UMBC UGC Instructions for New Course Request Form (revised 4/2016)

Course number & title: Enter the number and title of the course at the top of the page. Contact the Registrar's Office to confirm that the desired course number is available.

Date submitted: The date that the form will be submitted to the UGC.

Effective date: The semester the new course is in effect, if approved.

Contact information: Provide the contact information of the Chair or UPD of the department or program housing the course. If the course is not housed in a department or program, then provide the same information for the head of the appropriate academic unit. (See UGC Procedures) If another faculty member should also be contacted for questions about the request and be notified about UGC actions on the request, include that person's contact information on the second line.

Course number: For cross-listed courses, provide all the numbers for the new course.

Transcript title: Limited to 30 characters, including spaces.

Recommended Course Preparation: ***Please note that all 300 and 400 level courses should have either recommended course preparation(s) or prerequisite(s) and that 100 or 200 level courses may have them.***
Here fill in what previous course(s) a student should have taken to succeed in the course. These recommendations will NOT be enforced by the registration system. Please explain your choices in the "rationale" (discussed below).

Prerequisite: ***Please note that all 300 and 400 level courses should have either recommended course preparation(s) or prerequisite(s)*** Here fill in course(s) students need to have taken before they enroll in this course. These prerequisites will be enforced through the registration system. Please explain your choices in the "rationale" (discussed below).

NOTE: Please use the words "AND" and "OR", along with parentheses as appropriate, in the lists of prerequisites and recommended preparation so that the requirements specified will be interpreted unambiguously.

NOTE: Unless otherwise indicated, a prerequisite is assumed to be passed with a "D" or better.

# of credits: To determine the appropriate number of credits to assign to a course please refer to the UMBC Credit Hour Policy which articulates the standards for assignment and application of credit hours to all courses and programs of study at UMBC regardless of degree level, teaching and learning formats, and mode of instruction.

Maximum total credits: This should be equal to the number of credits for courses that cannot be repeated for credit. For courses that may be repeated for credit, enter the maximum total number of credits a student can receive from this course. E.g., enter 6 credits for a 3 credit course that may be taken a second time for credit, but not for a third time. Please note that this does NOT refer to how many times a class may be retaken for a higher grade.

Grading method(s): Please review the grading methods document (this link can be found on the UGC forms page) before selecting a grading option. Please do not select all three grading options by default.

Proposed catalog description: Provide the exact wording of the course description as it will appear in the next undergraduate catalog. Course proposals should be a) no longer than 75 words, b) stated in declarative sentences in language accessible to students, and c) avoid reference to specific details that may not always pertain (e.g., dates, events, etc.). Course descriptions should not repeat information about prerequisites (which are always listed alongside the course description)."

Rationale: Please explain the following:
a) Why is there a need for this course at this time?
b) How often is the course likely to be taught?
c) How does this course fit into your department's curriculum?
d) What primary student population will the course serve?
e) Why is the course offered at the level (ie. 100, 200, 300, or 400 level) chosen?
f) Explain the appropriateness of the recommended course preparation(s) and prerequisite(s).
g) Explain the reasoning behind the P/F or regular grading method.
h) Provide a justification for the repeatability of the course.

Cross-listed courses: Requests to create cross-listed courses must be accompanied by letters of support via email from all involved department chairs. Proposals for new courses or the addition of a cross-listing to an existing course must include as a part of the rationale the specific reason why cross-listing is appropriate. Email from all involved department chairs is also required when cross-listing is removed and when a cross-listed course is discontinued. Please note that Special
Topics courses cannot be cross-listed.

Course Outline: Provide a syllabus with main topics and a weekly assignment schedule which includes complete citations for readings with page numbers as appropriate. Explain how students' knowledge and skills will be assessed.

Note: the UGC form is a Microsoft Word form. You should be able to enter most of the information by tabbing through the fields. The document is protected. In the rare case that you need to unprotect the document, use the password 'ugcform'. Beware that you will lose all the data entered in the form's fields if you unlock and lock the document.

UMBC UGC New Course Request: ENME 420 Energy Sources for the Future

Date Submitted: 10 May 2017^ Proposed Effective Date: January 1, 2018

	Name	Email	Phone	Dept
Dept Chair or UPD	Warren DeVries	warrendv@umbc.edu	x56767	ME
Other Contact	Carlos A. Romero Talamás	romero@umbc.edu	X58049	ME

COURSE INFORMATION:

Course Number(s)	ENME 420
Formal Title	Energy Sources for the Future
Transcript Title (≤30c)	Energy Sources for the Future
Recommended Course Preparation	
Prerequisite **NOTE:** Unless otherwise indicated, a prerequisite is assumed to be passed with a "D" or better.	Completion of ENME 304, 321, 332L and 360, with a grade of "C" or better.
# of Credits Must adhere to the UMBC Credit Hour Policy	3.00
Repeatable for additional credit?	☐ Yes ☒ No
Max. Total Credits	3.00 This should be equal to the number of credits for courses that cannot be repeated for credit. For courses that may be repeated for credit, enter the maximum total number of credits a student can receive from this course. E.g., enter 6 credits for a 3 credit course that may be taken a second time for credit, but not for a third time. Please note that this does NOT refer to how many times a class may be retaken for a higher grade.
Grading Method(s)	☒ Reg (A-F) ☐ Audit ☐ Pass-Fail

PROPOSED CATALOG DESCRIPTION (Approximately 75 words in length. Please use full sentences.**)**

This course explores existing and future energy sources using simple mathematical relations and principles of physics and thermodynamics. Topics include the concepts of energy, energy generation, storage, transmission, efficiency, and exponential growth and decay. These concepts are applied to compare advantages and disadvantages of existing energy sources: fossil carbon-based, biofuels, solar, wind, nuclear fission, and geothermal, as well as future concepts such as nuclear fusion.

RATIONALE FOR NEW COURSE

Energy, particularly its generation and distribution, is one of the foundations of mechanical engineering, and this course will satisfy a technical elective requirement in the curriculum. The course has been offered annually as a special topics course since Spring 2013; with enrollment ranging between 16-34. The plan is to offer the course in the Fall semester. A quarter to a third of the department's seniors have taken this as a special topics course, and we expect that to continue. ENME 400 level technical electives requires completion of ENME 300 level courses covering a variety of topics: concepts of energy, thermodynamics, heat transfer, and data analysis, among others. The course is graded traditionally, with tests, an exam, assignments that may be algorithmic or writing-intensive, and participate in class in discussions.

ATTACH COURSE SYLLABUS (mandatory):

ENME 489
Energy Sources for the Future

Instructor
Asst. Prof. Carlos A. Romero-Talamás
Department of Mechanical Engineering, UMBC
Email: romero@umbc.edu

Office Hours
MoWeFr 12:00 pm to 12:50 pm.
Office: Engineering Bldg. Room 212

Class Meeting Hours and Location
MoWe 2:30PM - 3:45PM
ITE 229

Final exam date: Friday, December 15th , 1:00 pm to 3:00 pm.

Course Description
Energy sources, and their effect on our environment, are becoming of increasing importance to our everyday lives. From public policy to global climate change, the way we plan our energy resources utilization now will have far reaching consequences for generations to come. Research and development on improving existing sources of energy and on finding new ones is on the rise. However, public support for these endeavors is sometimes misguided by exaggerated or charlatan claims about their advantages or disadvantages.

The aim of this course is to review both existing and possible future energy sources using, when possible, the simplest mathematical relations. The set of tools we will develop will include a review of the concepts of energy, energy generation, storage, transmission, efficiency, and exponential growth and decay. We will apply these concepts to compare advantages and disadvantages between existing energy sources: fossil carbon-based, biofuels, solar, wind, nuclear fission, and geothermal, as well as possible future concepts such as nuclear fusion and Space based power generation.

Assignments will include a combination of reading material from selected books, reports, documentaries, and news articles, and will be divided between writing of essays and the solving of problems.

Course Materials
There is no required textbook for this course. Course materials will be composed of class presentations, notes, and reading assignments (posted on Blackboard) that may include news articles and scientific research articles, among others.

Course Outline

Note: The topics covered per week and exam dates are approximate and subject to change.

Week	Topic
1 **(08/30 – 09/08)**	The scientific method; scientific and technical data searches
2 **(09/04 – 09/08)**	The tools of science and the 'back of the envelope' approach. Data analysis.
3 **(09/11 – 09/15)**	Concepts of energy, the laws of thermodynamics, electricity generation, efficiency.
4 **(09/18 – 09/22)**	Energy consumption in today's world and trends.
5 **(09/25 – 09/29)**	Energy storage.
6 **(10/02 – 10/06)**	Carbon-based fossil fuels: coal, oil, gas.
7 **(10/09 – 10/13)**	Solar energy: thermal and photovoltaic.
8 **(10/16 – 10/20)**	10/18 Midterm. Continue solar energy.
9 **(10/23 – 10/27)**	Wind energy.
10 **(10/30 – 11/03)**	Continue Wind energy.
11 **(11/06 – 11/10)**	Geothermal energy.
12 **(11/13 – 11/17)**	Energy from biomass.
13 **(11/20 – 11/24)**	Nuclear fission basics. accidents.
14 **(11/27 – 12/01)**	Nuclear fission: types of reactors, accidents.
15 **(12/04 – 12/08)**	Nuclear fusion: the promise and challenges.
16 **(12/11)**	Continue nuclear fusion.

Assignments Grading Scheme

Grades will be based on a combination of class participation, including discussions and presentations (20%), homework (20%), a midterm exam (30%), and a final exam (30%).

Unless otherwise specified, students should upload their assignments to Blackboard in pdf format.

Besides periodic assignments on topics covered in the course, every student will be required to submit a news article (as a single pdf file, uploaded to Blackboard) before every class and be prepared to discuss it with the class.

Students with disabilities

Students with disabilities should contact the instructor as soon as possible to accommodate particular needs in the course materials, lectures, and classroom.

Attendance Policies

University policy will be followed with respect to absences due to illness, religious observances, participation in University activities, and compelling circumstances beyond the student's control.

If the University is closed or a class is cancelled due to an emergency or inclement weather, classes will be rescheduled for the earliest possible date. If closure occurs for an extended period of time (i.e., over more than two scheduled lectures), attempts will be made to continue the lectures, homework, and participation over Internet or teleconferencing, and/or email and messaging when appropriate.

Academic Integrity

"By enrolling in this course, each student assumes the responsibilities of an active participant in UMBC's scholarly community in which everyone's academic work and behavior are held to the highest standards of honesty. Cheating, fabrication, plagiarism, and helping others to commit these acts are all forms of academic dishonesty, and are wrong. Academic misconduct could result in disciplinary action that may include, but is not limited to, suspension or dismissal. To read the full Student Academic Conduct Policy, consult the UMBC Student Handbook, the Faculty Handbook, or the UMBC policies section of the UMBC Directory." UMBC Faculty Senate, February 13, 2001.

ENME489

Assignment 2

This assignment is due 1 week from the time of posting in Blackboard. The work should be uploaded to the Blackboard website, as a single file, in pdf format.

The answers may be typed or handwritten and scanned. However, any part of the document that is not legible or clear will not be graded. All your derivations and expressions should be commented, showing that you understand every step of the solutions.

1. Integrate the logistics equation, $\frac{dN}{dt} = \frac{\alpha N(K-N)}{K}$ (where α and K are known constants) in the following way to solve for $N(t)$:
   a. Recast the equation by making the variable change $x = \frac{N}{K}$.
   b. Integrate the resulting equation as was done in class (by separating variables and integrating both sides of the equation – hint: use partial fractions on the dx side), and use the initial condition $x(t=0) = x_o = \frac{N_o}{K}$ to solve for the integration constant. After integration, change back to $N(t)/K$. Your answer should be $N(t)$ in terms of N_o, α, K, and t.
   c. Find the time, t_m, at which $\frac{dN}{dt}$ is maximum in terms of N_o, α, and K. To do this, differentiate the expression obtained in part (a) and equate it to zero, i.e., $\left.\frac{d^2x}{dt^2}\right|_{t=t_m} = 0$. Replace the variable $x(t)$ with $N(t)/K$ found in part (b) and solve for t_m.
   d. Using a computer program of your choice, plot $N(t)$ for the following values: $\alpha = 0.25$, $N_o = 1$, and $K = 200$, in the time range from 0 to 100.
   e. Using the same parameters as in part (d), plot $\frac{dN}{dt}$. Note that since you solved for $N(t)$ in part (b), all you need to do is replace this result in the original equation to obtain $\frac{dN}{dt}$ explicitly dependent on t.
   f. Give the numerical value for t_m using the parameters stated in part (d).

For the plots in parts (d) and (e), no hand-sketches are allowed, only computer-generated plots. Indicate the program you used, and show the lines of code used to generate the plot.

2. Using the file ENME489_Assignment_02_data_AnnualEnergyData.xls plot the Total Site-Delivered Energy Use for "Government Total" vs year (your x-axis should have fiscal years clearly labeled). Assuming the uncertainties in obtaining the data are all the same, use the method of Maximum Likelihood covered in class to obtain the **a** and **b** parameters of a **linear fit** for the three cases in parts *a*, *b*, and *c* below. Plot the data points with the line that corresponds to the fit overlaid on the chart, and indicate the equation of each line. You should have all lines and data points in a single plot, and clearly indicate each line.
    a. Data range 1975 – 1985 (inclusive).
    b. Data range 1995 – 2013 (inclusive).
    c. Data range 1975 – 2013 (inclusive).
    d. Using the linear fit for part *a* to calculate what the total consumption will be in 2020.
    e. Using the linear fit for part *c* to calculate what the total consumption will be in 2020.

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Group Assignment

You and your team are part of an elite 'skunk works' design division. You are tasked with providing a rough design for a car that can run for 100 km, with the different energy storage methods described in the table below. Assume the car gets its traction from an **electric motor** (only!), and that it requires 0.3 kWh/km. (The energy storage system outputs electric current - using a dynamo/generator if requried, and transfers that energy to the traction electric motors.) Use the order of magnitude approach to justify:

a) Size.
b) Weight of the energy source, and total vehicle weight.
c) Give and approximate cost of energy storage and of vehicle with energy storage.
d) Provide a sketch of your design, and mention how it would be charged and what the charging station would look like.

Notes:

- Upload your presentation slides to blackboard before your presentation. (Each student from every group should upload a copy of the presentation.)
- Your target audience is composed of all your classmates plus the instructor.
- The sketches and visual aids need only give a sense of proportion of the vehicle including its energy source and the charging station.
    - To earn your grade, you will have to present your results in class, on a presentation that must not exceed 3 minutes (including setup time for visual aids). There will be 1 minute for questions from the audience.
    - Everyone in your group should participate in the presentation.
    - You may use up to 3 visual aids (i.e., pdf or power point slides on the projector), and you may request to use the instructor's computer, but you should arrange to load the files well in advance of the presentation.

Group	Names	Energy Storage Method
1	Michael Allen, Theophilus Aluko	Springs. Use mcmaster.com part number 9640K182
2	Steven Cole, Collin Geibel	Height difference of mass: Mass composed of lead
3	Kevin Ingutia, Nathan Katz	Pressurized air
4	Parth Khandge, Marcus Moore,	Flywheel
5	Kyle Niemeyer, Mary Sabatino	Lead-acid (car) batteries
6	David Smart, Igor Soloninko	Hydrogen fuel cell
7	Victor Torres , Tuan-Anh Van	Thermal Storage with oil as working fluid and steam cycle
8	Nicholas Zhuravlev, Joseph Welch	Electric capacitors

ENME489
Energy Sources for the Future
Midterm Exam

Name ______________________________

Date ______________________________

Instructions:

- Write your name in all pages, and number each page.
- For all questions below, clearly and concisely state your answers.
- Only ordinary electronic calculators are allowed.

Formulary:

- Kinetic Energy = $\frac{1}{2}mv^2$ (m = mass, v = velocity).
- Gravitational potential energy = m g h (g = 9.8 m/s^2, h = height).
- Electrical Power = I*V (I = current, V = Voltage).
- Volume of a sphere = $\frac{4}{3}\pi r^3$ (r = radius).
- Bernoulli's equation: $p_1 + \frac{1}{2}\rho {v_1}^2 = p_2 + \frac{1}{2}\rho {v_2}^2$ (p = pressure, ρ = density, v = flow velocity).
- Stored electrical energy in capacitors = $\frac{1}{2}CV^2$ (C = capacitance, V = voltage).
- Power = F*v (F = force, v = velocity).
- Energy required to elevate temperature in a mass = m C ΔT (m = mass, C = heat capacity, ΔT = temperature difference).
- Logarithm identity: Ln(a) – Ln(b) = Ln(a/b).

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1. If a lake is about one eighth (1/8) covered by water hyacinths when you first look at it, and completely covered 3 weeks (21 days) later, what is the water hyacinth doubling time? [10 points]

2. From the map above

a. Give an order of magnitude estimate for the area of the State of Arizona in m^2. [5 points]

b. Assuming that at best Arizona receives $1kW/m^2$ of solar power, what is the order of magnitude maximum power from the Sun, in Watts, that could be collected in the State? [5 points]

3. A spherical asteroid that is 1 km in diameter, with a density of 5300 kg/m^3, traveling at 33 km/s with respect to Earth, is on course to collide with our planet. A mission to prevent this is devised using a large spacecraft powered by solar energy that will gently land on the surface of the asteroid, and then start to push back using electric (plasma) thrusters, until the asteroid reaches zero velocity with respect to Earth. This deceleration must be completed in 1000 days. (Assume 100% efficiency in converting electricity to thrust, and neglect mass changes in the system.)
   a. What is the kinetic energy of the asteroid? [5 points]
   b. What is the continuous power required, in watts, for the deceleration? [5 points]
   c. Assuming solar power is $1.3kW/m^2$in space, and 40% solar cell efficiency, what size solar array, in m^2, should the spacecraft have to power the electric thrusters and complete the task? [5 points]
   d. Is the solar array area bigger or smaller than the state of Arizona? [1 point]

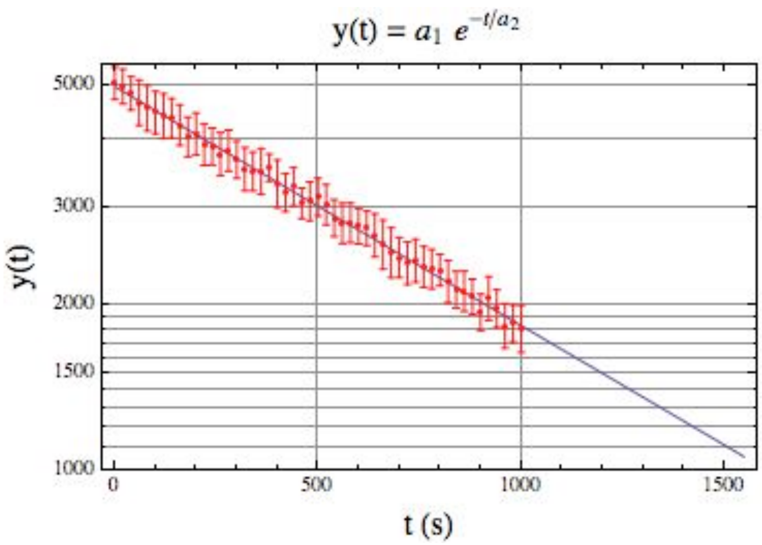
4. Certain chemical battery of the AAA size has 1.5 Volts between the terminals and is rated at 850 mAh (that is, the batteries can deliver up to 850 mA in one hour). How much energy is stored in the battery? [10 points]

5. In the logistics equation, $\frac{dN}{dt} = cN\frac{(K-N)}{K}$, where c and K are constants,

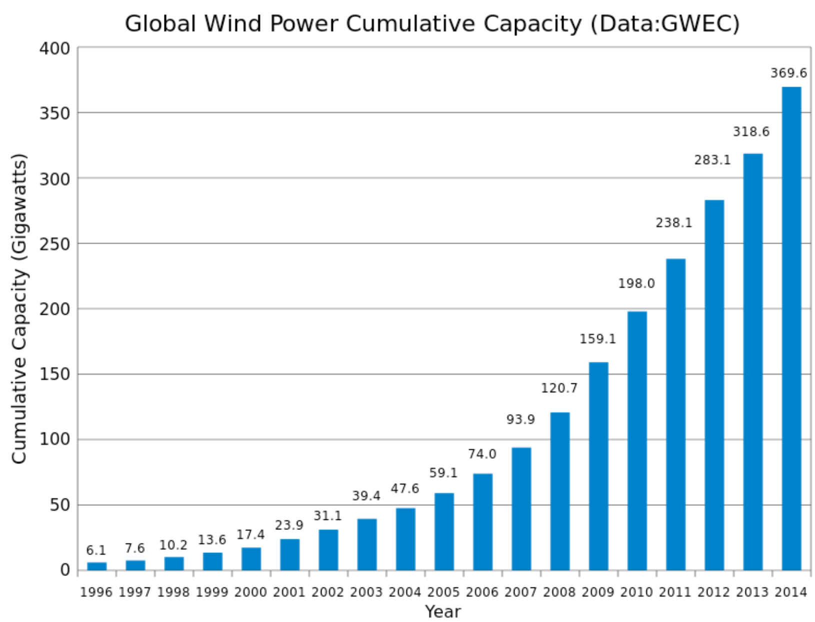
   a. What is the meaning of K? [5 points]
   b. Sketch, qualitatively, the shape of $\frac{dN}{dt}$ versus time. [10 points]
   c. Sketch, qualitatively, the shape of N over time. [10 points]

6. Derive, starting from the Bernoulli equation, the absolute maximum power that one could obtain from wind, for a circular section of radius r, an initial velocity v1, and a density of air ρ. The result should be expressed in terms of r, v_1, ρ, and the exit velocity v_2. [20 points]

7. The plot below shows experimental data and its fit (where y-axis is in logarithmic scale, and the t-axis is linear). Using the plot grid lines as aid, find a_1 and a_2 for the fit function y(t) below. [10 points].



8. Assuming exponential growth continues as in the figure below, approximately at which year should we expect to have 1.5 TW of cumulative wind power capacity? [5 points]



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Year in review—EROI or energy return on (energy) invested

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There have been five foremost empirical efforts regarding energy return on investment (EROI) analysis over the past few years, including the topics of: (1) whether corn ethanol is a net energy yielder; (2) a summary of the *state of EROI* for most major fuel types; (3) alternative applications of EROI, such as energy return on water invested (EROWI); (4) the relation between EROI and the economy; and (5) an attempt to calculate the minimum EROI for a sustainable society. This paper offers a review of these five main areas of interest and provides a history of the development of EROI as well as a review of some of the various definitions of EROI and how they apply to EROI analyses. The paper concludes by listing numerous areas of improvement that are needed within EROI research.

Keywords: EROI; net energy; peak oil

Introduction

During the past few years, there have been five main efforts related to energy return on investment (EROI), although the total number of papers is not large. The first is a very intense and public discussion as to whether corn-based ethanol, a fuel whose advocates suggest can be an important substitute for foreign (i.e., non-U.S.) gasoline, is a net energy gainer or not. The second main effort was a fairly intense effort by our own laboratory to summarize what is known about the EROI of most major fossil fuels and renewable resources. The third was several papers by Nate Hagens and others pertaining to the framework for EROI analyses and the relation of EROI to both the economy and to water use. The fourth was an attempt to examine how EROI, or more specifically how declining EROI, might impact economic activity. Finally, the fifth was a series of papers, again generated from within our laboratory, about the potential importance of EROI for our economic system including an attempt to understand and calculate what the minimum EROI for a sustainable society might be. This paper gives some background and definitional material and then summarizes these research efforts in the above order.

What is EROI?

EROI is the ratio of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question. It is most usually applied to, for example, the energy to find and produce oil or grow, harvest, and process biofuels. It should not be confused with conversion efficiency, as often happens in the literature, which is the conversion of one fuel type to another (e.g., making gasoline from oil). EROI and its variants are sometimes called the assessment of energy surplus, energy balance, or net energy analysis. Some practitioners prefer the use of EROEI or ERoEI; however, we prefer EROI because of its historical use and because we think energy return on financial investment should be occasionally part of the analytical landscape. In all cases when EROI is used in any way it is important to define exactly what you are doing, as we discuss below in the section titled "more explicit definitions of EROI." EROI is calculated from the following simple equation, although the devil is in the details:

$$\text{EROI} = \frac{\text{Energy gained}}{\text{Energy required to get that energy}}$$

The numerator and denominator are usually assessed in the same units so that the ratio so derived is dimensionless, e.g., 30:1, which can be expressed as "thirty to one." This implies that a particular process yields 30 Joules on an investment of 1 Joule (or Kcal per Kcal or barrels per barrel, etc.). The boundary of an EROI analysis is usually the mine-mouth, well-head, farm gate, etc. We call this more explicitly EROI_{mm}, which is only loosely related, at least in the short term, to the financial concept of energy return on monetary investment. In the long term they are probably highly connected, especially when various corrections for energy quality are included.

Advocates of EROI analysis, including ourselves, believe that it offers a new and insightful approach to examining various energy sources in ways markets can not. We do not believe, however, that EROI by itself is necessarily sufficient for policy decisions; rather, it is just the tool we prefer the most, especially when EROI analyses show stark differences among competing energy sources. Therefore, we believe that it should always be done and done comprehensively for any major political or financial decision about energy. For example, comprehensive EROI analyses showed that the EROI for corn-based ethanol was marginal at best, and even a modest understanding of the implications of that result would mean that small perturbations in the corn-based ethanol production process, such as high corn prices, would have large impacts on profits. This could have saved many people from large financial losses as numerous large corn ethanol distilleries went bankrupt this past year. To take an ecumenical perspective it is probably best to undertake both financial *and* EROI analyses and if the results are the same the policy prescription may be obvious, and if not there may be a rich area for further understanding by asking "why?". Additional dimensions that might be incorporated into both analyses include environmental and labor intensities.

It is especially important to consider where possible how the EROI may change over time, as well as how EROI might change as scale changes, e.g., laboratory versus pilot plant versus commercial facilities. For example, EROI for oil has decreased steadily over the last century while that for coal seems to undulate up and down, and, according to both published work (Cleveland *et al.*[1] versus Cleveland[2]) and some newer work on The Oil Drum, the EROI of cellulosic ethanol may vary significantly as the scale of production changes.[1–3]

History of EROI

To our knowledge the first formal use of the term *EROI* was in Cleveland *et al.*[1] and Hall *et al.*,[4] although the concept was used explicitly (but called net energy) in Hall's Ph.D. dissertation analysis of the energetics of migrating fish and early studies of industrial energy and trends in U.S. petroleum extraction.[4–7] Other studies by Herendeen and Plant[8] and Herendeen[9] focused on a concept called the "Energy Cost of Energy," which is ostensibly the same idea as EROI. Other early conceptions were obvious in papers by economist Kenneth Boulding[9a] and especially ecologist Howard Odum.[10,11] At one time there was considerable public interest in the concept, and for example the Hall and Cleveland[7] paper was featured on page 1 of the Wall Street Journal. During that time there was also a great deal of discussion and some financing for studies of the high fossil energy requirements for the nuclear fuel cycle. But as gasoline prices declined and memories of the "energy crises" of the 1970s faded, interest in the concept also faded. There has been a small resurgence of interest in the concept in recent years as oil prices increased, and there certainly are many, including us, who believe that the concept will be critical for the future of the U.S. economy. As we develop later, however, there has been little discussion (except Murphy) as of this writing of the concept in relation to, for example, President Obama's ambitious renewable energy plans, even though it would seem critical.[12] Nor have there been any governmental programs or funding to undertake such analyses in a scientific and objective fashion or to ensure that appropriate data is being obtained.

More explicit definitions of EROIs

Explicit definitions for EROI were pursued in the late 1970s and revisited in the late 1990s by Robert Herendeen.[13,14] More recently, Mulder and Hagens stated that there is a need for a better way to think about EROI rather than just whether it is positive or negative at the well-head or farm gate.[15] They were especially concerned that too many studies had been published with varying EROI numbers for what were supposedly the same processes. For example, in the case of corn ethanol, at least three different methods of net energy analysis had been employed in the literature, resulting in three different estimates of EROI that were mutually "incommensurable."[15] They believe that since the calculation of EROI is difficult and many numbers are usually included, explicit statements of the boundaries of each individual EROI analysis is necessary to avoid spurious comparisons. To aid in that effort, Mulder and Hagens[15] define different calculations of EROI, depending on what inputs are used, as first order, second order, and third order. First-order EROIs include only direct energy inputs and outputs. Second-order EROIs include energy and nonenergy indirect inputs as well, and also credit for coproduct outputs. Finally, third-order EROIs include "externalities" of the production process, such as the cost of water depletion due to corn ethanol production.

We agree with these authors and believe that we need a good, consistent, and more comprehensive way of thinking about the meaning of the magnitude of the EROIs of various fuels. In our opinion, many of the EROI arguments made so far are simplistic, or at least incomplete, because the "energy break even" point most frequently used (see below), while usually sufficient to discredit or, if high, support a candidate fuel, measures EROI at the well-head or farm gate only and may omit large costs or benefits that occur beyond the point of extraction. Furthermore, it seems to us that many of the EROI analyses performed to date are generated from the perspective of defeating or defending a particular fuel rather than objectively assessing various potential alternatives.

To that end, Hall, Balogh, and Murphy gave a number of additional subdefinitions of EROI.[16] First, these authors suggested that we need some way to understand the magnitude and the meaning of the overall EROI we might eventually derive for all of a nation or society's fuels collectively by summing all gains from fuels and all costs of obtaining them (i.e., *societal* EROI).

$$\mathrm{EROI}_{soc} = \frac{\text{Summation of the energy content of all fuels delivered}}{\text{Summation of all the energy costs of getting those fuels}}$$

They also introduced new concepts that start with EROI at the mine-mouth (or well-head, farm gate, etc.) called EROI_{mm}, which includes the energy to find and produce the fuel. This is the most common use of EROI and the one that we advocate as most important to understand. Hall *et al.*[16] however, thought that in addition it would be useful to take the concept further along the energy "food chain." We call the next step EROI at the "point of use," or EROI_{pou}, which includes the energy to find, produce, refine, and transport to point of use:

$$\mathrm{EROI}_{pou} = \frac{\text{Energy returned to society}}{\text{Energy required to get and deliver that energy}}$$

The next level was EROI_{ext} "extended EROI," which modifies the equation to include the energy required not only to get and deliver but also to use the energy, including, for example, the energy used to maintain bridges, highways, cars, etc., that are necessary to use gasoline or other transportation fuels. They define it formally as:

$$\mathrm{EROI}_{ext} = \frac{\text{Energy returned to society}}{\text{Energy required to get, deliver, and use that energy}}$$

The three definitions of EROI listed above are applications of the first-, second-, and third-order theory of EROI calculations presented by Mulder and Hagens.[15] Perhaps someone could combine these two approaches to get a truly comprehensive EROI.

Methods for determining EROI

Data from the Energy Information Administration, (EIA) or the European counterpart, the International Energy Agency (IEA), and British Petroleum (BP) are very helpful in determining the energy out (numerator). In general these output data sets appear well-maintained and easy to navigate; however, since they are collected by different agencies with different definitions and goals in mind, the method of collection and manner in which the data is presented is almost always incongruous (for example does "oil" include "petroleum liquids" from gas wells?). One of the best, or at least easiest, sources of determining the energy costs (denominator) within an EROI estimate are the statistics published every five years by the Census Bureau called the 2002 Census of Mineral Industries, which provides the

Table 1. **Chain-type quantity indexes for energy inputs by industry (2000 = 100), from the Bureau of Economic Analysis**[18]

	2002	2003	2004	2005	2006	2007
Petroleum and coal products	106.037	57.496	62.611	143.385	130.457	155.559

Numbers reported here vary by a factor of 2 to 3 between years of relative economic stability.

data for the energy use of each major sector of the economy.[17] However, cost data tend to be for direct energy used or produced, but not indirect (e.g., that used off site to make materials used on site).

Possible decline in quality of energy cost data

We also found an apparent degradation in the data maintained on energy intensity of different U.S. industries as maintained by the U.S. Department of Commerce. For example, the reported energy from natural gas used to get oil and gas went from a majority to negligible from 1997 to 2002—something that seems impossible. Cleveland (Ref. 2 and personal communication) has also commented on this, saying that some 30 people that were once responsible for 30 divisions of the economy, had been replaced by one. For another example, a search at the Bureau of Economic Analysis, revealed interesting values under the title "Chain-Type Quantity Indexes for Energy Inputs by Industry [2000 = 100]" (Table 1).[18] We are not quite sure what this index measures, but assuming it is some measure of energy inputs, we find it hard to believe that the cost of energy inputs for these industries in the United States during a period of relative economic stability would vary by a factor of 2 or 3 between years as these data show, especially while also being reported to 5 or 6 significant digits.

Boundaries

This brings us to the biggest problem in performing EROI analyses: *boundaries*. The same boundaries must be used when examining both the energy gained and the energy costs of an EROI analysis. For example, an EROI estimate for oil extraction that incorporates all direct and indirect costs associated with exploration, drilling, and production is usually compared with the energy gained by performing those activities, essentially the energy content of the oil at the well-head, i.e., $EROI_{mm}$. Costs outside the mine-mouth boundary, such as environmental and social costs, should not be included. However, by changing the boundaries—for example, when calculating either $EROI_{pou}$ or $EROI_{ext}$—other costs and gains can and should be included. For example, comparing the energy content of the *gasoline* with the energy costs of *exploration, drilling*, and *production of oil* would be incorrect, as only the costs up to the well-head have been accounted for, while the refining and transportation costs, i.e., costs that are required to deliver gasoline to the consumer, are not included.

Because of these boundary issues, and because most businesses, governments, and entities of all kinds record financial data much more often than energy data, many times we must convert monetary costs to energy costs. To do so we often calculate *energy intensity* conversion numbers ourselves or get them from the literature. Energy intensity is defined generally as the energy output per dollar input, and the inverse is sometimes called economic efficiency. The most general method, which is fairly straightforward, is attained by dividing total national energy consumption by the national statistics for gross domestic product (GDP), which was about 8.7 MJ used per dollar in 2005 and somewhat less than that in 2008. Time series of this number are given in Figure 1 and generally decline reflecting both inflation and, at least in most people's minds, improvements in efficiency.

Specific energy intensity values can be derived for specific components of society. Accurate and comprehensive estimates of this type were generated at the University of Illinois decades ago using an energy version of Leontief Input–Output tables.[13] Unfortunately, these numbers are now quite outdated. Newer estimates for much more aggregated divisions of the U.S. economy can be found in the Carnegie-Mellon energy calculator web site.[19] Herendeen (personal communication) has estimated that about 14 MJ were used per dollar spent

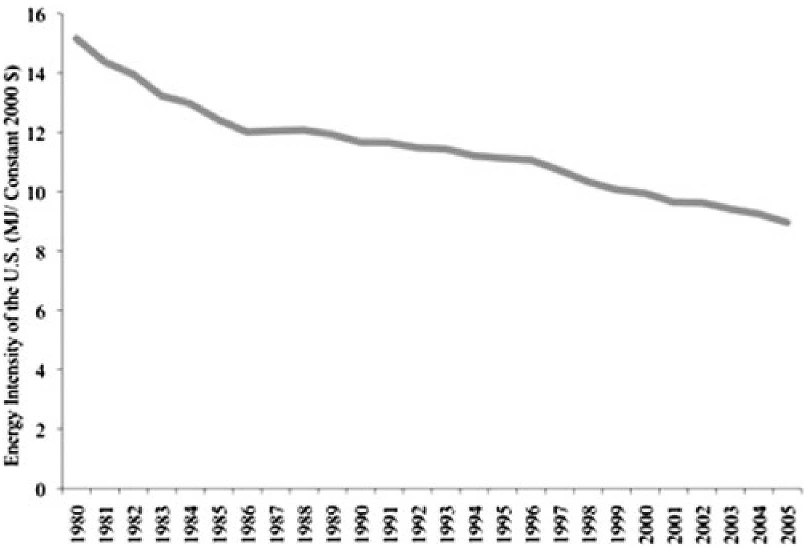

Figure 1. **Energy intensity of the U.S. economy from 1980 through 2005, measured as megajoules (MJ) per dollar.**

in heavy industry in 2005. Gagnon and Hall estimated that for oil and gas exploration and production, i.e., situations in which energy should probably be cheaper since the oil companies are selling to themselves, about 20 MJ are used per dollar spent in 2005.[20] These numbers can be used to estimate rough costs for many fuels where economic but not energy data are available (see Ref. 16).

Further analysis is needed for the aggregate national energy intensity values as market globalization has intertwined the economies of the world. For example, there is an ongoing debate as to whether or not the U.S. economy has become more or less energy-intense over the past 20 years. One side argues that as economies become wealthy they use less energy per dollar output, i.e., become more efficient.[21] At first glance, the data seem to support this hypothesis, as the increase in GDP in the United States from 1904 until 1984 was accompanied by a nearly linear increase in the use of fuels.[1] That relation seems to have broken down subsequently, as the GDP grew about 40% more recently while energy use increased only a little. Some argue that the supposed decline in energy intensity over the past century is due to other things, such as outsourcing heavy industry, or as Kaufmann found, switching fuels away from coal toward oil and natural gas.[22] Finally, Shadowstats argues that since 1984, the U.S. government, wishing to "downsize" inflation, has essentially "cooked the books" by continuously changing the criteria used to calculate official inflation rates.[23] If they are correct, then real GDP has been continuously and progressively overestimated, and there may have been little or no increase in the efficiency with which energy has been turned into GDP.

We now present what we believe are the five most important results of EROI research in the past several years.

Main topics in recent EROI literature

Does corn-based ethanol yield net energy gains?

Many forget that the corn-based ethanol debate has long existed.[24,25] Ethanol was initially named "gasohol," and there were papers published in *Science* to that end titled "Gasohol: Does it or doesn't it. . .produce positive net energy?"[25] More recently the debate has resurfaced to produce most of the relatively sparse current literature on net energy analysis, and it has focused, somewhat unfortunately, on trying to answer the same question that the Chambers paper did 30 years ago, i.e., whether there is a net gain or a loss in energy from making ethanol from corn (see Farrell *et al.* as well as the many responses in the June 23, 2006, issue of *Science* for a fairly thorough discussion of this issue).[26] The general criteria used in much of this "energy break even" issue is whether the energy returned as fuel is greater than the energy invested in growing or otherwise obtaining it, i.e., if the EROI is greater than 1.0:1.0. If the energy returned is greater than the energy invested, then the general argument seems to be that the fuel or project "should be done," and if not, then it should not.

At one extreme, Patzek[27] and Pimentel and Patzek[28] argue that ethanol from corn requires more energy for its production than is gained in the fuel so produced. Others, summarized in Farrell *et al.*[26] and Hammerschlag,[29] report EROI calculations with a clear energy surplus, with from 1.2 to 1.6 units of energy delivered for each unit invested. The crux of the argument usually centers around: (1) the boundaries of the numerator, i.e., whether one should include some energy credit for nonfuel coproducts, such as residual animal feed, e.g., soybean husks or dry distiller's grains; (2) the boundaries of the denominator—that is, whether or not to include the energy required to compensate for environmental impacts in the future, e.g., for lost future production occasioned by soil erosion, or for other costs, e.g., labor; and (3) the quality of the fuels used and produced, e.g., liquid is presumably more valuable than solid or gaseous.

Such arguments are likely to be much more important in the future as other relatively low quality fuels (e.g., oil sands or shale oil) are increasingly considered or developed to replace conventional oil and gas, both of which are likely to be more expensive and probably less available in the not-so-distant future. If the alternatives require much oil and or gas for their production, which is often the case, e.g., natural gas use in fertilizer production, then an increase in the price of oil or gas will not necessarily make the alternatives cheaper and more available as a fuel. We believe that for most fuels, especially alternative fuels, the energy gains are reasonably well understood but the boundaries of the denominator, especially with respect to environmental issues, are poorly understood and even more poorly quantified. Thus, we think that most EROIs, including those we consider here, are higher (i.e., more favorable) than they would be if we had complete information.

We believe also that the research on corn ethanol has been overly focused on showing positive or negative net energy accounts, rather than emphasizing the low EROI of all commercial scale liquid biomass fuels. Mulder and Hagens agree and have used a new variant of EROI to measure how much of a certain fuel must be produced to deliver one unit of net energy.[15] This approach emphasizes the low yield of such fuels. They calculate the gross amount of fuel required according to the equation:

$$\text{Gross amount of energy required} = \text{EROI}/(\text{EROI} - 1)$$

Using that equation and given an EROI of 11:1 for oil, to deliver one unit of net energy from oil would require the extraction of 1.1 units.[2] In other words, to deliver 1 barrel of oil would require the extraction of the energy equivalent of 1.1 barrels of oil. In the optimal case for ethanol—that is, using an EROI of 1.6:1—to deliver one unit of net energy would require the growth and distillation of 2.7 units. Thus, due solely to the difference in EROI, an additional 1.6 units (2.7–1.1) of ethanol (or its equivalent as some other fuel) must be distilled to deliver 1 unit of net energy to society. Figure 2 uses this equation to compare some published EROI values for corn ethanol to those of oil. The larger message to be gleaned from this mathematical exercise is that the relation between low EROI and net energy is not linear. In other words, if the EROI of a fuel decreases from 10 to 9, then the amount of energy needed to deliver one unit of net energy increases from 1.1 to 1.125. However, if the EROI decreases from 1.5 to 1.1, i.e., less than half the decrease from 10 to 9, then that same amount increases from 3 to 11 units of energy.

Another way to view the impact of low EROI fuels, such as corn ethanol, is by looking at the net energy gain from the production of a fuel source as a percent of the fuel delivered to society. One liter of a fuel with an EROI of 100:1 delivers 99% of that fuel to society [mathematically, it is calculated as $((\text{EROI} - 1)/\text{EROI}) \times 100$]. On the other hand, 1 liter of a fuel with an EROI of 2:1 delivers 50% of that fuel to society. Viewing EROI from this perspective, it is easy to see that decreasing EROI from 100 to 80 has much less of an impact than decreasing EROI from 5 to 1 (Fig. 3). This rapid decline in net energy is referred to as the Net Energy Cliff, and would occur if we shifted to liquid biomass fuels.[30]

Effect of technological improvements

Liska *et al.* analyzed time trends in the production efficiency of corn ethanol refineries.[31] Most refineries used a dry mill process powered by

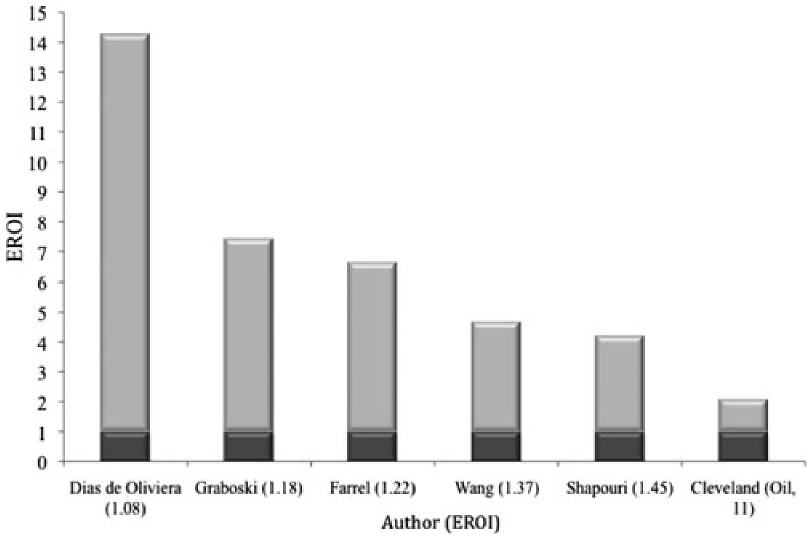

Figure 2. **Comparison of the amount of gross energy needed (*light gray*) to deliver one unit of net energy (*dark gray*). *Y*-axis is "unit of energy," which can be interpreted as any unit of energy, such as a joule, barrel of oil equivalent, etc.**[56–59]

natural gas. Their graph, supplemented by their text, indicates that the amount of energy used to generate a liter of alcohol has dropped to approximately half of what Farrell *et al.*[26] gave in 2006. The eight corn-ethanol scenarios they reported on had net energy ratio (NER) values, apparently the same as EROI, from 1.29 to 2.23, and greenhouse gas intensities ranging from 31 to 76 gCO2e per MJ (see their results). For the most common biorefinery types, which are represented by the first five scenarios, NER (EROI) ranged from 1.50 to 1.79. We found, however, that their results are sometimes difficult to interpret. For example, the *y*-axis of their Figure 1 is labeled "Thermal Energy Efficiency," and efficiency means output over input, yet the units are given as intensity, i.e., MJ per liter of ethanol, which is perhaps the inverse of efficiency. Thus, their research summary may indicate that with experience and technical refinements the EROI of corn-based ethanol has been increasing, and by implication is likely to continue to increase.

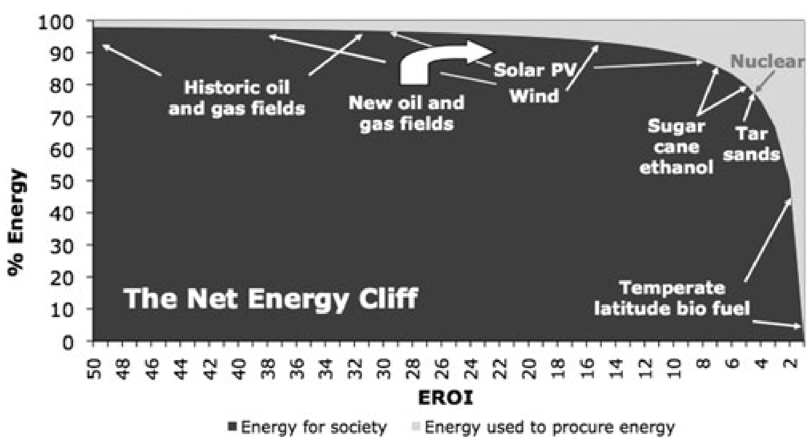

Figure 3. **The "Net Energy Cliff." As EROI approaches 1:1 the ratio of the energy gained (*dark gray*) to the energy used (*light gray*) from various energy sources decreases exponentially.**

Table 2. Existing magnitude and approximate EROI of various energy resources for the United States, from various sources listed

Resource	Year	Magnitude (EJ/yr)	EROI (X:1)	Reference
Fossil fuels				
Oil and gas	1930	5	>100	2
Oil and gas	1970	28	30	1, 4
Oil and gas	2005	9	11 to 18	2
Discoveries	1970		8	1, 4
Production	1970	10	20	1, 4
World oil production	1999	200	35	21
Imported oil	1990	20	35	32
Imported oil	2005	27	18	32
Imported oil	2007	28	12	32
Natural gas	2005	30	10	32
Coal (mine-mouth)	1950	n/a	80	2
Coal (mine-mouth)	2000	5	80	2
Bitumen from tar sands	n/a	1	2 to 4	32
Shale oil	n/a	0	5	32
Other nonrenewable				
Nuclear	n/a	9	5 to 15	32, 51
Renewables				
Hydropower	n/a	9	>100	32
Wind turbines	n/a	5	18	34
Geothermal	n/a	<1	n/a	32
Wave energy	n/a	<<1	n/a	32
Solar collectors				
Flate plate	n/a	<1	1.9	4
Concentrating collector	n/a	0	1.6	4
Photovoltaic	n/a	<1	6.8	52
Passive solar	n/a	n/a	n/a	32
Biomass				
Ethanol (sugarcane)	n/a	0	0.8 to 10	4, 53
Corn-based ethanol	n/a	<1	0.8 to 1.6	26
Biodiesel	n/a	<1	1.3	32

What are typical EROIs for our main fuels?

There has been a surprisingly small amount of work done on calculating EROI, given its critical importance. Cleveland *et al.*[1] and Hall *et al.*[4] summarized what was known about quantitative estimates for various fuels as of about the early 1980s. At that time there was a considerable amount of federal- and state-supported energy research and quite a bit of analysis undertaken, although the support has basically vanished. Believing that these estimates were outdated, Hall, in collaboration with about a dozen students and with support from the Santa Barbara Family Foundation and The Association for the Study of Peak Oil-USA (ASPO-USA), undertook a comprehensive summary of what was known about EROI as of 2008. Twelve students spent a very intensive month searching the literature. They found few additional peer-reviewed (or other) studies beyond those reported in Hall *et al.*,[4] and very little in the way of new, very different results. The results of this workshop were published in six postings on The Oil Drum.[32] The main results of this initial analysis are given here as Table 2.

Although each posting evoked massive amounts of commentary, essentially no new peer-reviewed papers were offered. There were many off-the-cuff calculations of much higher or lower EROIs for someone's favorite or least-favorite fuel (especially some very high numbers for nuclear), but there was little new peer-reviewed quality work. We extend that request for additional studies here.

Cleveland provided one of the more recent EROI analyses in which he estimated the EROI of drilling for oil and gas within the United States.[2] Building upon earlier work, he found that the EROI has decreased from about 100:1 in the 1930s, 30:1 in the 1970s, and between 18:1 (no quality correction) to 11:1 (corrected for apparent increase in use of electricity) in about 2000.[1,2,4] From this literature we believe that the EROI of our most important fuels is declining over time. The case seems strongest for oil and gas, while the data for coal is less convincing, or perhaps less consistently analyzed. Coal showed a decline in EROI in a 1984 publication from about 80:1 to about 30:1, but published results jumped again in about 1990 so that more recent numbers tend to be 80:1.[1,2] It is not clear whether this pattern is real, reflecting greater surface mining, accounting changes in the U.S. Department of Commerce, or just bizarre. At any rate, the energy content of coal has been decreasing so that the maximum mined *energy* for U.S. coal was in 1998 even though the tonnage has increased since that time (Energy Watch Group 2007).[33]

An exception to the dearth of papers on EROI, and a literature review that may set the standards for others to follow, is Kubiszewski *et al.* which is a "meta analysis" (i.e., an analysis combining the results of several related studies) of a considerable number of studies of the EROI of wind turbines.[34] She concludes that in general larger turbines have a more favorable EROI and that the average EROI of many studies is about 18:1, not counting any additional infrastructure costs for dealing with the highly variable nature of wind.

The impact of EROI analyses on other resources besides energy

Mulder *et al.* have undertaken an important analysis of the amount of water that is required (extracted and returned or consumed) per unit of fuel delivered to society, which they called EROWI, or energy return on water invested (MJ out per liter of water in).[35] They found that the net EROWI for corn-ethanol production is 0.087 while that for diesel production is 285.3, a difference of 4 *orders of magnitude*. If we are forced to use biomass fuels because of petroleum depletion, these authors believe it will have large impact on other aspects of our economy, such as food production and even water availability in some regions.

Consideration of EROI in relation to quantity of resource

The utility of a fuel depends upon not only its quality but also how much of it there is—that is, its quantity. For example, hydroelectric power may often have a very high EROI, especially at very favorable sites, but at least in the United States and most other developed nations, the total quantity of electricity that can be delivered is usually relatively small compared to the energy needs of the country. This is somewhat less true for mountainous, rainy, low-population countries, such as Switzerland or Costa Rica, but even in these countries significant quantities of fossil fuels are used to generate electricity.

This issue may be especially important for various "nontraditional" solar sources of energy, such as wind energy, biodiesel, and photovoltaics, which, although somewhat promising from an EROI perspective (perhaps 18:1, 2 or 3:1 and 8:1, respectively, not including the energy cost of backups), are thus far so tiny in magnitude that they are unlikely to be a large player for years or even decades. Although such fuels are quickly increasing in use, few people understand the degree to which they are overshadowed by fossil fuels. For example, for most recent years before the financial collapse of 2008, the per annum *increase* in world or U.S. traditional fuel consumption (oil, gas, and coal) was greater than the *total annual use* of all the nontraditional solar (i.e., wind turbines and photovoltaics). Thus, at this point, wind and photovoltaic are in no way displacing fossil fuels but simply adding more energy to the increasing amount of all types that we use.

For the United States the quantitative and qualitative relations of the major fuels have been published as the "balloon graph" diagram (Fig. 4).[36] This diagram gives some idea of the difficulties ahead of us if we are to replace fossil fuels with

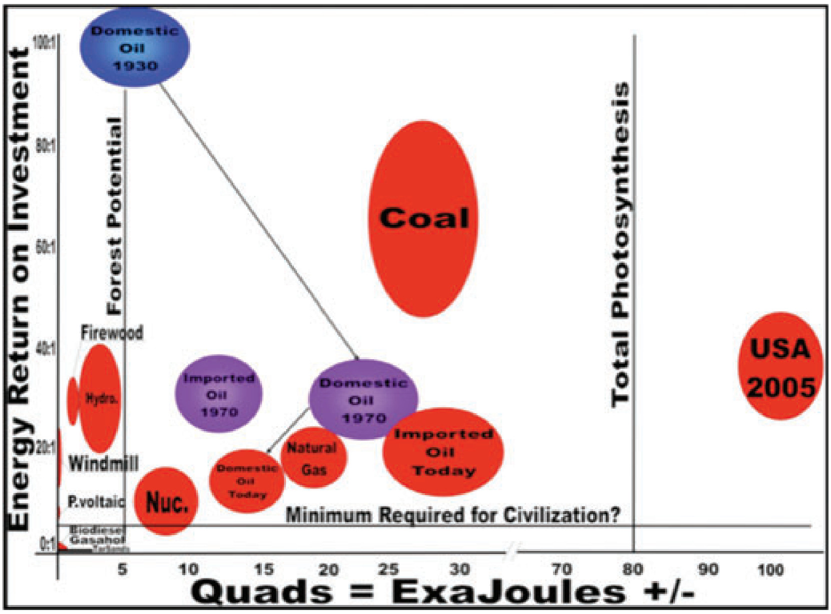

Figure 4. "Balloon graph" representing quality (EROI – *y*-axis) and quantity (*x*-axis) of the United States economy for various fuels at various times. Arrows connect fuels from various times (i.e., domestic oil in 1930, 1970, 2005 – "today"), and the size of the "balloon" represents part of the uncertainty associated with EROI estimates, i.e., larger "balloons" represent more uncertainty. The horizontal line indicates that there is some minimum EROI that is needed to make society work, and the vertical line to the *left* indicates one estimate of maximum forestry potential and the vertical line to the *right* is David Pimentel's earlier estimate of total photosynthesis in the United States (Source: U.S. EIA, Cutler Cleveland and C. Hall's own EROI work in preparation). (In color in *Annals* online.)

something else, at least if we retain anything like the same quantitative energy use. On the other hand, there are some unconventional sources of traditional fuels that provide vast quantities of energy reserves, but at low EROIs. The Alberta, Canada, oil sands, for example, contain about 170 billion barrels of proven oil reserves, second only to Saudi Arabia.[37] However, they are mined as bitumen requiring large amounts of natural gas, water, and other inputs, decreasing the EROI to around 2-4:1, although some newer technologies may be somewhat higher.[38] Therefore, the low EROI of this fuel places it as a direct competitor with biodiesel and other biofuels, but due to the sheer vastness of the resource itself it may play a much larger role in the next few decades. Tar sands are probably best perceived as a "rate-limited" rather than "resource-limited" fuel, as it may be very difficult to scale the process up to many times today's rates because of the need for gas, water and human infrastructure.[32]

The enormous energy and financial changes during 2008 (oil prices running up to nearly $150 a barrel in early July 2008 and then crashing down to less than $40 a barrel in December), and the complex "collapse" of many of the U.S. financial markets brought a decrease in the total quantity of oil consumed globally. We think we are seeing the manifestation of predictions made by geologist and "peak oiler" Colin Campbell, that rather than having a clear peak in oil production we are more likely to see an "undulating plateau," where peak-induced restrictions in oil supply will cause large economic downturns.[39] These downturns will then in turn release the pressure on oil prices, leading to increased oil use and production again and so on, resulting in an undulating plateau rather than a sharp peak (Fig. 5). This seems to have taken place between 2004 to 2008, and the financial crash has enormously decreased demand while starving the petroleum industries of capital so that, if nothing else, the second 6 months of 2008 injected uncertainty into forecasts of oil prices and production/consumption levels, all of which make predicting the future extremely difficult. Our inability to find major new oil fields since

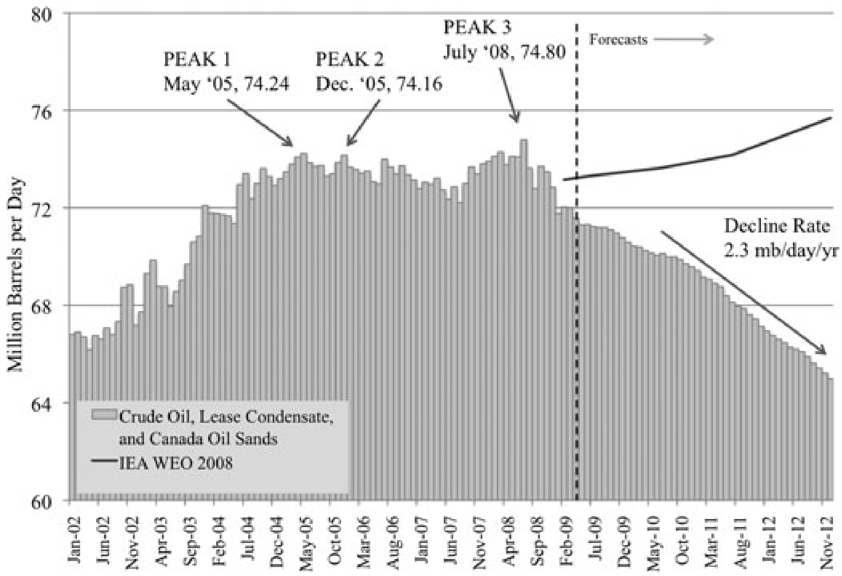

Figure 5. World crude oil, lease condensate, and Canada oil sands production showing an undulating plateau during the years of 2004–2008, and forecasts through 2012.[60]

the 1960s, the clear exhaustion of many important older oil fields, and the low financial investments in oil infrastructure as prices and financial markets collapsed in 2008 make it unlikely that we will ever pass the peak of oil in 2005 and all petroleum liquids in July of 2008.

Relation of EROI to economic activity

Energy has been linked, often nearly one for one, with national and global economic production.[4] The early production functions of traditional economists, in contrast, usually posit economic production as a function of only capital and labor.[40] These models tend to have a very large residual (or error), i.e., about half of economic production can not be explained by simultaneous changes to either or both of capital and/or labor. Economists usually attribute this to human innovation, often called technology.[41,42] However, Cleveland *et al.*,[1] Hall *et al.*,[4] Ayers and Ware,[43] and others have shown in great detail how our economy was tightly linked to energy use or sometimes applying that energy more precisely. When physicist Kummel[44,45] (see also Hall *et al.*[46]) added in energy to these production functions, the residual disappeared, implying that what economists have called technology is usually simply applying more energy to the process. In fact, he found that energy was more important than either capital or labor. Sometimes gains can be made by precise application of energy in manufacturing processes as a technical advance, but, at least historically, this has not led to less energy consumption as a whole in the United States. Thus, technological advance, which many economists hold out as the key to the future in finding "more energy supplies," may be a little harder to come by than many infer.

The most comprehensive analysis of the potential impact of changing (generally declining) EROI of the economy that we are aware of is given in Hall, Powers, and Schoenberg.[36] They looked at the impact of the diversion of the output to the energy sector (which is of course necessary for the economy to function at all). They divided the output into investment and consumption, and investment further into that for energy, that for infrastructure maintenance, and that for discretionary investments, which presumably was available only when the other investments had been met. They also assumed that discretionary consumption would be available only after the basic food, shelter, and clothing needs for the population had been met. In other words, they assume that energy inputs, maintenance, and basic human needs must be met if the economy is to function, and only after that are discretionary investments or consumption possible. They found

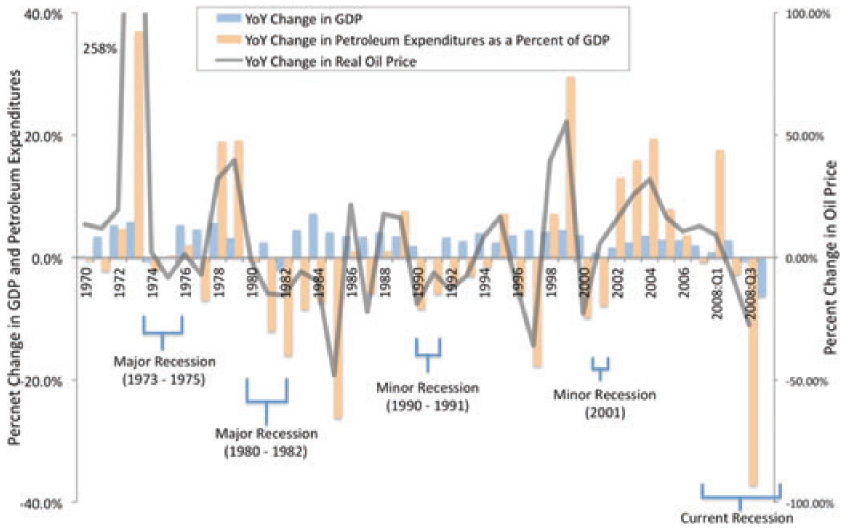

Figure 6. **Year on year (YoY) changes in GDP, petroleum expenditures as a percent of GDP, and real oil prices. Changes in oil prices were plotted using the secondary vertical axis (*right*) as they have a higher volatility over the data period. All data is for the United States. (In color in *Annals* online.)**

through empirical analysis of the disposition of GDP (i.e., starting with 100% of GDP) that during the "energy crises" of the 1970s, i.e., by comparing 1970 and 1980, discretionary investments were reduced by about one-half as the increased cost of fuel during that decade went from roughly 5 to 14% of GDP. Likewise, discretionary spending and investments were reduced during the increases in fuel costs from 2000 to 2007. Their model of the U.S. economy suggests that discretionary spending will be reduced further and nearly disappear by 2050. Such a change in our economy appears clear today as many people are reducing their own discretionary spending—for example, according to newspapers in Puerto Rico, tourism has decreased by 7.7% compared to 1 year ago (*San Juan Star*, June 1, 2009). These authors call this the "Cancun effect," as much of the American middle class, and the rest of the world, finds it harder to take a vacation.

Recent work by two economists, Jeff Rubin[47] and James Hamilton,[48] further examined the impact of energy on economies considering whether or to what degree the increase in the price of oil caused (or did not) the financial problems of the second half of 2008. Both conclude that the recent financial turmoil has an origin, at least in large part, in the increased price of oil through mid-2008. They also show how important oil prices were to economic growth/stability, as every major recession in the past 40 years was proceeded by a spike in the price of oil (Fig. 6).

There may exist, however, a more fundamental way to think about this issue.

Figure 7 is a Hubbert Curve representing the use of a nonrenewable resource, e.g., oil, through time, from first discovery to peak use to eventual near-total depletion. Oil production in the United States, for example, is half-way down the descending limb after a peak in 1970. The dotted line parallel to the ascending phase represents the expansion of economies that have grown as the energy to fuel them grew and extraction occurred at high EROIs. This period has served as the foundation for the development of economic and financial theory, i.e., the common conception that economic activity can expand indefinitely. This exponential growth phase led to economic theories that suggested that geologic limits are unimportant for economic growth, such as the conclusion of Barnett and Morse's book, *Scarcity and Growth*, in which they claim that increasing prices, substitution, and technological development, among other market-based factors, will be enough to counteract the potentially negative economic impacts of resource depletion.[49] So the fundamental question becomes: can economic growth continue indefinitely in the face of peak oil?

There are many other studies, including the aforementioned studies by Rubin[47] and Hamilton,[48] that

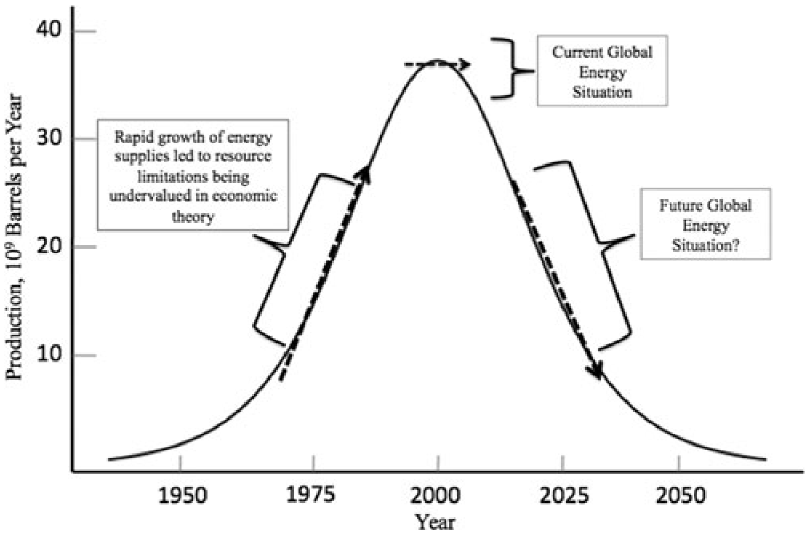

Figure 7. **Theoretical Hubbert Curve. Text added by authors.**[61]

show that economic activity is very closely related, and may even be dependent upon its energy supply.[1,4] Where will the second (financial) line in Figure 7 go when we reach the peak of the Hubbert Curve? This is no longer a question to be answered in the future, as indeed both global oil production and total U.S. energy use peaked in the first decade of the new millennium (Fig. 5). We think that the huge market "adjustments" of the second half of 2008 represent in part the market catching up to declining energy and EROIs. So maybe a more appropriate question is not whether or not economies can grow indefinitely, but rather, in the face of declining EROIs and fossil energy supplies, can there be much real economic growth at all? How will this effect the new application of Keynesian economics and its debt that is being undertaken by the governments of many countries, including our own?

Calculation of minimum EROI

An interesting and important question as we contemplate lower EROI fuels for the future is "what is the minimum EROI necessary for society to run?"[16] While the arguments about the EROI of, for example, corn ethanol, were centered on whether the EROI was positive or negative, a new paper by Hall *et al.*[16] calculated the minimum EROI necessary to power society. To do this, Hall *et al.*[16] assumed an $EROI_{mm}$ for oil of 10:1 and then calculated the $EROI_{pou}$ and $EROI_{ext}$ for the transportation system within the United States. Transportation costs of delivering the oil were included in the calculation of $EROI_{pou}$, and then construction and maintenance costs of roads and vehicles were included in the calculation of $EROI_{ext}$. Thus, the boundary of analysis increases incrementally from $EROI_{mm} < EROI_{pou} < EROI_{ext}$. They found that for either oil or corn ethanol the minimum EROI for society is roughly 3:1 (Table 3). In other words, U.S. society needs fuels that produce net surplus energy in the amount of 3:1 in order to "pay" for infrastructure metabolism, such as road and bridge maintenance. This has important implications for the alternative fuels industry, as almost all corn ethanol projects report EROIs of less than 2:1.

Conclusion: the necessity for, but poor state of, EROI research

We are amazed that there are no government, private, or nongovernmental organization programs or entities dedicated to attempting to understand and calculate EROI and its effects as well and as objectively as possible given that it may be the largest determinant of many aspects of our future. For example, enormous amounts of private and taxpayers' money were spent on corn ethanol, whereas any modest understanding of EROI should have indicated that even the highest EROI was too low to make much of a net impact as a fuel on the

Table 3. Approximate values and percentages of costs (or losses) in delivering gasoline/diesel and corn ethanol to the end-user[16]

	Gasoline/diesel		Corn-based ethanol	
Input energy	Exajoules	Percent	Exajoules[g]	Percent
Crude oil in the ground, total ethanol required	46[d]	100	9.0	100
$EROI_{mm}$	10:1		1.3:1	
Losses				
Nonfuel refinery products[a]	7.8	17	0.0	0
Energy used in refining[b]	4.6	10	0.0	0
Cost of extraction/production (i.e., initial energy invested)	4.6	10	3.9	43
Transport to consumer[c]	1.5[e]	3	0.24	2
Energy cost of transportation infrastructure	10.9	24	1.9	22
Total costs	29.4	64	6.1	67
Final energy delivered to consumer (billion gallons)	16.5 (126)	36	2.9 (36)	32
Total costs/total delivered	1.8		2.1	
Energy delivered/initial energy invested	4.14		0.5	
Minimum EROI to provide transportation service	~3:1[f]		~3:1[f]	

[a]EIA accessed 2007 (http://www.eia.doe.gov/bookshelf/brochures/gasoline/index.html).
[b]Szklo and Schaeffer.[54]
[c]Mudge *et al.*[55]
[d]EIA accessed 2009 (http://tonto.eia.doe.gov/dnav/pet/pet_cons_top.asp).
[e]This number was calculated by taking 5% of the energy being transported, which is 46 EJ less the nonfuel refinery products, energy used in refining, and accounting for the EROI of extraction, or $0.05 * (46 - 7.8 - 4.6 - 4.6) = 1.5$. However, to remain consistent in the table, the percentage reported is 3, which corresponds to 1.5 of 46.
[f](energy delivered + total costs)/energy delivered.
[g]Energy content of ethanol is 21.46 MJ/L, taken from Ref. 26.

national scale. We are concerned that new subsidies that are inevitable with President Obama's energy plan may end up supporting, as was the case with corn ethanol, fuels that are not energetically or economically competitive or perhaps even viable. We believe that comprehensive EROI analysis can and should serve as a critical vetting platform on which different energy sources are compared.

Specific assessments or improvements that are needed now include:

(1) Most fundamentally, an enormous overhaul of how we undertake and catalogue national assessments of energy used in all aspects of our lives.
(2) For example, the quantity and quality of the data on "energy costs of energy generating industries" must be enormously increased. Specifically, we need much better data and analyses on:
   - Energy costs of the U.S. oil and gas industry
   - Energy costs of mining and transporting coal
   - Energy used in, e.g., our food system
   - Energy costs and gains of various conservation systems, such as housing insulation
(3) Derivations of the energy cost of backup, distribution, and transportation systems and so on for wind turbines, photovoltaics, and other intermittent sources need to be calculated so that a more comprehensive and realistic EROI for these important new sources can be derived.
(4) Estimates of jobs created per energy invested or generated for any and all of the alternatives.
(5) A better understanding of the relation between energy use and economic activity. Most existing economic models have been of little or no help in predicting or helping us adjust to peak oil and subsequent economic effects of 2005–2008, and the arguments of many economists that somehow the market will blindly guide us

through all of this is a very dangerous assumption.

Last, our nation is obsessed with getting more fuels, especially liquid fuels, but has little understanding that probably this will not be possible and that substitutes for oil and gas are of much lower quality and quantity. Total energy use in the United States has most likely peaked and is (or will soon be) falling, with EROI probably falling even more steeply. Thus, we need to think very differently about our energy future. For example, we might be able to gain far more net oil and gas energy by insulating oil- or gas-heated houses or by installing (wood-based) regional cogeneration facilities or pellet stoves in homes in the cold cities of the United States, freeing fuels once used for heating. Transportation systems should not be about moving people efficiently over commuting routes (i.e., higher fuel-efficiency standards) but rather getting or allowing people to live near where they work. As another example, the United States throws out about one-quarter of the food it produces.[50] Since the food system uses about 20% of our national energy, we could save 5% of our total energy use by not wasting food (D. Pimentel, personal communication). This is nearly 10 times more energy than we generate now from all windmills and photovoltaics. We need more such comprehensive thinking rather than simply pushing forward in the old way on an energy base that is declining in quantity and, with respect to declining EROI, quality.

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Conflicts of interest

The authors declare no conflicts of interest.

References

1. Cleveland, C.J., R. Costanza, C.A.S. Hall & R. Kaufmann. 1984. Energy and the U.S. economy: a biophysical perspective. *Science* **225:** 890–897.
2. Cleveland, C.J. 2005. Net energy from oil and gas extraction in the United States, 1954–1997. *Energy* **30:** 769–782.
3. Rapier, R. 2008. Cutting through the Coskata Cellulosic Ethanol Hype. http://www.theoildrum.com/node/4454.
4. Hall, C.A.S., C.J. Cleveland & R. Kaufmann. 1986. *Energy and Resource Quality: The Ecology of the Economic Process*. Wiley. New York.
5. Hall, C.A.S. 1972. Migration and metabolism in a temperate stream ecosystem. *Ecology* **53:** 585–604.
6. Hall, C.A.S. 1975. The biosphere, the industriosphere and their interactions. *Bull. At. Sci.* **31:** 11–21.
7. Hall, C.A.S. & C.J. Cleveland. 1981. Petroleum drilling and production in the U.S.: yield per effort and net energy analysis. *Science* **211:** 576–579.
8. Herendeen, R. & R.L. Plant. 1981. Energy analysis of four geothermal technologies. *Energy* **6:** 73–82.

9a. Boulding, K. 1966. The Economics of the Coming Spaceship Earth. Sixth Resources for the Future Forum on Environmental Quality in a Growing Economy. Washington, D.C. March 8th.

9. Herendeen, R. 1988. Net energy considerations. In *Economic Analysis of Solar Thermal Energy Systems*. R. West & F. Kreith, Eds.: 255–273. MIT Press. Cambridge, MA.
10. Odum, H.T. 1971. *Environment, Power, and Society*. John Wiley and Sons, Inc. New York.
11. Odum, H.T. 1973. Energy, ecology and economics. *Ambio* **2:** 220–227.
12. Murphy, D. 2009. Some thoughts on the Obama Energy Agenda from the Perspective of Net Energy. http://netenergy.theoildrum.com/node/5073#more.
13. Herendeen, R. & C. Bullard. 1975. The energy costs of goods and services 1963 and 1967. *Energy Policy* **3:** 268–278.
14. Bullard, C.W., B. Hannon & R.A. Herendeen. 1975. *Energy Flow through the US Economy*. University of Illinois Press. Urbana.
15. Mulder, K. & N.J. Hagens. 2008. Energy return on investment: towards a consistent framework. *AMBIO* **37:** 74.
16. Hall, C.A.S., S. Balogh & D.J. Murphy. 2009. What is the minimum EROI that a sustainable society must have? *Energies* **2:** 25–47.
17. U.S. Bureau of the Census. 2005. *2002 Census of Mineral Industries*. Washington, DC, USA.
18. Bureau of Economic Analysis. 2009. http://www.bea.gov/industry/gpotables/gpo˙action.cfm?anon=865, release date: April 28th, 2009.
19. Carnegie-Mellon Economic Input-Output Life Cycle Assessment. 2009. http://www.eiolca.net/cgi-bin/dft/use.pl.
20. Gagnon, N. & C.A.S. Hall. 2009. A preliminary investigation of the energy return on energy investment

for global oil and gas production. *Energies* **2:** 490–503.

21. Yandle, B., M. Bhattarai & M. Vijayaraghavan. 2004. Environmental kuznets curves: a review of findings, methods, and policy implications. *PERC* **2:** 1–38.
22. Kaufmann, R. 2004. The mechanisms for autonomous energy efficiency increases: a cointegration analysis of the US Energy/GDP Ratio. *Energy J.* **25:** 63–86.
23. Shadow Government Statistics. 2008. www.shadowstats.com.
24. Chambers, R.S., R.A. Herendeen, J.J. Joyce & P.S. Penner. 1979. Gasohol: does it or doesn't it. . .produce positive net energy? *Science* **206:** 789–795.
25. Herendeen, R. & S. Brown. 1987. A comparative analysis of net energy from woody biomass. *Energy* **12:** 75–84.
26. Farrell, A.E., R.J. Pelvin, B.T. Turner, *et al*. 2006. Ethanol can contribute to energy and environmental goals. *Science* **311:** 506–508.
27. Patzek, T. 2004. Thermodynamics of the corn-ethanol biofuel cycle. *Crit. Rev. Plant Sci.* **23:** 519–567.
28. Pimentel, D. & T.W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Nat. Resour. Res.* **14:** 65–74.
29. Hammerschlag, R. 2006. Ethanol's energy return on investment: a survey of the literature 1990–present. *Environ. Sci. Technol.* **40:** 1744–1750.
30. Mearns, E. 2008. The Global Energy Crises and its Role in the Pending Collapse of the Global Economy. Presented at the Royal Society of Chemists, October 29th, Aberdeen, Scotland.
31. Liska, A.J., H.S. Yang, V.R. Bremer, *et al*. 2008. Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol. *J. Ind. Ecol.* **00:** 1–17.
32. Hall, C.A.S. 2008. Reports published on The Oil Drum. http://www.theoildrum.com/node/3412, http://www.theoildrum.com/node/3786, http://www.theoildrum.com/node/3800, http://www.theoildrum.com/node/3810, http://www.theoildrum.com/node/3839, http://www.theoildrum.com/node/3877, http://www.theoildrum.com/node/3910, http://www.theoildrum.com/node/3949.
33. Energy Watch Group. 2007. Coal: resources and future production. EWG-Series No 1/2007, Ottobrunn, Germany.
34. Kubiszewski, I., C.J. Cleveland & P.K. Endres. 2010. Meta-analysis of net energy return for wind power systems. *Renewable Energy* **35:** 218–225.
35. Mulder, K., N. Hagens & B. Fisher. 2009. Burning water: a comparative analysis the energy return on water invested. *AMBIO* In press.
36. Hall, C.A.S., R. Powers & W. Schoenberg. 2008. In peak oil, EROI, investments and the economy in an uncertain future. In *Renewable Energy Systems: Environmental and Energetic Issues*. D. Pimentel, Ed.: 113–136. Elsevier. London.
37. EIA. Energy Information Administration. 2008. Country Analysis Briefs. Accessed January 15th 2009, http://www.eia.doe.gov/emeu/cabs/Canada/Full.html.
38. Murphy, D. 2009. EROI Update: Preliminary Results Using Toe-to-Heel Air Injection. http://netenergy.theoildrum.com/node/5183#more.
39. Campbell, C. 2005. The Dawn of the Second Half of the Age of Oil. ASPO News Letter, No. 50, article 479. http://www.peakoil.ie/newsletter/479.
40. Czech, B. 2009. The neoclassical production function as a relic of anti-George politics: implications for ecological economics. *Ecol. Econ.* **68:** 2193–2197.
41. Denison, E. F. 1979. Explanations of declining productivity growth. *Survey of Current Business* **59:** 1–24.
42. Denison, E.F. 1984. International comparisons of productivity and causes of the slowdown. In *Accounting for Slower Economic Growth*. J.W. Kendrick, Ed.: 1–45. Cambridge. Ballinger.
43. Ayers, R. & B. Ware. 2005. Accounting for growth: the role of physical work. *Structural Change and Economic Dynamics* **16:** 181–209.
44. Kümmel, R. 1982. The impact of energy on industrial growth. *Energy – The International Journal* **7:** 189–203.
45. Kümmel, R. 1989. Energy as a factor of production and entropy as a pollution indicator in macroeconomic modeling. *Ecol. Econ.* **1:** 161–180.
46. Hall, C.A.S., D. Lindenberger, R. Kummel, *et al*. 2001. The need to reintegrate the natural sciences with economics. *BioScience* **51:** 663–673.
47. Rubin, J. 2008. *Just How Big is Cleveland?* StrategEcon, CIBC World Markets Inc., October 31, 2008.
48. Hamilton, J. 2009. Causes and Consequences of the Oil Shock of 2007–08. In *Brookings Papers on Economic Activity*. D. Romer & J. Wolfers, Eds: 1–68. Conference series. Brookings Institute.
49. Barnett, H.J. & R. Morse. 1952. *Scarcity and Growth: The Economics of Natural Resource Availability*. John Hopkins Press. Baltimore, MD.
50. Martin, A. 2008. One Country's Table Scraps, Another Country's Meal. *New York Times*, May 18th, 2008.
51. Lenzen, M. 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: a review. *Energy Conversion Manage.* **49:** 2178–2199.

52. Battisti, R. & A. Corrado. 2005. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy* **30:** 952–967.
53. Goldemberg, J. 2007. Ethanol for a sustainable energy future. *Science* **315:** 808–810.
54. Szklo, A. & R. Schaeffer. 2007. Fuel specification, energy consumption and CO2 emission in oil refineries. *Energy* **32:** 1075–1092.
55. Mudge, R.R., D.J. Kulash & D.L. Bodde. 1982. *Energy Use in Freight Transportation.* Congressional Budget Office. U. S. Congress.
56. Dias De Oliveira, M.E., B.E. Vaughan & E.J.J. Rykiel. 2005. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. *BioScience* **55:** 593–602.
57. Graboski, M. 2002. Fossil Energy Use in the Manufacture of Corn Ethanol. National Corn Growers Association. Chesterfield, MO.
58. Wang, M. 2001. Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies. Argonne National Laboratory. Report no. ANL/ESD/TM-163. Argonne, IL.
59. Shapouri, H., J.A. Duffield, A. McAloon & M. Wang. 2004. The 2001 Net Energy Balance of Corn-Ethanol. Paper Presented at the Corn Utilization and Technology Conference, Indianapolis, Indiana.
60. Eriksen, T. 2009. World Oil Production Update—May 2009. http://www.theoildrum.com/node/5395.
61. Hubert, M.K. 1971. The energy resources of the earth. *Sci. Am.* **224:** 60–70.