done when a current of one ampere passes through a resistance of one ohm for one second.

Mb/d: Millions of barrels per day.

Photovoltaic (PV): Producing a voltage when exposed to radiant energy (especially sunlight).

Net energy (sometimes referred to as Net Energy Gain or NEG): A concept used in energy economics that refers to the ratio between the energy expended to harvest an energy source and the amount of energy gained from that harvest.

Power: The rate of doing work, measured in watts (joules per second). (See Horsepower above.)

Transesterification: A process that converts animal fats or more commonly plant oils into biodiesel. In more technical terms: the reaction of a triglyceride (fat/oil) with an alcohol to form esters (a class of organic compounds formed from an organic acid and an alcohol) and glycerol (glycerine). The reaction is often catalyzed by the addition of a strong alkaline like sodium hydroxide (lye). The products of the reaction are mono-alkyl ester (biodiesel) and glycerol.

Trombe wall: A typical feature of passive solar design, a trombe wall is a very thick, south-facing wall that is painted black and made of a material that absorbs a lot of heat. A pane of glass or plastic glazing, installed a few inches in front of the wall, helps hold in the heat. The wall heats up slowly during the day. Then as it cools gradually during the night, it gives off its heat inside the building.

UCG: Underground coal gasification. Where practical, this technology could gasify coal more cheaply than above-ground IGCC power plants (gasification of coal is a stage in CCS, see above).

Watt: A unit of power equal to 1 joule per second.

> **Watt-hour:** A unit of energy equal to the power of one watt operating for one hour.
>
> **Kilowatt (KW):** Thousand watts.
>
> **KWH:** Thousand watt-hours.
>
> **Megawatt (MW):** Million watts.
>
> **MWH:** Million watt-hours.
>
> **Gigawatt (GW):** Billion watts.
>
> **GWH:** Billion watt-hours.
>
> **Terawatt (TW):** Trillion watts.
>
> **TWH:** Trillion watt-hours.

Work: The transfer of energy from one physical system to another, especially the transfer of energy to a body by the application of a force that moves the body in the direction of the force. It is calculated as the product of the force and the distance through which the body moves and is expressed in joules, ergs, and foot-pounds.

WHAT IS "ENERGY"?

Energy is often defined as "the capacity of a physical system to do work," while work is said to be "force times distance traveled." But these definitions quickly become circular, as no one has seen "force" or "energy" apart from the effect that they have upon matter (which itself is difficult to define in the final analysis).

However hard it may be to define, we know that energy is the basis of everything: without it, nothing happens. Plants don't grow, cars don't move, and our homes get uncomfortably cold in the winter. Physicists may discuss energy in relation to stars and atoms, but energy is equally important to ecosystems and human economies: without sources of energy, living things die and economies grind to a halt.

Throughout history, most of the energy that humans have used has come to them in the form of food—the energy of sunlight captured and stored in plants (and in animals that eat plants). At the same time, humans have exerted energy, mostly by way of their muscles, in order to get what they wanted and needed, including food. It was essential that they harvested more food-energy than they expended in striving for it; otherwise, starvation resulted.

With animal domestication, primary energy still came by way of food, but much of that food (often of a sort that people couldn't eat) was fed to animals, whose muscles could be harnessed to pull plows, carts, and chariots.

People have also long used non-food energy by burning wood (a store of solar energy) for heat.

More recently, humans have found ways to "digest" energy that millions of years ago was chemically stored in the form of fossil fuels—"digesting" it not in their stomachs, but in the engines of machines that do work that human or animal muscles used to do; indeed, we have invented machines to do far more things than we were capable of previously, including work that human muscles could never do. Because fossil fuels represent energy stored in a more concentrated form than is found in the food we eat; because we can use fuel to power a great variety of machines; and because it has been possible to harvest fossil fuels in enormous and growing quantities, humankind has been able to build an interconnected global economy of unprecedented scope. However, fossil fuels are by their very nature finite, depleting resources. So, during recent decades enormous and increasing interest has been paid to the development of non-fossil, "alternative" energy sources.

Today, when we discuss national or global energy problems, we are mostly concerned about the energy for our machines. Most of the energy that humans use is still, in essence, solar energy—sunlight captured in food crops or forests; ancient sunlight stored in fossil fuels; sunlight heating air and fanning winds whose power can be harnessed with turbines; or sunlight transformed directly into electricity via photovoltaic panels. However, some non-solar forms of energy are also now available to us: tidal power captures the gravitational influence of the Moon and other celestial bodies; geothermal power uses Earth's heat, and nuclear power harnesses the energy given off by the decay of radioactive elements.

Even though we use more energy sources today than our ancestors did, and we use them in more ingenious and impressive ways, one vitally important principle still applies today as in the past, when our energy concerns had more directly to do with sunlight, green plants, and muscles: we must still expend energy to obtain energy, and our continued success as a species very much depends on our ability to obtain more energy from energy-harvesting efforts than we spend in those efforts.

LOU DEMATTEIS

Here's one benefit of the maze of pipelines and infrastructures driven through indigenous homelands in the Amazon; a daring new game for a young indigenous boy.

ISTOCK

The leading sources of CO_2 emissions in the U.S. are coal-fired power plants like this one. There are increased efforts to regulate major greenhouse gas polluters, and new emphases on developing so-called "clean coal" technologies of carbon capture and "sequestration" (burial). But the benefits of these measures are uncertain, and sequestration is in its infancy. As with nuclear waste, the question becomes: how long can buried coal gases stay buried? That aside, most U.S. coal now comes from mountain-top removal mining (see back cover and chapter four) which is transforming the glorious mountains of several states into wastelands, and will never qualify as "clean." In any case, coal reserves are far lower than have been reputed, making long term viability doubtful.

Two

NINE KEY CRITERIA: COMPARING ENERGY SYSTEMS AND THEIR LIMITS

IN EVALUATING ENERGY SOURCES, it is essential first to give attention to the criteria being used. Some criteria give us good information about an energy source's usefulness for specific applications. For example, an energy source like oil shale that is a solid material at room temperature and has low energy density per unit of weight and volume is highly unlikely to be good as a transport fuel unless it can first somehow profitably be turned into a liquid fuel with higher energy density (i.e., one that contains more energy per unit of weight or volume). Other criteria gauge the potential for a specific energy source to power large segments of an entire society. Micro-hydro power, for example, can be environmentally benign, but its yield cannot be sufficiently increased in scale to provide a significant portion of the national energy budget of the U.S. or other industrial countries.

In general, it is important to identify energy sources that are capable of being scaled up to produce large quantities of energy, that have high economic utility, and that have minimal environmental impacts, particularly those impacts having to do with land use and water requirements, as well as with greenhouse gas emissions. Only sources that pass these tests are capable of becoming our future *primary* energy sources—that is, ones capably of supplying energy on the scale that fossil fuels currently do.

The economic utility and scalability of any energy source are determined by three main factors: the size of the resource base, the energy density of the resource itself, and the quantity and nature of other resources and infrastructures needed to process and employ the energy source in question.

Economist Douglas Reynolds, in a paper discussing the energy density of energy sources (which he terms "energy grade"), writes:

> Energy is the driving force behind industrial production and is indeed the driving force behind any economic activity. However, if an economy's available energy resources have low grades, i.e. low potential productivity, then new technology will not be able to stimulate economic growth as much. On the other hand, high-grade energy resources could magnify the effect of technology and create tremendous economic growth. High-grade resources [i.e., ones that have high energy density] can act as magnifiers of technology, but low-grade resources can dampen the forcefulness of new technology. This leads to the conclusion that it is important to emphasize the role of the inherent nature of resources in economic growth more fully. [3]

But economic utility is not the only test an energy source must meet. If there is anything to be learned from the ongoing and worsening climate crisis, it is that the environmental impacts of energy sources must be taken very seriously indeed. The world cannot afford to replace oil, coal, and gas with other energy sources that might pose a survival challenge to future generations.

So here, then, are nine energy evaluation criteria. In the section following this one, we will describe a tenth, net energy.

1. Direct Monetary Cost

This is the criterion to which most attention is normally paid. Clearly, energy must be affordable and competitively priced if it is to be useful to society. However, the immediate monetary cost of energy does not always reflect its *true* cost, as some energy sources may benefit from huge hidden state subsidies, or may have externalized costs (such as grave environmental impacts that later need correction). The monetary cost of energy resources is largely determined by the other criteria listed below.

The cost of energy typically includes factors such as the costs of resource extraction and refining or other resource modification or improvement, and transport. The repayment of investment in infrastructure (factories for building solar panels; nuclear power plants; refineries; and power lines, pipelines, and tankers) must also inevitably be reflected in energy prices.

However, prices can also be skewed by subsidies or restrictions of various kinds—including tax breaks to certain kinds of energy companies, pollution regulations, government investment in energy research and development, and government investment in infrastructure that favors the use of a particular kind of energy.

2. Dependence on Additional Resources

Very few energy sources come in an immediately useable form. One such example: Without exerting effort or employing any technology we can be warmed by the sunlight that falls on our shoulders on a spring day. In contrast, most energy sources, in order to be useful, require some method of gathering, mining, or processing fuels and then converting the resulting energy. In turn this usually entails some kind of apparatus, made of some kind of additional materials (for example, oil-drilling equipment is

TABLE 1A: TODAY'S ENERGY COST

Cost of existing power generation (cents per kWh)

Coal	2 to 4
Natural gas	4 to 7
Hydropower	1
Nuclear	2.9
Wind	4.5 to 10
Biomass power	4 to 9
Solar PV	21 to 83
Geothermal	10
Solar thermal	6 to 15
Tidal	10
Wave	12

Table 1A. These are approximate costs of production for eleven energy sources. (Residential electricity consumers typically pay from $.10 to $.20 per kWh.) Source: U.S. Federal Regulatory Commission, 2007.[4]

TABLE 1B: COST OF NEW ENERGY

Cost of new energy ($/kW)

Coal	1900-5800
Natural gas	500-1500
Hydropower	NA
Nuclear	4500-7500
Wind	1300-2500
Biomass power	NA
Solar PV	3900-9000
Geothermal	2600-3500
Solar thermal	3000-5000
Tidal	NA
Wave	NA

Table 1B. "New generation" refers to the infrastructure cost of introducing the capacity to produce one kilowatt on an ongoing basis; it does not refer to the cost of the actual generated power per kilowatt hour. Source: U.S. Federal Regulatory Commission, 2007.[5]

made from steel and diamonds). And sometimes the extraction or conversion process uses additional resources (for example, the production of synthetic diesel fuel from tar sands requires enormous quantities of water and natural gas, and the production of biofuels requires large quantities of water). The amount or scarcity of the added materials or resources, and the complexity and cost of the various apparatuses required at different stages, thus constitute important limiting factors on most modes of energy production.

The requirements for ancillary resources at early stages of production, in order to yield a given quantity of energy, are eventually reflected in the price paid for the energy. But this is not always or entirely the case. For example, many thin-film photovoltaic panels incorporate materials such as gallium and indium that are non-renewable and rare, and that are being depleted quickly. While the price of thin-film PV panels reflects and includes the current market price of these materials, it does not give much indication of future limits to the scaling up of thin-film PV resulting from these materials' scarcity.

3. Environmental Impacts

Virtually all energy sources entail environmental impacts, but some have greater impacts than others. These may occur during the acquisition of the resource (in mining coal or drilling for oil, for example), or during the release of carbon energy from the resource (as in burning wood, coal, oil, or natural gas). Other impacts occur in the conversion of the energy from one form to another (as in converting the kinetic energy of flowing water into electricity via dams and hydro-turbines); or in the potential for catastrophic events, as with nuclear energy production; or in waste disposal problems. Others may be intrinsic to the production process, such as injury to forests or topsoils from various forms of biofuels production.

Some environmental impacts are indirect and subtle. They can occur during the manufacture of the equipment used in energy harvesting or conversion. For example, the extraction and manipulation of resources used in manufacturing solar panels may entail significantly more environmental damage than the operation of the panels themselves.

AMAZON WATCH

4. Renewability

If we wish our society to continue using energy at industrial rates of flow not just for years or even decades into the future, but for centuries, then we will require energy sources that can be sustained more or less indefinitely. Energy resources like oil, natural gas, and coal are clearly non-renewable because the time required to form them through natural processes is measured in the tens of millions of years, while the quantities available will only be able to power society, at best, for only a few decades into the future at current rates of use. In contrast, solar photovoltaic and solar thermal energy sources rely on sunlight, which for all practical purposes is not depleting and will presumably be available in similar quantities a thousand years hence.

It is important to repeat once again, however, that the *equipment* used to capture solar or wind energy is not itself renewable, and that scarce, depleting, non-renewable resources and significant amounts of energy may be required to manufacture much crucial equipment.

Some energy sources *are* renewable yet are still capable of being depleted. For example, wood can be harvested from forests that regenerate themselves; however, the *rate* of harvest is crucial: if over-harvested, the trees will be unable to re-grow quickly enough and the forest will shrink and disappear.

Even energy sources that are renewable and that do not suffer depletion are nevertheless limited by the size of the resource base (as will be discussed next).

5. Potential Size or Scale of Contribution

Estimating the potential contribution of an energy source is obviously essential for macro-planning purposes, but such estimates are always subject to error—which can sometimes be enormous. With fossil fuels, amounts that can be reasonably expected to be extracted and used on the basis of current extraction technologies and fuel prices are classified as *reserves*, which are always a mere fraction of *resources* (defined as the total amount of the substance present in the ground). For example, the U.S. Geological Survey's first estimate of national coal reserves, completed in 1907, identified 5000 years' worth of supplies. In the decades since, most of those "reserves" have been reclassified as "resources." Reserves are downgraded to resources when new limiting factors are taken into account, such as (in the case of coal) seam thickness and depth, chemical impurities, and location of the deposit.

Today, only 250 years' worth of useable U.S. coal supplies are officially estimated to exist—a figure that is still probably much too optimistic (as the National Academy of Sciences concluded in its 2007 report, *Coal: Research and Development to Support National Energy Policy*).

On the other hand, reserves can sometimes grow as a result of the development of new extraction technologies, as has occurred in recent years with U.S. natural gas supplies: while the production of conventional American natural gas is declining, new underground fracturing technologies have enabled the recovery of "unconventional" gas from low-porosity rock, significantly increasing the national natural gas production rate and expanding U.S. gas reserves.

The estimation of reserves is especially difficult when dealing with energy resources that have little or no extraction history. This is the case, for example, with methane hydrates, regarding which various experts have issued a very wide range of estimates of both total resources and extractable future supplies. The same is also true of oil shale, and to a lesser degree tar sands, which have limited extraction histories.

Estimating potential supplies of renewable resources such as solar and wind power is likewise problematic, as many limiting factors are often initially overlooked. With regard to solar power, for example, a cursory examination of the ultimate resource is highly encouraging: the total amount of energy absorbed by Earth's atmosphere, oceans, and land masses from sunlight annually is approximately 3,850,000 exajoules (EJ)—whereas the world's human population uses currently only about 498 EJ of energy per year from all sources combined[6], an insignificant fraction of the previous figure. However, the factors limiting the amount of sunlight that can potentially be put to work for humanity are numerous, as we will see in more detail below.

Consider the case of methane harvested from municipal landfills. In this instance, using the resource provides an environmental benefit: methane is a more powerful greenhouse gas than carbon dioxide, so harvesting and burning landfill gas (rather than letting it diffuse into the atmosphere) reduces climate impacts while also providing a local source of energy. If landfill gas could power the U.S. electrical grid, then the nation could cease mining and burning coal. However, the potential size of the landfill gas resource is woefully insufficient to support this. Currently the nation derives about 11 billion kWh per year from landfill gas for commercial, industrial, and electric utility uses. This figure could probably be doubled if more landfills were tapped.[7] But U.S. electricity consumers use close to 200 times as much energy as that. There is another wrinkle: If society were to become more environmentally sensitive and energy efficient, the result would be that the amount of trash going into landfills would decline—and this would reduce the amount of energy that could be harvested from future landfills.

6. Location of the Resource

The fossil fuel industry has long faced the problem of "stranded gas"—natural gas reservoirs that exist far from pipelines and that are too small to justify building pipelines to access them. Many renewable resources often face similar inconveniences and costs caused by distance.

The locations of solar and wind installations are largely dictated by the availability of the primary energy source; but often, sun and wind are most abundant in sparsely populated areas. For example, in the U.S. there is tremendous potential for the development of wind resources in Montana and North and South Dakota; however, these are three of the least-populous states in the nation. Therefore, to take full advantage of these resources it will be necessary to ship the energy to more populated regions; this will typically require building new high-capacity long distance power lines, often at great expense, and causing sometimes severe environmental impacts. There are also excellent wind resources offshore along the Atlantic and Pacific coasts, nearer to large urban centers. But taking advantage of these resources will entail building and operating turbines in deep water and connecting them to the grid onshore—not an easy task. Similarly, the nation's best solar resources are located in the Southwest, far from population centers in the Northeast.

Thus, taking full advantage of these energy resources will require more than merely the construction of wind turbines and solar panels: much of the U.S. electricity grid will need to be reconfigured, and large-capacity, long-distance transmission lines will need to be constructed. Parallel challenges exist for other countries.

7. Reliability

Some energy sources are continuous: coal can be fed into a boiler at any desired rate, as long as the coal is available. But some energy sources, such as wind and solar, are subject to rapid and unpredictable fluctuations. Wind sometimes blows at greatest intensity at night, when electricity demand is lowest. The sun shines for the fewest hours per day during the winter—but consumers are unwilling to curtail electricity usage during winter months, and power system operators are required to assure security of supply throughout the day and year.

Intermittency of energy supply can be managed to a certain extent through storage systems—in effect, batteries. However, this implies yet further infrastructure costs as well as energy losses. It also places higher demands on control technology. In the worst instance, it means building much more electricity generation capacity than would otherwise be needed.[8]

8. Energy Density

A. Weight (or Gravimetric) Density

This refers to the amount of energy that can be derived from a standard weight unit of an energy resource.

For example, if we use the megajoule (MJ) as a measure of energy and the kilogram (kg) as a measure of weight, coal has about 20 to 35 MJ per kg, while natural gas has about 55 MJ/kg, and oil around 42 MJ/kg. (For comparison's sake, the amount of food that a typical weight-watching

American eats throughout the day weighs a little over a kilogram and has an energy value of about 10 MJ, or 2400 kilocalories.)

However, as will be discussed in more detail below, an electric battery typically is able to store and deliver only about 0.1 to 0.5 MJ/kg, and this is why electric batteries are problematic in transport applications: they are very heavy in relation to their energy output. Thus electric cars tend to have limited driving ranges and electric aircraft (which are quite rare) are able to carry only one or two people.

Consumers and producers are willing to pay a premium for energy resources with a higher energy density by weight; therefore it makes economic sense in some instances to convert a lower-density fuel such as coal into a higher-density fuel such as synthetic diesel, even though the conversion process entails both monetary and energy costs.

B. Volume (or Volumetric) Density

This refers to the amount of energy that can be derived from a given volume unit of an energy resource (e.g., MJ per liter).

Obviously, gaseous fuels will tend to have lower volumetric energy density than solid or liquid fuels. Natural gas has about .035 MJ per liter at sea level atmospheric pressure, and 6.2 MJ/l when pressurized to 200 atmospheres. Oil, though, can deliver about 37 MJ/l.

In most instances, weight density is more important than volume density; however, for certain applications the latter can be decisive. For example, fueling airliners with hydrogen, which has high energy density by weight, would be problematic because it is a highly diffuse gas at common temperatures and surface atmospheric pressure; indeed a hydrogen airliner would require very large tanks even if the hydrogen were super-cooled and highly pressurized.

The greater ease of transporting a fuel of higher volume density is reflected in the fact that oil moved by tanker is traded globally in large quantities, while the global tanker trade in natural gas is relatively small. Consumers and producers are willing to pay a premium for energy resources of higher volumetric density.

C. Area density

This expresses how much energy can be obtained from a given land area (e.g., an acre) when the energy resource is in its original state. For example, the area energy density of wood as it grows in a forest is roughly 1 to 5 million MJ per acre. The area grade for oil is usually tens or hundreds of millions of MJ per acre where it occurs, though oilfields are much rarer than forests (except perhaps in Saudi Arabia).

Area energy density matters because energy sources that are already highly concentrated in their original form generally require less investment and effort to be put to use. Douglas Reynolds makes the point:

> If the energy content of the resource is spread out, then it costs more to obtain the energy, because a firm has to use highly mobile extraction capital [machinery], which must be smaller and so cannot enjoy increasing returns to scale. If the energy is concentrated, then it costs less to obtain because a firm can use larger-scale immobile capital that can capture increasing returns to scale.[9]

Thus energy producers will be willing to pay an extra premium for energy resources that have high area density, such as oil that will be refined into gasoline, over ones that are more widely dispersed, such as corn that is meant to be made into ethanol.

9. Transportability

The transportability of energy is largely determined by the weight and volume density of the energy resource, as discussed above. But it is also affected by the state of the source material (assuming that it is a substance)—whether it is a solid, liquid, or gas. In general, a solid fuel is less convenient to transport than a gaseous fuel, because the latter can move by pipeline (pipelines can transport eight times the volume with a doubling of the size of the pipes). Liquids are the most convenient of all because they can likewise move through hoses and pipes, and they take up less space than gases.

Some energy sources cannot be classified as solid, liquid, or gas: they are energy fluxes. The energy from sunlight or wind cannot be directly transported; it must first be converted into a form that can—such as hydrogen or electricity.

Electricity is highly transportable, as it moves through wires, enabling it to be delivered not only to nearly every building in industrialized nations, but to many locations within each building.

Transporting energy always entails costs—whether it is the cost of hauling coal (which may account for over 70 percent of the delivered price of the fuel), the cost of building and maintaining pipelines and pumping oil or gas, or the cost of building and maintaining an electricity grid. Using the grid entails costs too, since energy is lost in transmission. These costs can be expressed in monetary terms or in energy terms, and they must also be included in calculations to determine net energy gains or losses, as we will be discussing in detail in the next section.

It is arguable that net energy should simply be presented as tenth in this list of limiting energy factors. However, we believe this factor is so important as to deserve a separate discussion.

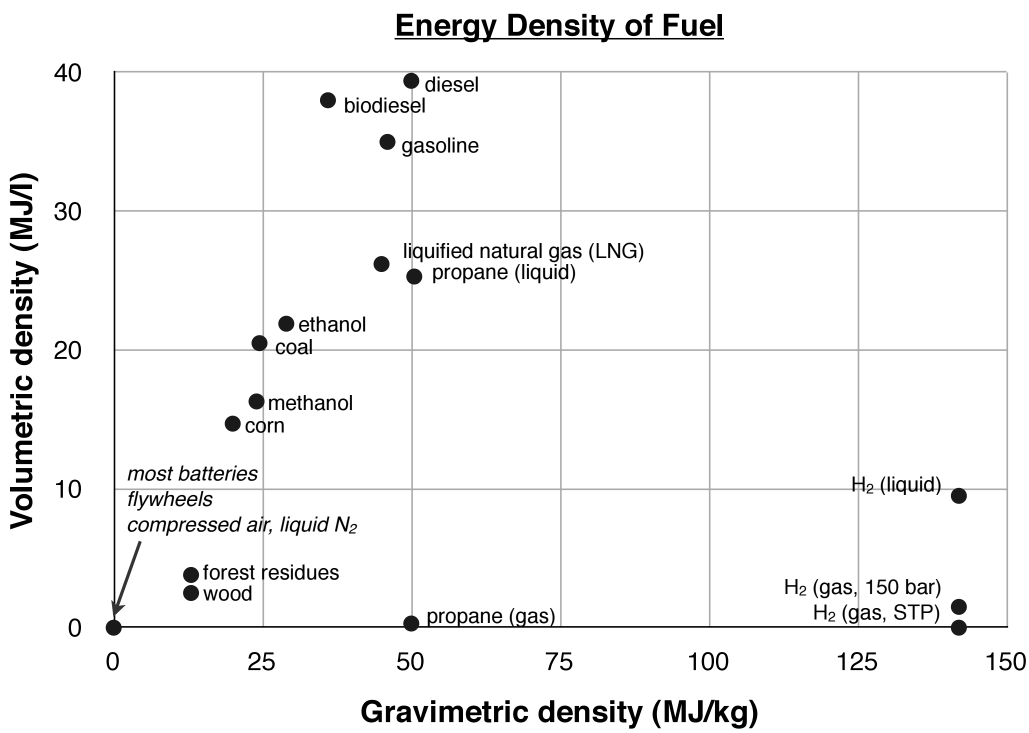


DIAGRAM 1: VOLUMETRIC AND GRAVIMETRIC DENSITY OF FUELS. *A hypothetical fuel with ideal energy density characteristics would occupy the upper right-hand corner of the diagram. Energy sources appearing in the lower left-hand corner have the worst energy density characteristics. H2 refers to hydrogen—as a super-cooled liquid, as a pressurized gas, and at "standard temperature and pressure."*

TEDDER

Possibly most promising among alternative renewable energies is windpower, already in wide use in northern Europe and parts of the U.S. "Net energy" for wind production tends to be higher than competitors, and potential future U.S. volume is substantial. A major problem is intermittency—wind does not always blow. Another is location and the need to cheaply transport the energy via power lines over long distances. Promising as it is, the total potential of wind, even combined with other alternative sources, remains below the level needed to sustain the present scale of industrial society. (See chapters two and three.)

Three

THE TENTH CRITERION: "*NET ENERGY*" (EROEI)

As already mentioned, *net energy* refers to the ratio of the amount of energy produced to the amount of energy expended to produce it. Some energy must always be invested in order to obtain any new supplies of energy, regardless of the nature of the energy resource or the technology used to obtain it. Society relies on the net energy surplus gained from energy-harvesting efforts in order to operate all of its manufacturing, distribution, and maintenance systems.

Put slightly differently, net energy means the amount of useful energy that's left over after the amount of energy invested to drill, pipe, refine, or build infrastructure (including solar panels, wind turbines, dams, nuclear reactors, or drilling rigs) has been subtracted from the total amount of energy produced from a given source. If ten units of energy are "invested" to develop additional energy sources, then one hopes for 20 units or 50 or 100 units to result. "Energy out" must exceed "energy in," by as much as possible. Net energy is what's left over that can be employed to actually do further work. It can be thought of as the "profit" from the investment of energy resources in seeking new energy.

RETURNS ON INVESTMENTS (EROEI)

The net energy concept bears an obvious resemblance to a concept familiar to every economist or businessperson—*return on investment,* or *ROI.* Every investor knows that it takes money to make money; every business manager is keenly aware of the importance of maintaining a positive ROI; and every venture capitalist appreciates the potential profitability of a venture with a high ROI. Maintaining a positive *energy return on energy invested* (EROEI) is just as important for energy producers, and for society as a whole. (Some writers, wishing to avoid redundancy, prefer the simpler EROI; but since there is a strong likelihood for some readers to assume this means *energy returned on money invested*, we prefer the longer and more awkward term). The EROEI ratio is typically expressed as production per single unit of input, so 1 serves as the denominator of the ratio (e.g., 10/1 or 10:1). Sometimes the denominator is simply assumed, so it may be noted that the EROEI of the energy source is 10—meaning, once again, that ten units of energy are yielded for every one invested in the production process. An EROEI of less than 1—for example, .5 (which might also be written as .5/1 or .5:1) would indicate that the energy being yielded from a particular source is only half as much as the amount of energy being invested in the production process. As we will see, very low net energy returns may be expected for some recently touted new energy sources like cellulosic ethanol. And as we will also see, the net energy of formerly highly productive sources such as oil, and natural gas, which used to be more than 100:1, have steadily declined to a fraction of that ratio today.

Sometimes energy return on investment (EROEI) is discussed in terms of "energy payback time"—i.e., the amount of time required before an energy-producing system (such as an array of solar panels) will need to operate in order to produce as much energy as was expended to build and install the system. This formulation makes sense for systems (such as PV panels) that require little or nothing in the way of ongoing operational and maintenance costs once the system itself is in place.

REPLACEMENT OF HUMAN ENERGY

If we think of net energy not just as it impacts a particular energy production process, but as it impacts society as a whole, the subject takes on added importance.

When the net energy produced is a large fraction of total energy produced (for example, a net energy ratio of 100:1), this means that the great majority of the total energy produced can be used for purposes other than producing more energy. A relatively small portion of societal effort needs to be dedicated to energy production, and most of society's efforts can be directed toward activities that support a range of specialized occupations not associated with energy production. This is the situation we have become accustomed to as the result of having a century of access to cheap, abundant fossil fuels—all of which offered relatively high energy-return ratios for most of the 20th century.

On the other hand, if the net energy produced is a small fraction of total energy produced (for example a ratio of 10:1 or less), this means that a relatively large portion of available energy must be dedicated to further energy production, and only a small portion of society's available energy can be directed toward other goals. This principle applies regardless of the type of energy the society relies on—whether fossil energy or wind energy or energy in the form of food crops. For example, in a society where energy (in the form of food calories) is acquired principally through labor-intensive agriculture—which yields a low and variable energy "profit"—most of the population must be involved in farming in order to provide enough energy profit to maintain a small hierarchy of full-time managers, merchants, artists, government officials, soldiers, beggars, etc., who make up the rest of the society and who spend energy rather than producing it.

HEYDAY FOR FOSSIL FUELS

In the early decades of the fossil fuel era (the late 19th century through most of the 20th century), the quantities of both total energy *and* net energy that were liberated by mining and drilling for these fuels was unprecedented. It was this sudden abundance of cheap energy that enabled the growth of industrialization, specialization, urbanization, and globalization, which have dominated the past two centuries.

In that era it took only a trivial amount of effort in exploration, drilling, or mining to obtain an enormous energy return on energy invested (EROEI). At that time, the energy industry understandably followed the best-first or "low-hanging fruit" policy for exploration and extraction. Thus the coal, oil, and gas that were highest in quality and easiest to access tended to be found and extracted preferentially. But with every passing decade the net energy (as compared to total energy) derived from fossil fuel extraction has *declined* as energy producers have had to prospect in more inconvenient places and to rely on lower-grade resources. In the early days of the U.S. oil industry, for example, a 100-to-one energy profit ratio was common, while it is now estimated that current U.S. exploration efforts are declining to an average one-to-one (break-even) energy payback rate[10].

In addition, as we will see in some detail later in this report, currently advocated alternatives to conventional fossil fuels generally have a much lower EROEI than coal, oil, or gas did in their respective heydays. For example, industrial ethanol production from corn is now estimated to have at best a 1.8:1 positive net energy balance[11]; it is therefore nearly useless as a primary energy source. (It is worth noting parenthetically that the calculation cited for ethanol may actually overstate the net energy gain of industrial ethanol because it includes the energy value of a production byproduct—distillers dried grains with solubles (DDGS), which can be fed to cattle—in the "energy out" column; but if the focus of the analysis is simply to assess the amount of energy used to produce one unit of corn ethanol, and the value of DDGS is thus disregarded, the EROEI is even lower, at 1.1, according to the same study.)

HOW EROEI SHAPES SOCIETY

As mentioned earlier, if the net energy profit available to society declines, a higher percentage of society's resources will have to be devoted directly to obtaining energy, thus increasing its cost. This means that less energy will be available for all of the activities that energy makes possible.

Net energy can be thought of in terms of the number of people in society that are required to engage in energy production, including food production. If energy returned exactly equals energy invested (EROEI = 1:1), then everyone must be involved in energy production activities and no one can be available to take care of society's other needs.

In pre-industrial societies, most of the energy collected was in the form of food energy, and most of the energy expended was in the form of muscle power (in the U.S., as recently as 1850, over 65 percent of all work being done was muscle-powered, versus less than 1 percent today, as fuel-fed machines do nearly all work). Nevertheless, exactly the same net-energy principle applied to these food-based energy systems as applies to our modern economy dominated by fuels, electricity, and machines. That is, people were harvesting energy from their environment (primarily in the form of food crops rather than fossil fuels), and that process itself required the investment of energy (primarily through the exertion of muscle power); success depended on the ability to produce more energy than was invested.

When most people were involved in energy production through growing or gathering food, societies were simpler by several measurable criteria: there were fewer specialized full-time occupations and fewer kinds of tools in use.

Archaeologist Lynn White once estimated that hunter-gatherer societies operated on a ten-to-one net energy basis (EROEI = 10:1).[12] In other words, for every unit of effort that early humans expended in hunting or wild plant gathering, they obtained an average of ten units of food energy in return. They used the surplus energy for all of the social activities (reproduction, child rearing, storytelling, and so on) that made life sustainable and rewarding.

Since hunter-gatherer societies are the simplest human groups in terms of technology and degree of social organization, 10:1 should probably be regarded as the minimum sustained average societal EROEI required for the maintenance of human existence (though groups of humans have no doubt survived for occasional periods, up to several years in duration, on much lower EROEI).

The higher complexity of early agrarian societies was funded not so much by increased EROEI as by higher levels of energy investment in the form of labor (farmers typically work more than hunters and gatherers) together with the introduction of food storage, slavery, animal domestication, and certain key tools such as the plow and the yoke. However, the transition to industrial society, which entails much greater levels of complexity, could only have been possible with both the higher total energy inputs, and the much higher EROEI, afforded by fossil fuels.

EROEI LIMITS ENERGY OPTIONS

Both renewable and non-renewable sources of energy are subject to the net energy principle. Fossil fuels become useless as energy sources when the energy required to extract them equals or exceeds the energy that can be derived from burning them.

This fact puts a physical limit to the portion of resources of coal, oil, or gas that should be categorized as reserves, since net energy will decline to the break-even point long before otherwise extractable fossil energy reserves are exhausted.

Therefore, the need for society to find replacements for fossil fuels may be more urgent than is generally recognized. Even though large amounts of fossil fuels remain to be extracted, the transition to alternative energy sources must be negotiated while there is still sufficient net energy available to continue powering society while at the same time providing energy for the transition process itself.

Net energy may have a direct effect on our ability to maintain industrial society at its present level. If the net energy for all combined energy sources declines, increasing constraints will be felt on economic growth, but also upon new adaptive strategies to deal with the current climate and energy crises. For example, any kind of adaptive energy transition will demand substantial new investments for the construction of more energy-efficient buildings and/or public transport infrastructure. However, such requirements will come at the same time that substantially more investment will be needed in energy production systems. Societies may simply be unable to adequately fund both sets of needs simultaneously. Noticeable symptoms of strain would include rising costs of bare necessities and a reduction in job opportunities in fields not associated with basic production. Supplying the energy required simply to maintain existing infrastructure, or to maintain aspects of that infrastructure deemed essential, would become increasingly challenging.

EROEI: DISTINCT FROM EFFICIENCY

The EROEI of energy *production* processes should not be confused with the efficiency of energy *conversion* processes, i.e., the conversion of energy from fossil fuel sources, or wind, etc., into useable electricity or useful work. Energy conversion is always less than 100 percent efficient—some energy is invariably wasted in the process (energy cannot be destroyed, but it can easily be dissipated so as to become useless for human purposes)—but conversion processes are nevertheless crucial in using energy. For example, in an energy system with many source inputs, common *energy carriers* are extremely helpful. Electricity is currently the dominant energy carrier, and serves this function well. It would be difficult for consumers to make practical use of coal, nuclear energy, and hydropower without electricity. But *conversion* of the original source energy of fossil fuels, uranium, or flowing water into electricity entails an energy cost. It is the objective of engineers to reduce that energy cost so as to make the conversion as efficient as possible. But if the energy source has desirable characteristics, even a relatively high conversion cost, in terms of "lost" energy, may be easily borne. Many coal power plants now in operation in the U.S. have an energy conversion efficiency of only 35 percent.

Similarly, some engines and motors are more efficient than others in terms of their ability to turn energy into work.

EROEI analysis does not focus on conversion efficiency *per se*, but instead takes into account all reasonable costs on the "energy invested" side of the ledger for energy *production* (such as the energy required for mining or drilling, and for the building of infrastructure), and then weighs that total against the amount of energy being delivered to accomplish work.

Because this report is a layperson's guide, we cannot address in any depth the technical process of calculating net energy.

NET ENERGY EVALUATION: IMPRECISE BUT ESSENTIAL FOR PLANNING

The use of net energy or EROEI as a criterion for evaluating energy sources has been criticized on several counts.[13] The primary criticism centers on the difficulty in establishing system boundaries that are agreeable to all interested parties, and that can easily be translated from analyzing one energy source to another. Moreover, the EROEI of some energy sources (such as wind, solar, and geothermal) may vary greatly according to the location of the resources versus their ultimate markets. Advances in the efficiency of supporting technology can also affect net energy. All of these factors make it difficult to calculate figures that can reliably be used in energy planning.

This difficulty only increases as the examination of energy production processes becomes more detailed: Does the office staff of a drilling company actually *need* to drive to the office to produce oil? Does the kind of car matter? Is the energy spent filing tax returns actually necessary to the manufacture of solar panels? While such energy costs are usually not included in EROEI analysis, some might argue that all such ancillary costs should be factored in, to get more of a full picture of the tradeoffs.[14]

Yet despite challenges in precisely accounting for the energy used in order to produce energy, net energy factors act as a real constraint in human society, regardless of whether we ignore them or pay close attention to them, because EROEI will determine if an energy source is able successfully to support a society of a certain size and level of complexity. Which alternative technologies have sufficiently high net energy ratios to help sustain industrial society as we have known it for the past century? Do any? Or does a combination of alternatives? Even though there is dispute as to exact figures, in situations where EROEI can be determined to be very low we can conclude that the energy source in question cannot be relied upon as a primary source to support an industrial economy.

Many criticisms of net energy analysis boil down to an insistence that other factors that limit the efficacy of energy sources should also be considered. We agree. For example, EROEI does not account for limits to *non-energy* inputs in energy production (such as water, soil, or the minerals and metals needed to produce equipment); it does not account for undesirable non-energy outputs of the energy production process—most notably, greenhouse gases; it does not account for energy quality (the fact, for example, that electricity is an inherently more versatile and useful energy delivery medium than the muscle power of horses); and it does not reflect the scalability of the energy source (recall the example of landfill gas above).

Energy returns *could* be calculated to include the use of non-energy inputs—e.g., Energy Return on *Water* Invested, or Energy Return on *Land* Invested. As net energy declines, the energy return from the investment of non-energy inputs is also likely to decline, perhaps even faster. For example, when fuel is derived from tar sands rather than from conventional oil fields, more land and water are needed as inputs; there is an equivalent situation when substituting biofuels for gasoline. Once society enters a single-digit average EROEI era, i.e., less than 10:1 energy output vs. input, a higher percentage of energy *and* non-energy resources (water, labor, land, and so on) will have to be devoted to energy production. This is relevant to the discussion of biofuels and similar low energy-gain technologies. At first consideration, they may seem better than fossil fuels since they are produced from renewable sources, but they use non-renewable energy inputs that have a declining net yield (as higher-quality resources are depleted). They may require large amounts of land, water, and fertilizer; and they often entail environmental damage (as fossil fuels themselves do). All proposed new sources of energy should be evaluated in a framework that considers these other factors (energy return on water, land, labor, etc.) as well as net energy.[15] Or, conceivably, a new multi-faceted EROEI could be devised.

In any case, while net energy is not the only important criterion for assessing a potential energy source, this is not a valid reason to ignore it. EROEI is a necessary—though not a complete—basis for evaluating energy sources. It is one of *five* criteria that we believe should be regarded as having make-or-break status. The other critical criteria, already discussed in Part I. above, are: renewability, environmental impact, size of the resource, and the need for ancillary resources and materials. If a potential energy source cannot score well with all five of these criteria, it cannot realistically be considered as a future primary energy source. Stated the other way around, a potential primary energy source can be disqualified by doing very poorly with regard to just one of these five criteria.

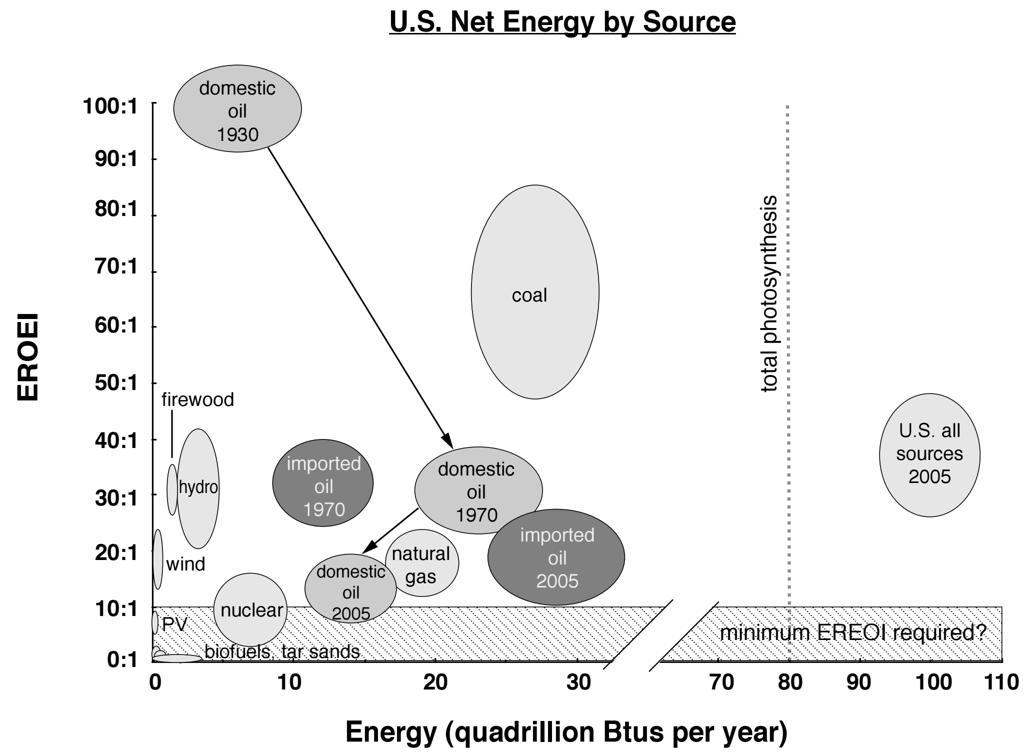


DIAGRAM 2: THE NET ENERGY (AND MAGNITUDE OF CONTRIBUTION) OF U.S. ENERGY SOURCES

This "balloon graph" of U.S. energy supplies developed by Charles Hall, Syracuse University, represents net energy (vertical axis) and quantity used (horizontal axis) of various energy sources at various times. Arrows show the evolution of domestic oil in terms of EROEI and quantity produced (in 1930, 1970, and 2005), illustrating the historic decline of EROEI for U.S. domestic oil. A similar track for imported oil is also shown. The size of each "balloon" represents the uncertainty associated with EROEI estimates. For example, natural gas has an EROEI estimated at between 10:1 and 20:1 and yields nearly 20 quadrillion Btus (or 20 exajoules). "Total photosynthesis" refers to the total amount of solar energy captured annually by all the green plants in the U.S. including forests, food crops, lawns, etc. (note that the U.S. consumed significantly more than this amount in 2005). The total amount of energy consumed in the U.S. in 2005 was about 100 quadrillion Btus, or 100 exajoules; the average EROEI for all energy provided was between 25:1 and 45:1 (with allowance for uncertainty). The shaded area at the bottom of the graph represents the estimated minimum EROEI required to sustain modern industrial society: Charles Hall suggests 5:1 as a minimum, though the figure may well be in the range of 10:1.[16]

RODRIGO BUENDIA/AFP/GETTY IMAGES

In the Ecuadorian and Peruvian Amazon, indigenous people such as the Achuar, are routinely confronted with oil spills in rivers (such as this one), and runoffs into lakes and forests; pipelines shoved through traditional lands, oil fires, gas excursions, waste dumping, smoke, haze and other pollutants as daily occurrences, leading to very high cancer rates, and community breakdowns similar to those in the Niger delta, Indonesia and elsewhere. Achuar communities have been massively protesting, and recently successful lawsuits against Chevron and Texaco have made international headlines.

USAF ARCHIVES

This giant photovoltaic array—70,000 panels on 140 acres of Nellis Airforce base in Nevada—leads sci-fi types to fantasize much larger arrays in space, or mid-ocean, but solar comes in all sizes. Other kinds of systems include "concentrating solar thermal" and passive solar, as used in many private homes. With sunlight as the resource, planetary supply is unlimited. But, it's intermittent on cloudy days, and often seasonally, reducing its reliability as a large scale primary energy, compared to operator-controlled systems like coal, gas, or nuclear. Other limits include materials costs and shortages and relatively low "net energy" ratios.

Four

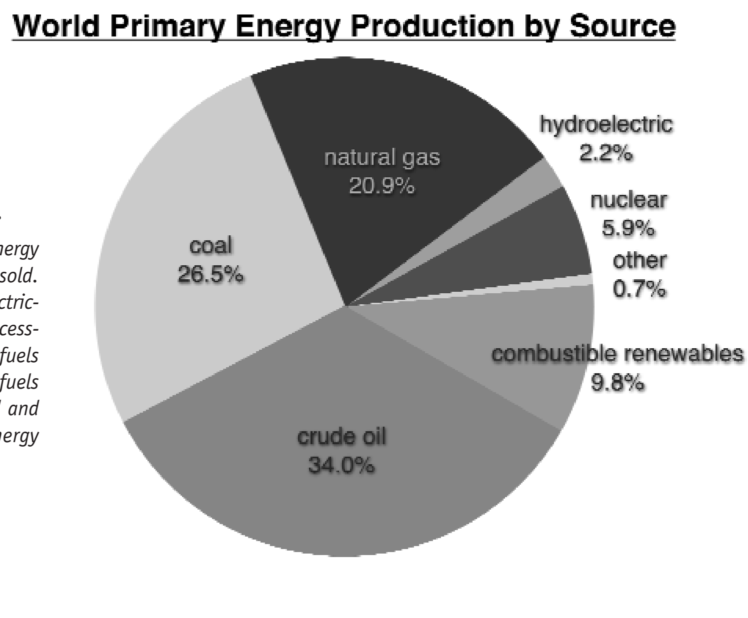
ASSESSING & COMPARING EIGHTEEN ENERGY SOURCES

IN THIS CHAPTER, we will discuss and compare in further detail key attributes, both positive and negative, of eighteen specific energy sources. The data on net energy (EROEI) for most of these are drawn largely from the work of Dr. Charles Hall, who, together with his students at the State University of New York in Syracuse, has for many years been at the forefront of developing and applying the methodology for calculating energy return ratios.[17]

We will begin by considering presently dominant energy sources, case-by-case, including oil, coal, and gas so that comparisons can be made with their potential replacements. After fossil fuels we will explore the prospects for various non-fossil sources. Altogether, eighteen energy sources are discussed in this section, listed approximately in the order of the size of their current contribution to world energy supply.

DIAGRAM 3: WORLD PRIMARY ENERGY PRODUCTION BY SOURCE.

This chart refers to commercial energy sources, produced to be bought and sold. This includes transportation fuels, electricity, and energy used in industrial processes, but not traditional or distributed fuels like firewood or off-grid PV. 'Other' fuels include commercial geothermal, wind and photovoltaic power. Source: Energy Information Administration[18].



1. OIL

ANACORTES REFINERY WALTER SIEGMUND

As the world's current largest energy source, oil fuels nearly all global transportation—cars, planes, trains, and ships. (The exceptions, such as electric cars, subways and trains, and sailing ships, make up a statistically insignificant portion of all transport). Petroleum provides about 34 percent of total world energy, or about 181 EJ per year. The world currently uses about 75 million barrels of crude oil per day, or 27 billion barrels per year[19], and reserves amount to about one trillion barrels (though the figure is disputed).

PLUS: Petroleum has become so widely relied upon because of several of its most basic characteristics: It is highly transportable as a liquid at room temperature and is easily stored. And it is energy dense—a liter of oil packs 38 MJ of chemical energy, as much energy as is expended by a person working two weeks of 10-hour days.[20]

Historically, oil has been cheap to produce, and can be procured from a very small land footprint.

MINUS: Oil's downsides are as plain as its advantages.

Its negative environmental impacts are massive. Extraction is especially damaging in poorer nations such as Ecuador, Peru, and Nigeria, where the industry tends to spend minimally on the kinds of remediation efforts that are required by law in the U.S.; as a result, rivers and wetlands are poisoned, air is polluted, and indigenous people see their ways of life devastated.

Meanwhile, burning oil releases climate-changing carbon dioxide (about 800 to 1000 lbs of CO_2 per barrel[21], or 70 kg of CO_2 per GJ), as well as other pollutants such as nitrogen oxides and particulates.

Most importantly, oil is non-renewable, and many of the world's largest oilfields are already significantly depleted. Most oil-producing nations are seeing declining rates of extraction, and future sources of the fuel are increasingly concentrated in just a few countries—principally, the members of the Organization of Petroleum Exporting Countries (OPEC). The geographic scarcity of oil deposits has led to competition for supplies, and sometimes to war over access to the resource. As oil becomes scarcer due to depletion, we can anticipate even worse oil wars.[22]

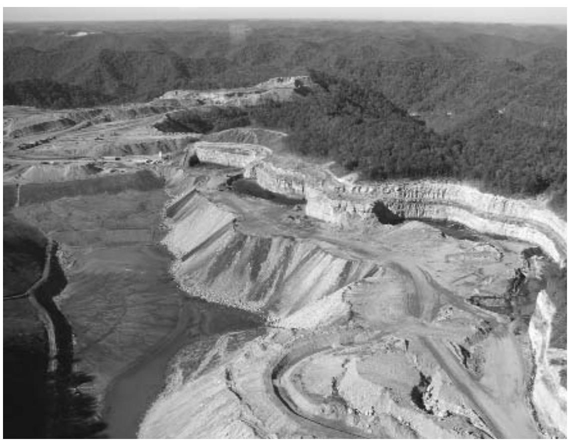
EROEI: The net energy (compared to gross energy) from global oil production is difficult to ascertain precisely, because many of the major producing nations do not readily divulge statistics that would make detailed calculations possible. About 750 joules of energy are required to lift 15 kg of oil 5 meters—an absolute minimum energy investment for pumping oil that no longer simply flows out of the ground under pressure (though much of the world's oil still does). But energy is also expended in exploration, drilling, refining, and so on. An approximate total number can be derived by dividing the energy produced by the global oil industry by *the energy equivalent of the dollars spent* by the oil industry for exploration and production (this is a rough calculation of the amount of energy used in the economy to produce a dollar's worth of goods and services). According to Charles Hall, this number—for oil and gas together—was about 23:1 in 1992, increased to about 32:1 in 1999, and has since declined steadily, reaching 19:1 in 2005. If the recent trajectory is projected forward, the EROEI for global oil and gas would decline to 10:1 soon after 2010. Hall and associates find that for the U.S. (a nation whose oil industry investments and oil production statistics are fairly transparent), EROEI at the wellhead was roughly 26:1 in 1992, increased to 35:1 in 1999, and then declined to 18:1 in 2006.[23]

It is important to remember that Hall's 19:1 estimate for the world as a whole is an average: some producers enjoy much higher net energy gains than others. There are good reasons to assume that most of the high-EROEI oil producers are OPEC-member nations.

PROSPECTS: As mentioned, oil production is in decline in most producing countries, and nearly all the world's largest oilfields are seeing falling production. The all-time peak of global oil production probably occurred in July, 2008 at 75 million barrels per day.[24] At the time, the per-barrel price had skyrocketed to its all-time high of $147. Since then, declining demand and falling price have led producing nations to cut back on pumping. Declining price has also led to a significant slowing of investment in exploration and production, which virtually guarantees production shortfalls in the future. It therefore seems unlikely that the July 2008 rate of production will ever be exceeded.

Declining EROEI and limits to global oil production will therefore constrain future world economic activity unless alternatives to oil can be found and brought on line extremely rapidly.

2. COAL


VIVIAN STOCKMAN/OHIO VALLEY ENVIRONMENTAL COALITION

The Industrial Revolution was largely made possible by energy from coal. In addition to being the primary fuel for expanding manufacturing, it was also used for space heating and cooking. Today, most coal is burned for the production of electricity and for making steel.

Coal has been the fastest-growing energy source (by quantity) in recent years due to prodigious consumption growth in China, which is by far the world's foremost producer and user of the fuel. The world's principal coal deposits are located in the U.S., Russia, India, China, Australia, and South Africa. World coal reserves are estimated at 850 billion metric tons (though this figure is disputed), with annual production running at just over four billion tons. Coal produces 134.6 EJ annually, or 27 percent of total world energy. The U.S. relies on coal for 49 percent of its electricity and 23 percent of total energy.[25]

Coal's energy density by weight is highly variable (from 30 MJ/kg for high-quality anthracite to as little as 5.5 MJ/kg for lignite).

PLUS: Coal currently is a cheap, reliable fuel for the production of electricity. It is easily stored, though bulky. It is transportable by train and ship (transport by truck for long distances is rarely feasible from an energy and economic point of view).

MINUS: Coal has the worst environmental impacts of any of the conventional fossil fuels, both in the process of obtaining the fuel (mining) and in that of burning it to release energy. Because coal is the most carbon-intensive of the conventional fossil fuels (94 kg of CO_2 are emitted for every GJ of energy produced), it is the primary source of greenhouse gas emissions leading to climate change, even though it contributes less energy to the world economy than petroleum does.

Coal is non-renewable, and some nations (U.K. and Germany) have already used up most of their original coal reserves. Even the U.S., the "Saudi Arabia of coal," is seeing declining production from its highest-quality deposits.

EROEI: In the early 20th century, the net energy from U.S. coal was very high, at an average of 177:1 according to one study[26], but it has fallen substantially to a range of 50:1 to 85:1. Moreover, the decline is continuing, with one estimate suggesting that by 2040 the EROEI for U.S. coal will be 0.5:1[27].

PROSPECTS: While official reserves figures imply that world coal supplies will be sufficient for a century or more, recent studies suggest that supply limits may appear globally, and especially regionally, much sooner. According to a 2007 study by Energy Watch Group of Germany, world coal production is likely to peak around 2025 or 2030, with a gradual decline thereafter. China's production peak could come sooner if economic growth (and hence energy demand growth) returns soon. For the U.S., coal production may peak in the period 2030 to 2035.

New coal technologies such as carbon capture and storage (CCS) could theoretically reduce the climate impact of coal, but at a significant economic and energy cost (by one estimate, up to 40 percent of the energy from coal would go toward mitigating climate impact, with the other 60 percent being available for economically useful work; there would also be an environmental cost from damage due to additional mining required to produce the extra coal needed to make up for the energy costs from CCS). [28]

Coal prices increased substantially in 2007-2008 as the global economy heated up, which suggests that the existing global coal supply system was then near its limit. Prices have declined sharply since then as a result of the world economic crisis and falling energy demand. However, prices for coal will almost certainly increase in the future, in inflation- or deflation-adjusted terms, as high-quality deposits are exhausted and when energy demand recovers from its lowered level due to the current recession.

3. NATURAL GAS

GAS FLARE AT NATURAL GAS PLANT — ISTOCK

Formed by geological processes similar to those that produced oil, natural gas often occurs together with liquid petroleum. In the early years of the oil industry, gas was simply flared (burned at the wellhead); today, it is regarded as a valuable energy resource and is used globally for space heating and cooking; it also has many industrial uses where high temperatures are needed, and it is increasingly burned to generate electricity. Of the world's total energy, natural gas supplies 25 percent; global reserves amount to about 6300 trillion cubic feet, which represents an amount of energy equivalent to 890 billion barrels of oil.[29]

PLUS: Natural gas is the least carbon-intensive of the fossil fuels (about 53 kg CO_2 per GJ). Like oil, natural gas is energy dense (more so by weight than by volume), and is extracted from a small land footprint. It is easily transported through systems of pipelines and pumps, though it cannot be transported by ship as conveniently as oil, as this typically requires pressurization at very low temperatures.

MINUS: Natural gas is a hydrocarbon fuel, which means that burning it releases CO_2 even if the amounts are less than would be the case to yield a similar amount of energy from coal or oil. Like oil, natural gas is non-renewable and depleting. Environmental impacts from the production of natural gas are similar to those with oil. Recent disputes between Russia, Ukraine, and Europe over Russian natural gas supplies underscore the increasing geopolitical competition for access to this valuable resource. International transport and trade of liquefied natural gas (LNG) entails siting and building offloading terminals that can be extremely hazardous.

EROEI: The net energy of global natural gas is even more difficult to calculate than that of oil, because oil and gas statistics are often aggregated. A recent study that incorporates both direct energy (diesel fuel used in drilling and completing a well) and indirect energy (used to produce materials like steel and cement consumed in the drilling process) found that as of 2005, the EROEI for U.S. gas fields was 10:1.[30] However, newer "unconventional" natural gas extraction technologies (coal-bed methane and production from low-porosity reservoirs using "fracing" technology) probably have significantly lower net energy yields: the technology itself is more energy-intensive to produce and use, and the wells deplete quickly, thus requiring increased drilling rates to yield equivalent amounts of gas. Thus as conventional gas depletes and unconventional gas makes up a greater share of total production, the EROEI of natural gas production in North America will decline, possibly dramatically.

PROSPECTS: During the past few years, North America has averted a natural gas supply crisis as a result of the deployment of new production technologies, but it is unclear how long the reprieve will last given the (presumably) low EROEI of these production techniques and the fact that the best unconventional deposits, such as the Barnett shales of Texas, are being exploited first. European gas production is declining and Europe's reliance on Russian gas is increasing—but it is difficult to tell how long Russia can maintain current flow rates.

In short, while natural gas has fewer environmental impacts than the other fossil fuels, especially coal, its future is clouded by supply issues and declining EROEI.

4. HYDROPOWER

RIO PARANAIBA DAM, PORTUGAL

MURILOIF

Hydropower is electric current produced from the kinetic energy of flowing water. Water's gravitational energy is relatively easily captured, and relatively easily stored behind a dam. Hydro projects may be enormous (as with China's Three Gorges Dam) or very small ("microhydro") in scale. Large projects typically involve a dam, a reservoir, tunnels, and turbines; small-scale projects usually simply employ the "run of the river," harnessing energy from a river's natural flow, without water storage.

Hydropower currently provides 2,894 Terawatt hours (TWh) of electricity annually worldwide, and about 264 TWh in the U.S.; of all *electrical* energy, hydropower supplies 19 percent worldwide (with 15 percent coming from large hydropower), and 6.5 percent in the U.S. This represents 6 percent of total energy globally and 3 percent nationally.[31]

PLUS: Unlike fossil energy sources, with hydropower most energy and financial investment occurs during project construction, while very little is required for maintenance and operations. Therefore electricity from hydro is generally cheaper than electricity from other sources, which may cost two to three times as much to generate.

MINUS: Energy analysts and environmentalists are divided on the environmental impacts of hydropower. Proponents of hydropower see it as a clean, renewable source of energy with only moderate environmental or social impacts. Detractors of hydropower see it as having environmental impacts as large as, or larger than, those of some conventional fossil fuels. Global impacts include carbon emissions primarily during dam and reservoir construction and methane releases from the drowned vegetation. Regional impacts result from reservoir creation, dam construction, water quality changes, and destruction of native habitat. The amount of carbon emissions produced is very site-specific and substantially lower than from fossil fuel sources. Much of the debate about hydropower centers on its effects on society, and whether or not a constant supply of water for power, irrigation, or drinking justifies the occasional requirement to relocate millions of people. Altogether, large dam and reservoir construction projects have required relocations of about 40 to 80 million people during the last century. Dam failure or collapse is also a risk in some cases, especially in China.

EROEI: Hydropower's EROEI ranges roughly from 11.2:1 to 267:1, varying enormously by site. Because hydropower is such a variable resource, used in many different geographical conditions and involving various technologies, one generalized EROEI ratio cannot describe all projects. The EROEI for favorable or even moderate sites can be extremely high, even where environmental and social impacts are severe.

PROSPECTS: Globally, there are many undeveloped dam sites with hydropower potential, though there are few in the U.S., where most of the best sites have already been developed. Theoretically, hydropower could be accessible at some level to any population near a constant supply of flowing water.

The International Hydropower Association estimates that about one-third of the realistic potential of world hydropower has been developed. In practice, the low direct investment cost of fossil fuels, combined with the environmental and social consequences of dams, have meant that fossil fuel-powered projects are much more common.

Dams have the potential to produce a moderate amount of additional, high-quality electricity in less-industrialized countries, but continue to be associated with extremely high environmental and social costs. Many authors see "run-of-river" hydropower (in which dams are not constructed) as the alternative future, because this does away with the need for massive relocation projects, minimizes the impacts on fish and wildlife, and does not release greenhouse gases (because there is generally no reservoir), while it retains the benefits of a clean, renewable, cheap source of energy. However, the relatively low power density of this approach limits its potential.

5. NUCLEAR

Electricity from controlled nuclear fission reactions has long been a highly contentious source of energy. Currently, 439 commercial power-generating reactors are operating worldwide, 104 of them in the U.S. Collectively they produced 2,658 TWh world-wide in 2006, and 806 TWh in the U.S. This represents about 6 percent of world energy, 8 percent of all energy consumed in the U.S., and 19 percent of U.S. electricity.[32]

All commercial reactors in the U.S. are variants of light water reactors. Other designs continue to be subjects of research.

PLUS: Nuclear electricity is reliable and relatively cheap (with an average generating cost of 2.9 cents per kW/h) once the reactor is in place and operating. In the U.S., while no new nuclear power plants have been built in many years, the amount of nuclear electricity provided has grown during the past decade due to the increased efficiency and reliability of existing reactors.

The nuclear cycle emits much less CO_2 than the burning of coal to produce an equivalent amount of energy (though it is important to add that uranium mining and enrichment, and plant construction, still entail considerable carbon emissions). This reduced CO_2 emission rate has led some climate protection spokespeople to favor nuclear power, at least as a temporary bridge to an "all-renewable" energy future.

MINUS: Uranium, the fuel for the nuclear cycle, is a *not* a renewable resource. The peak of world uranium production is likely to occur between 2040 and 2050[33], which means that nuclear fuel is likely to become more scarce and expensive during the next few decades. Already, the average grade of uranium ore mined has declined substantially in recent years as the best reserves have been depleted. Recycling of fuel and the employment of alternative nuclear fuels are possible, but the needed technology has not been adequately developed.

Nuclear power plants are extremely costly to build, so much so that unsubsidized nuclear plants are not economically competitive with similar-sized fossil-fuel plants. Government subsidies in the U.S. include: *(1)* those from the military nuclear industry, *(2)* non-military government subsidies, and *(3)* artificially low insurance costs. New power plants also typically entail many years of delay for design, financing, permitting, and construction.

The nuclear fuel cycle also brings substantial environmental impacts, which may be even greater during the mining and processing stages than during plant operation even when radiation-releasing accidents are taken into account. Mining entails ecosystem removal, the release of dust, the production of large amounts of tailings (equivalent to 100 to 1,000 times the quantity of uranium extracted), and the leaching of radiation-emitting particles into groundwater. During plant operation, accidents causing small to large releases of radiation can impact the local environment or much larger geographic areas, potentially making land uninhabitable (as occurred with the explosion and radiation leakage in the Chernobyl reactor in the former Soviet Union in 1986).

Storage of radioactive waste is also highly problematic. High-level waste (like spent fuel) is much more radioactive and difficult to deal with than low-level waste, and must be stored onsite for several years before transferal to a geological repository.

So far, the best-known way to deal with waste, which contains doses of radiation lethal for thousands of years, is to store it in a geological repository, deep underground. The long-proposed site at Yucca Mountain in Nevada, the only site that has been investigated as a repository in the U.S., has recently been canceled. Even if the Yucca Mountain site had gone ahead, it would not have been sufficient to store the U.S. waste already awaiting permanent storage. More candidate repository sites will need to be identified soon if the use of nuclear power is to be expanded in the U.S. Even in the case of ideal sites, over thousands of years waste could leak into the water table. The issue is controversial even after extremely expensive and extensive analyses by the Department of Energy.

Nearly all commercial reactors use water as a coolant. As water cools the reactor, the water itself becomes warmed. When heated water is then discharged back into lakes, rivers, or oceans the resultant heat pollution can disrupt aquatic habitats.

During the 2003 heat wave in France, several nuclear plants were shut because the river water was too hot. And in recent years, a few reactors have had to be shut down due to water shortages, highlighting a future vulnerability of this technology in a world where over-use of water and extreme droughts from climate change are becoming more common.

Reactors must not be sited in earthquake-prone regions due to the potential for catastrophic radiation release in the event of a serious quake. Nuclear reactors are often cited as potential terrorist targets and as potential sources of radioactive materials for the production of terrorist "dirty bombs."

EROEI: A review by Charles Hall *et al.*[34] of net energy studies of nuclear power that have been published to date found the information to be "idiosyncratic, prejudiced, and poorly documented." The largest issue is determining what the appropriate boundaries of analysis should be. The review concluded that the most reliable EROEI information is quite old (showing results in the range of 5 to 8:1), while newer information is either highly optimistic (15:1 or more) or pessimistic (low, even less than 1:1). An early study cited by Hall indicated that the high energy inputs during the construction phase are one of the major reasons for the low EROEI—which also means there are substantial greenhouse gas (GHG) emissions during construction.

NUCLEAR WASTE STORAGE FACILITY, YUCCA MT, NEVADA M.KNIAZKOV/GETTY IMAGES

PROSPECTS: The nuclear power industry is set to grow, with ten to twenty new power plants being considered in the U.S. alone. But the scale of growth is likely to be constrained mostly for reasons discussed above.

Hopes for a large-scale deployment of new nuclear plants rest on the development of new technologies: pebble-bed and modular reactors, fuel recycling, and the use of thorium as a fuel. The ultimate technological breakthrough for nuclear power would be the development of a commercial fusion reactor. However, each of these new technologies is problematic for some reason. Fusion is still decades away and will require much costly research. The technology to extract useful energy from thorium is highly promising, but will require many years and expensive research and development to commercialize. The only breeder reactors in existence are either closed, soon to be closed, abandoned, or awaiting re-opening after serious accidents. Examples of problematic breeders include BN-600 (in Russia, which will end its life by 2010); Clinch River Breeder Reactor (in the U.S., construction abandoned in 1982 because the U.S. halted its spent-fuel reprocessing program thus making breeders pointless); Monju (in Japan, being brought online again after a serious sodium leak and fire in 1995); and Superphénix (in France, closed in 1998). Therefore, realistically, nuclear power plants constructed in the short and medium term can only be incrementally different from current designs.

In order for the nuclear industry to grow sufficiently so as to replace a significant portion of energy now derived from fossil fuels, scores if not hundreds of new plants would be required, and soon. Given the expense, long lead-time entailed in plant construction, and safety issues, the industry may do well merely to build enough new plants to replace old ones that are nearing their retirement and decommissioning.

Hall *et al*. end their review of nuclear power by stating: "In our opinion we need a very high-level series of analyses to review all of these issues. Even if this is done, it seems extremely likely that very strong opinions, both positive and negative, shall remain. There may be no resolution to the nuclear question that will be politically viable."

6. BIOMASS


BEDOUIN COOKING, EYGPT
ISTOCK

Consisting of wood and other kinds of plant materials, as well as animal dung, various forms of biomass still account annually for about 13 percent of the world's total energy consumption and are used by up to 3 billion people for cooking and heating.[35] (Note: Most official comparative tallies of energy from various sources, such as those from the IEA and EIA, omit the contribution of "traditional" or noncommercial biomass usage; since these official sources are cited repeatedly herein, the careful reader will find that adding the 13 percent contribution of biomass to the percentage figures for other energy sources yields a total that is greater than 100 percent. The only remedy for this in the present text would have been the re-calculation of statistics from the official sources, but that would merely have added a different potential source of confusion.)

Nontraditional "new" forms of biomass usage generally involve converting wood, crops, manures, or agricultural "waste" products into liquid or gaseous fuel (see ethanol and biodiesel, below), using it to generate electricity, or using it to cogenerate heat and electricity. World electric power generation from biomass was about 183 TWh in 2005 from an installed capacity of 40 GW, with 27 percent of this coming from biogas and municipal solid waste.[36]

Wood fuels presently account for 60 percent of global forest production (most of the remaining 40 percent is used for building materials and paper) and, along with agricultural residues (such as straw), contribute 220 GWh for cooking and heating energy. Forests are a huge renewable resource, covering 7 percent of the Earth's surface, but net deforestation is occurring around the globe, especially in South America, Indonesia, and Africa.[37] Deforestation is caused mostly by commercial logging and clearing of land for large-scale agriculture, *not* by traditional wood gathering, which is often sustainably practiced. However, in many areas wood use and population pressure are leading to deforestation and even desertification.

Cogeneration or Combined Heat and Power (CHP) plants can burn fossil fuels or biomass to make electricity and are configured so that the heat from this process is not wasted but used for space or water heating. Biomass CHP is more efficient at producing heat than electricity, but can be practical on both counts if there is a local source of excess biomass and a community or industrial demand nearby for heat and electricity. Biomass plants are being built in the U.S., in northern Europe, and also in Brazil (where they are associated with the sugar processing industry). The rate of growth of biopower has been around 5 percent per year over the last decade.[38] Biomass power plants are only half as efficient as natural gas plants and are limited in size by a fuelshed of around 100 miles, but they provide rural jobs and reliable base-load power (though in temperate climates biomass availability is seasonal, and biomass storage is particularly inefficient with high rates of loss).[39]

Biomass conversion technologies (as opposed to direct use via burning) can be divided into three categories. *Biochemical* methods use fermentation and decomposition to create alcohols (primarily ethanol) and landfill gas. Oil extracted from plants, animals or algae can be converted *chemically* into biodiesel. In *thermochemical* processes, biomass is heated (pyrolized) and broken down into carbon and flammable syngases or bio-oil (depending on the speed and temperature of pyrolysis and the feedstock). Bio-oil can be used like fuel oil or refined into biodiesel, while syngas has properties similar to natural gas. There is growing interest in using thermochemical processes to make biofuels, since the leftover carbon (called biochar) can be added to farm fields to improve soil fertility and sequester carbon.[40]

The biochemical process of decay in the absence of oxygen produces biogas, which occurs naturally in places where anaerobic decay is concentrated, like swamps, landfills, or cows' digestive systems. Industrial manufacture of biogas uses bacteria to ferment or anaerobically digest biodegradable material, producing a combustible mixture consisting of 50 to 75 percent methane plus other gases.[41] Biogas can be used like natural gas and burned as fuel in anything from a small cookstove to an electricity plant. Small-scale biogas is utilized all over the world, both in households and for industry.

Biogas can be produced on an industrial scale from waste materials, but it is difficult to find estimates of the possible size of this resource. The National Grid in the U.K. has suggested that waste methane can be collected, cleaned and added to the existing U.K. natural gas pipeline system. That agency estimates that if all the country's sewage, food, agriculture and manufacturing biowastes were used, half of all U.K. residential gas needs could be met. Burning biogas for heat and cooking offers 90 percent energy conversion efficiency, while using biogas to generate electricity is only 30 percent efficient.[42]

PLUS: Biomass is distributed widely where people live. This makes it well suited for use in small-scale, region-appropriate applications where using local biomass is sustainable. In Europe there has been steady growth in biomass CHP plants in which scrap materials from wood processing or agriculture are burned, while in developing countries CHP plants are often run on coconut or rice husks. In California, dairy farms are using methane from cow manure to run their operations. Biogas is used extensively in China for industry, and 25 million households worldwide use biogas for cooking and lighting.[43]

Burning biomass and biogas is considered to be carbon neutral, since unlike fossil fuels these operate within the biospheric carbon cycle. Biomass contains carbon that would ordinarily be released naturally by decomposition or burning to the atmosphere over a short period of time. Using waste sources of biogas like cow manure or landfill gas reduces emissions of methane, a greenhouse gas twenty-three times more potent than carbon dioxide.

MINUS: Biomass is a renewable resource but not a particularly expandable one. Often, available biomass is a waste product of other human activities, such as crop residues from agriculture, wood chips, sawdust and black liquor from wood products industries, and solid waste from municipal trash and sewage. In a less energy-intensive agricultural system, such as may be required globally in the future, crop residues may be needed to replenish soil fertility and will no longer be available for power generation. There may also be more competition for waste products in the future, as manufacturing from recycled materials increases.

Using biomass for cooking food has contributed to deforestation in many parts of the world and it is associated with poor health and shortened lifespans, especially for women who cook with wood or charcoal in unvented spaces. Finding a substitute fuel or increasing the efficiency of cooking with wood is the goal of programs in India, China and Africa.[44] In order to reduce greenhouse gas emissions, it is probably more desirable to re-forest than to use wood as fuel.

EROEI: Energy return estimates for biomass are extremely variable. Biomass is generally more efficiently used for heat than for electricity, but electricity generation from biomass can be energetically favorable in some instances. Biogas is usually made from waste materials and utilizes decomposition, which is a low energy-input process, so it is inherently efficient. Regarding the EROEI of ethanol and biodiesel, see below.

PROSPECTS: Wood, charcoal, and agricultural residues will almost certainly continue to be used around the world for cooking and heating. There is a declining amount of biomass-derived materials entering the waste stream because of increased recycling, so the prospect of expanding landfill methane capture is declining. Use of other kinds of biogas is a potential growth area. Policies that support biogas expansion exist in India and especially in China, where there is a target of increasing the number of household-scale biogas digesters from an estimated 1 million in 2006 to 45 million by 2020.

7. WIND POWER


TRADITIONAL WINDMILL IN THE NETHERLANDS / QUISTNIX

One of the fastest-growing energy sources in the world, wind power generation expanded more than five-fold between 2000 and 2007. However, it still accounts for less than 1 percent of the world's electricity generation, and much less than 1 percent of total energy. In the U.S., total production currently amounts to 32Twh, which is 0.77 percent of total electricity supplied, or 0.4 percent of total energy.

Of all new electricity generation capacity installed in the U.S. during 2007 (over 5,200 MW), more than 35 percent came from wind. U.S. wind energy production has doubled in just two years. In September 2008, the U.S. surpassed Germany to become the world leader in wind energy production, with more than 25,000 MW of total generating capacity. [45] (Note: In discussing wind power, it is important to distinguish between nameplate production capacity—the amount of power that theoretically could be generated at full utilization—and the actual power produced: the former number is always much larger, because winds are intermittent and variable.)

Wind turbine technology has advanced in recent years, with the capacity of the largest turbines growing from 1 MW in 1999 to up to 5 MW today. The nations currently leading in installed wind generation capacity are the United States, Germany, Spain, India, and China. Wind power currently accounts for about 19 percent of electricity produced in Denmark, 9 percent in Spain and Portugal, and 6 percent in Germany and the Republic of Ireland. In 2007-2008 wind became the fastest-growing energy source in Europe, in quantitative as well as percentage terms.

PLUS: Wind power is a renewable source of energy, and there is enormous potential for growth in wind generation: it has been estimated that developing 20 percent of the world's wind-rich sites would produce seven times the current world electricity demand.[46] The cost of electricity from wind power, which is relatively low, has been declining further in recent years. In the U.S. as of 2006, the cost per unit of energy production capacity was estimated to be comparable to the cost of new generating capacity for coal and natural gas: wind cost was estimated at $55.80 per MWh, coal at $53.10/MWh, and natural gas at $52.50 (however, once again it is important with wind power to stress the difference between nameplate production capacity and actual energy produced).[47]

MINUS: The uncontrolled, intermittent nature of wind reduces its value when compared to operator-controlled energy sources such as coal, gas, or nuclear power. For example, during January 2009 a high pressure system over Britain resulted in very low wind speeds combined with unusually low temperatures (and therefore higher than normal electricity demand). The only way for utility operators to prepare for such a situation is to build extra generation capacity from other energy sources. Therefore, adding new wind generating capacity often does not substantially decrease the need for coal, gas, or nuclear power plants; it merely enables those conventional power plants to be used less while the wind is blowing. However, this creates the need for load-balancing grid control systems.

Another major problem for wind generation is that the resource base is often in remote locations. Getting the electricity from the local point-of-generation to a potentially distant load center can be costly. The remoteness of the wind resource base also leads to increased costs for development in the case of land with difficult terrain or that is far from transportation infrastructure.

Being spread out over a significant land area, wind plants must compete with alternative development ideas for these land resources, especially where multiple simultaneous usages are impossible.

The dramatic cost reductions in the manufacture of new wind turbines over the past two decades may slow as efficiencies are maximized and as materials costs increase.

Though wind turbines have been generally accepted by most communities, there has been concern about "visual pollution" and the turbines' danger to birds.

EROEI: The average EROEI from all studies worldwide (operational and conceptual) was 24.6:1. The average EROEI from just the operational studies is 18.1:1. This compares favorably with conventional power generation technologies.[48]

In the U.S., existing wind power has a high EROEI (18:1), though problems with electricity storage may reduce this figure substantially as generating capacity grows. EROEI generally increases with the power rating of the turbine, because *(1)* smaller turbines represent older, less efficient technologies; *(2)* larger turbines have a greater rotor diameter and swept area, which is the most important determinant of a turbine's potential to generate power; and *(3)* since the power available from wind increases by the cube of an increase in the wind speed, and larger turbines can extract energy from winds at greater heights, wind speed and thus EROEI increase quickly with the height of the turbine.

The net energy ratio for wind power can range widely depending on the location of a turbine's manufacture and installation, due to differences in the energy used for transportation of manufactured turbines between countries, the countries' economic and energy structure, and recycling policies. For example, production and operation of an E-40 turbine in coastal Germany requires 1.39 times more energy than in Brazil. The EROEI for sea-based turbines is likely to be lower due to maintenance needs resulting from the corrosive effects of sea spray.

PROSPECTS: Wind is already a competitive source of power. For structural reasons (its long-term cost of production is set by financing terms upon construction and does not vary in the short term), wind benefits from *feed-in tariffs* to protect it from short-term electricity price fluctuations; but overall it will be one of the cheapest sources of power as fossil fuels dwindle—and one with a price guaranteed not to increase over time. In the E.U. its penetration is already reaching 10 to 25 percent in several nations; prospects in the U.S. are in some ways better, as growth is not limited by the geographical constraints and population density found in Europe (with more land covered by cities, that leaves fewer good sites for turbines).

Intermittency can be dealt with to some extent, as the European experience shows, by a combination of smart grid management and infrequent use of the existing fossil-fuel-fired capacity; even though a large amount of thermal power generation capacity will still be required, less coal and gas will need to be burned. Nevertheless, until windmill power can mine ores, produce cement, and make steel and alloys and the machine tools to make components, then wind turbine costs are going to be highly connected to fossil fuel prices, and those costs will impact power prices.

In the U.S., substantial further development of wind power will require significant investment in upgrading the national electricity grid.

8. SOLAR PHOTOVOLTAICS (PV)

Photovoltaic (PV) cells generate electricity directly from sunlight. PV cells usually use silicon as a semiconductor material. Since an enormous amount of energy is transmitted to the Earth's surface in the form of solar radiation, tapping this source has great potential. If only 0.025 percent of this energy flow could be captured, it would be enough to satisfy world electricity demand.

In 2006 and 2007, photovoltaic systems were the fastest growing energy technology in the world (on a percentage basis), increasing 50 percent annually. At the beginning of 2008, world PV installed capacity stood at 12.4 GW.

The goals of PV research are primarily to *(1)* increase the efficiency of the process of converting sunlight into electricity (the typical efficiency of an installed commercial single-crystalline silicon solar panel is 10 percent, meaning that only 10 percent of the energy of sunlight is converted to electrical energy, while 24.7 percent efficiency has been achieved under laboratory conditions); and *(2)* decrease the cost of production (single-crystalline silicon panels average $3.00 per watt installed, while new photovoltaic materials and technologies, especially thin-film PV materials made by printing or spraying nanochemicals onto an inexpensive plastic substrate, promise to reduce production costs dramatically, though usually at a loss of efficiency or durability).[49]

PLUS: The solar energy captured by photovoltaic technology is renewable—and there is a lot of it. The cumulative average energy irradiating a square meter of Earth's surface for a year is approximately equal to the energy in a barrel of oil; if this sunlight could be captured at 10 percent efficiency, 3,861 square miles of PV arrays would supply the energy of a billion barrels of oil. Covering the world's estimated 360,000 square miles of building rooftops with PV arrays would generate the energy of 98 billion barrels of oil each year.

The price for new installed PV generating capacity has been declining steadily for many years.

Unlike passive solar systems, PV cells can function on cloudy days.[50]

MINUS: The functionality of PV power generation varies not only daily, but also seasonally with cloud cover, sun angle, and number of daylight hours. Thus, as with wind, the uncontrolled, intermittent nature of PV reduces its value as compared to operator-controlled energy sources such as coal, gas, or nuclear power.

Sunlight is abundant, but diffuse: its area density is low. Thus efforts to harvest energy from sunlight are inevitably subject to costs and tradeoffs with scale: for example, large solar installations require suitable land, water for periodic cleaning, roads for access by maintenance vehicles, and so on.

Some of the environmental impacts of manufacturing PV systems have been analyzed by Alsema *et al.* and compared to the impacts of other energy technologies.[51] This study found PV system CO_2 emissions to be greater than those for wind systems, but only 5 percent of those from coal burning. A potential impact would be the loss of large areas of wildlife habitat if really large industrial-scale solar arrays were built in undeveloped desert areas.

EROEI: Explicit net energy analysis of PV energy is scarce. However, using "energy pay-back time" and the lifetime of the system, it is possible to determine a rough EROEI. From a typical life-cycle analysis performed in 2005, Hall *et al.* calculated an EROEI of 3.75:1 to 10:1.[52]

Some of these EROEI values are likely to change as research and development continue. If present conditions persist, EROEI may decline since sources of silicon for the industry are limited by the production capacity of semiconductor manufacturers.

PROSPECTS: Despite the enormous growth of PV energy in recent years, the incremental increase in oil, gas, or coal production during a typical recent year has exceeded all existing photovoltaic energy production. Therefore if PV is to become a primary energy source, the rate of increase in capacity will need to be even greater than is currently the case.

Because of its high up-front cost, a substantial proportion of installed PV has been distributed on home roofs and in remote off-grid villages, where provision of conventional electricity sources would be impractical or prohibitively expensive. Commercial utility-scale PV installations are now appearing in several nations, partly due to the lower price of newer thin-film PV materials and changing government policies.[53]

The current economic crisis has lowered the rate of PV expansion substantially, but that situation could be reversed if government efforts to revive the economy focus on investment in renewable energy.

However, if very large and rapid growth in the PV industry were to occur, the problem of materials shortages would have to be addressed in order to avert dramatic increases in cost. Materials in question—copper, cadmium-telluride (CdTe), and copper-indium-gallium-diselenide (CIGS)—are crucial to some of the thin-film PV materials to which the future growth of the industry (based on lowering of production costs) is often linked. With time, PV production may be constrained by lack of available materials, the rate at which materials can be recovered or recycled, or possibly by competition with other industries for those scarce materials. A long-term solution will hinge on the development of new PV materials that are common and cheap.

Concentrating PV, which uses lenses to focus sunlight onto small, highly efficient silicon wafers, is achieving ever-lower costs and ever-higher efficiencies, and could be competitive with coal, nuclear, and natural gas power generation on an installed per-watt capacity basis within just a few years. Nevertheless, this technology is still in its infancy and even if it can be developed further the problem of intermittency will remain.

9. ACTIVE (CONCENTRATING) SOLAR THERMAL

This technology typically consists of installations of mirrors to focus sunlight, creating very high temperatures that heat a liquid which turns a turbine, producing electricity. The same power plant technology that is used with fossil fuels can be used with solar thermal since the focusing collectors can heat liquid to temperatures from 300°C to 1000°C. Fossil fuel can be used as a backup at night or when sunshine is intermittent.

There is a great deal of interest and research in active solar thermal and a second generation of plants is now being designed and built, mostly in Spain. Worldwide capacity will soon reach 3 GW.

PLUS: Like PV, active solar thermal makes use of a renewable source of energy (sunlight), and there is enormous potential for growth. In the best locations, cost per watt of installed capacity is competitive with fossil-fuel power sources. Solar thermal benefits from using already mature power plant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technology and needs less land than a photovoltaic array of the same generating capacity.

MINUS: Again like PV, concentrating solar thermal power is intermittent and seasonal. Some environmental impacts are to be expected on the land area covered by mirror arrays and during the construction of transmission lines to mostly desert areas where this technology works best.

EROEI: The energy balance of this technology is highly variable depending on location, thus few studies have been done. In the best locations (areas with many sunny days per year), EROEI is likely to be relatively high.

PROSPECTS: There is considerable potential for utility-scale deployment of concentrating solar thermal power. Some analysts have even suggested that all of the world's energy needs could be filled with electrical power generated by this technology. This would require covering large areas of desert in the southwestern U.S., northern Africa, central Asia, and central Australia with mirrors, as well as constructing high-power transmission lines from these remote sites to places where electricity demand is highest. Such a project is possible in principle, but the logistical hurdles and financial costs would be daunting. Moreover, some intermittency problems would remain even if the sunniest sites were chosen.

Leaving aside such grandiose plans, for nations that lie sufficiently close to the equator this appears to be one of the most promising alternative sources of energy available.[54]

Recently a startup project called Desertec has proposed raising an estimated $570 billion for the construction of an enormous active solar thermal installation in the Sahara Desert to supply 15 percent of Europe's electricity needs.Concentrating solar thermal plants in Spain are now testing a heat storage module,[55] which can maintain power delivery during nights and perhaps longer periods of low sunshine. Since thermal energy is much cheaper to store than electricity, this could represent an advantage over wind or PV power if the Spanish tests are successful.

10. PASSIVE SOLAR


SOLAR WINDOWS
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This simple approach consists of capturing and optimizing natural heat and light from the sun within living spaces without the use of collectors, pumps, or mechanical parts, thus reducing or eliminating the need for powered heating or lighting. Buildings are responsible for a large percentage of total energy usage in most countries, and so passive solar technologies are capable of offsetting a substantial portion of energy production and consumption that might otherwise come from fossil fuels. A passive solar building is designed *(1)* to maintain a comfortable average temperature, and *(2)* to minimize temperature fluctuations. Such a building usually takes more time, money, and design effort to construct, with extra costs made up in energy savings over time.

Passive solar heating takes three dominant forms: glazing surfaces to help capture sunlight; *trombe walls*, and other features for heat storage; and insulation to maintain relatively constant temperatures. Other important factors include orienting the long side of the building toward the sun, determining the appropriate sizing of the mass required to retain and slowly release accumulated heat after the sun sets, and determining the size of the trombe wall necessary to heat a given space. (Of course, the size of the entire building is also an issue—a passive solar design for a monster home makes no sense.)

Other passive uses of sunlight in buildings include passive solar cooling and daylighting (using windows and openings to make use of natural light).

PLUS: Depending on the study, passive solar homes cost less than, the same as, or up to 5 percent more than other custom homes; however, even in the latter case the extra cost will eventually pay for itself in energy savings. A passive solar home can only provide heat for its occupants, not extra electricity, but if used on all new houses passive systems could go a long way toward replacing other fuels.

Incorporating a passive solar system into the design of a new home is generally cheaper than fitting it onto an existing home. A solar home "decreases cooling loads and reduces electricity consumption, which leads to significant decline in the use of fossil fuels."[56] Passive solar buildings, in contrast to buildings with artificial lighting, may also provide a healthier, more productive work environment.

MINUS: Limitations to passive solar heating can include inappropriate geographic location (clouds and colder climates make solar heating less effective), and the relative difficulties of sealing the house envelope to reduce air leaks while not increasing the chance of pollutants becoming trapped inside. The heat-collecting, equator-facing side of the house needs good solar exposure in the winter, which may require spacing houses further apart and using more land than would otherwise be the case.

EROEI: Strictly speaking, it is not appropriate to use EROEI calculations in this instance since there is no "energy out" for the equation. Passive solar design is essentially a matter of using the "free energy" of nature to replace other forms of energy that would otherwise need to be used for heating and lighting. It is extremely site-specific, and architects rarely obtain quantitative feedback on systems they have designed, so determining general figures for savings is difficult (but a range from 30 to 70 percent is typical). If the system is built into the house from the beginning, then energy savings can be obtained with few or no further investments.

PROSPECTS: Designing buildings from the start to take advantage of natural heating and lighting, and to use more insulation and solar mass, has tremendous potential to reduce energy demand. However, in many cases high-efficiency buildings require more energy for construction, (construction energy is not generally considered in savings calculations, which are typically done only on operational energy).

Until now, higher up-front construction costs have discouraged mass-scale deployment of passive solar homes in most countries. Higher energy prices will no doubt gradually alter this situation, but quicker results could be obtained through shifts in building regulations and standards, as has been shown in Germany. There, the development of the voluntary Passivhaus standard has stimulated construction and retrofitting of more than 20,000 passive houses in northern Europe.[57] The Passivhaus is designed to use very little energy for heating. Passive solar provides space heating, and superinsulation and controlled outdoor air exchange (usually with heat exchanger) reduces heat loss.

Buildings in industrialized nations have generally become more efficient in recent years; however declines in averaged energy use per square foot have generally been more than offset by population growth and the overbuilding of real estate (the average size of buildings has grown), so that the total amount of energy used in buildings has continued to increase. Thus, population and economic growth patterns need to be part of the "green building" agenda, along with the increasing use of passive solar design elements.[58]

11. GEOTHERMAL ENERGY

Derived from the heat within the Earth, geothermal energy can be "mined" by extracting hot water or steam, either to run a turbine for electricity generation or for direct use of the heat. High-quality geothermal energy is typically available only in regions where tectonic plates meet and volcanic

GEOTHERMAL BOREHOUSE, ICELAND/ LYDUR SKULASON

and seismic activity are common. Low-temperature geothermal direct heat can be tapped anywhere on Earth by digging a few meters down and installing a tube system connected to a heat pump.

Currently, the only places being exploited for geothermal electrical power are where hydrothermal resources exist in the form of hot water or steam reservoirs. In these locations, hot groundwater is pumped to the surface from two to three km deep wells and used to drive turbines. One example: The Geysers installation in Northern California, occupying 30 square miles along the Sonoma and Lake County border, comprises the world's largest complex of geothermal power plants. The fifteen power plants there have a total net generating capacity of about 725 MW of electricity—enough to power 725,000 homes, or a city the size of San Francisco. The Geysers meets the typical power needs of Sonoma, Lake, and Mendocino counties, as well as a portion of the power needs of Marin and Napa counties.

Power can also be generated from hot dry rocks by pumping turbine fluid (essentially water) into them through three to ten km deep boreholes. This method, called Enhanced Geothermal System (EGS) generation, is the subject of a great deal of research, but no power has been generated commercially using EGS. If perfected, EGS could enable geothermal power to be harvested in far more places than is currently practical.

In 2006, world geothermal power capacity was about 10 GW.[59] Annual growth of geothermal power capacity worldwide has slowed from 9 percent in 1997 to 2.5 percent in 2004.

However, the use of direct heat using heat pumps or piped hot water has been growing 30 to 40 percent annually, particularly in Europe, Asia, and Canada.[60] (This is a fundamentally different technology from geothermal electricity production, even though the basic resource—heat from the Earth—is the same.)

PLUS: Geothermal power plants produce much lower levels of carbon emissions and use less land area as compared to fossil fuel plants. They can also run constantly, unlike some other renewable energy systems, such as wind and solar.

Geothermal direct heat is available everywhere (and geothermal heat pumps are among the few non-fossil fuel options for space heating), although it is less cost-effective in temperate climates. Countries rich in geothermal resources (such as Sudan, Ethiopia, Colombia, Ecuador, much of the Caribbean, and many Pacific islands) could become less dependent on foreign energy.

MINUS: In addition to geography and technology, high capital cost and low fossil fuel prices are major limiting factors for the development of geothermal electricity production. Technological improvements (especially the further development of EGS) are necessary for the industry to continue to grow. Water can also be a limiting factor, since both hydrothermal and dry rock systems consume water.

The sustainability of geothermal power generating systems is a cause of concern. Geothermal resources are only renewable if heat removal is balanced by natural replenishment of the heat source. Some geothermal plants have seen declines in temperature, most probably because the plant was oversized for the local heat source.

There is likely to be some air, water, thermal, and noise pollution from the building and operation of a geothermal plant, as well as solid waste buildup and the possibility of induced seismic activity near it.

EROEI: The calculated net energy for hydrothermal power generation has ranged, depending on the researcher, from 2:1 to 13:1. This discrepancy reflects differences in efficiency due to site characteristics and the lack of a unified methodology for EROEI analysis, as well as disagreements about system boundaries, quality-correction, and future expectations.[61]

There are no calculations of EROEI values for geothermal direct heat use, though for various reasons it can be assumed that they are higher than those for hydrothermal electrical power generation. As a starting point, it has been calculated that heat pumps move three to five times the energy in heat that they consume in electricity.

PROSPECTS: There is no consensus on potential resource base estimates for geothermal power generation. Hydrothermal areas that have both heat and water are rare, so the large-scale expansion of geothermal power depends on whether EGS and other developing technologies will prove to be commercially viable. A 2006 MIT report estimated U.S. hydrothermal resources at 2,400 to 9,600 EJ, while dry-heat geothermal resources were estimated to be as much as 13 million EJ.[62]

Until EGS is developed and deployed, limited hydrothermal resources will continue to be important regionally.

Meanwhile, direct geothermal heat use via heat pumps provides one of the few available alternatives to the use of fossil fuels or wood for space heating, and is therefore likely to see an increased rate of deployment in colder climates.

12. ENERGY FROM WASTE

LANDFILL, U.K.

ISTOCK

Trash can be burned to yield energy, and methane can be captured from landfills. All told, the world derives over 100 TWh of electricity, and an even greater amount of useful heat energy, from waste, amounting to about 1 percent of all energy used globally.

In the U.S., 87 trash incinerating generation plants produce about 12.3 TWh of electricity per year. Municipal waste is also burned for power in Europe; Taiwan, Singapore, and Japan incinerate 50 to 80 percent of their waste. There are 600 incineration plants producing energy worldwide. However, the practice is mostly restricted to high-income countries because such plants are expensive to operate and the waste stream in low-income nations typically has low calorific value. One estimate for total energy produced is 450 TWh, but this includes heat energy as well as electricity.[63]

The capture of landfill gas yields 11 TWh of electricity and 77 billion cubic feet of gas for direct use annually in the U.S. (from 340 out of a total of 2,975 landfills).[64] In Europe, landfill gas provides 17 TWh of electricity as well as heat energy, for a total of 36.3 TWh of biogas energy; there, recovery of biogas is now mandatory.

PLUS: Industrial waste products contain embodied energy; thus efforts to recover that energy can be thought of as a way of bringing greater efficiency to the overall industrial system. Energy production from waste does not entail the extraction of more natural resources than have already been used in the upstream activities that generated the waste (other than the resources used to build and operate the waste-to-energy plants themselves).

MINUS: Waste incineration releases into the environment whatever toxic elements are embodied in the waste products that are being burned—including dioxin, one of the most deadly compounds known. Moreover, incinerators emit more CO_2 per unit of energy produced than coal-fired, natural-gas-fired, or oil-fired power plants.

If energy efficiency is the goal, a better systemic solution to dealing with wastes would be to minimize the waste stream. Moreover, a zero-waste approach is one of the fastest, cheapest, and most effective strategies to protect the climate and the environment: significantly decreasing waste disposed in landfills and incinerators could reduce greenhouse gases by an amount equivalent to the closing of one-fifth of U.S. coal-fired power plants. However, if economic activity continues to decline, as a result of slower economic growth, less waste will be produced, one of the up-sides of financial decline.

EROEI: Little information is available on the net energy from waste incineration or landfill gas capture. If system boundaries are narrowly drawn (so that only direct energy costs are included), the EROEI from landfill gas capture is likely to be high. EROEI from trash incineration is likely to decline as more investment is directed toward preventing toxic materials from being released from burners.

PROSPECTS: If and when zero-waste policies are more generally adopted, the amount of waste available to be burned or placed into landfills will decline dramatically. Therefore waste-to-energy projects should not be regarded as sustainable over the long term, nor should this energy source be regarded as being scalable—that is, it is unlikely to be dramatically increased in overall volume.

13. ETHANOL

Ethanol is an alcohol made from plant material—usually sugar cane or corn—that is first broken down into sugars and then fermented. It has had a long history of use as a transportation fuel beginning with the Model T Ford. In 2007, 13.1 billion gallons of ethanol were produced globally. Thirty-eight percent of this was produced from sugar cane in Brazil, while another 50 percent was manufactured from corn in the U.S.[65] There has been a high rate of growth in the industry, with a 15 percent annual increase in world production between 2000 and 2006. Ethanol can be substituted for gasoline, but the total quantity produced is still only a small fraction of the 142 trillion gallons of gasoline consumed in the U.S. each year.[66]

Ethanol can be blended with gasoline and used in existing cars in concentrations of up to 10 percent. For percentages higher than this, engine modifications are needed since ethanol is more corrosive than gasoline. New cars are already being manufactured that run on 100 percent ethanol, on the 25/75 ethanol/gasoline "gasohol" blend used in Brazil, or the 85/15 ("E85") blend found in the United States.

Corn ethanol has become highly controversial because of problems associated with using a staple food plant such as corn as a fuel, and the resulting

ETHANOL PLANT, SOUTH DAKOTA ISTOCK

diversion of huge amounts of land from food production to fuel production. Another problem is that ethanol plants are themselves usually powered by fossil fuels.[67] However, there is now growing interest in making ethanol from non-food plant materials like corn stover, wheat chaff, or pine trees. One potential feedstock is the native prairie plant switchgrass, which requires less fossil fuel input for cultivation than corn. However, making cellulosic ethanol out of these non-food feedstocks is a technology in its infancy and not yet commercialized.

Potential ethanol resources are limited by the amount of land available to grow feedstock. According to the Union of Concerned Scientists (UCS), using all of the corn grown in the U.S. with nothing left for food or animal feed would only displace about 15 percent of U.S. gasoline demand by 2025.[68] Large-scale growing of switchgrass or other new cellulose crops would require finding very large acreages on which to cultivate them, also aggravating shortages of agricultural lands.

PLUS: Ethanol has the portability and flexibility of oil and can be used in small amounts blended with gasoline in existing vehicles. The distribution infrastructure for gasoline could be gradually switched over to ethanol as new cars that run on higher ethanol concentrations are phased in, though current pipelines would eventually have to be replaced as ethanol is highly corrosive.

Cellulosic ethanol is widely considered to be a promising energy source since it has potentially less environmental impact with respect to land use and lifecycle greenhouse gas emissions than fossil fuels. The UCS reports that it has the potential to reduce greenhouse gas emissions by 80 to 90 percent compared to gasoline.[69] However, this conclusion is disputed, and there are still serious technical problems with producing cellulosic ethanol on a commercial scale.

MINUS: There are approximately 45 MJ per kilogram contained in both finished gasoline and crude oil, while ethanol has an energy density of about 26 MJ per kilogram and corn has only 16 MJ per kilogram. In general, this means that large amounts of corn must be grown and harvested to equal even a small portion of existing gasoline consumption on an energy-equivalent level, which will undoubtedly expand the land area that is impacted by the production process of corn-based ethanol.

Increases in corn ethanol production may have helped to drive up the price of corn around the world in 2007, contributing to a 400 percent rise in the price of tortillas in Mexico.[70] Ethanol and other biofuels now consume 17 percent of the world's grain harvest.

There are climate implications to corn ethanol production as well. If food crops are used for making transportation fuel rather than food, more land will have to go into food production somewhere else. When natural ecosystems are cleared for food or ethanol production, the result is a "carbon debt" that releases 17 to 420 times more CO_2 than is saved by the displacement of fossil fuels.[71] The situation is better when dealing with existing cropland, but not much: Since fossil fuels are necessary for growing corn and converting it into ethanol, the finished fuel is estimated to offer only a 10 to 25 percent reduction in greenhouse gas emissions as compared to gasoline,[72] though even this level of reduction is questionable, as it relies on calculations involving DDGS; considering only liquid fuels, there is likely less or no greenhouse gas reduction. Corn ethanol also uses three to six gallons of water for every gallon of ethanol produced and has been shown to emit more air pollutants than gasoline.

EROEI: There is a range of estimates for the net energy of ethanol production since EROEI depends on widely ranging variables such as the energy input required to get the feedstock (which is high for corn and lower for switchgrass and cellulose waste materials) and the nature of the process used to convert it to alcohol.

There is even a geographic difference in energy input depending on how well suited the feedstock crop is to the region in which it is grown. For example, there is a definite hierarchy of corn productivity by state within the U.S.: in 2005, 173 bushels per acre (10,859 kg/ha) were harvested in Iowa, while only 113 bushels per acre were harvested in Texas (7,093 kg/ha). This is consistent with the general principle of "gradient analysis" in ecology, which holds that individual plant species grow best near the middle of their gradient space; that is near the center of their range in environmental conditions such as temperature and soil moisture. The climatic conditions in Iowa are clearly at the center of corn's gradient space. Statistics suggest that corn production is also less energy-intensive at or near the center of corn's gradient space.[73] This would imply a diminishing EROEI for ethanol production as the distance from Iowa increases, meaning that the geographic expansion of corn production will produce lower yields at higher costs. Indeed, ethanol production in Iowa and Texas yield very different energy balances, so that in Iowa the production of a bushel of corn costs 43 MJ, while in Texas it costs 71 MJ.

Calculated net energy figures for corn ethanol production in the U.S. range from less than 1:1 to 1.8:1.[74]

Ethanol from sugar cane in Brazil is calculated to have an EROEI of 8:1 to 10:1, but when made from Louisiana sugar cane in the U.S., where growing conditions are worse, the EROEI is closer to 1:1.[75] Estimates for the projected net energy of cellulose ethanol vary widely, from 2:1 to 36:1.[76] However, such projections must be viewed skeptically, given the absence of working production facilities.

These EROEI figures differ largely because of co-product crediting (i.e., adding an energy return figure to represent the energy replacement value of usable by-products of ethanol production—principally DDGS). In the USDA's figures for energy use in ethanol production, EROEI is 1.04 prior to the credits. But some analysts argue that co-product crediting is immaterial to the amount of energy required to produce ethanol. Distillation is highly energy intensive, and even more so in the case of cellulosic ethanol because the initial beer concentration is so low (about 4 percent compared to 10 to 12 percent for corn). This dramatically increases the amount of energy needed to boil off the remaining water. At absolute minimum, 15,000 BTU of energy are required in distillation alone per gallon of ethanol produced (current corn ethanol plants use about 40,000 BTU per gallon). This sets the limit on EROEI. If distillation were the only energy input in the process, and it could be accomplished at the thermodynamic minimum, then EROEI would be about 5:1. But there are other energy inputs to the process and distillation is not at the thermodynamic minimum.

Sugar cane EROEI estimates and cellulosic estimates that are frequently cited exclude non-fossil fuel energy inputs. For example, 8 to 10:1 EROEI numbers for the production of ethanol from sugar cane in Brazil exclude all bagasse (dry, fibrous residue remaining after the extraction of juice from the crushed stalks of sugar cane) burned in the refinery—which is clearly an energy input, though one that is derived from the sugar cane itself. Cellulosic ethanol EROEI estimates often assume that the lignin recovered from biomass is sufficient not only to fuel the entire plant, but to export 1 to 2 MJ of electricity per liter of ethanol produced (which is then credited back to the ethanol). However, this assumption is based on a single lab study that has not been replicated. The questions of whether these non-fossil energy inputs should be included or excluded in net energy calculations, and how such inputs should be measured and evaluated, are contested.

PROSPECTS: Ethanol's future as a major transport fuel is probably dim except perhaps in Brazil, where sugar cane supplies the world's only economically competitive ethanol industry. The political power of the corn lobby in the United States has kept corn ethanol subsidized and has kept investment flowing, but the fuel's poor net energy performance will eventually prove it to be uneconomic. The technical problems of processing cellulose for ethanol may eventually be overcome, but land use considerations and low EROEI will likely limit the scale of production.

14. BIODIESEL

BIODIESEL BUS, BARCELONA

This is a non-petroleum-based diesel fuel made by *transesterification* of vegetable oil or animal fat (tallow)—a chemical treatment to remove glycerine, leaving long-chain alkyl (methyl, propyl, or ethyl) esters. Biodiesel can be used in unmodified diesel engines either alone, or blended with conventional petroleum diesel. Biodiesel is distinguished from straight vegetable oil (SVO), sometimes referred to as "waste vegetable oil" (WVO), "used vegetable oil" (UVO), or "pure plant oil" (PPO). Vegetable oil can itself be used as a fuel either alone in diesel engines with converted fuel systems, or blended with biodiesel or other fuels.

Vegetable oils used as motor fuel or in the manufacture of biodiesel are typically made from soy, rape seed ("canola"), palm, or sunflower. Considerable research has been devoted to producing oil for this purpose from algae, with varying reports of success (more on that below).

Global biodiesel production reached about 8.2 million tons (230 million gallons) in 2006, with approximately 85 percent of production coming from the European Union, but with rapid expansion occurring in Malaysia and Indonesia.[77]

In the United States, average retail (at the pump) prices, including Federal and state fuel taxes, of B2/B5 are lower than petroleum diesel by about 12 cents, and B20 blends are the same as petrodiesel. B99 and B100 generally cost more than petrodiesel except where local governments provide a subsidy. (The number following "B" in "B20," "B99," etc., refers to the percentage of biodiesel in the formulation of the fuel; in most instances, the remaining percentage consists of petroleum diesel. Thus "B20" fuel consists of 20 percent biodiesel and 80 percent petroleum diesel.)

PLUS: Biodiesel's environmental characteristics are generally more favorable than those of petroleum diesel. Through its lifecycle, biodiesel emits one fifth the CO_2 of petroleum diesel, and contains less sulfur. Some reports suggest that its use leads to longer engine life, which presumably would reduce the need for manufacturing replacement engines.[78] When biodiesel is made from waste materials like used vegetable oil, the net environmental benefits are more pronounced.

MINUS: The principal negative impact of expanding biodiesel production is the need for large amounts of land to grow oil crops. Palm oil is the most fruitful oil crop, producing 13 times the amount of oil as soybeans, the most-used biodiesel feedstock in the United States. In Malaysia and Indonesia, rainforest is being cut to plant palm oil plantations, and it has been estimated that it will take 100 years for the climate benefits of biodiesel production from each acre of land to make up for the CO_2 emissions from losing the rainforest.[79] Palm oil production for food as well as fuel is driving deforestation across Southeast Asia and reducing rainforest habitat to the point where larger animal species, such as the orangutan, are threatened with extinction.[80] Soybean farming in Brazil is already putting pressure on Amazonian rainforests. If soybeans begin to be used extensively for biofuels this pressure will increase.

EROEI: The first comprehensive comparative analysis of the full life cycles of soybean biodiesel and corn grain ethanol has concluded that biodiesel has much less of an impact on the environment and a much higher net energy benefit than corn ethanol, but that neither can do much to meet U.S. energy demand.[81] Researchers tracked all the energy used for growing corn and soybeans and converting the crops into biofuels. They also examined how much fertilizer and pesticide corn and soybeans required and the quantities of greenhouse gases, nitrogen oxides, phosphorus, and pesticide pollutants each released into the environment. The study showed a positive energy balance for both fuels; however, the energy returns differed greatly: soybean biodiesel currently returns 93 percent more energy than is used to produce it (1.93:1), while corn grain ethanol provides, according to this study, only 25 percent more energy (1.25:1). When discussing such distinctions, it is important to recall that industrial societies emerged in the context of energy returns in the double digits—50:1 or more, meaning fifty times as much energy yielded as invested.

Other researchers have claimed that the net energy of soybean biodiesel has improved over the last decade because of increased efficiencies in farming, with one study calculating an EROEI of 3.5:1.[82] Palm oil biodiesel has the highest net energy, calculated by one study at 9:1.[83]

PROSPECTS: There are concerns, as with ethanol, that biodiesel crops will increasingly compete with food crops for land in developing countries and raise the price of food. The need for land is the main limitation on expansion of biodiesel production and is likely to restrict the potential scale of the industry.[84] Water is also a limiting factor, given that world water supplies for agricultural irrigation are already problematic.

Biodiesel can also be made from algae, which in turn can be grown on waste carbon sources, like the CO_2 scrubbed from coal-burning power plants or sewage sludge. Saltwater rather than freshwater can be used to grow the algae, and there is optimism that this technology can be used to produce significant amounts of fuel. However, the process is still in a developmental stage. Limiting factors may be the need for large closed bioreactors, water supply, sunshine consistency, and thermal protection in cold climates.[85]

Biodiesel from waste oil and fats will continue to be a small and local source of fuel, while algae-growing shows promise as a large-scale biodiesel technology only if infrastructure and maintenance costs can be minimized.

15. TAR SANDS

Sometimes called "oil sands," this controversial fossil fuel consists of bitumen (flammable mixtures of hydrocarbons and other substances that are components of asphalt and tar) embedded in sand or clay.

OIL SANDS OPEN PIT MINING

IEN EARTH

The resource is essentially petroleum that formed without a geological "cap" of impervious rock (such as shale, salt, or anhydrite) being present to prevent lighter hydrocarbon molecules from rising to the surface, and that therefore volatized rather than remaining trapped underground.

Tar sands can be extracted through an *in situ* underground liquefaction process by the injection of steam, or by mining with giant mechanized shovels. In either case, the material remains fairly useless in its raw state, and requires substantial processing or upgrading, the finished product being referred to as "syncrude."

The sites of greatest commercial concentration of the resource are in Alberta, Canada and the Orinoco Basin of Venezuela (where the resource is referred to as heavy oil). Current production of syncrude from operations in Canada amounts to about 1.5 million barrels per day, which accounts for 1.7 percent of total world liquid fuels production, or a little less than 0.7 percent of total world energy. Reserves estimates range widely, from less than 200 billion barrels of oil equivalent up to 1.7 trillion barrels in Canada; for Venezuela the most-cited reserves estimate of extra heavy crude is 235 billion barrels, though in both cases it is likely that a large portion of what has been classified as "reserves" should be considered unrecoverable "resources" given the likelihood that deeper and lower-quality tar sands will require more energy for their extraction and processing than they will yield.

PLUS: The only advantages of tar sands over conventional petroleum are that *(1)* large amounts remain to be extracted, and *(2)* the place where the resource exists in greatest quantity (Canada) is geographically close and politically friendly to the country that imports the most oil (the U.S.).

MINUS: Tar sands have all of the negative qualities associated with the other fossil fuels (they are nonrenewable, polluting, and climate-changing), but in even greater measure than is the case with natural gas or conventional petroleum. Tar sands production is the fastest-growing source of Canada's greenhouse gas emissions, with the production and use of a barrel of syncrude ultimately doubling the amount of CO_2 that would be emitted by the production and use of a barrel of conventional petroleum. Extraction of tar sands has already caused extensive environmental damage across a broad expanse of northern Alberta.

All of the techniques used to upgrade tar sands into syncrude require other resources. Some of the technologies require significant amounts of water and natural gas—as much as 4.5 barrels of water and 1200 cubic feet (34 cubic meters) of natural gas for each barrel of syncrude.

As a result, syncrude is costly to produce. A fixed per-barrel dollar cost is relatively meaningless given recent volatility in input costs; however, it is certainly true that production costs for syncrude are much higher than historic production costs for crude oil, and compare favorably only with the higher costs for the production of a new marginal barrel of crude using expensive new technologies.

EROEI: For tar sands and syncrude production, net energy is difficult to assess directly. Various past net energy analyses for tar sands range from 1.5:1 to 7:1, with the most robust and recent of analyses suggesting a range of 5.2:1 to 5.8:1.[86] This is a small fraction of the net energy historically derived from conventional petroleum.

PROSPECTS: The International Energy Agency expects syncrude production in Canada to expand to 5 mb/d by 2030, but there are good reasons for questioning this forecast. The environmental costs of expanding production to this extent may be unbearable. Further, investment in tar sands expansion is now declining, with more than US$60 billion worth of projects having been delayed in the last three months of 2008 as the world skidded into recession. A more realistic prospect for tar sands production may be a relatively constant production rate, rising perhaps only to 2 or 3 million barrels per day.

16. OIL SHALE

If tar sands are oil that was "spoiled" (in that the shorter-chained hydrocarbon molecules have volatized, leaving only hard-to-use bitumen), oil shale (or kerogen, as it is more properly termed) is oil that was undercooked: it consists of source material that was not buried at sufficient depth or for long enough to be chemically transformed into the shorter hydrocarbon chains found in crude oil or natural gas.

Deposits of potentially commercially extractable oil shale exist in thirty-three countries, with the largest being found in the western region of the U.S. (Colorado, Utah, and Wyoming). Oil shale is used to make liquid fuel in Estonia, Brazil, and China; it is used for power generation in Estonia, China, Israel, and Germany; for cement production in Estonia, Germany, and China; and for chemicals production in China, Estonia, and Russia. As of 2005, Estonia accounted for about 70 percent of the world's oil shale extraction and use. The percentage of world energy currently derived from oil shale is negligible, but world resources are estimated as being equivalent to 2.8 trillion barrels of liquid fuel.[87]

PLUS: As with tar sands, the only real upside to oil shale is that there is a large quantity of the resource in place. In the U.S. alone, shale oil resources are estimated at 2 trillion barrels of oil equivalent, nearly twice the amount of the world's remaining conventional petroleum reserves.

MINUS: Oil shale suffers from low energy density, about one-sixth that of coal. The environmental impacts from its extraction and burning are very high, and include severe air and water pollution and the release of half again as much CO_2 as the burning of conventional oil. The use of oil shale for heat is far more polluting than natural gas or even coal. Extraction on a large scale in the western U.S. would require the use of enormous amounts of water in an arid region.

EROEI: Reported EROEI for oil produced from oil shale is generally in the range of 1.5:1 to 4:1[88]. Net energy for this process is likely to be lower than the production of oil from tar sands because of the nature of the material itself.

PROSPECTS: During the past decades most commercial efforts to produce liquid fuels from oil shale have ended in failure. Production of oil shale worldwide has actually declined significantly since 1980. While low-level production is likely to continue in several countries that have no other domestic fossil fuel resources, the large-scale development of production from oil shale deposits seems unlikely anywhere for both environmental and economic reasons.

17. TIDAL POWER

TIDAL POWER PLANT, RANCE RIVER, FRANCE DANI

Generation of electricity from tidal action is geographically limited to places where there is a large movement of water as the tide flows in and out, such as estuaries, bays, headlands, or channels connecting two bodies of water.

The oldest tidal power technology dates back to the Middle Ages, when it was used to grind grain. Current designs consist of building a barrage or dam that blocks off all or most of a tidal passage; the difference in the height of water on the two sides of the barrage is used to run turbines. A newer technology, still in the development stage, places underwater turbines called tidal stream generators directly in the tidal current or stream.

Globally, there is about 0.3 GW of installed capacity of tidal power[89], most of it produced by the barrage built in 1966 in France across the estuary of the Rance River (barrages are essentially dams across the full width of a tidal estuary).

PLUS: Once a tidal generating system is in place, it has low operating costs and produces reliable, although not constant, carbon-free power.

MINUS: Sites for large barrages are limited to a few places around the world. Tidal generators require large amounts of capital to build, and can have a significant negative impact on the ecosystem of the dammed river or bay.

EROEI: No calculations have been done for tidal power EROEI as yet. For tidal stream generators this figure might be expected to be close to that of wind power (an average EROEI of 18:1) since the turbine technologies for wind and water are so similar that tidal stream generators have been described as “underwater windmills.” However, tidal EROEI figures would likely be lower due to the corrosiveness of seawater and thus higher construction and maintenance energy use. The EROEI of barrage systems might be somewhat comparable to that of hydroelectric dams (EROEI in the range of 11.2:1 to 267:1), but will likely be lower since the former only generate power for part of the tidal cycle.

PROSPECTS: One estimate of the size of the global annual potential for tidal power is 450 TWh, much of it located on the coasts of Asia, North America, and the United Kingdom.[90] Many new barrage systems have been proposed and new sites identified, but the initial cost is a difficulty. There is often strong local opposition, as with the barrage proposed for the mouth of the River Severn in the U.K. Tidal stream generators need less capital investment and, if designed and sited well, may have very little environmental impact. Prototype turbines and commercial tidal stream generating systems are being tested around the world.

18. WAVE ENERGY

Designed to work offshore in deeper water, wave energy harvests the up-and-down, wind-driven motion of the waves. Onshore systems use the force of breaking waves or the rise and fall of water to run pumps or turbines.

The commonly quoted estimate for potential global wave power generation is about 2 TW[91], distributed mostly on the western coasts of the Americas, Europe, southern Africa, and Australia,

PELAMIS WAVE ENERGY CONVERTER. EUROPEAN MARINE ENERGY TEST CENTRE

where wind-driven waves reach the shore after accumulating energy over long distances. For current designs of wave generators the economically exploitable resource is likely to be from 140 to 750 TWh per year.[92] The only operating commercial system has been the 2.25 MW Agucadora Wave Park off the coast of Portugal. (However, this was recently pulled ashore, and it is not clear when it will be redeployed).

Research into wave energy has been funded by both governments and small engineering companies, and there are many prototype designs. Once the development stage is over and the price and siting problems of wave energy systems are better understood, there may be more investment in them. In order for costs to decrease, problems of corrosion and storm damage must be solved.

PLUS: Once installed, wave energy devices emit negligible greenhouse gases and should be cheap to run. Since the majority of the world's population lives near coastlines, wave energy is convenient for providing electricity to many. It may also turn out to provide an expensive but sustainable way to desalinate water.

MINUS: In addition to high construction costs, there are concerns about the environmental impact of some designs, as they may interfere with fishing grounds. Interference with navigation and coastal erosion are also potential problems. Wave energy fluctuates seasonally as well as daily, since winds are stronger in the winter, making this a somewhat intermittent energy source.

EROEI: The net energy of wave energy devices has not been thoroughly analyzed. One rough estimate of EROEI for the Portuguese Pelamis device is 15:1.[93]

PROSPECTS: Wave power generation will need more research, development, and infrastructure build-out before it can be fairly assessed. More needs to be understood about the environmental impacts of wave energy "farms" (collections of many wave energy machines) so that destructive siting can be avoided. The best devices will need to be identified and improved, and production of wave devices will need to become much cheaper.

OTHER SOURCES

In addition to the eighteen energy sources discussed above, there are some other potential sources that have been discussed in the energy literature, but which have not reached the stage of application. These include: ocean thermal (which would produce energy from the temperature differential between surface and deep ocean water), "zero-point" and other "free energy" sources (which are asserted to harvest energy from the vacuum of space, but which have never been shown to work as claimed), Earth-orbiting solar collectors (which would beam electrical energy back to the planet in the form of microwave energy), Helium 3 from the Moon (Helium 3 does not exist in harvestable quantities on Earth, but if it could be mined on the Moon and brought back by shuttle, it could power nuclear reactors more safely than uranium does), and methane hydrates (methane frozen in an ice lattice—a material that exists in large quantities in tundra and seabeds, but has never successfully been harvested in commercially signifiant quantities). Of these, only methane hydrate has any prospect of yielding commercial amounts of energy in the foreseeable future, and even that will depend upon significant technological developments to enable the collecting of this fragile material. Methanol and butanol are not discussed here because their properties and prospects differ little from those of other biofuels.

Thus, over the course of the next decade or two, society's energy almost certainly must come from some combination of the eighteen sources above. In the next section we explore some of the opportunities for combining various of these alternative energy options to solve the evolving energy crisis.

TABLE 2: COMPARING CURRENT FUEL SOURCES

	Annual electricity produced (TWh)	Reserves	EROEI
Fossil Fuels	11,455	finite	Coal 50:1 Oil 19:1 Natural gas 10:1

	Annual electricity produced (TWh)	Potential electricity production (TWh)	EROEI
Hydropower	2894	8680	11:1 to 267:1
Nuclear	2626	5300	1.1:1 to 15:1
Wind	160	83,000	18:1
Biomass power	218	NA	NA
Solar PV	8	2000	3.75:1 to 10:1
Geothermal	63	1000 – 1,000,000	2:1 to 13:1
Solar thermal	1	up to 100,000	1.6:1
Tidal	.6	450	~ 6:1
Wave	~ 0	750	15:1

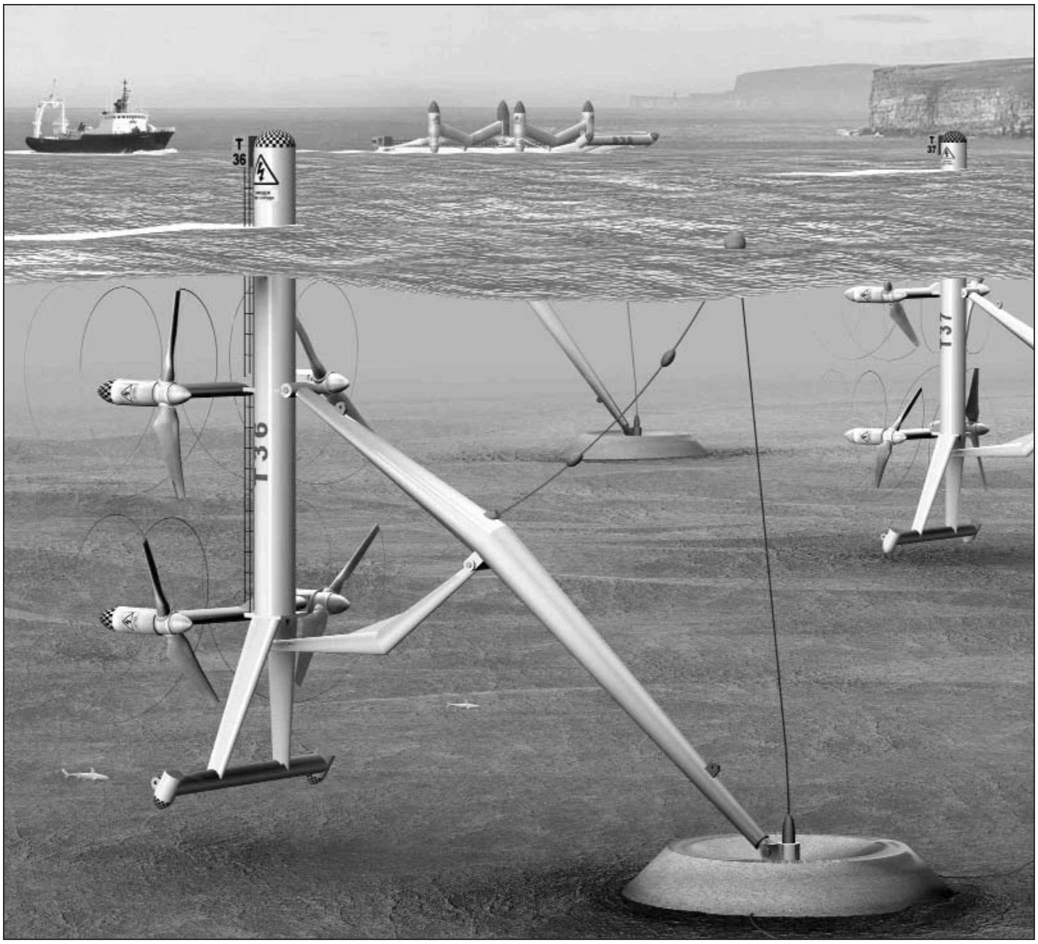
Table 2. Global annual electricity generation in terawatt-hours, estimated existing reserve or potential yearly production, and EROEI.[94] The largest current source of electricity (fossil fuels) has no long-term future, while the sources with the greatest potential are currently the least developed.

TABLE 3. COMPARING LIQUID FUEL SOURCES

	Global production (million barrels/year)	Reserves (trillion barrels)	EROEI
Oil	27,000	1.2	19:1
Tar sands	548	3.3	5.2:1 to 5.8:1
Oil shale	1.6	2.8	1.5:1 to 4:1

	Global production (million barrels/year)	Potential production (million barrels/year)	EROEI
Ethanol	260	1175	0.5:1 to 8:1
Biodiesel	5	255	1.9:1 to 9:1

Table 3. Liquid fuels: Current global annual production, reserves, potential production, and EROEI.[95]



TIDAL STREAM PARTNERS: PROTOTYPE

Wave energy systems, such as depicted here, remain highly theoretical in practical terms. So far, the only operating commercial system is the Agucadora Wave Park off the coast of Portugal, recently pulled from service. Research continues, however, as wave energy releases no greenhouse gasses and for communities near shorelines it may yet prove practical, and with a high net energy potential. It could form a useful part of any mix of alternative renewable energy systems.

Five

TOWARD A FUTURE ENERGY MIX

A CURSORY EXAMINATION of our current energy mix yields the alarming realization that about 85 percent of our current energy is derived from three primary sources—oil, natural gas, and coal—that are non-renewable, whose price is likely to trend higher (and perhaps very steeply higher) in the years ahead, whose EROEI is declining, and whose environmental impacts are unacceptable. While these sources historically have had very high economic value, we cannot rely on them in the future. Indeed, the longer the transition to alternative energy sources is delayed, the more difficult that transition will be unless some practical mix of alternative energy systems can be identified that will have superior economic and environmental characteristics.

A process for designing an energy system to meet society's future needs must start by recognizing the practical limits and potentials of the available energy sources. Since *primary* energy sources (ones that are capable of replacing fossil fuels in terms of their percentage of the total energy supplied) will be the most crucial ones for meeting those needs, it is important to identify those first. Secondary sources (ones that are able to supply only a few percent of total energy) will also play their roles, along with "energy carriers" (forms of energy that make energy from primary sources more readily useful—as electricity makes the energy from coal useful in millions of homes).

A future primary energy source, at a minimum, must meet these make-or-break standards:

- It must be capable of providing a substantial amount of energy—perhaps a quarter of all the energy currently used nationally or globally;
- It must have a net energy yield of 10:1 or more;
- It cannot have unacceptable environmental (including climate), social, or geopolitical impacts (such as one nation gaining political domination over others); and
- It must be renewable.

A PROCESS OF ELIMINATION

Assuming that oil, natural gas, and coal will have rapidly diminishing roles in our future energy mix, this leaves fifteen alternative energy sources with varying economic profiles and varying environmental impacts. Since even the more robust of these are currently only relatively minor contributors to our current energy mix, this means our energy future will look very different from our energy present. The only way to find out what it might look like is to continue our process of elimination.

If we regard large contributions of climate-changing greenhouse gas emissions as a non-negotiable veto on future energy sources, that effectively removes tar sands and oil shale from the discussion. Efforts to capture and sequester carbon from these substances during processing would further reduce their already-low EROEI and raise their already-high production costs, so there is no path that is both economically realistic and environmentally responsible whereby these energy sources could be scaled up to become primary ones. That leaves thirteen other candidates.

Biofuels (ethanol and biodiesel) must be excluded because of their low EROEI, and also by limits to land and water required for their production. (Remember: We are not suggesting that any energy source cannot play *some* future role; we are merely looking first for primary sources—ones that have the potential to take over all or even a significant portion of the current role of conventional fossil fuels.)

Energy-from-waste is not scalable; indeed, the "resource" base is likely to diminish as society becomes more energy efficient.

That leaves ten possibilities: nuclear, hydro, wind, solar PV, concentrating solar thermal, passive solar, biomass, geothermal, wave, and tidal.

Of these, nuclear and hydro are currently producing the largest amounts of energy. Hydropower is not without problems, but in the best instances its EROEI is very high. However, its capacity for growth in the U.S. is severely limited—there are not enough available undammed rivers—and worldwide it cannot do more than triple in capacity. Nuclear power will be slow and expensive to grow. Moreover, there are near-term limits to uranium ores, and technological ways to bypass those limits (e.g., with thorium reactors) will require time-consuming and expensive research. In short, both hydrower and nuclear power are unlikely candidates for rapid expansion to replace fossil fuels.

Biomass energy production is likewise limited in scalability, in this case by available land and water, and by the low efficiency of photosynthesis. America and the world could still obtain more energy from biomass, and production of *biochar* (a form of charcoal, usually made from agricultural waste, used as a soil amendment) raises the possibility of a synergistic process that would yield energy while building topsoil and capturing atmospheric carbon (though some analysts doubt this because pyrolysis, the process of making charcoal, emits not only CO_2 but other hazardous pollutants as well). Competition with other uses of biomass for food and for low-energy input agriculture will limit the amount of plant material available for energy production. Realistically, given the limits mentioned, biomass cannot be expected to sustainably produce energy on the scale of oil, gas, or coal.

Passive solar is excellent for space heating, but does not generate energy that could be used to run transportation systems and other essential elements of an industrial society.

That leaves six sources: Wind, solar PV, concentrating solar thermal, geothermal, wave, and tidal—which together currently produce only a tiny fraction of total world energy. And each of these still has its own challenges—like intermittency or limited growth potential.

Tidal, wave power, and geothermal electricity generation are unlikely to be scalable; although geothermal heat pumps can be used almost anywhere, they cannot produce primary power for transport or electricity grids.

Solar photovoltaic power is still expensive. While cheaper PV materials are now beginning to reach the market, these generally rely on rare substances whose depletion could limit deployment of the technology. Concentrating PV promises to solve some of these difficulties; however, more research is needed and the problem of intermittency remains.

With good geographical placement, wind and concentrating solar thermal have good net energy characteristics and are already capable of producing power at affordable prices. These may be the best candidates for non-fossil primary energy sources—yet again they suffer from intermittency.

Thus there is no single "silver-bullet" energy source capable of replacing conventional fossil fuels directly—at least until the problem of intermittency can be overcome—though several of the sources discussed already serve, or are capable of serving, as secondary energy sources.

This means that as fossil fuels deplete, and as society reduces reliance on them in order to avert catastrophic climate impacts, we will have to use every available alternative energy source strategically. Instead of a silver bullet, we have in our arsenal only BBs, each with a unique profile of strengths and weaknesses that must be taken into account.

But since these alternative energy sources are so diverse, and our ways of using energy are also diverse, we will have to find ways to connect source, delivery, storage, and consumption into a coherent system by way of common energy carriers.

COMMON CARRIERS: ELECTRICITY AND HYDROGEN

While society uses oil and gas in more or less natural states (in the case of oil, we refine it into gasoline or distil it into diesel before putting it into our fuel tanks), we are accustomed to transforming other forms of energy (such as coal, hydro, and nuclear) into electricity—which is energy in a form that is easy and convenient to use, transportable by wires, and that operates motors and a host of other devices with great efficiency.

With a wider diversity of sources entering the overall energy system, the choice of an energy carrier, and its further integration with transportation and space heating (which currently primarily rely on fossil fuels directly), become significant issues.

For the past decade or so energy experts have debated whether the best energy carrier for a post-fossil fuel energy regime would be electricity or hydrogen.[96] The argument for hydrogen runs as follows: Our current transportation system (comprised of cars, trucks, ships, and aircraft) uses liquid fuels almost exclusively. A transition to electrification would take time, retooling, and investment, and would face difficulties with electricity storage (discussed in more detail below): moreover, physical limits to the energy density by weight of electric batteries would mean that ships, large trucks, and aircraft could probably never be electrified in large numbers. The problem is so basic that it would remain even if batteries were substantially improved.

Hydrogen could more effectively be stored in some situations, and thus might seem to be a better choice as a transport energy carrier. Moreover, hydrogen could be generated and stored at home for heating and electricity generation, as well as for fueling the family car.

However, because hydrogen has a very low energy density per unit of volume, storage is a problem in this case as well: hydrogen-powered airplanes would need enormous tanks representing a substantial proportion of the size of the aircraft, and automobiles would need much larger tanks as well.

Moreover, several technological hurdles must be overcome before fuel cells—which would be the ideal means to convert the energy of hydrogen into usable electricity—can be widely affordable. And since conversion of energy is never 100 percent efficient, converting energy from electricity (from solar or wind, for example) to hydrogen for storage before converting it back to electricity for final use will inevitably entail significant inefficiencies.

The problems with hydrogen are so substantial that many analysts have by now concluded that its role in future energy systems will be limited (we are likely never to see a "hydrogen economy"), though for some applications it may indeed make sense.

Industrial societies already have an infrastructure for the delivery of electricity. Moreover, electricity enjoys some inherent advantages over fossil fuels: it can be converted into mechanical work at much higher efficiencies than can gasoline burned in internal combustion engines, and it can be transported long distances much more easily than oil (which is why high-speed trains in Europe and Japan run on electricity rather than diesel).

But if electricity is chosen as a systemic energy carrier, the problems with further electrifying transport using renewable energy sources such as wind, solar, geothermal, and tidal power remain: how to overcome the low energy density of electric batteries, and how to efficiently move electricity from remote places of production to distant population centers?[97]

ENERGY STORAGE AND TRANSMISSION

The energy densities by weight of oil (42 megajoules per kilogram), natural gas (55 MJ/kg), and coal (20 to 35 MJ/kg) are far higher than those of any electricity storage medium currently available. For example, a typical lead-acid battery can store about 0.1 MJ/kg, about one-fifth of 1 percent of the energy-per-pound of natural gas. Potential improvements to lead-acid batteries are limited by chemistry and thermodynamics, with an upper bound of less than 0.7 MJ/kg.

Lithium-ion batteries have improved upon the energy density of lead-acid batteries by a factor of about 6, achieving around 0.5 MJ/kg; but their theoretical energy density limit is roughly 2 MJ/kg, or perhaps 3 MJ/kg if research on the substitution of silicon for carbon in the anodes is realized in a practical way. On the other hand, supplies of lithium are limited, and therefore not scaleable.

It is possible that other elements could achieve higher energy storage by weight. In principle, compounds of hydrogen-scandium, if they could be made into a battery, could achieve a limit of about 5 MJ/kg. Thus the best existing batteries get about 10 percent of what is physically possible and 25 percent of the demonstrated upper bound.

Energy can be stored in electric fields (via capacitors) or magnetic fields (with superconductors). While the best capacitors today store one-twentieth the energy of an equal mass of lithium-ion batteries, a new company called EEstor claims a ceramic capacitor capable of 1 MJ/kg. Existing magnetic energy storage systems store around 0.01 MJ/kg, about equal to existing capacitors, though electromagnets made of high-temperature superconductors could in theory store about 4 MJ per liter, which is similar to the performance of the best imaginable batteries.

Chemical potential energy (a property of the atomic or molecular structure of materials that creates the potential for energy to be released and converted into usable forms—as is the case with fossil fuels and other combustible matter) can be stored as inorganic fuel that is oxidized by atmospheric oxygen. Zinc air batteries, which involve the oxidation of zinc metal to zinc hydroxide, could achieve about 1.3 MJ/kg, but zinc oxide could theoretically beat the best imagined batteries at about 5.3 MJ/kg.

Once again, hydrogen can be used for storage. Research is moving forward on building-scale systems that will use solar cells to split water into hydrogen and oxygen by day and use a fuel cell to convert the gases to electricity at night.[98] However, as discussed above, this technology is not yet economical.[99]

Better storage of electricity will be needed at several points within the overall energy system if fossil fuels are to be eliminated. Not only will vehicles need efficient batteries, but grid operators relying increasingly on intermittent sources like wind and solar will need ways to store excess electricity at moments of over-abundance for times of peak usage or scarcity. Energy storage on a large scale is already accomplished at hydroelectric dams by pumping water uphill into reservoirs at night when there is a surplus of electricity: energy is lost in the process, but a net economic benefit is realized in any case. This practice could be expanded, but it is limited by the number and size of existing dams, pumps, and reservoirs. Large-scale energy storage by way of giant flywheels is being studied, but such devices are likely to be costly.

The situation with transmission is also daunting. If large amounts of wind and solar energy are to be sourced from relatively remote areas and integrated into national and global grid systems, new high-capacity transmission lines will be needed, along with robust two-way communications, advanced sensors, and distributed computers to improve the efficiency, reliability, and safety of power delivery and use.

For the U.S. alone, the cost of such a grid upgrade would be $100 billion at a minimum, according to one recent study.[100] The proposed new system that was the basis of the study would include 15,000 circuit miles of extremely high voltage lines, laid alongside the existing electric grid infrastructure, starting in the Great Plains and Midwest (where the bulk of the nation's wind resources are located) and terminating in the major cities of the East Coast. The cost of building wind turbines to generate the amount of power assumed in the study would add another $720 billion, spent over a fifteen-year period and financed primarily by utilities and investors.

Yet, this hypothetical project would enable the nation to obtain only 20 percent of its electricity from wind by 2024. If a more rapid and complete transition away from fossil fuels is needed or desired, the costs would presumably be much higher.

However, many energy analysts insist that long high-capacity power lines would *not* be needed for a renewable energy grid system: such a system would best take advantage of regional sources—off-shore wind in the U.S. Northeast, active solar thermal in the desert Southwest, hydropower in the Northwest, and biomass in the forested Southeast. Such a decentralized or "distributed" system would dispense not only with the need for costly high-capacity power line construction but would also avoid fractional power losses associated with long-distance transmission.[101] Still, problems remain: one of the advantages of a continent-scale grid system for renewables would be its ability to compensate for the intermittency of energy sources like wind and solar. If skies are overcast in one region, it is likely that the sun will still be shining or winds blowing elsewhere on the continent. Without a long-distance transmission system, there must be some local solution to the conundrum of electricity storage.

TRANSITION PLANS

As noted above, there is an existing literature of plans for transitioning U.S. or world energy systems away from fossil fuels. It would be impossible to discuss those plans here in any detail, except to remark that some of those proposals include nuclear power[102] while some exclude it[103]. And some see a relatively easy transition to solar and wind[104], while others do not[105].

The present analysis, which takes into account EROEI and other limits to available energy sources, suggests first that the transition is inevitable and necessary (as fossil fuels are rapidly depleting and are also characterized by rapidly declining EROEI), and that the transition will be neither easy nor cheap. Further, it is reasonable to conclude from what we have seen that a full replacement of energy currently derived from fossil fuels with energy from alternative sources is probably impossible over the short term; it may be unrealistic to expect it even over longer time frames.

The core problem, which is daunting, is this: How can we successfully replace a concentrated store of solar energy (i.e., fossil fuels, which were formed from plants that long ago bio-chemically captured and stored the energy of sunlight) with a *flux* of solar energy (in any of the various forms in which it is available, including sunlight, wind, biomass, and flowing water)?

It is not within the purpose of this study to design yet another detailed transition plan. Such exercises are useful, but inevitably decisions about how much of a hypothetical energy mix should come from each of the potential sources (wind, solar, geothermal, etc.) depend on projections regarding technological developments and economic trends. The final plan may consist of a complex set of scenarios, with increasing levels of detail adding to the document's value as an analytical tool; yet all too often real-world political and economic events turn such scenarios into forgotten pipe-dreams.

The actual usefulness of energy transition plans is more to show what is possible than to forecast events. For this purpose, even very simple exercises can sometimes be helpful in pointing out problems of scale. For example, the following three scenarios for world energy, which assume only a single alternative energy source using extremely optimistic assumptions, put humanity's future energy needs into a sobering cost perspective.[106]

Scenario 1: The World at American Standards. If the world's population were to stabilize at 9 billion by 2050, bringing the entire world up to U.S. energy consumption (100 quadrillion BTU annually) would require 6000 quads per year. This is more than twelve times current total world energy production. If we assume that the cost of solar panels can be brought down to 50 cents per watt installed (one tenth the current cost and less than the current cost of coal), an investment of $500 trillion would be required for the transition, not counting grid construction and other ancillary costs—an almost unimaginably large sum. This scenario is therefore extremely unlikely to be realized.

Scenario 2: The World at European Standards. Since Europeans already live quite well using only half as much energy as Americans, it is evident that a U.S. standard of living is an unnecessarily high goal for the world as a whole. Suppose we aim for a global per-capita consumption rate 70 percent lower than that in the United States. Achieving this standard, again assuming a population of 9 billion, would require total energy production of 1800 quads per year, still over three times today's level. Cheap solar panels to provide this much energy would cost $150 trillion, a number over double the current world annual GDP. This scenario is conceivable, but still highly unlikely.

Scenario 3: Current per-Capita Energy Usage. Assume now that current world energy usage is maintained on a per-capita basis. If people in less-industrialized nations are to consume more, this must be compensated for by reduced consumption in industrial nations, again with the world's population stabilizing at 9 billion. In this case, the world would consume 700 quads of energy per year. This level of energy usage, if it were all to come from cheap solar panels, would require $60 trillion in investment—still an enormous figure, though one that might be achievable over time. (Current average per-capita consumption globally is 61 gigajoules per year; in Qatar it is 899 GJ per year, in the U.S. it is 325 GJ per year, in Switzerland it is 156 GJ per year, and in Bangladesh it is 6.8 GJ per year. The range is very wide. If Americans were to reduce their energy use to the world average, this would require a contraction to less than one-fifth of current consumption levels, but this same standard would enable citizens of Bangladesh to increase their per-capita energy consumption nine-fold.)

Of course, as noted above, all three scenarios are extremely simplistic. On one hand, they do not take into account amounts of energy already coming from hydro, biomass, etc., which could presumably be maintained: it would not be necessary to produce all needed energy from new sources. But on the other hand, costs for grid construction and electrification of transport are not included. Nor are material resource needs accounted for. Thus on balance, the costs cited in the three scenarios are if anything probably dramatically understated.

The conclusion from these scenarios seems inescapable: unless energy prices drop in an unprecedented and unforeseeable manner, the world's economy is likely to become increasingly energy-constrained as fossil fuels deplete and are phased out for environmental reasons. It is highly unlikely that the entire world will ever reach an American or even a European level of energy consumption, and even the maintenance of current energy consumption levels will require massive investment.

ISTOCK

TABLE 4. ENERGY USE BY (SELECTED) COUNTRIES, 2006 *(Source: U.S. Energy Information Administration[107])*

COUNTRY	Per capita energy use (Million Btu)	Total energy use (Quadrillion Btu)
Afghanistan	0.6	0.018
Albania	34.3	0.123
Algeria	46.6	1.536
Angola	13.7	0.165
Argentina	79	3.152
Australia	276.9	5.611
Austria	187.2	1.534
Bangladesh	5	0.743
Belgium	265.1	2.751
Benin	4.9	0.039
Bolivia	24.2	0.218
Botswana	33.1	0.059
Brazil	51.2	9.635
Bulgaria	121.5	0.897
Burkina Faso	1.3	0.019
Burma (Myanmar)	5	0.236
Cambodia	0.7	0.01
Cameroon	5	0.088
Canada	427.2	13.95
Chad	0.3	0.003
Chile	77.6	1.254
China	56.2	73.808
Colombia	29.8	1.305
Congo (Kinshasa)	1.6	0.097
Costa Rica	43.6	0.178
Croatia	92.1	0.414
Cuba	35.1	0.399
Czech Republic	176.6	1.808
Denmark	161.3	0.879
Ecuador	31	0.42
Egypt	32.2	2.544
El Salvador	19.2	0.131
Estonia	175.2	0.232
Ethiopia	1.4	0.103
France	180.7	11.445
Germany	177.5	14.629
Ghana	7.1	0.159
Greece	139.1	1.487
Greenland	149.3	0.008
Guatemala	16.3	0.202
Guinea	2.4	0.023
Guyana	29.4	0.023
Haiti	3.3	0.028
Honduras	17.3	0.127
Hong Kong	167.7	1.164
Hungary	114.7	1.145
Iceland	568.6	0.17
India	15.9	17.677
Indonesia	17.9	4.149
Iran	118.2	7.686
Iraq	46.6	1.247
Ireland	173.4	0.704
Israel	123.5	0.848
Italy	138.7	8.069
Japan	178.7	22.786
Jordan	52.2	0.308
Kazakhstan	195.3	2.975
Kenya	5.6	0.202
Korea, North	41.1	0.949
Korea, South	193.4	9.447
Kuwait	469.8	1.136
Laos	3.6	0.023
Lebanon	53.3	0.207
Liberia	2.5	0.008
Libya	132	0.779
Lithuania	97	0.348
Madagascar	2.2	0.042
Malaysia	104.8	2.557
Mali	1.1	0.013
Mexico	68.5	7.357
Mongolia	33	0.096
Morocco	15.2	0.508
Mozambique	10.6	0.218
Namibia	29.3	0.06
Nepal	2.4	0.068
Netherlands	250.9	4.137
New Zealand	211.2	0.864
Nicaragua	12.8	0.071
Niger	1.3	0.017
Nigeria	7.8	1.023
Norway	410.8	1.894
Pakistan	14.2	2.298
Peru	21.6	0.613
Philippines	14.2	1.271
Poland	100.1	3.856
Qatar	1,023.3	0.906
Romania	75.2	1.678
Russia	213.9	30.386
Rwanda	1.4	0.013
Saudi Arabia	255	6.891
Senegal	6.9	0.084
Sierra Leone	2.8	0.017
Singapore	476.8	2.142
Solomon Islands	5.4	0.003
Somalia	1.2	0.01
South Africa	117.2	5.177
Spain	161.2	6.51
Sri Lanka	10.5	0.218
Sudan	4.8	0.185
Swaziland	15	0.017
Sweden	245.8	2.216
Switzerland	170.7	1.284
Syria	42.9	0.81
Taiwan	200.6	4.569
Tanzania	2.1	0.08
Thailand	57.9	3.741
Turkey	55.5	3.907
Uganda	1.2	0.035
Ukraine	125.9	5.871
United Arab Emirates	577.6	2.464
United Kingdom	161.7	9.802
United States	334.6	99.856
Uruguay	38.8	0.134
Venezuela	124.4	3.191
Vietnam	16.6	1.404
Yemen	12.4	0.267
Zambia	11.1	0.126
Zimbabwe	15	0.183

ANITA BOWEN

In many cities of the world, there's a renaissance in bicycle travel, and new public accommodations to bicyclists: pathways, car-free roads and parks, new rules of the road that favor bicycles, bike racks on public busses, bike cars on commute trains, etc. All seem small-scale compared to the immensity of the energy crisis, but they create a "can do" spirit, self-reliance, and a transformational ethic, so other conservation steps—emphasis on light rail, dedicated bus lanes, fees for cars downtown, higher parking rates—begin to be practical. And it's fun and healthy.

Six

THE CASE FOR CONSERVATION

THE CENTRAL ISSUE REMAINS—how to continue supplying energy in a world where resources are limited and declining. The solution becomes much easier if we find ways to proactively *reduce* energy demand. And that project in turn becomes easier if there are fewer of us wanting to use energy (that is, if population shrinks rather than continuing to increase).

Based on all that we have discussed, the clear conclusion is that the world will almost certainly have considerably less energy available to use in the future, not more, though (regrettably) this strong likelihood is not yet reflected in projections from the International Energy Agency or any other notable official source. Fossil fuel supplies will almost surely decline faster than alternatives can be developed to replace them. New sources of energy will in many cases have *lower* net energy profiles than conventional fossil fuels have historically had, and they will require expensive new infrastructure to overcome problems of intermittency, as we have discussed.

Moreover, the current trends toward declining energy demand, combined with falling investment rates for new energy supplies (especially for fossil fuels), resulting from the ongoing global economic crisis, are likely to continue for several years, thus complicating both a general recognition of the problem and a coordinated response.

How far will supplies fall, and how fast? Taking into account depletion-led declines in oil and natural gas production, a leveling off of energy from coal, and the recent shrinkage of investment in the energy sector, it may be reasonable to expect a reduction in global energy availability of 20 percent or more during the next quarter century. Factoring in expected population growth, this implies substantial *per-capita* reductions in available energy. These declines are unlikely to be evenly distributed among nations, with oil and gas importers being hardest hit, and with the poorest countries seeing energy consumption returning to pre-industrial levels (with energy coming almost entirely from food crops and forests and work being done almost entirely by muscle power).

Thus, the question the world faces is no longer *whether* to reduce energy consumption, but *how*. Policy makers could choose to manage energy unintelligently (maintaining fossil fuel dependency as long as possible while making poor choices of alternatives, such as biofuels or tar sands, and insufficient investments in the far more promising options such as wind and solar). In the latter case, results will be catastrophic. Transport systems will wither (especially ones relying on the most energy-intensive vehicles—such as airplanes, automobiles, and trucks). Global trade will contract dramatically, as shipping becomes more costly. And energy-dependent food systems will falter, as chemical input and transport costs soar. All of this could in turn lead to very high long-term unemployment and perhaps even famine.

However, if policy makers manage the energy downturn intelligently, an acceptable quality of life could be maintained in both industrialized and less-industrialized nations at a more equitable level than today; at the same time, greenhouse gas emissions could be reduced dramatically. This would require a significant public campaign toward the establishment of a new broadly accepted conservation ethic to replace current emphases on never-ending growth and over-consumption at both personal and institutional-corporate levels. We will not attempt here a full list of the needed shifts, but they might well include the following practical, engineering-based efforts:

- Immediate emphasis on and major public investment in construction of highly efficient rail-based transit systems and other public transport systems (including bicycle and pedestrian pathways), along with the redesign of cities to reduce the need for motorized human transport.[108]
- Research, development, and construction of electricity grid systems that support distributed, intermittent, renewable energy inputs.
- Retrofit of building stock for maximum energy efficiency (energy demand for space heating can be dramatically reduced through super-insulation of structures and by designing to maximize solar gain).[109]
- Reduction of the need for energy in water pumping and processing through intensive water conservation programs (considerable energy is currently used in moving water, which is essential to both agriculture and human health).[110]

As well, the following policy-based initiatives will be needed:

- Internalization of the full costs of energy to reflect its true price. Elimination of perverse energy subsidies, especially all upstream and production-side state support. Encourage government "feed-in tariffs" that favor ecologically sustainable renewable energy production.
- Application of the ten energy assessment criteria listed in this document to all energy technologies that are currently being proposed within the UN climate negotiations, for "technology transfer" from rich countries to poor.
- Re-localization of much economic activity (especially the production and distribution of essential bulky items and materials) in order to lessen the need for transport energy[111]; correspondingly, a reversal of the recent emphasis on inherently wasteful globalized economic systems.
- Rapid transition of food systems away from export oriented industrial production, toward more local production for local consumption, thus reducing mechanization, energy inputs, petro-chemicals and transport costs. Also, increased backing for permaculture, and organic food production. And, firm support for traditional local Third World farming communities in their growing resistance to industrial export agriculture.
- A major shift toward *re-ruralization*, i.e., creating incentives for people to move back to the land, while converting as much urban land as possible to sustainable food production, including substantial suburban lands currently used for decorative lawns and gardens.
- Abandonment of *economic growth* as the standard for measuring economic progress, and establishment of a more equitable universal standard of "sufficiency."
- Increase of reserve requirements on lending institutions to restrain rampant industrial growth until price signals are aligned to reflect full costs. Restrictions on debt-based finance.
- Development of indicators of economic health to replace the current GDP calculus with one that better reflects the general welfare of human beings.
- *Re-introduction* of the once popular "import substitution" (from the 1930s) model whereby nations determine to satisfy basic needs—food, energy, transport, housing, healthcare, etc.—*locally* if they possibly can, rather than through global trade.
- Establishment of international protocols on both energy assessment (including standards for assessing EROEI and environmental impacts) and also technology assessment. The latter should include full lifecycle energy analysis, along with the prin-

ciples of "polluter pays" and the "precautionary principle."

- Adoption of international depletion protocols for oil, gas and coal—mandating gradual reduction of production and consumption of these fuels by an annual percentage rate equal to the current annual depletion rate, as outlined in the present author's previous book, *The Oil Depletion Protocol*, so as to reduce fuel price volatility.
- Transformation of global trade rules to reward governments for, rather than restraining them from, protecting and encouraging the localization of economic production and consumption patterns.
- Aggressive measures for "demand-side management" that reduce overall energy needs, particularly for power grids. This would be part of a society-wide "powering down," i.e., a planned reduction in overall economic activity involving energy, transport and material throughputs, emphasizing conservation over new technology as the central solution to burgeoning problems.
- International support for women's reproductive and health rights, as well as education and opportunity, as important steps toward mitigation of the population crisis, and its impact on resource depletions.
- The return of control of the bulk of the world's remaining natural resources from corporations and financial institutions in the industrialized countries to the people of the less industrialized nations where those resources are located.

The goal of all these efforts must be the realization of a no-growth, *steady-state* economy, rather than a growth-based economy. This is because energy and economic activity are closely tied: without continuous growth in available energy, economies cannot expand. It is true that improvements in efficiency, the introduction of new technologies, and the shifting of emphasis from basic production to provision of services can enable some economic growth to occur in specific sectors without an increase in energy consumption. But such trends have inherent bounds. Over the long run, static or falling energy supplies must be reflected in economic stasis or contraction. However, with proper

planning there is no reason why, under such circumstances, an acceptable quality of life could not be maintained.[113] For the world as a whole, this might entail the design of a deliberate plan for global redistribution of energy consumption on a more equitable basis, with industrial nations reducing consumption substantially, and less-industrial nations increasing their consumption somewhat in order to foster global "sufficiency" for all peoples. Such a formula might partly make up for centuries of colonial expropriation of the resources of the world's poor countries, a historical factor that had much to do with the rapid industrial growth of the wealthy resource-hunting countries during the past 150 years. Addressing this disparity might help provide the poorer countries a chance for survival, if not equity.

Here's some good news: A considerable literature exists on how people in recently affluent nations can reduce energy consumption while actually increasing levels of personal satisfaction and community resilience.[114] The examples are legion, and include successful community gardens, rideshare, job-share, and broad local investment and conservation programs, such as Jerry Mander briefly mentions in the Foreword, including most notably the Transition Towns movement that is now sweeping Europe and beginning in the U.S. as well.

While the subject is, strictly speaking, beyond the scope of this booklet, it must also be noted and underscored that global conservation efforts are and will be required with regard to *all* natural resources (not just energy resources). The Earth's supplies of high-grade ores are limited, and shortages of a wide range of minerals, including phosphorus, coltan, and zinc, are already occurring or expected within the next few decades if current consumption patterns continue. Deforestation, loss of topsoil due to erosion, and the (in many cases) catastrophic and irreversible decline of wild fish species in the oceans are also serious problems likely to undermine economic activity and human well-being in the years ahead. Thus, all standard operating assumptions about the future of industrial society are clearly open to doubt.

Societal adaptation to resource limits inevitably also raises the question of population. When population grows but the economy remains the same size, there are fewer economic goods available per person. If energy and material constraints effectively impose a cap on economic growth, then the only way to avert continuing declines in per-capita access to economic goods is to limit population by, for example, providing economic incentives for smaller families rather than larger ones (Note: in the United States larger families are now rewarded with lower taxes), as well as easy access to birth control, and support for poor women to obtain higher levels of education. Policy makers must begin to see population shrinkage as a goal, rather than an impediment to economic growth.

In his book *Energy at the Crossroads*[115], Vaclav Smil shows the relationship between per capita energy consumption and various indices of well-being. The data appear to show that well-being requires at least 50 to 70 GJ per capita per year. As consumption above that level slightly expands, a sense of well being also expands, but only up to about 100 GJ per capita, a "safety margin" as it were. Remarkably however, above and beyond that level of consumption, there is no increase in a sense of well being. In fact the more consumptive and wealthy we become, the less content and satisfied we apparently are. One wonders whether the effort needed to expand material wealth and consumption have their own built-in dissatisfactions in terms of challenges to free time, added daily pressures, reduced family contact, engagement with nature, and personal pleasures. North America's energy consumption is currently about 325 GJ per annum. Using these indices as goals, and with a general notion of the total amount of energy that will be available from renewable energy sources, it should then be possible to set a target for a population size and consumption levels that would balance these factors.

Energy conservation can take two fundamental forms: curtailment and efficiency. *Curtailment* describes situations where uses of energy are simply discontinued (for example, we can turn out the lights in rooms as we vacate them). *Efficiency* describes situations where less energy is used to provide an equivalent benefit (a related example would be the replacement of incandescent bulbs with compact fluorescents or LEDs). Efficiency is typically preferred, since few people want to give up tangible benefits, but efficiency gains are subject to the law of diminishing returns (the first ten percent gain may be cheap and easy, the next ten percent will be somewhat more costly, and so on), and there are always ultimate limits to possible efficiency gains (it is impossible to light homes at night or to transport goods with zero energy expenditure). Nevertheless, much could be achieved over the short term in energy efficiency across all sectors of the economy.

Curtailment of use is the quickest and cheapest solution to energy supply problems. Given the reality that proactive engagement with the inevitable energy transition has been delayed far too long, curtailment (rather than efficiency or replacement with alternative sources) will almost certainly need to occur, especially in wealthy nations. But even granting this, proactive effort will still be crucial, as planned and managed curtailment will lead to far less societal disruption than ad hoc, uplanned curtailment in the forms of electrical blackouts and fuel crises.

The transition to a steady-state economy will require a revision of economic theories and a redesign of financial and currency systems.[116] These efforts will almost certainly be required in any case if the world is to recover from the current economic crisis.

Realistic energy descent planning must begin at all levels of society. We must identify essential economic goods (obviously including food, water, shelter, education, and health care) and decouple these from discretionary consumption that in recent decades has been encouraged merely to stoke economic growth.

The UN negotiations on climate change leading up to the Copenhagen climate summit in December 2009, have presented an opportunity for the world to consider the centrality of energy conservation in cutting greenhouse gases, yet it is barely part of the official UN climate agenda. Much of the current policy discussion misguidedly focuses on expanding renewable energy sources, with little to no consideration of their ecological, economic, and practical limits. Energy efficiency is receiving increasing attention, but it must be seen as part of a clear conservation agenda aimed at reducing global demand for energy overall.

Surprisingly, a recent US-China memorandum of understanding on energy and climate listed conservation as its top bullet point among shared concerns. If the world's two largest energy consumers in fact believe this is their top priority, then it needs to come to the fore in global climate discussions.

However, the mandate of the UN climate talks does not include an official multilateral process to cooperate on energy descent. Negotiators increasingly express concern over energy supply issues but are without an international forum in which to address them.

The national security community appears now to take seriously threats related both to climate change and energy supply vulnerability. This could set a new context for post-Copenhagen international efforts to address these collective concerns so as to avoid violent conflict over depleting energy resources and climate disaster.

* * *

Our energy future will be defined by limits, and by the way we respond to those limits. Human beings can certainly live within limits: the vast majority of human history played out under conditions of relative stasis in energy consumption and economic activity; it is only in the past two centuries that we have seen spectacular rates of growth in economic activity, energy and resource consumption, and human population. Thus, a deliberate embrace of limits does not amount to the end of the world, but merely a return to a more normal pattern of human existence. We must begin to appreciate that the 20th century's highly indulgent, over-consumptive economic patterns were a one-time-only proposition, and cannot be maintained.

If the energy transition is wisely managed, it will almost certainly be possible to maintain, within this steady-state context, many of the benefits that our species has come to enjoy over the past decades—better public health, better knowledge of ourselves and our world, and wider access to information and cultural goods such as music and art.

As society adopts alternative energy sources, it will at the same time adopt new attitudes toward consumption, mobility, and population. One way or another, the transition away from fossil fuels will mark a turning point in history as momentous as the Agricultural Revolution or the Industrial Revolution.

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A familiar sight from Chevron and Texaco oil development in the Ecuadorian Amazon: giant oil fires in open waste pits.

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