Chapter 2
Energy Return on Investment (EROI), Liquid Fuel Production, and Consequences for Wildlife

Jason M. Townsend, Charles A. S. Hall, Timothy A. Volk, David Murphy, Godfrey Ofezu, Bobby Powers, Amos Quaye and Michelle Serapiglia

Much of our way of life in industrialized nations is possible only because of the abundance of cheap energy at our disposal. Gasoline, even at US$ 10/gal, is still exceedingly cheap relative to its value. For millennia, most humans were engaged primarily in securing food and basic resources to ensure survival, that is, "hewing wood and hauling water." Now the average American has 60–80 "energy slaves" doing their basic work for them, using the energy equivalent of roughly 8 gal of gasoline each day. One gallon of gasoline has the energy of about 36,000 kcal, or 150 MJ. This energy can be used to provide heat or burned in an engine to transport goods, pump water, etc. at an efficiency of roughly 20 %, generating about 30 MJ of useful work for about US$ 4 at today's prices, or about 13 ¢/MJ of work. A strong person might be able to expend some 6000 kcal (25.2 MJ) in a day, also at an efficiency of around 20 %. Thus, over a 10-h day, that person might be able to deliver about 5 MJ of useful work. However, even at minimum wages, that would cost some US$ 70, so that 1 MJ costs about US$ 14. Thus, with a gasoline-powered device, you can get more than 100 times the work for a dollar than you can get with a person. The price of gasoline would therefore have to increase by a factor of about 110 for it to make economic sense to do such basic physical work with a person rather than a gasoline motor.

Since virtually all economic activity involves physical work in one way or another [43, 44], the availability of cheap energy in both the USA and the world has

J. M. Townsend (✉) · C. A. S. Hall · T. A. Volk · D. Murphy · G. Ofezu · B. Powers · A. Quaye · M. Serapiglia
Department of Environmental and Forest Biology, State University of New York (SUNY), 1 Forestry Drive, Syracuse, NY 13210, USA
e-mail: townsend.jason.m@gmail.com

C. A. S. Hall
e-mail: chall@esf.edu

T. A. Volk
e-mail: tavolk@esf.edu

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allowed an enormous expansion in the ability of humans to expropriate the biosphere and its products, a vast expansion in the global economy, and a considerable expansion of the human population and its attendant consumption of goods and services. All of this has occurred with significant negative impacts on ecosystems and wildlife around the world, as demand for products and services grow; as chainsaws and bulldozers greatly increase the abilities of our muscles to transform nature; and as pollution from the creation, consumption, and disposal of these products is released into ecosystems. In some select situations, increased consumption of energy has resulted in partial compensation to the environment (such as when we use equipment and pumping systems to restore wetland habitat) and increased the power of our wildlife management tools [19]. Nevertheless, the overwhelming effect of fossil fuel use on wildlife has been negative.

Energy supplies in the world are dominated by fossil fuels, including oil (35.1 %), coal (22.6 %), and natural gas (21.7 %; [111]). The remaining sources of energy include traditional biomass (9.3 %); nuclear (6.9 %), hydroelectric (2.3 %), modern biomass (1.3 %); and other alternative or ambient energy sources (0.8 %). The distribution is similar in the USA, with less traditional biomass and slightly higher proportions of oil and gas [106]. Energy will undoubtedly play a much more central role on the world stage in the years to come because the supply of oil to the world has likely peaked or will peak within the next few years for physical reasons and that of natural gas soon thereafter [6, 12, 110]. While we will probably never run completely out of oil, it certainly will be difficult to sustain growth in its extraction, or, possibly, even to maintain the current supply once it is no longer possible to expand production. Adding to the impact of Peak Oil, demand for oil and other sources of energy is growing rapidly in both the producer countries and the expanding economies of China and India, which together make up 37 % of the world's population. On the other hand, there seems to be substantial global supplies of solid fuel, including coal, tar sands, and, potentially, biomass. Their use is likely to be expanded following Peak Oil, with unintended consequences for wildlife species and their habitats. Thus, given the importance and potential limitations of oil, the immediate issue of concern is for liquid fuels. Within that aegis, a critical issue is energy return on investment (EROI). Given the considerable controversy associated with the EROIs of various fuels, for example, whether corn-based ethanol delivers a positive or negative EROI, careful development of the concept is important.

EROI Background

The concept of EROI is simply the energy returned from an activity compared to the energy invested in that process. The basic equation is:

EROI = Energy gained from an activity/Energy used in that activity

EROI is probably familiar, at least intuitively, to most wildlife biologists. An organism has to gain more energy than it expends, otherwise it will starve to death. In addition, if an organism is to reproduce, it must make a significant energy profit over the year. To our knowledge, the concept of EROI was first made explicit (as net energy gain from an investment) in research on energy expenditures of fish during migration [39] and later in the application of the idea to fuels in the USA [15, 44], but the concept certainly existed in the earlier work of sociologist Leslie White (for example, [118]), ecologist Howard T. Odum [85], and economist Kenneth Boulding [10]. When discussing EROI, there are times that other factors beyond simply heat units, calories or joules, need to be taken into consideration, such as differences in the quality of the energy invested or of the energy produced. For example, you can have the same number of kilojoules of protein and carbohydrate, but the quality of the energy is different because each has the potential to do different types or amounts of biological work. Similarly, there is a difference in the energy quality of electricity versus fossil-fuel energy. Both proteins and electricity are of a higher quality and usually can do, per kilojoule, more work useful for survival and reproduction or for economic activity than can carbohydrates or a raw fossil fuel like coal.

An additional point is that EROI should not be confused with conversion efficiency, which is the efficiency with which one "fuel" or energy source is transformed or upgraded to another, for example, generating electricity from fossil fuels. However, losses associated with these transformations are included in the EROI calculation if that transformation is within the boundaries of the situation where EROI is being calculated. Finally, the denominator for EROI is usually calculated from the perspective of energy that is already delivered, or readily deliverable, to society that is then used to get the new energy. For example, accessing new oil reserves may require energy used previously in a steel mill to make pipes or bits, and hence that energy has already been delivered to society. Likewise, oil is usually pumped from the ground by burning natural gas to generate electricity to run pumps. That gas or the electricity can usually be transferred to the rest of society very readily, but instead has been diverted to get the oil. Therefore, we would consider both of these costs as existing energy that has been diverted from society. The determination of EROI becomes somewhat confusing in some situations, and it is always necessary to explain clearly the boundaries for any calculation. For example, one might take 1 barrel of bitumen from a tar sands field and use it to generate another barrel delivered to society, in other words 2 barrels generate 1 barrel delivered to society. One might say the EROI here is 0.5:1, but it seems to be a different situation from using natural gas already delivered or immediately deliverable to society to make more oil. Here, it is a conversion issue, involving the efficiency by which the resource can be converted to a product delivered to society. The EROI in this case is not one for one or one for two because there are costs and impacts associated with the process, but it is not quite clear what it should be. For example, there are very large environmental costs associated with oil from tar sands, including the release of about two times more CO_2 per barrel delivered, very large displacement of natural ecosystems, and very large pollution in the downstream watershed. These environmental costs are sometimes hard to translate into energy costs, but certainly increase the energy required to compensate for lost forest services and water quality. We believe that the best answer for determining EROI is not to undertake analysis from a "one-size-fits-all" perspective, but rather that, if the case is difficult, the author should attempt to explain in words and possibly diagrams what he or she thinks the costs and gains are, and then why he or she chose one or another set of outputs and inputs to derive the EROI, and add in some sensitivity analysis based on the assumptions. A standard protocol for generating EROI values has been derived by Murphy et al. [78], but was not necessarily used for all studies reviewed here.

In this chapter, EROI will be expressed as the ratio of the units of stored energy in the form of biomass and the biofuel produced from it to the (usually) fossil-fuel energy invested in biomass cultivation and harvest and biofuel production. For example, an EROI of 10:1 signifies a return of 10 units of biomass energy for every 1 unit of energy invested.

EROI Boundary Issue

Probably the largest source of disagreement for EROI calculations and comparisons among different studies is the definition of the boundaries for numerator and especially for the denominator. Figure 2.1 gives our overview of the boundaries issue for inputs, in this case for a liquid fuel resource, such as oil. The upper diagram shows the energy used directly on site to generate the product. This energy would include the energy used to turn a bit, to pressurize the field, to pump the product, and the much smaller muscular energy used by the worker. Indirect energy would include the energy used to make the pipes, concrete, etc. used on site, including their depreciation. So far, there are few arguments as long as authors of these studies are clear about where they have drawn their system boundaries, and what is being included as energy inputs within those boundaries.

Some analysts think that the boundaries should be extended further for EROI calculations. One area that people increasingly agree should be included is the energy required to compensate for environmental degradation as a result of extracting the energy. These costs can be substantial, but it is often difficult to determine how much energy cost to attribute to this degradation and what other factors beyond the direct on-site extractions are associated with the energy production. For example, extensive areas of wetlands were destroyed or degraded to produce oil in southern Louisiana in past decades. Although the loss to waterfowl habitat is relatively straightforward to calculate, should an energy cost be attributed to that loss? And when hurricane Katrina came ashore, its impacts on New Orleans were greater because there were less wetlands to dissipate the wind energy of the hurricane, and consequently more fossil fuel energy has to be used now to rebuild New Orleans. There are real energy costs associated with past oil extraction, but it is hard to quantify the amount of additional energy required for recovery and rebuilding due to the loss of wetlands. The energy costs of manufacturing fertilizers to replace those lost from soil eroded during the production of biomass crops would be easier to calculate, although the costs of the loss of the physical structure of the soil would be difficult.

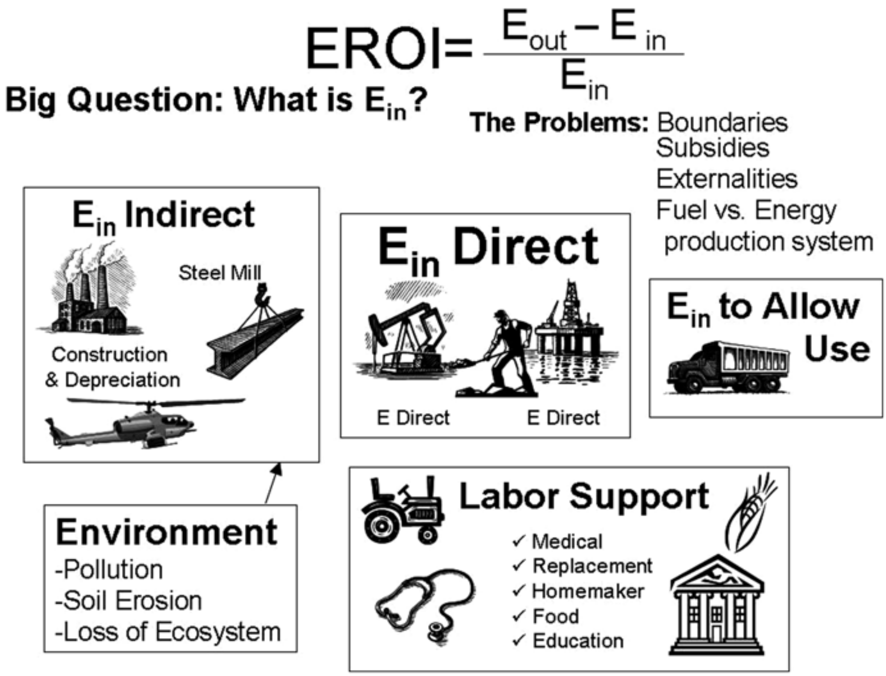

Fig. 2.1 A representation of the boundary issues related to energy return on investment (*EROI*) analysis. The energy costs one might include in an analysis are given more or less in order of general acceptability. The *central panel* represents on-site direct energies used (E_{in} Direct), the *upper left panel* (E_{in} Indirect) represents off-site energies used to generate equipment used, the *lower left panel* represents energies used to compensate for environmental impact (Environment), the *bottom right panel* represents energies used to support labor needed in these systems (Labor Support), and the *upper right side panel* represents the energy required to make the machines and infrastructure required to use the energy (E to Allow Use)

Another, more controversial, energy cost that might be included in an EROI calculation is the energy used to support the workers and pay their depreciation and replacement costs. These costs could include the energy used in society to give their paycheck meaning, cover their medical care, and support their families, so there would be a replacement worker when the original worker dies. Probably few would include that calculation, but we consider the cost of depreciation of machinery, so why not the worker? Finally, we might wish to include the energy used to enable the use of that energy. Thus, there is energy used to construct automobiles, trucks, bridges, and roads that allow the use of that energy. Since people want energy services, such as miles driven, but only rarely energy itself, there is some argument for this concept. When Hall et al. [45] included these costs, they concluded that it took a minimum EROI of 3:1 at the wellhead to use one unit of fuel in a truck, including the energy required to build and maintain the truck, the roads and bridges, and so on. This energy would not include the energy for depreciation of the workers in the oil field and highway, that is, the energy to maintain their families whose children would produce more workers when the original worker "wore out."

Most analysts have drawn their boundaries to include only direct and indirect inputs, and hence their estimates of EROI are almost certainly high. Some have made an effort to include a few of the environmental costs associated with energy processes. But, the total energy required to bring the energy to society and to be able to use it is much more and suggests that most EROIs are calculated in a way that makes them appear very favorable [16, 29]. We have to be very careful when we advocate the use of a low EROI fuel, such as corn-based ethanol. And, we must recognize that we have not undertaken such thorough analyses for petroleum either. Including the full range of energy costs in the extended boundaries given above would almost certainly eliminate the energy profit of even the most optimistic analysis of corn-based ethanol. On the other hand, maybe it is best to use the narrowest and most defensible boundaries. At a minimum, because authors choose to draw the boundaries for energy inputs into the systems in different places, it is essential that these boundaries be clearly defined so that results can be compared among studies.

The EROI concept, derived principally in ecology, has enormous importance to our society and its economics even with these methodological uncertainties, especially as we deplete the main reservoirs of the most important fossil fuels that run our economy—oil, natural gas, and eventually coal. Oil and natural gas are enormously useful because of their energy density, ease of transport, storage, ready conversion into heat or mechanical work, and, of course, their very high EROIs (Table 2.1). Coal, in comparison to oil and natural gas, is less energy dense and far more difficult to move or convert efficiently and cleanly to a useable form of energy. These three fossil fuels provided the basis for the rapid expansion of many economies since the beginning of the Industrial Revolution. In the past, only a relatively small amount of energy was required to find, produce, and deliver the next unit of these energies to society, so that their EROIs were very high, typically 30 or 100:1 [13, 42, 44]. An important issue for society is that the EROI for these key fossil fuels appears to be decreasing (Table 2.1, Fig. 2.2). As the enormous wealth of much of the modern world comes principally from our ability to mobilize oil and gas on an immense scale and at a low investment cost in energy and in dollars, "the end of cheap oil" (and gas) will create tremendous challenges to society and to science [51]. No matter how we choose to respond to these challenges, the results will likely have huge impacts.

The Potential Role of Markets and Technology

Some economists assure us that Peak Oil and other such resource limitations are problems that markets will solve, just as it did after the "oil crises" of the 1970s [1, 67, 73]. They claim that a lot more oil remains to be found and developed and that any possible peak in oil extraction is many decades away. Their review of past

Table 2.1 Energy return on investment (EROI) estimated for oil and alternative liquid fuels; most available data are for the USA. Magnitude is for 2005. EROIs ≤4 are not viable sources of energy for our current industrial civilization

Resource	Magnitude	EROI (X:1)[a]		Reference
	(EJ/year)	Max (year)	Recent (year)	
World oil production	200	35 (1995)	19 (2006)	[33]
US domestic oil		>1000	5 (2005)	[37]
Discovery		>1000	5 (2005)	[44]
Production	9	30 (1970)	10 (2005)	[13]
US imported oil	13	30 (1970)		[44]
Bitumen tar sands	~1	2–4		[88]
Shale oil	<1	5		[14]
Sugarcane ethanol	<1	4–9		[72, 84]
Corn ethanol	<1	~1		[84, 87]
Lignocellulosic ethanol	<1	1–10		[87, 103]
Biodiesel	<1	1–3		[87, 97]

[a] Numbers are ratios of units returned to one unit invested

projected peaks for different nations, that did not occur, gives some credibility to their analysis, although some of those peaks have occurred subsequently. A major component of their argument is that technological advances will allow the finding of substantially greater amounts of oil and will increase the efficacy of extracting the remaining oil. In particular, it is assumed that technology will increase the proportion of the oil in place that can be removed, which is currently an average of about 36 %, but this number has a very wide variance depending upon the field [22]. In fact, one might argue that market responses did negate the oil crises of the 1970s in that oil prices certainly decreased. However, what actually happened was that even as US oil extraction peaked in 1970 and subsequently declined to a value of about 50 % of that peak, oil extraction simply shifted to still largely untapped global fields in other parts of the world. As a result, the increasing oil consumption in the USA was made up through increased imports from the rest of the world. In 1970, the USA produced 4.5 billion barrels of oil and its net imports of oil were 1.2 billion barrels. By 2005, US oil extraction was down to 3.0 billion barrels and net imports had increased to 4.6 billion barrels. There has been an uptick in production and a decline in use since, so that in 2011, production was 3.6 and imports 3.1 billion barrels [107]. A similar peak for global oil extraction has or will occur in the not too distant future [12, 22]. Technology can be very important, but most extraction technologies, with the partial exception of horizontal drilling and 3-D imaging, have been around for a long time. Technology is in a race with depletion, and depletion appears to be winning based on the declining EROI of US and global oil [20, 43].

The most important technology, according to many of the “optimists,” would be to develop a substitute for oil. As we reach and pass the peak of global oil production, will we be able to find another source of liquid fuel with the desirable

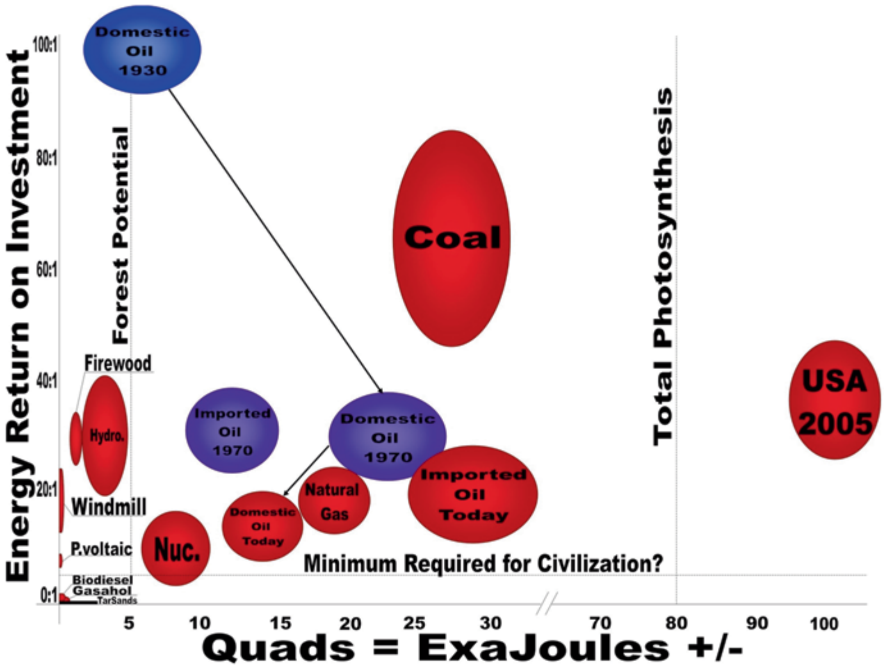

Fig. 2.2 Overview of quantities (x-axis) and qualities (*energy return on investment,* EROI, on y-axis) of energy resources available to the US economy in 2005. In this diagram, the *blue balloon* represents energy characteristics as of about 1930 (oil, in terms of finding oil), *purple* as of about 1980, and *red balloons* as of about 2005. The size of the balloon is irrelevant except to indicate the range of EROI uncertainty, but the location is important. This diagram gives an idea of the problems associated with developing alternative fuels, as we need energy resources that are located near the center of the diagram, but most candidates are very near one or another axis, or both. *Minimum* EROI is an estimate of the minimum EROI required for civilization when all costs for using it are considered, and *Forest Potential* represents one estimate of the amount of energy that might be supplied sustainably from US forest net growth. *Total photosynthesis* is an estimate of all photosynthesis that occurs on US land and inland waters

properties of conventional oil? Most who have studied this issue argue that even if there were substitutes for oil, they would require an extraordinary effort in terms of dollar investments, energy investments, and time to bring them on line in a manner sufficiently timely to offset the decline in oil availability [51]. An important aspect of this challenge is that the EROI of many alternatives is low or very low relative to oil, and those few sources with a relatively high EROI are seriously limited in supply relative to needs. As a result, the proposed alternative in many cases requires a proportionately larger exploitation of the resource base and/or greater material and financial investments per unit of energy delivered. In addition, it appears that relatively high EROIs are required for many aspects of civilization that we now take for granted [40]. Some of these alternatives will have correspondingly larger environmental impacts. The remainder of this paper

Table 2.2 As ~100 EJ of energy are consumed annually in the USA in 2010, each number can be considered a rough percentage. These values do not include natural energies, such as solar, that run agriculture or ecosystems [108]

Energy source	Quantity used[a]		Known reserves
	Quads	EJ	
Oil			
Domestic	12.8	13.5	25.2 billion barrels[b]
Imported	24.9	26.3	1200 billion barrels
Total	37.7	39.8	1222 billion barrels
Natural gas			
Dry domestic	17.5	18.5	317.6 trillion ft^3[c]
Net imports	3.2	3.4	6200 trillion ft^3
Total	20.7	21.9	
Coal	21.3	22.5	500 billion short t[d]
Nuclear	7.8	8.2	
Geothermal	0.3	0.4	
Solar			
Biomass	3.1	3.3	
Hydroelectric	2.7	2.9	
Wind	0.2	0.3	
Photovoltaic	0.1	0.1	
Total	6.5	6.8	
All energy sources	94.6	99.9	

[a] 1 quad = 1.055 EJ
[b] 1 barrel oil = 42 gal of crude oil = 6.12 GJ
[c] 1000 ft^3 of natural gas = 26.853 m^3 = 1.055 GJ
[d] 1 short t = 2000 lb = 0.907 t = 26.57 GJ

will review some published estimates of the EROI of conventional fuels, and examine the properties, potential magnitude, and EROI of some proposed alternatives to oil.

EROI of Traditional Fossil Fuels

Early work on EROI tended to focus on fossil fuels that generally had EROIs of at least 20 or 30:1 and in the case of coal, probably much higher (Table 2.1). In addition, the potential supply of these fuels was very large, roughly 10–30 quads/year (quadrillion BTU, the usual number used to report such data: 1 quad = 1.054 EJ), a number to be kept in mind when we examine alternatives. For perspective, total energy consumption in the USA in 2005 was 99.9 quads (94.6 EJ) and was slightly less in 2012 (Table 2.2). It is likely that conventional fuels, or at least oil and perhaps natural gas, will be less available relative to "demand" in the near future. Consequently, the prices of these conventional fuels will increase considerably; and, as a result, many people suggest that this will make alternative fuels, which are presently not competitive economically, both affordable and available. As an example of possible price increases, during the 1970s, an approximately 10 % shortfall in the availability of oil caused an increase in the price by about a factor of 10. In addition, there are many other reasons why a nation such as the USA might wish to develop alternative fuels, including the need to reduce our dependence on oil and other foreign energy sources and rely more on domestically generated fuels, the pressing need to reduce greenhouse gas emissions, the importance of reducing other environmental impacts that are associated with fossil fuels, and the need to revitalize parts of the US economy. The following sections review the strengths and weaknesses of a selection of the most important of these fuels. There is a great deal of interest in improving the technology for producing these fuels, and this has the potential to change the EROIs of these systems in the future. Nevertheless, the reader should remember statements made in the past to the effect of "when oil reaches X dollars a barrel then technology Y will become competitive." The price of oil has increased by a factor of at least 20 since we first heard those statements in the early 1970s, but oil continues to be our dominant fuel, while many of the alternatives, such as shale oil, remain in the research stage! As the price of the predominant fuel increases, so does the energy consumed in production of alternative fuels and, hence, their economic costs. This has kept the relative cost of different fuels remarkably constant since 1970.

EROI of Proposed Liquid Fuel Alternatives

Liquid fuels, such as biomass-based ethanol and biodiesel, are the most advocated and studied alternatives to fossil fuels. Biomass can be defined as recently derived organic material that is available, at least potentially, on a recurring and sustainable basis. It is produced from a wide range of agricultural and industrial activities, as well as in natural ecosystems. The most common feedstocks for biofuels are agricultural and forestry products and residues. These potential feedstocks can be divided into three main categories: (1) monocultures of annual food crops grown mainly on fertile lands, such as corn, soybeans, sunflowers, and canola (rapeseed); (2) mono- and polycultures of perennial woody and herbaceous crops grown on both fertile and marginal lands, such as willow (*Salix* spp.) and switchgrass (*Panicum vergatum*); and (3) waste products such as yellow grease (vegetable oil from food services), corn stover, and forestry residue. Use of food-based feedstocks (corn in the case of ethanol and soybeans in the case of biodiesel) is considered "first generation." The use of first-generation feedstocks has become a controversial social issue because of the food versus fuel debate, in addition to the energy and environmental issues discussed here (for example, [53]). Nonfood-based perennial feedstocks, such as switchgrass, and short-rotation woody crops and forestry products are considered "second-generation" fuels that have the potential to resolve the food versus fuel conflicts. Biofuel production in the USA during 2011 consisted

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