



Sustainability of the Corn-Ethanol Biofuel Cycle

Tad W. Patzek

*Department of Civil and Environmental Engineering
U.C. Berkeley*

Berkeley, CA

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College of Engineering, Berkeley, CA

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Executive Summary

Sustainability and renewability of energy supply are key to survival of our civilization. Biofuels supplied by industrial agriculture are praised by many as the major source of clean renewable energy for the future. It is, therefore, important to quantify the impact of industrially produced biofuels on the biosphere. In this Report, I define sustainability, sustainable cyclic processes, and quantify the degree of non-renewability of a major biofuel: ethanol obtained from industrially-grown corn.

In 2004, the U.S. may produce the record 12 giga liters of ethanol from corn, satisfying $\sim 1.2\%$ of its automotive fuel demand. Current plans are to expand ethanol production to 20 giga liters per year. Industrial corn-ethanol “cycle” relies on mining the nonrenewable fossil fuels and the environment. The fossil energy inputs into corn farming include: nitrogen, phosphate and potash fertilizers, calcinated lime, herbicides and insecticides, machinery, genetically-modified hybrid seeds, irrigation, electricity, diesel fuel and gasoline, and methane and LPG for drying and power generation. The fossil energy inputs into ethanol production are fuels for corn processing, fermentation, distillation, and ethanol dewatering, as well as transportation. The cycle outputs are heat, ethanol, which is burned to obtain useful work, as well as depleted soil, water and air, all contaminated with the chemical byproducts of use of the nonrenewable resources.

First, I demonstrate that more fossil energy is used to produce ethanol from corn than the ethanol’s calorific value. Analysis of the carbon cycle shows that all leftovers from ethanol production must be returned back to the fields to prevent the irreversible mining of soil humus. This finding demonstrates that production of ethanol from whole plants (corn stalk, leaves, and roots) is utterly unsustainable. I also show that in 2004 ethanol production will generate 8 million tonnes of CO_2 over and above the amount of CO_2 generated by burning gasoline with 115% of the ethanol energy content to account for oil recovery, refining, and transport.

Second, I calculate the cumulative *available* free energy, or *exergy* consumed in corn farming and ethanol production, and estimate the *minimum* amount of work necessary to restore the key non-renewable resources consumed by the corn-ethanol cycle. This amount of work is compared with the *maximum* useful work obtained from the ideal corn-ethanol cycle. It appears that if the ethanol energy is used to power a car engine, the minimum restoration work is about 6

times the maximum useful work from the cycle. This ratio drops down to 2, if an ideal fuel cell is used to process the ethanol.

Third, I estimate the taxpayers' subsidies of the industrial corn-ethanol cycle at \$3.8 billion in 2004. The parallel subsidies by the environment are estimated at \$1.8 billion in 2004. The latter estimate will probably double when the restoration costs of aquifers, streams and rivers, and the Gulf of Mexico are also included.

In summary, it seems that the industrial ethanol-from-corn cycle consumes natural resources in quantities that exceed several times the useful work obtained from it. Corn-ethanol is a nonrenewable biofuel, whose negative impact on the environment is, surprisingly, several times larger than those of the traditional fossil fuels.

Corn-ethanol brings *no* energy savings and *no* lessening of the U.S. energy dependency on foreign crude oil, natural gas, and liquified petroleum gas. The opposite happens, we import more methane, LPG, and crude oil. We then burn these fuels to produce corn-ethanol and, finally, we burn the ethanol in our cars at the additional cost of extensive environmental damage.

I am against all oxygenates in fuel: MTBE and ethanol. New computerized car engines can limit emissions quite efficiently. In the most air-polluted regions of the country, some gasoline reformulation may be required. Last, but not least, we need to talk about the more efficient cars that produce less emissions, and not about the costly and otherwise unnecessary oxygenates.

Chapter 1

Introduction

The U.S. is the single largest corn producer in the world. Large overproduction of subsidized cheap corn forces corn producers and processors to invent new ingenious uses for their product. In terms of large negative impact on the society and the environment, ethanol and high-fructose syrup, both produced from corn, are the obvious leaders [15,53]. Almost 20% of the U.S. corn production is now diverted to produce ethanol. Hence, in this Report I will *de facto* argue that the U.S. corn production should be reduced by at least 20% with significant benefits to the taxpayers and the planet.

1.1 Corn Highlights

- Corn is the single largest U.S. crop.
- Corn is farmed on ~28 million hectares, and the average yield of moist corn kernels is ~8600 kg/ha.
- 44% of world's corn is produced in U.S., 1% in Canada.
- All of the U.S. corn fields are fertilized.
- Corn requires more fertilizer than any other crop.
- Corn erodes soil much faster than it can reform.
- Corn needs 50-100 cm water, 15% of corn is irrigated.
- Corn farmers receive \$10 billion in price subsidies.
- Over 12 billion liters of corn-ethanol will be produced in the U.S. in 2004.
- U.S. goal: Produce 20 billion liters of ethanol from corn annually.
- Ethanol producers receive ~\$3.8 billion annually from the federal government and state governments and ~\$1.8 billion from the environment.

1.2 Energy Inputs to Corn Production

Fossil energy is essential to industrial agriculture. The following are the major energy inputs to industrial corn farming:

- Nitrogen fertilizers (all fossil energy)
- Phosphate, Potash, and Lime (mostly fossil energy)
- Herbicides and Insecticides (all fossil energy)
- Fossil fuels: diesel, gasoline, liquified petroleum gas (LPG), and natural gas (NG)
- Electricity (mostly fossil energy)
- Transportation (all fossil energy)
- Corn Seeds and Irrigation (mostly fossil energy)
- Machinery, roads, silos, plants (mostly fossil energy)
- Labor (mostly fossil energy)

Corn produced at a large expense of fossil energy is then transformed with even more fossil energy into pure ethanol.

1.3 Report Layout

This Report is divided into three parts, each of which can be read more-less independently. In Part I, I discuss the mass balance of corn processing, and the energy balance of corn farming and ethanol production. The First Law analysis of the corn-ethanol production process is *fundamentally incomplete*, and gives rise to endless confusion and arguments, which all become moot once a more complete Second Law analysis is performed. Therefore, in Part II, I overview the fundamentals of thermodynamics, define the linear processes and cycles, irreversibility and sustainability, as well as the free energy available relative to the environmental conditions, or *exergy*. In Part III, I apply the concepts developed in Part II to a more complete analysis of the following questions:

1. Is ethanol production from corn a sustainable process?
2. If it is not sustainable, how unsustainable is it?
3. Can process changes result in making ethanol production from corn sustainable?

In particular, in Part III, I discuss the Carbon Cycle, the Water Cycle and the Corn-Ethanol Cycle, and calculate the minimum work required to restore the nonrenewable resources consumed to produce corn-ethanol.

My goal is to question the sweeping statements made by many scientists, similar to the following [12]:

Fast and efficient fuel reforming is one of the critical steps in producing H₂ for fuel cells and the “hydrogen economy,” and ethanol is now the most available and economically renewable fuel...

...Recent studies indicate that the energy in the fuel-ethanol is at least 1.34 times the energy used in its production.

Chapter 2

Part I – Mass & Energy Balance

Here, I will revisit the classical story of ethanol from corn: the cumulative mass and energy balance of corn farming and subsequent ethanol production. There have been several well-known predecessors who told their versions of this story before. Professor DAVID PIMENTEL of Cornell is the world-famous agricultural expert from Cornell University, author of the CRC *Handbook of Energy Utilization in Agriculture* [43], the monograph *Food, Energy, and Society* [45], and dozens of publications on the subjects of ethics and energy efficiency of agriculture, e.g., [44, 46, 49–51]. Here I will only use his most recent analysis of production of corn-ethanol, published in 2003 [47]. Doctor MICHAEL WANG, CHRISTOPHER SARICKS, and MAY WU are the authors of the 1997 Argonne National Laboratory Report, *Fuel-Cycle Fossil Energy Use and Greenhouse Gas Emissions of Fuel Ethanol Produced from the U.S. Midwestern Corn* [70], which told quite a different version of the corn-ethanol story. Mr. HOSEIN SHAPOURI, JAMES DUFFIELD, and MICHAEL WANG co-wrote the most recent 2002 USDA Report: *The Energy Balance of Corn Ethanol: An Update* [58], which was less rosy than than the Argonne Report, but considerably more optimistic than Professor PIMENTEL's analysis. I joined the corn-ethanol story in late 2002, after reading the thought-provoking book, *Food, Energy, and Society* by PIMENTEL. Subsequently, in Spring 2003, I decided to teach a Freshman Seminar at Cal on the subject of corn ethanol, and published with the students our own version of the story, *Ethanol from Corn: Clean Renewable Fuel for the Future, or Drain on Our Resources and Pockets?* [42], highly critical of the Argonne Report, and also critical of the 2002 USDA Report.

The new twist in my current story is the consistent split of all energy flows into the *specific energies* in MJ/kg, and *mass fluxes* in kg/ha-crop. This split will make my explanations clearer, and the possible errors easier to spot and correct. However nicely told, the classical ethanol-from-corn story is fundamentally incomplete and should be treated as Part I of the Ethanol Biofuel Trilogy.

The next two parts of this Trilogy can only be told in the somewhat exotic language of the Second Law of thermodynamics, which describes the passage of Time and limits the possible directions of natural processes.

2.1 Mass Balance of Corn

Mass will be usually expressed in kilograms per hectare. One hectare is 10000 m² or 2.47 acres.

In 2001-2003, corn in the U.S. was harvested from $\sim 28 \times 10^6$ hectares [38]. The average corn yield varied from 130 bushels per acre in 2002, to 138.2 bushels/acre in 2001, and 142.2 bushels/acre in 2003. [38].

Definition 1 One equivalent bushel is defined as 56 pounds of corn kernels at the base moisture (15% by mass) [1]. \square

Therefore, the mean corn yield over the last 3 years was just below 8600 kg/ha of *moist* corn kernels, or $8600 \times 0.85 = 7300$ kg/ha of *dry* corn kernels.

Table 2.1: Average dry mass composition of corn kernels in wet milling [73]

Component	% by mass
Starch	66
Oil	3.9
Gluten feed (21% protein)	24
Gluten meal (60% protein)	5.7
Losses	0.4

Since ethanol (EtOH) is made from the hydrolyzed starch with the theoretical efficiency of 0.51, 1 kg of dry corn kernels may yield $0.66 \times 0.51 = 0.337$ kg of water-free EtOH with zero losses, see **Table 2.1**. Therefore, from 1 hectare, one may theoretically produce 2460 kg EtOH, given the dry corn yield above. Of course there are losses in the corn-to-ethanol conversion process, and the practical efficiency will be lower.

Remark 1 In the U.S., the customary unit of reporting efficiency of corn conversion to ethanol is gallons EtOH per bushel, e.g., [59]. Using the standard EtOH density of 0.796 kg/L, the theoretical efficiency of 0.337 kg EtOH/kg dry kernels (0.423 L EtOH/kg dry kernels) translates into 2.85 gallons EtOH/dry bushel = 2.42 gallons EtOH/equivalent bushel of corn with 15% moisture. \square

2.2 Major Energy Inputs to Corn Production

Most energy inputs will be expressed in MJ/kg of active ingredient in the input. For example, ammonia contains 82% nitrogen (active component); therefore, the specific energy input in MJ to obtain one kg of ammonia will be divided by 0.82.

Table 2.2: Average application rates of corn field chemicals in 2001 [37]

Compound	True kg/ha	Fraction ha w/ applied	Mean kg/ha
N	148.8	0.96	142.8
P ₂ O ₅ ^a	62.5	0.79	49.4
K ₂ O ^a	93.5	0.65	60.8
Herbicides	2.54	0.98	2.49
Insecticides	1.08	0.29	0.31

^aUSDA [37] reports “P” and “K” but, according to Ms. BARBARA TIDWELL of the NASS/MISO Customer Service, they mean P₂O₅ and K₂O.

2.2.1 Field Chemicals

- **Nitrogen** is a component of many important structural, genetic and metabolic compounds in plant cells. It is a major component of chlorophyll, amino acids, cell energy carriers (ATP/ADP), and genetic material (DNA/RNA).
- **Phosphorus** is one the primary structural components of cell membranes. It is involved in the photosynthesis (ADP/ATP), synthesis of proteins and vitamins, and occurs in important enzymes.
- **Potassium** activates enzymes that produce proteins and sugars. It maintains water content and, hence, the turgor (rigidity) of plant cells.
- **Calcinated lime** is used to increase the pH of soil acidified by nitrogen fertilizer. The ideal pH for corn is 6.6.
- **Herbicides**, such as Atrazine, Acetochlor, S-Metolachlor, Dicamba, Nicosulfuron, etc. are used to protect corn from weeds.
- **Insecticides**, such as Chlorpyrifos, Terbufos, Carbofuran, Tefluthrin, etc. are used to protect corn from insects.

The average application rates of major field chemicals used in corn farming are reported in **Table 2.2**.

Specific Energy of Nitrogen Fertilizer

Nitrogen fertilizers are derived from ammonia, nitric acid, and carbon dioxide. Practically all ammonia is produced from natural gas and nitrogen in the HABER-BOSCH process [16, 74, 75]. The energy efficiency of the HABER-BOSCH process has been improved by 1/3 over the last 60 years, see **Figure 2.1**. Therefore, age of ammonia-producing plant does matter. ERNST WORRELL *et al.*

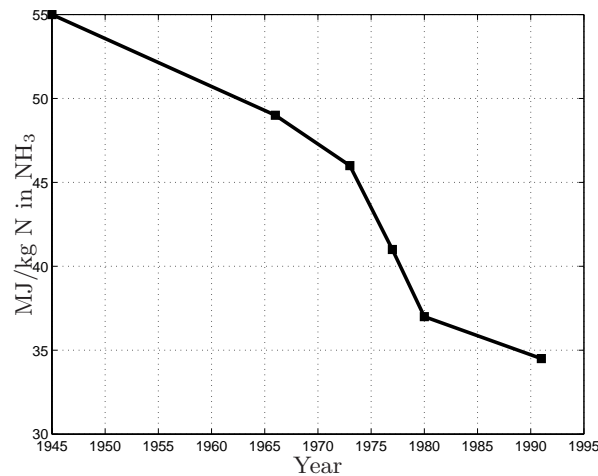


Figure 2.1: History of energy efficiency of ammonia production in MJ/kg N. Source: G. KONGSHAUG [16].

have compiled [74] the ages and outputs of 44 largest U.S. ammonia plants, see **Figure 2.2**. Most of these plants were built in the 1960's, and some were later revamped and expanded. The fact remains, however, that the major U.S. plants were built 40 years ago, and some were revamped 20-30 years ago. Another example comes from Europe: When in 1995 ammonia synthesis in modern European plants consumed approx. 36.93 MJ/kg N, older plants needed about 43.08 MJ/kg N [4] at the same time. Therefore, for nitrogen fertilizer production I will use the average efficiency of 30-year old plants. I will also assume that all nitrogen fertilizer applied to the U.S. corn fields is represented by ammonium nitrate.

KONGSHAUG analyzed energy efficiency of ammonia production and divided ammonia plants into three classes: "Modern," "Average European plants," and "30-years old plants." Using his terminology, the major nitrogen fertilizers are produced with the following specific energy inputs *per unit mass of nitrogen* in them.

Ammonia, NH₃, has 82% of nitrogen by mass. Following KONGSHAUG [16], I will assume the following *net* energy consumption to produce ammonia:

30 Years Old	47	MJ/kg N	
Average Europe	39	MJ/kg N	(2.1)
Modern	34.5	MJ/kg N	

Urea, CO(NH₂)₂, has 45% of nitrogen by mass, and is obtained from ammonia and carbon dioxide: $2\text{NH}_3 + \text{CO}_2 \rightarrow \text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O}$. The net energy consump-

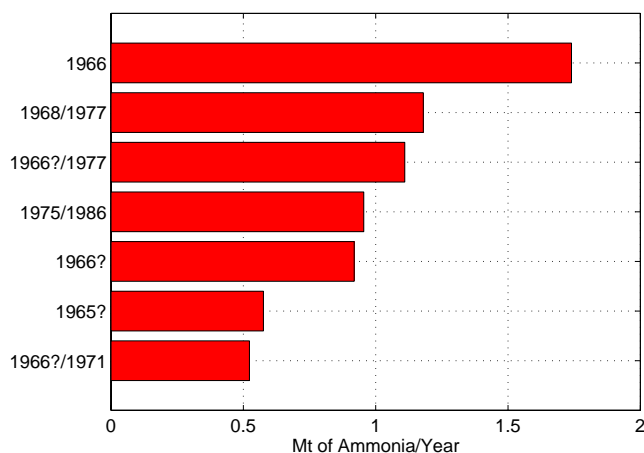


Figure 2.2: Together, these seven largest plants produce 40% of the U.S. ammonia. The first dates refer to plant opening. Some of the plants were later expanded and revamped, as indicated by the second dates. Source: ERNST WORRELL *et al.*, [74].

tion [16] is:

$$\begin{array}{rcl}
 \text{30 Years Old Ammonia} & + & 10 = 57 \text{ MJ/kg N} \\
 \text{Average Europe Ammonia} & + & 9 = 48 \text{ MJ/kg N} \\
 \text{Modern Ammonia} & + & 7.2 = 42 \text{ MJ/kg N}
 \end{array} \quad (2.2)$$

Ammonium Nitrate, NH_4NO_3 , has 35% nitrogen by mass, and is produced from nitric acid and ammonia: $\text{HNO}_3 + \text{NH}_3 \rightarrow \text{NH}_4\text{NO}_3$. Nitric acid is obtained by burning ammonia over catalyst to produce NO_x . One of the by-products of ammonium nitrate production is nitrous oxide N_2O , a potent greenhouse gas. With 97% conversion of ammonia to AN, the energy consumption is

$$\begin{array}{rcl}
 \text{30 Years Old Ammonia} & + & 4 = 51 \text{ MJ/kg N} \\
 \text{Average Europe Ammonia} & + & 2 = 41 \text{ MJ/kg N} \\
 \text{Modern Ammonia} & + & 0.43 = 35 \text{ MJ/kg N}
 \end{array} \quad (2.3)$$

Other Energy Inputs to Fertilizer Production

Primary particulation of fertilizers is carried out in prilling and granulation processes. These units can also be used for a second pass of product building blocks (for mixed fertilizers), in addition to compaction and bulk blending units. The energy requirement for primary particulation is $\sim 0.25\text{--}0.5$ MJ/kg product, and for secondary granulation and compaction $0.7\text{--}1.1$ MJ/kg product [16]. Here I have used 0.5 MJ/kg of AN. The energy costs of natural gas recovery, compression, purification and transportation, and fertilizer packaging, if any, are

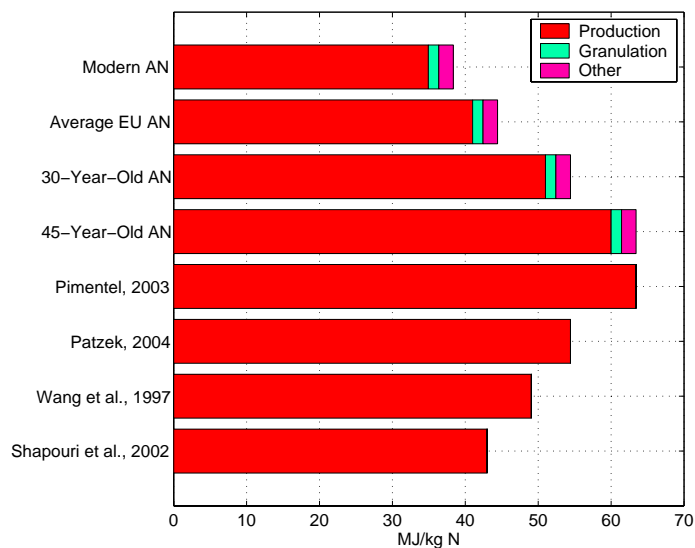


Figure 2.3: The various estimates of the unit energy consumption to produce ammonium nitrate (AN). The estimates by SHAPOURI *et al.* are listed in [58], by WANG *et al.* in [70], and PIMENTEL's estimate [47] of 78.1 MJ/kg N was adjusted down to the 45-year-old AN.

Table 2.3: Specific energy consumption and application rates of nitrogen fertilizer

Active Ingredient	Specific Energy MJ/kg	Application Rate kg/ha	Source
N	63.43	148.0	Pimentel, 2003
N	54.43	148.8	Patzek, 2004
N	43.00	140.0	Shapouri <i>et al.</i> , 2003
N	49.06	153.0	Wang <i>et al.</i> , 1997
N	54.43 ^a	150.0	Berthiaume <i>et al.</i> , 2001

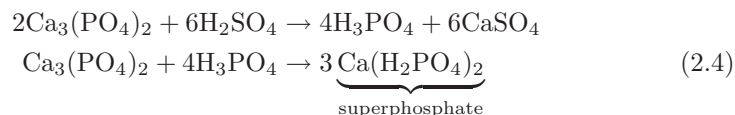
^a Berthiaume *et al.* [3] do not give the specific N, P, K, Ca fertilizer energies, only the specific exergies. I have *assumed* that the specific energies of BERTHIAUME *et al.* are equal to my estimates, and used their reported application rates.

estimated cautiously at 2 MJ/kg N. The various estimates of net energy inputs into nitrogen fertilizer production are shown in **Figure 2.3** and listed in **Table 2.3**. In all the tables below, the estimates by SHAPOURI *et al.* come from their 2002 report [58], by WANG *et al.* from [70], and by BERTHIAUME *et al.* from [3]. Since BERTHIAUME *et al.* have reported only specific exergy consumption, I have

used my energy consumption estimates to represent theirs. I have also corrected and/or amended the various estimates as noted below.

Specific Energy Requirements for Phosphorus Fertilizers

Phosphate and phosphoric acid are produced from the igneous *fluorapatite* $\text{Ca}_{10}(\text{PO}_4)_6(\text{F}, \text{OH})_2$, and the sedimentary *francolite* $\text{Ca}_{10}(\text{PO}_4)_{6x}(\text{CO}_3)_x(\text{F}, \text{OH})_{2+x}$. For example, superphosphate may be produced as follows:



Calcium sulphate (gypsum) produced in reaction (2.4)₁ may be precipitated as *dihydrate*, using milder conditions, 26-32% P_2O_5 at 70-80°C, or *hemihydrate*, using 40-52% P_2O_5 at 90-110°C. Even though it demands more energy, the hemihydrate reaction is preferred because it optimizes use of sulphuric acid. The energy costs of gypsum disposal are omitted here.

Unlike the European Fertilizer Manufacturers Association (EFMA), which maintains an informative web site, the U.S. does not have clear statistics of the types of phosphorus (and other) fertilizers used. From the USGS and U.S. Census Bureau documents, e.g., [31] and references therein, it may be deduced that calcium phosphates (triple superphosphate and single superphosphate) dominate in the U.S., followed by Di-Ammonium Phosphate (DAP).

Just as with nitrogen fertilizers, phosphate fertilizers have different contents of active ingredient, here P_2O_5 . For example, triple superphosphate is 46% P_2O_5 , single superphosphate 18-20%, and di-ammonium phosphate 46%. The specific energy consumption for phosphorus and its application rates are listed in **Table 2.4**.

In this analysis, I will use the single superphosphate as the reference phosphorus fertilizer. The typical energy consumption for the 30 years old technology is given by KONGSHAUG [16], see **Table 2.4**. In contrast to the energy input for nitrogen fertilizer, the data for phosphorus vary widely between 5.1 MJ/kg P_2O_5 and 26.4 MJ/kg P_2O_5 [49]. EFMA uses 15.8 MJ/kg P_2O_5 [4].

Table 2.4: Energy consumption in superphosphate production [16]

Process	MJ/kg P_2O_5
Phosphate mining	> 0.3
Apatite mining	2.9
Dihydrate process	2.5
Hemihydrate process	6.5

Therefore, the typical U.S. energy consumption is $0.3+6.5 = 6.8$ MJ/kg P_2O_5 as single superphosphate.

Table 2.5: Specific energy consumption and application rates of phosphorus fertilizers

Active Ingredient	Specific Energy MJ/kg	Application Rate kg/ha	Source
P_2O_5	17.44	53.0	Pimentel, 2003
P_2O_5	6.80	62.5	Patzek, 2004
P_2O_5	4.76	54.0	Shapouri <i>et al.</i> , 2003
P_2O_5	11.40	56.0	Wang <i>et al.</i> , 1997
P_2O_5	6.80	55.0	Berthiaume <i>et al.</i> , 2001

Specific Energy Requirements for Potassium Fertilizers

The energy requirements for potassium vary from 4.0 MJ/kg K_2O [36] to 13.7 MJ/kg K_2O [41]. EFMA uses 9.3 MJ/kg K_2O [4]. The typical energy requirements to produce different potassium fertilizers are listed in **Table 2.6**. Here I will use the muriate of potash (MOP), or KCl, as the typical potassium fertilizer. Production of KCl is mainly carried out by shaft mining and beneficiation. The most energy efficient potash processes, based on a high quality sylvanite salt, require only 1.5 MJ/kg MOP (2.5 MJ/kg K_2O). The energy consumption varies however a lot, and estimates up to 6 MJ/kg MOP are reported for mining of more mixed salts [16].

Here I will treat KCl as an admixture to a superphosphate fertilizer, and give it an identical energy consumption of 6.8 MJ/kg K_2O . The specific energy inputs and application rates for the potassium fertilizers are listed in **Table 2.7**.

Table 2.6: Energy consumption in potassium fertilizer production [16]

Fertilizer	K%	MJ/kg K_2O
Chloride	52	6.8 (additive to phosphates)
Sulphate	49	
Nitrate	45	13.5 (KNO_3 solution evaporation) 43 MJ/kg N

Table 2.7: Specific energy consumption and application rates of potassium fertilizer

Active Ingredient	Specific Energy MJ/kg	Application Rate kg/ha	Source
K ₂ O	13.77	57.0	Pimentel, 2003
K ₂ O	6.80	93.5	Patzek, 2004
K ₂ O	8.71	85.0	Shapouri <i>et al.</i> , 2003
K ₂ O	5.30	66.0	Wang <i>et al.</i> , 1997
K ₂ O	6.80	85.0	Berthiaume <i>et al.</i> , 2001

Specific Energy Requirements for Calcinated Lime

Lime must be added to de-acidify soil after heavy use of nitrogen fertilizers. Calcinated lime, CaO, is obtained from limestone and dolomites. The calcination process is energy-intensive, and generates one mole of CO₂ per one mole of CaO. EFMA uses 2.97 MJ/kg CaO [4], but here I will follow the Australian Academy of Sciences and assume that only 1.75 MJ/kg CaO is used to produce calcinated lime.

Lime application rate is not commonly reported by the USDA. The suggested application rate is 1.8 times the application rate of nitrogen [66], but there are reports of several times higher application rates, e.g., [47].

Table 2.8: Specific energy consumption and application rates of calcinated lime

Active Ingredient	Specific Energy MJ/kg	Application Rate kg/ha	Source
CaO	1.33	699.0	Pimentel, 2003
CaO	1.75	333.0 ^a	Patzek, 2004
CaO	1.70	276.0	Shapouri <i>et al.</i> , 2003
CaO	1.70	276.0 ^b	Wang <i>et al.</i> , 1997
CaO	1.75	270.0	Berthiaume <i>et al.</i> , 2001

^aSHAPOURI *et al.*'s data (Table 2 in [58]) with the two zero entries omitted.

^bWANG *et al.* [70] does not report lime use, I have corrected their estimates by adding the lime use reported by SHAPOURI *et al.* [58].

The total application rates of nitrogen, phosphorus and potash fertilizers, as well as that of calcinated lime are shown in **Figure 2.4**.

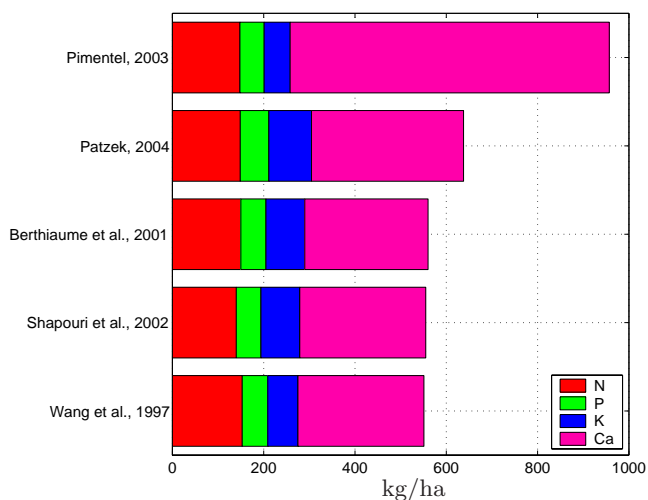


Figure 2.4: The total fertilizer application rates listed in Tables 2.3, 2.5, and 2.7.

Specific Energy Requirements for Herbicides and Insecticides

There are many active ingredients in commercial herbicides and insecticides, but all have very high specific energy requirements for their production. Here I have used the data collected in Table 5 in SHAPOURI *et al.*'s report [58].

Table 2.9: Specific energy consumption and application rates of herbicides

Specific Energy MJ/kg	Application Rate kg/ha	Source
422.00	2.10	Pimentel, 2003
261.00	2.54	Patzek, 2004
261.00	4.73	Shapouri <i>et al.</i> , 2003
237.30	3.07	Wang <i>et al.</i> , 1997

The specific energy inputs and application rates of herbicides and insecticides are listed in **Tables 2.9** and **2.10**. The overall application rates of herbicides and insecticides are also shown in **Figure 2.5**.

2.2.2 Specific Energy Requirements for Fossil Fuels

A unit mass of a fossil fuel gives out a specific amount of heat (its *calorific value*) when burned. The *Low Calorific Value* or *Net Calorific Value* (NCV) of a fossil fuel assumes that combustion products contain the water of combustion

Table 2.10: Specific energy consumption and application rates of insecticides

Specific Energy MJ/kg	Application Rate kg/ha	Source
422.00	0.15	Pimentel, 2003
268.40	1.08	Patzek, 2004
268.40	0.22	Shapouri <i>et al.</i> , 2003
243.00	0.22	Wang <i>et al.</i> , 1997

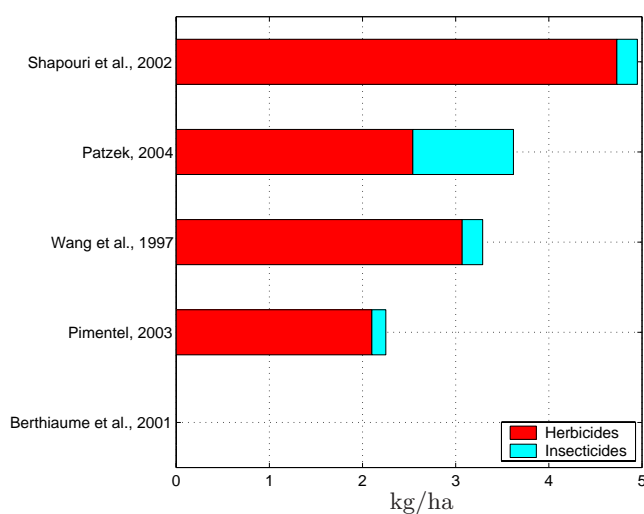


Figure 2.5: The total herbicide and insecticide application rates listed in Tables 2.9 and 2.10.

as vapor. The heat contained in this water is not recovered. Outside of power stations and fuel cells, water remains as vapor after combustion. Therefore, I use low calorific values of all liquid fuels. The *High* Calorific Value or *Gross* Calorific Value (GCV) assumes that combustion water is entirely condensed. The heat contained in this water is recovered. SHAPOURI *et al.* [58] seem to use GCV for all fuels. WANG *et al.* [70] give only the total amount of energy for each fossil fuel; therefore, their specific values are back-calculated for each fuel and agree with my estimates.

After deciding on a low calorific value for each fossil fuel, one needs to find the standard values for “average” gasoline, diesel fuel, LPG, and natural gas. Finding consensus was more difficult than I expected. The International Energy Agency’s (IEA) standards up to the year 2000 are listed in **Table 2.11**. IEA changed its standards for gasoline equivalent and diesel fuel equivalent in 2003.

Table 2.11: Standard Net Calorific Values of major fossil fuels [28, 63]

Fuel	Net Calorific Value
1 kg oil equiv. (oe)	41.868 MJ
1 kg coal equiv. (ce)	29.3 MJ
1 kg gasoline equiv.	1.070 kg oe = 44.8 MJ (46.8 ^a , 48.6 ^b)
1 kg diesel equiv.	1.035 kg oe = 43.3 MJ (45.7 ^a , 43.0 ^b)
1 kg LPG equiv.	1.130 kg oe = 47.3 MJ
1 kg NG	54 MJ (my estimate)

^aThe revised 2003 estimate by the International Energy Agency.

^b2004 estimate by Alternate Energy Systems.

For comparison, I am also quoting some NCV values from a technical paper by AES, a U.S. energy company [63]. For gasoline and diesel fuel equivalents, I simply averaged the three estimates in Table 2.11. For reference, the standard densities of liquid fuels used in this work are: gasoline, 0.7374 kg/L; diesel fuel, 0.8400 kg/L; LPG, 0.5422 kg/L; natural gas, 0.66535 kg/sm³.

The calorific values and average volumes of fossil fuels used in corn farming are listed in **Tables 2.12 – 2.15**. The cumulative volumes of all fossil fuels are shown in **Figure 2.6**.

Table 2.12: Calorific values and specific volumes of gasoline used in corn farming

Calorific Value MJ/kg	Volume L/ha	Source
56.32	56.0	Pimentel, 2003
47.00	29.0	Patzek, 2004
59.10	29.0	Shapouri <i>et al.</i> , 2003
47.00	30.6	Wang <i>et al.</i> , 1997
0.00	0.0	Berthiaume <i>et al.</i> , 2001

Notice, that not all sources account for all five fossil fuels, especially for LPG and natural gas. Both LPG and natural gas are used for corn drying and as fuel to power water pumps in irrigation. Their use varies greatly from one state to another, and from one season to another, see **Figure 2.7**.

Table 2.13: Calorific values and specific volumes of diesel fuel used in corn farming

Calorific Value MJ/kg	Volume L/ha	Source
50.24	90.0	Pimentel, 2003
44.00	80.0	Patzek, 2004
53.97	82.1	Shapouri <i>et al.</i> , 2003
44.00	77.5	Wang <i>et al.</i> , 1997
44.00	71.0	Berthiaume <i>et al.</i> , 2001

Table 2.14: Calorific values and specific volumes of Liquefied Petroleum Gas (LPG) used in corn farming

Calorific Value MJ/kg	Volume L/ha	Source
0.00	0.0	Pimentel, 2003
47.30	47.0	Patzek, 2004
52.60	59.0	Shapouri <i>et al.</i> , 2003
47.30	32.4	Wang <i>et al.</i> , 1997
47.30	252.0 ^a	Berthiaume <i>et al.</i> , 2001

^a Large quantities of LPG are used to dry wet corn in Quebec.

Table 2.15: Calorific values and specific volumes of natural gas used in corn farming

Calorific Value MJ/kg	Volume sm ³ /ha	Source
0.00	0.0	Pimentel, 2003
55.00	21.3	Patzek, 2004
61.90	14.0	Shapouri <i>et al.</i> , 2003
55.00	36.1	Wang <i>et al.</i> , 1997
0.00	0.0	Berthiaume <i>et al.</i> , 2001

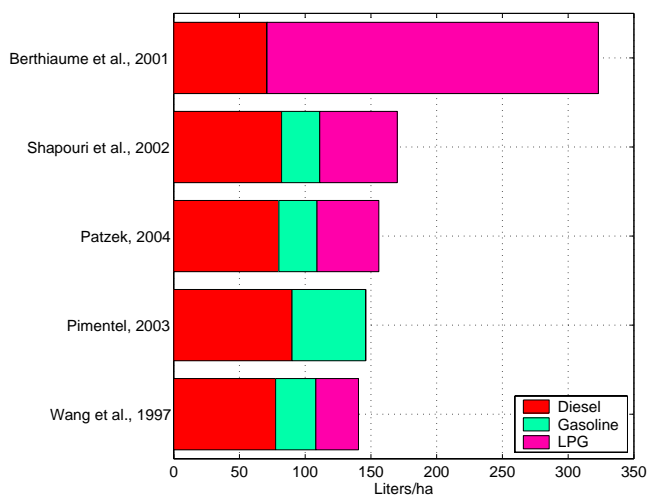


Figure 2.6: The total fossil fuel volumes listed in Tables 2.12 - 2.15.

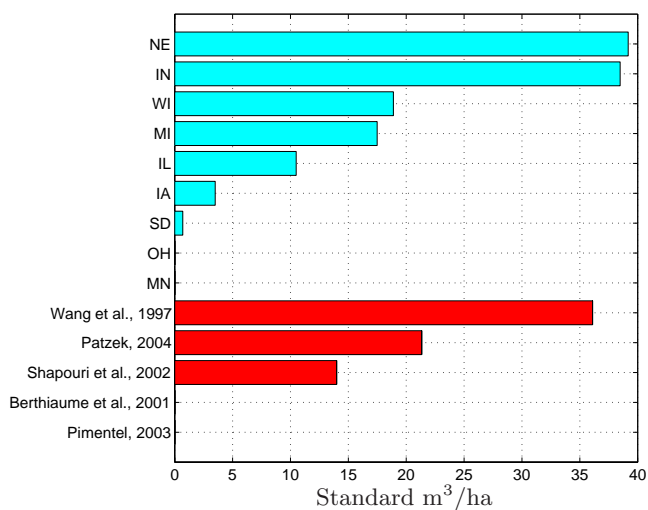


Figure 2.7: By-state and average use of methane in corn farming. The 1996 methane volume data from the largest corn-producing states are from SHAPOURI *et al.* [59]. Note the large variability of methane use depending on wet/dry weather.

2.2.3 Use of Electricity

The average electric energy spent on farming 1 hectare of corn is listed in **Table 2.16**. SHAPOURI *et al.* [59] have attempted to include the efficiency of fossil energy conversion into electricity in their estimates. I have not done it here

in the energy balance, but will consider all the steps in free energy conversion in the exergy balance below. The average and the state data are compared in **Figure 2.8**. As with natural gas, variability in electricity use is very large.

Table 2.16: Specific electric energy inputs to corn farming

Amount kWh/ha	Source
39.9	Pimentel, 2003
191.0	Patzek, 2004
207.6	Shapouri <i>et al.</i> , 2003
24.1	Wang <i>et al.</i> , 1997
132.0	Berthiaume <i>et al.</i> , 2001

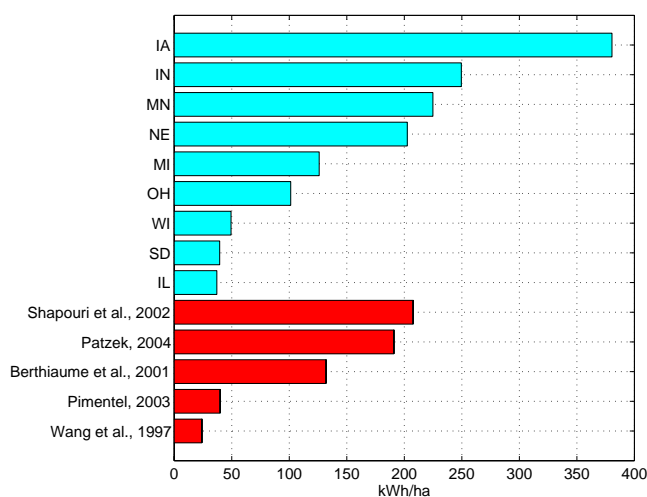


Figure 2.8: By-state and average use of electricity in corn farming. The 1996 electricity data from the largest corn-producing states are from SHAPOURI *et al.* [58]. Note the large variability of electricity use depending on wet/dry weather.

2.2.4 Averages Can Be Misleading...

- Depending on weather, *state-to-state* (regional), and *year-to-year* (temporal) variations in the use of electricity, liquid petroleum gas, and methane can be extreme.

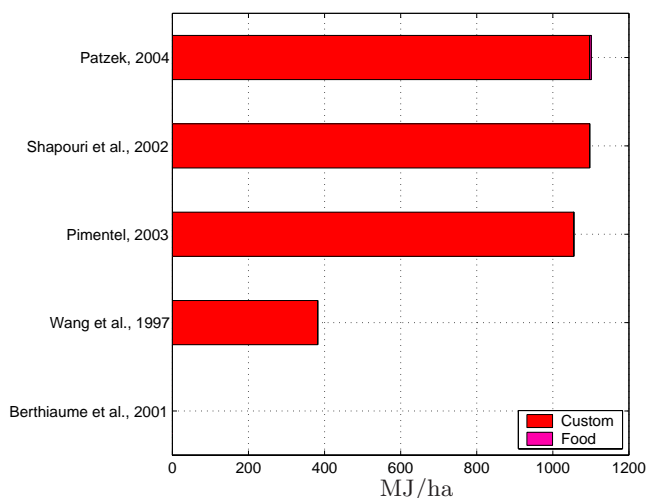


Figure 2.9: Energy use in labor.

- Therefore, a *single calculation* of energy efficiency of corn production for all states and all years is insufficient for the generalizations readily made from such a calculation. In other words, in the same corn growing season, the energy balance of corn ethanol production may be highly unfavorable in one state, and only somewhat unfavorable in another one.

2.2.5 Energy in Human Labor

Average labor time is 6.2 hrs/ha/crop per growth season (USDA-NASS, 1999) [47]. I will assume that a physical worker is on a 4000 kcal/day diet. The specific energy to sustain a worker is then

$$4 \times 10^6 \text{ cal/day} \times 4.186 \frac{\text{J}}{\text{cal}} \times \frac{1}{24} \frac{1}{\text{hr}} = 0.7 \frac{\text{MJ}}{\text{hr}}, \quad (2.5)$$

and it is negligible.

In my estimate, I have used SHAPOURI *et al.*'s [59] custom labor estimate plus the worker sustenance energy, see **Figure 2.9**.

2.2.6 Energy in Corn Seeds

The production of *hybrid* corn seeds is very energy intensive [48]. Two corn genotypes are needed. The pollen from one genotype is used, and the pollen from the other genotype must be prevented from pollinating the genotype from which the corn seed will be harvested. Because of all these manipulations, about 7 times *more* energy is required to produce hybrid seeds compared with the energy in the same mass of corn grain.

The following data have been used to estimate the specific energy requirements for corn seeds:

- The seed rate is 57,000 (Corn Belt) –74,000 (West) kernels per ha [73], p. 255.
- The mean weight of 1000 corn kernels is 0.332 kg [73], p. 202.
- The caloric value of corn kernels with 13-15% moisture is 15-16 MJ/kg.
- The production of hybrid corn requires about 104 MJ/kg [22].

Both SHAPOURI *et al.* [59], and WANG *et al.* [70] ignored the hybrid seed energy, and assigned just the diesel fuel energy for planting the seeds. I have amended their calculations with the seed energy, based on their reported seed rates, and moved their diesel fuel estimates to plant the corn to the fuel category.

2.2.7 Energy in Irrigation

Corn gets water mostly from rainfall, but some irrigation is required on average. In a dry season, irrigation rate may go up substantially, as seen from the electricity use by state reported in Figure 2.8. I have made the following assumptions to estimate the energy cost of corn irrigation:

- Only 15% of crop is irrigated, USDA-NASS, 1997, [47].
- On average 8.1 cm of water is used per acre, USDA-NASS, 1997, [47].
- Water is pumped on average from depth of 100 m.
- Pump efficiency, etc. is 0.75.

Then the specific energy requirement for irrigation is

$$\frac{1 \text{ m}}{100 \text{ cm}} \times 10,000 \frac{\text{m}^2}{\text{ha}} \times 1000 \frac{\text{kg}}{\text{m}^3} \times 100 \text{ m} \times 9.81 \frac{\text{m}}{\text{s}^2} / 0.75 = 131 \text{ MJ/cm-ha} \quad (2.6)$$

I have *lowered* PIMENTEL's 2003 estimate of irrigation energy to my estimate. Both SHAPOURI *et al.*, and WANG *et al.* have buried the irrigation energy in their use of electricity and methane, so they account for the irrigation indirectly, for the particular mixture of states and weather they considered. Since I use SHAPOURI *et al.*'s estimates for the fossil fuels, I have *not* included the irrigation energy in my calculations.

2.2.8 Energy in Transportation

The specific energy use in transportation related to corn farming has been estimated by WANG *et al.* [70], see **Table 2.17**. The total energy use is about 150 MJ/kg of corn, or 160 MJ/ha. This estimate is very sensitive to the number of commutes to and from the field by personnel using cars and pickup trucks.

Table 2.17: Specific energy used in transportation related to corn farming. Source: WANG *et al.*, 1997, [70]

Category	Plant→ Center	Center→ Mixer	Mixer→ Farm
Travel distance (km one way)	1700/ 850	80	50
Mode	barge/ rail	Class 8b truck	Class 6 truck
Energy use (kJ/kg)	71	25	53

Total energy use is 150 kJ/kg or ~ 160 MJ/ha + Commute of Personnel

Personal Commute

At 6.2 hr/ha/crop of labor, 20 l/100km gasoline use, and a 30 km round trip, the energy cost of commuting is

$$\begin{aligned} & \frac{6.2 \text{ hr/ha/crop}}{9 \text{ hr work day}} \times 60 \text{ km} \times 20 \frac{\text{liter}}{100\text{km}} \times \frac{1}{100} \times 0.74 \frac{\text{kg}}{\text{liter gasoline}} \times 47 \frac{\text{MJ}}{\text{kg gasoline}} \\ & = 288 \text{ MJ/ha-crop} \end{aligned} \quad (2.7)$$

Therefore a single commute *nearly triples* the overall transportation energy costs. This issue should be investigated further.

2.2.9 Machinery & Infrastructure

Industrial agriculture requires heavy machinery (trucks, tractors, ploughs, etc.), which must be replaced periodically. It also requires extensive infrastructure with a large environmental footprint (access roads, silos, pumps, driers, electricity generators, air-conditioners, etc.). The unit fossil energy input as hardware has been estimated at ~ 110 MJ/kg by PIMENTEL [47]. This estimate is roughly twice the energy required to produce 1 kg of steel. For the highly perfected, machined steel in farm equipment, it is a reasonable estimate and I accept it. The mass of hardware assigned by Pimentel to corn farming is 55 kg/ha, and I accept it too.

Both SHAPOURI *et al.* [59] and WANG *et al.* [70] omit this input altogether, but I have not amended their calculations.

2.2.10 Fossil Energy Inputs into Corn Production

The specific fossil energy requirements in industrial corn farming are shown in Figure 2.11. A few comments are in order.

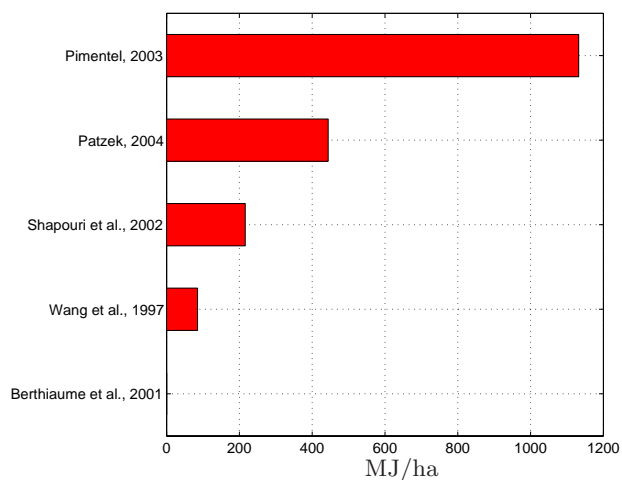


Figure 2.10: Specific energy use in transport related to corn farming. Note that PIMENTEL's estimate may contain an additional single commute to and from the field.

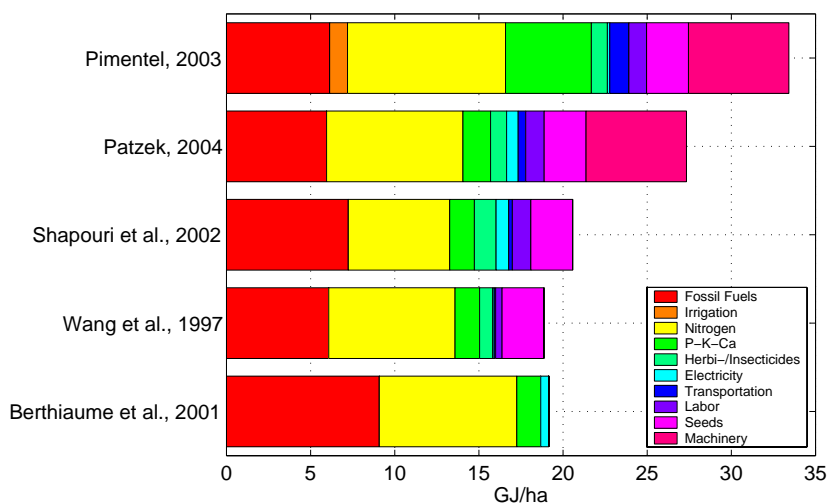


Figure 2.11: Major fossil energy inputs into corn farming.

- The lowered PIMENTEL's 2003 estimate of fossil fuel energy plus irrigation is identical with that by SHAPOURI *et al.*
- The lowered PIMENTEL's 2003 estimate of nitrogen fertilizer energy is higher than the uncorrected one by SHAPOURI *et al.*, which is too low. My estimate is in the middle.
- PIMENTEL's 2003 lime application rate is twice those of everyone else's.

It reflects the 1997 USDA average.

- PIMENTEL's 2003 transportation energy is 2-4 times higher than everyone else's. It may reflect 1-2 more commutes/ha/crop.
- SHAPOURI and WANG *et al.* have underestimated the fossil energy in seeds and left out the machinery and infrastructure.
- I have added my seed energy estimate to their inputs, but left the machinery out.
- BERTHIAUME *et al.* [3] have not included several energy inputs into corn farming, so their estimate is presented here only for comparison.
- The estimates of fossil energy inputs range from 19 GJ/ha (WANG) to 33 GJ/ha (PIMENTEL). My estimate is 27 GJ/ha.
- WANG *et al.*'s estimates are consistently too low. SHAPOURI *et al.*'s and my estimates are almost identical. The only significant difference is the inclusion of machinery into my estimates.
- The fossil energy use in corn farming is large and equivalent to 0.4 (WANG *et al.*) to 0.7 (PIMENTEL) metric tonne of gasoline per hectare and per crop.
- The average energy use in corn farming does not tell the whole story because of the very large variability of energy use by state, depending on the local weather conditions.
- All estimates, including mine, have had errors and/or omissions at one stage or another. I hope that by bringing the approaches of all authors into a common framework, most of the deficiencies of the prior analyses have been overcome.

2.2.11 Solar Energy Input into Corn Production

The solar energy impinging on 1 average hectare of corn field in the U.S. during the growth season is gigantic, and it dwarfs all fossil energy inputs *and* the calorific value of the 8600 kg of corn kernels harvested from this hectare, see **Figure 2.12**. In fact, only 1-3% of the solar energy is converted by plants into biomass [4].

In other words, the solar energy is *not* the limiting factor in corn production: soil, water, and the dissolved nutrients are. I will discuss this crucially important point later. Here it suffices to say that if the sun were the limiting factor, the Sahara desert would be the best place to grow corn [18].

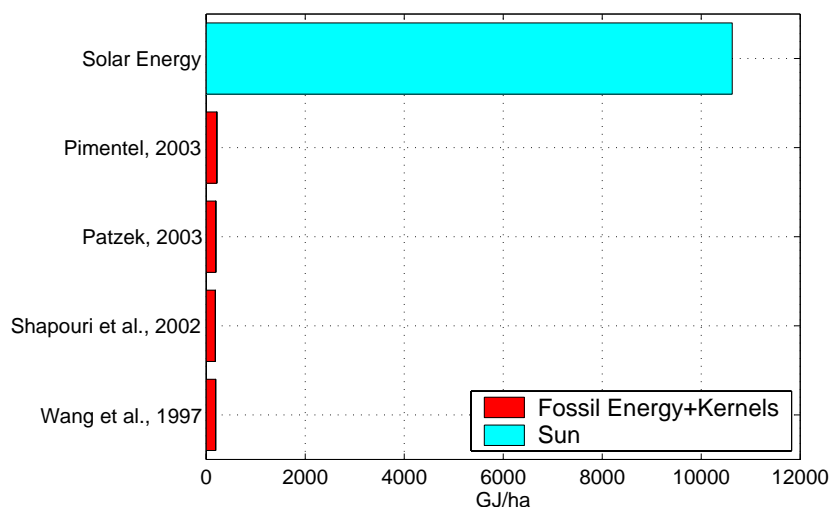


Figure 2.12: Comparison of the cumulative solar energy input and the fossil+grain energy inputs per hectare and per crop.

2.2.12 Soil Humus and Micro-Element Depletion by Corn Production

Because good soil quality sustains farming, one needs to account for the extraction by corn plants of soil humus and metals.

Definition 2 (Humus) is the soil component which develops over time by the decomposition of organic matter, plant and animal remains. \square

Soil humus is among the principal carbon pools on continents. One hectare of corn produces 8600 kg of corn kernels, cf. Section 2.1, and 8600 kg of stalk, leaves and roots [48]. MICHAUD [35] has estimated that about 2600 kg/ha-crop of soil humus is extracted by the corn monoculture with tillage. By scaling MICHAUD's results to the average U.S. corn yield, I have calculated that composting **all** 8600 kg of plant parts, returns about 2100 kg/ha of humus (4:1 ratio). Therefore, with the full composting of plant leftovers, corn depletes 500 kg/ha-crop of humus.

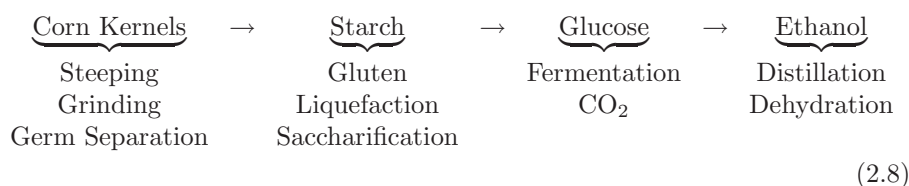
The net humus depletion by 500 kg/ha-crop could be replenished by returning to the field 2000 kg/ha of corn kernel leftovers from ethanol production. Otherwise, industrial corn farming is also *soil mining*, in addition to being crude oil, natural gas, and coal mining. I will come back to this point when I discuss the energy credits for ethanol production assumed by WANG *et al.* and SHAPOURI *et al.*.

All corn plant parts, other than starch in corn kernels should be composted and recycled to recover their N, P, K, C, Ca, Mg, Zn, B, Cu, Mn, etc.. However, most of the nitrogen and phosphorus and some other nutrients are translocated

from vegetative plant parts to the developing grain later in the season. A corn crop harvested with no recycling removes more than twice as much nitrogen, three times as much phosphorus, and 10 times as much potassium as when the crop is harvested for grain [72]. It also removes most of the soil metals essential to the well-being of corn plants. The need to recycle plant parts largely negates the now fashionable attempts to produce ethanol from the whole corn plants by harvesting everything from the corn field, see e.g., [40], while pretending that nature really does not need recycling. Of course, every ecosystem on the earth is highly optimized to recycle almost all mass it generates; otherwise it would not survive for a long time.

2.3 Major Energy Inputs to Ethanol Production

Conversion of corn kernels into 100% ethanol (EtOH) is a fossil energy-intensive process, which also generates significant gas emissions, as well as liquid and solid waste. Here I will consider only wet-milling of corn to convert it into glucose, which is subsequently fermented to industrial beer, and distilled to 96% ethanol. The final water removal is achieved in molecular sieves that exclude water, or by distillation with benzene, see Eq. (2.8). Fermentation is equivalent to catalytic burning, in which 49% of the input glucose is converted into carbon dioxide. This is why ethanol is often called “half-burned gasoline.” Dry milling is energetically similar, and need not be considered.



2.3.1 Corn Mass Balance Revisited

In Section 2.1, I calculated the theoretical efficiency of corn conversion into ethanol, in which every step is 100% efficient. Here, based on my estimates and conversations with industrial chemists, I will assume that the conversion of corn kernels into 100% ethanol incurs 12% losses by mass, see **Figure 2.13**. This assumption will not influence any my major conclusions, and may be relaxed if sufficient counter-arguments are made.

Four important conclusions can be drawn from Figure 2.13:

1. The correct high yield of ethanol from corn is now 0.372 L EtOH/kg dry corn kernels, or 2.5 gallons of EtOH per 56 lbs of dry corn kernels (“dry bushel”).
2. The USDA estimate of 2.66 gallons/bushel [59] is too high, and cannot be accepted based on the mass balance of corn with the average composition from the Corn Chemistry & Technology Handbook [73], see Table 2.1.

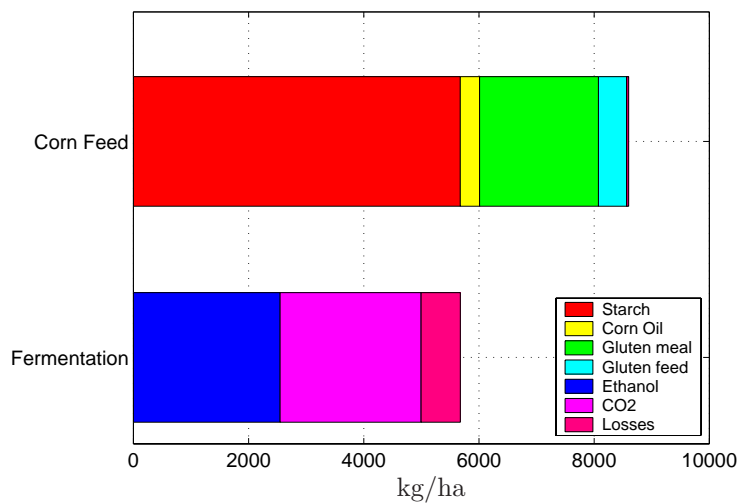


Figure 2.13: The result of practical corn conversion into ethanol is 0.372 L EtOH/kg dry corn kernels = 2.50 gal EtOH/dry bushel = 2.18 gal EtOH/wet bushel with 15% moisture.

3. The downward correction of the USDA estimate will lower the overall energy efficiency of the corn-to-ethanol conversion process.
4. The reported field corn yields must be multiplied by 0.85 to convert the harvested corn to water-free or “dry” corn, see **Figure 2.14**.

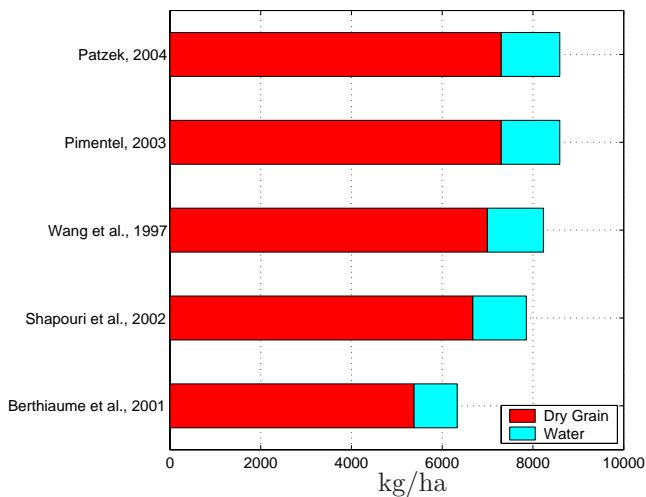


Figure 2.14: Average wet and dry corn yields.

2.3.2 Transport in Ethanol Plants

Transport of materials and people in-and-out of an ethanol plant requires energy, and there is some disagreement between PIMENTEL and PATZEK on one hand, and SHAPOURI *et al.* and WANG *et al.* on the other. Here it suffices to state that

- Corn kernels (8600 kg/ha), fuel (e.g., ~1200 kg of coal) must be transported *in*.
- Ethanol (~2500 kg/ha), gluten meal and feed (~2600 kg/ha) must be transported *out*
- Workers must travel *in-and-out*.
- Both SHAPOURI *et al.* and WANG *et al.* seem to underestimate these transport costs by a factor of 3-4.

2.3.3 Fossil Energy Inputs to Ethanol

Because transportation is but a small fraction of the total energy outlay in ethanol production, there is little disagreement in the various estimates of the total energy use to produce ethanol from corn, which are close to 15 MJ/L EtOH, see **Table 2.18**. This is easily seen when the total lengths of the bars in **Figure 2.15** are compared¹.

2.3.4 Energy Credits

Major disagreements surface when it comes to energy credits used by the different authors to offset the high energy cost of ethanol production. The idea is to somehow use the market or energy value of gluten meal and gluten feed, see Table 2.1, both by-products of wet milling of corn, to offset the fossil energy used to produce ethanol. Gluten meal is a more valuable by-product, but it is 4 times less abundant than gluten feed. The key assumptions made by the different authors are as follows:

- WANG *et al.* [70] assume energy credit as 30% of all energy inputs into ethanol production.
- SHAPOURI *et al.* [59] assume energy credit of 5.9 MJ/L of ethanol, justifying it as the replacement value of soybean meal with corn gluten feed and meal.

¹For comparison, a recent feasibility study for a new ethanol plant [29] projects 13.08 MJ/L EtOH in methane, and 1.675 MJ/L EtOH in electricity, for the total of 14.8 MJ/L EtOH, excluding transport and commute costs. This study contains numerous mistakes. For example, the efficiency of grain conversion into ethanol is overestimated, and the amount of feed water is significantly underestimated

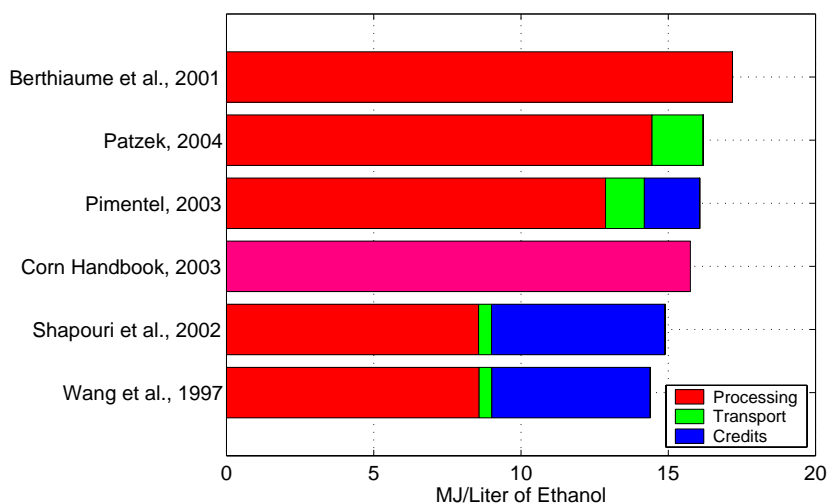


Figure 2.15: The average fossil energy inputs to ethanol production in a wet milling plant. The length of each bar is the total energy outlay to produce 1 liter of EtOH, and the blue parts denote the size of energy credits assumed by the different authors.

- PIMENTEL [47,48], assumes energy credit of 1.9 MJ/L of ethanol, justifying it as the replacement value of distiller's dried grain in *dry* milling, which is closer in composition to soybean meal (it contains 30% protein, 8% fat). Pimentel also argues that gluten feed does not replace soybean meal; in addition soybean plants fix nitrogen, and corn does not, so the replacement is really difficult to justify.
- I give ethanol **zero energy credit**, and want the ethanol plants to bear the transportation and disposal costs of gluten feed and meal, as well as all other solid and liquid waste from ethanol production. Some of the environmental restoration costs will be included in the discussion of the carbon and water cycles in ethanol production from corn. In Section 2.2.12, I have already argued that all ethanol processing leftovers should be returned to the field to replenish soil humus and micro-elements.

2.3.5 Overall Energy Balance of the Corn-Ethanol Process

With the energy credits or without, ethanol production from corn is the fossil energy losing proposition, even if the energy costs of environmental damage are *not* included, see **Figure 2.16**. The calorific value of corn kernels is also shown in this figure, to demonstrate the fraction of the energy inputs into ethanol production which is dissipated on fermentation, distillation and farming. The horizontal lines in the middle of each bar denote the corrected ethanol yield, cf. Section 2.3.1, given the corn yields shown in Figure 2.14.

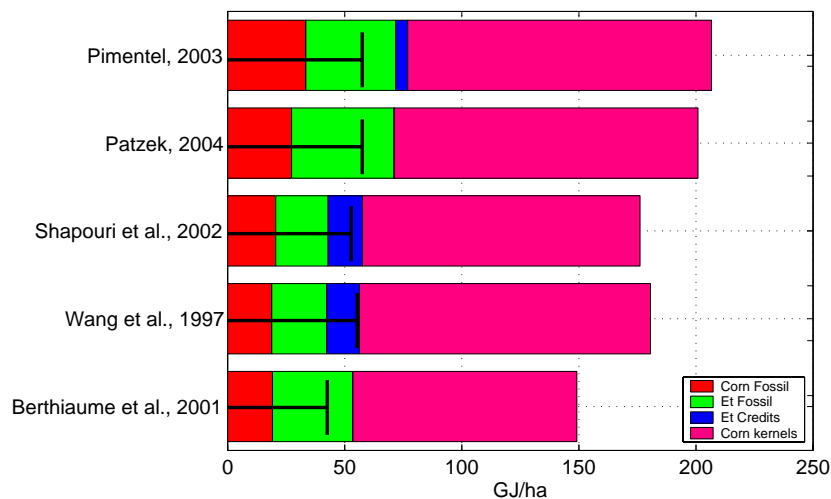


Figure 2.16: The overall energy balance of ethanol production. The two or three leftmost bars represent the specific fossil energy used in corn farming and ethanol production. The fossil energy inputs into ethanol production are the sum of the green bar and the blue energy credit bar for some authors. The rightmost bar is the calorific value of corn kernels harvested from 1 hectare. The total lengths of the horizontal bars represent all energy inputs into ethanol production. The horizontal lines with the vertical anchors represent the calorific value of ethanol obtained from one hectare of corn. Note that the total energy inputs into ethanol production are equivalent to over 4 metric tonnes of gasoline per hectare. The ethanol's calorific value is equal to 1 metric tonne of gasoline.

Table 2.18: Ethanol yield, specific energy inputs, and energy credits

Yield L/ha	Yield GJ/ha	Transport MJ/L	Fuel MJ/L	Total Inputs MJ/L	Credits MJ/L	Source
2706	57.51	1.32	14.75	16.07	1.88	Pimentel, 2003
2706	57.51	1.74	14.45	16.19	0.00	Patzek, 2004
2484	52.79	0.44	14.45	14.89	5.89	Shapouri <i>et al.</i> , 2002
2603	55.32	0.43	13.96	14.39	5.38	Wang <i>et al.</i> , 1997
2002	42.55	0.00	17.18	17.18	0.00	Berthiaume <i>et al.</i> , 2001

Chapter 3

Part II – Sustainability & Renewability

3.1 Why Is It Important?

On August 16, 2003, an informal check of Amazon.com revealed 4454 book titles with “sustain★.” In particular, there were 573 book titles with “sustain★” and “★culture”¹. The phrase *sustainable development* is firmly rooted in our consciousness. Therefore, one must ask the following question: Is sustainable *anything* possible in nature? In economy? Also, how *sustained* are the processes deemed by some as *sustainable*?

Human nature being what it is, destines us to choose a “truly great but brief, not a long and dull, career” [18] on the earth. After our eventual demise, the earth will be home to other less ambitious and impatient species. The name of the game, therefore, is to make the human presence on the earth as happy as possible, albeit not too short². These two tasks require careful thought and delicate balance of human actions. Neither has been present overwhelmingly in any country on any continent. In fact the opposite may be true, as the entropy on the earth increases, the government and societal actions resemble more and more episodic spasms, not forethought and deliberation. The current hot issues: the Hydrogen Economy, Ethanol from Corn, or the War on Terror are good examples.

¹My favorite: *Permaculture: Principles and Pathways Beyond Sustainability* by David Holmgren, published by Holmgren Design Services; (July 2003).

²Preaching alone will not do. People will never choose less fulfilling life styles without coercion. This is why communism, or any other totalitarian “ism,” can never work; they strive to convert the thinking individuals into slaves or working animals. Says PERCY WILLIAMS BRIDGMAN: “The *individual* is the unit in terms of which all our social concepts ultimately find their meanings.” [7], p.114, italics mine.



Figure 3.1: NICHOLAS GEORGESCU-ROEGEN, 1906-1994.

3.2 Disclaimer

The next eight sections of this report are punctuated with the verbatim quotations from, and my digestion of the most important book I have read in decades: *The Entropy and the Economic Process* by NICHOLAS GEORGESCU-ROEGEN (1906-1994), **Figure 3.1**, the great twentieth century thinker, economist, mathematician, historian and philosopher. The impact of this book on my thinking has been profound.



Figure 3.2: **Left:** NICOLAS LÉONARD SADI CARNOT, 1796-1832, a brilliant French engineer who conceived modern thermodynamics. **Right:** JAMES PRESCOTT JOULE, 1818-1889, established the equivalence between amounts of heat and mechanical work with his famous “paddle-wheel experiment.”

3.3 Preliminaries

In science, we divide actuality into two slices: one representing the *partial process* determined by our interest, and the second, its *environment*, see **Figure 3.3**. These two parts are separated by an *analytic*³ *boundary*. The boundary has two attributes, the first separates the process from the environment at any time (we can call this attribute the *interface*, or the *frontier*), and the second defines the *duration* of the process⁴. Often the terms *process* and *environment* are used interchangeably with *system* and *surroundings*. We may not describe a process by what happens inside or outside of it, but only by what crosses its boundary. Anything of interest crossing the boundary from the environment into the process is an *input*, and anything crossing the boundary in the opposite direction is an *output*. Solar energy is a typical example of only an input for any terrestrial process. The various materials abbreviated as “waste” are examples of only outputs.

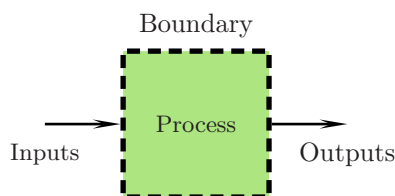


Figure 3.3: The *boundary* separates the process from the environment at any time (it is the *interface*), and it defines the *duration* of the process.

We *may not* describe a process by what happens inside or outside of it, but only by what crosses its boundary

3.4 Laws of Thermodynamics

The three empirical laws of *Classical Thermodynamics*⁵ were originated by JOULE, CLAUSIUS, THOMSON, PLANCK and NERNST, and are often formulated as follows:

First Law or the Energy Conservation Law (Joule, Clausius, Thomson)

- Energy can neither be created or destroyed;

³The word *analytic* means well-defined mathematically in space and/or time.

⁴The process is not defined outside its time interval.

⁵Started in 1824 with a memoir, *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance* [9], on the efficiency of steam engine by a French engineer, SADI CARNOT.

- The energy of the universe remains constant; or
- You can't win.



Figure 3.4: RUDOLF JULIUS EMMANUEL CLAUSIUS, 1822-1888, first stated in 1854 the basic idea of the second law of thermodynamics. He used it in showing that for a *Carnot cycle*, which transmits heat between two heat reservoirs at different temperatures and at the same time converts heat into work, the maximum work obtained from a given amount of heat depends solely upon the temperatures of the heat reservoirs and not upon the nature of the working substance.

Second Law or the Entropy Law (Clausius)

- Without the compensating changes elsewhere, heat can flow only from a hotter to a colder body; or
- With passing chronological time, the entropy of the universe tends towards a maximum; or
- You can't break even.

Third Law (Nernst and Planck)

- The entropy of any condensed substance, i.e., liquid or solid, has at zero absolute temperature the value zero; or
- Zero absolute temperature cannot be reached; or
- You have to stay in the game.

The story of *Classical Thermodynamics* is rather simple if we ignore the fine print. Energy comes in two qualities: (1) *free* or *available*, and (2) *bound* or



Figure 3.5: WILLIAM THOMSON (LORD KELVIN), 1824-1907, published between 1849 and 1852 three influential papers on the theory of heat. However, historians of science have already called attention to THOMSON's difficulties in reconciling a principle formulated by JAMES PRESCOTT JOULE with another principle formulated by NICOLAS LÉONARD SADI CARNOT, and to errors THOMSON made in his calculations. In the meantime, RUDOLF JULIUS EMMANUEL CLAUSIUS reconciled the two principles, and in 1854 he derived an expression for CARNOT's principle.

dissipated. Free energy can be transformed into mechanical work⁶. Like heat, free energy dissipates itself without any loss into bound energy. The material universe, therefore, changes spontaneously in such a way that free energy is degraded. The final outcome is a state where all energy is dissipated, the *Heat Death* as it was called in the earliest thermodynamics⁷.

For some technical reasons, which need not bother us now, *entropy* was defined by the formula:

$$\Delta S = \delta Q/T \quad (3.1)$$

where ΔS is the entropy *increment*, δQ is the *quantity* of heat transferred from a hotter to a colder body, and T is the absolute temperature at which the transfer is made. The entropy increments are always determined in the direction of *Time*⁸, from the *earlier* to the *later* moment in Time. So, if chronological Time τ_2 is later than another Time τ_1 , then the entropy of the universe (or another closed system) is

$$S(\tau_2) > S(\tau_1) \quad (3.2)$$

The *Entropy Law* is the simplest (and thus far only) law known to science, by

⁶Initially *free heat* was defined as the heat which can be exchanged between a hotter body and a colder one, and which can move a turbine in power station. If the hotter body, i.e., a steam boiler, remains unchanged, and the colder body, i.e., the environment, warms up, the amount of free heat goes down and the power station produces less electricity, as just happened in Europe during the record-breaking summer heat wave.

⁷BRIDGMAN disagrees, [7], p. 265.

⁸Time is a notion of extraordinary complexity. Here we use the historical or chronological *Time*, as opposed to the mechanical clock *time*.

which the existence of true *happening* in nature is recognized. The Entropy Law defines the boundaries of what *cannot* happen, but does not prescribe entirely what *can*. This loophole resulted in life. All life⁹ feeds on the environment of low-to-moderate entropy (highly organized ecosystems¹⁰, such as shallow sea water, a river or lake, a jungle, etc.), and is extinguished when entropy of the environment becomes too high (the degraded environment of sterile desert or chemically polluted water).



Figure 3.6: WILLIAM STANLEY JEVONS, 1835-1882. The first economist on record to ponder the problem of exhaustion of mineral resources on the earth.

3.5 Thermodynamics and Economics

Classical thermodynamics and *economics*¹¹ are thoroughly bonded. In fact, thermodynamics has been mostly a physical theory of economic value from its inception by CARNOT. Just as physical life, our whole economic life *feeds on low entropy*, e.g., on cloth, computers, lumber, copper plates and wires, aluminum, etc., all of which are highly organized structures. A slab of electrolytic aluminum is worth much more than the dispersed molecules of aluminum oxide, diffused so much as to be of no use to us.

In 1860 or so, WILLIAM STANLEY JEVONS, **Figure 3.6**, described the phenomenon of resource degradation and dilution as follows: “The expression “ex-

⁹Not only biological life, but also social life. Consider the following comment made by JOSEPH SAMAHA in the daily *Al Safir* of Beirut about the desperately dissipative, high-entropy political situation in the Middle East: “Let us expel every mediator. Let us banish every international organization. Let the situation collapse. Let electricity and water be cut off. Let the pumping of oil stop. Let theft prevail. Let the universities and schools close down. Let businesses go bankrupt. Let civilian life break down.” Source NYT, August 21, 2003.

¹⁰*eco* – From late Latin *oeco*- household, from Greek *oik*-, *oiko*-, from *oikos* house habitat or environment, *ecosystem* [71].

¹¹A social science concerned chiefly with description and analysis of the production, distribution, and consumption of goods and services; from Greek *oikonomica* – skilled in the management of a household [71].

haustion of our coal mines,” states the subject in the briefest form, but is sure to convey erroneous notions to those who do not reflect upon the long series of changes in our industrial condition which must result from the gradual deepening of our coal mines and the increased price of fuel. Many persons perhaps entertain a vague notion that some day our coal seams will be found emptied to the bottom, and swept clean like a coal-cellar. Our fires and furnaces, they think, will then be suddenly extinguished, and cold and darkness will be left to reign over a depopulated country. It is almost needless to say, however, that our mines are literally inexhaustible. We *cannot get* to the bottom of them; and though we may some day have to pay dear for fuel, it will never be *positively* wanting¹². Today we may substitute “crude oil” or “natural gas” for “coal”, and JEVONS’ statement will be as true¹³.

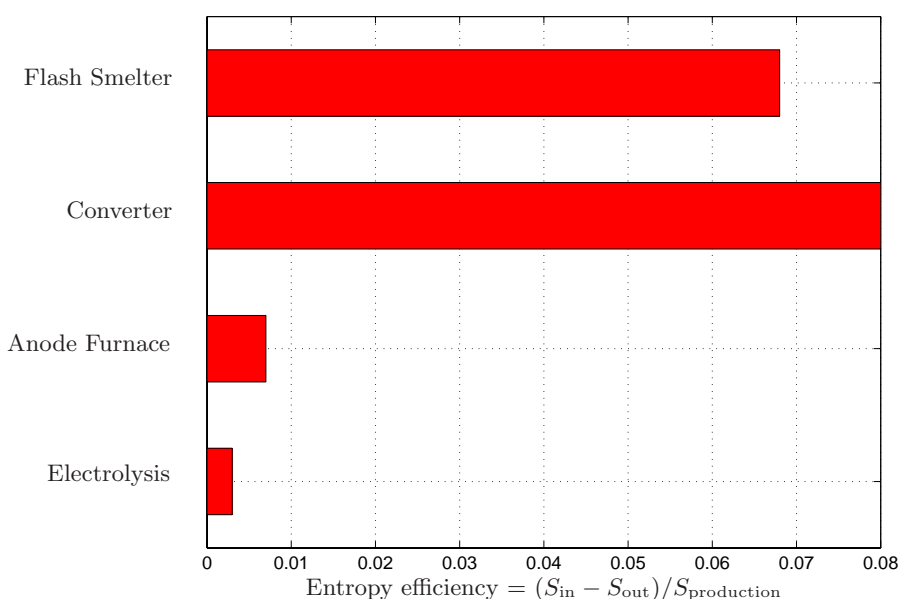


Figure 3.7: The Second Law efficiency of copper production is incredibly small. The steps in sorting the copper atoms are: Ore Concentration 2% \rightarrow 30% Cu (not shown); Smelter 30% \rightarrow 63% Cu; Converter 63% \rightarrow 99.1% Cu; Anode furnace 99.1% \rightarrow 99.55% Cu; and Electrolysis 99.55% \rightarrow 99.99% Cu. Source: STEFAN GÖSSLING, *Entropy Production as a Measure for Resource Use*, University of Hamburg, 2001.

In particular, thermodynamics explains to us why *land* has economic *value*, as opposed to *price*, and in economics it usually does not¹⁴. Even though land cannot be consumed, it derives its economic value from two physical facts: (1)

¹² [32], *Preface*, pp. vi-vii, my italics.

¹³In fact, it is more difficult to extract crude oil than coal. After we are done with exploiting an oilfield, 1/2 to 2/3 of the oil present initially in the rock interstices is left there forever.

¹⁴With the notable exception of [18]. Look, for example, how fertile land is paved over with

it allows humans to catch the most vital form of low entropy, the sunlight, and (2) they stopped making it on the earth in large quantities. Other physical and chemical characteristics of fertile land¹⁵ are *scarce* in a different sense: (1) the amount of low entropy in the soil is finite and it decreases *continuously* and *irrevocably*, and (2) a given amount of low entropy can be used *only once*.

A different example of the irrevocably lost low entropy is given by mining of a copper ore and transforming it into pure metallic copper. If we take a sheet of manufactured copper metal, it was made of: (1) copper ore, (2) other raw and processing materials, (3) electricity from fossil fuels, and (4) mechanical work. All these factors ultimately resolve into an orderly structure of primary materials (e.g., highly concentrated copper atoms in the ore, fuel, electricity), i.e., to *environmental low entropy* and nothing else. The free energy used in production to deliver mechanical work or to heat the ore is *irrevocably lost*.

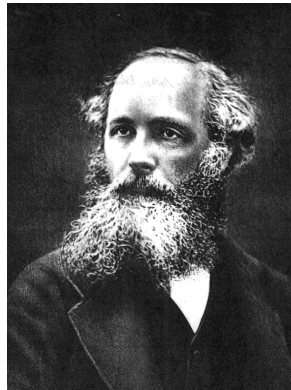


Figure 3.8: JAMES CLERK MAXWELL, 1831-1909, one of the greatest physicists in history.

We cannot *bootleg* any entropy¹⁶ by means of an ingenious process or device. Just like a MAXWELL (**Figure 3.8**) demon¹⁷, we have merely sorted the copper atoms from all others, but in order to achieve this end-result we have used up irrevocably a greater amount of low entropy than the difference between the entropy of the copper metal and that of the copper ore. In view of **Figure**

little protest, in general. This land destruction continues regardless of whether its price is low or high.

¹⁵Natural soil fertilizers, soil-bonding humus, interstitial water, etc.

¹⁶In the 1930's, the young physicists became so confused by statistical thermodynamics that a famous thermodynamicist, PERCY WILLIAMS BRIDGMAN, wrote an essay on the impossibility of constructing a machine that "shall violate the second law of thermodynamics on a scale large enough to be commercially profitable." In [7], pp. 236-268.

¹⁷J. CLERK MAXWELL imagined a tiny demon posted near a microscopic swinging door separating two gases *A*, and *B* of equal temperature. The demon is instructed to open and close the door "so as to pass only the swifter molecules from *A* to *B*, and only the slower molecules from *B* to *A*." [8] Clearly this demon can make the gas in *B* hotter and in *A* cooler. Therefore, Maxwell's demon creates low entropy – or does he?

3.7, it would be a great mistake to compare just the latter two entropies and exclaim: “Lo! Man has created low entropy from high!” [18]. This claim, in effect, is made by all those who say that copper can be manufactured *sustainably*. The copper scrap recycling programs are successful, only because scrap copper (and aluminum) requires less low entropy than any other way of reconstituting metallic copper¹⁸. Nevertheless, insofar as fossil energy is used, by recycling we only postpone the inevitable exhaustion of low entropy in the environment.

3.6 Economic Activity

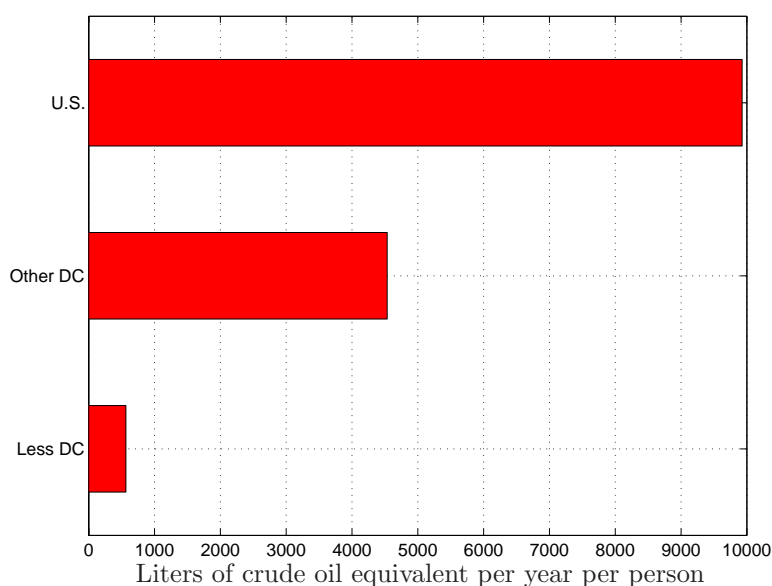


Figure 3.9: The 2001 per capita energy consumption in the U.S., other Developed Countries (DC), and the less Developed Countries. Source: The U.S. DOE Energy Information Agency.

Economists have a tendency to represent the economic process by a *closed system*, that is to ignore the *continuous inflow* of low entropy from the environment¹⁹. But from a physical point of view, the economic process is entropic; it neither consumes nor creates mass or energy, but only transforms low entropy to high. To make things worse, the entropy generation process in the environment is spontaneous, and goes on by itself without human intervention. The material production process, in contrast, depends on the intervention of humans, who like the MAXWELL demon, sort and direct environmental entropy according to

¹⁸According to STEFAN GÖSSLING, entropy generation per ton of copper produced from ore is 52 MJ/K, and only 12 MJ/K for copper produced from scrap.

¹⁹GEORGESCU-ROGEN, [18], Chapters IX and X.

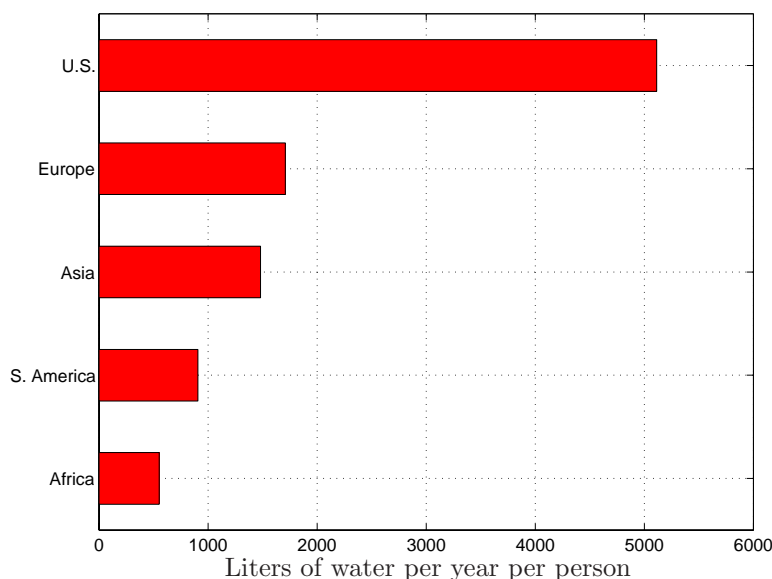


Figure 3.10: The 1990 per capita total (personal + industrial) water consumption in the U.S., and elsewhere. Source: Water Quality Association, 151 Naperville Road Lisle, IL 60532-1088, USA.

the process rules²⁰. This sorting activity is not a part of natural environmental processes and creates high entropy, i.e., waste, at a (much) faster rate than the biological life processes. *From a purely material point of view, the economic process always transforms low entropy into waste.* So what possibly would be the justification for the economic activity? As described by GEORGESCU-ROEGEN, the true output of an economic process is not mere production of waste, but the *enjoyment of life*²¹. It is not a coincidence that the very country which on July 4, 1776, declared: “We hold these truths to be self-evident, that all men are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are Life, Liberty and the *pursuit of Happiness*,” uses over twice as much free energy per capita than any other country on the earth, **Figures 3.9- 3.11**. In general, abundant free energy equals enjoyment of life. The converse statement is as true in real life as it is in Logic, see **Figure 3.12**.

²⁰When watching an SUV commercial, I often see a monster truck carelessly damaging a low-entropy fragile ecosystem, a pristine meadow, river bed, or an alpine mountain slope. Thus the SUV commercials are a good metaphor for the interactions of the present-day economics with the environment.

²¹One should be careful, however. Following GEORGESCU-ROEGEN’s logic, a water-jet skier who, by burning fuel and dumping the unburned fuel mix into clear water, generates more entropy than a fly fisherman, should feel more enjoyment! One the other hand, if the fly fisherman generates high entropy by killing several fish, his enjoyment may be stronger.

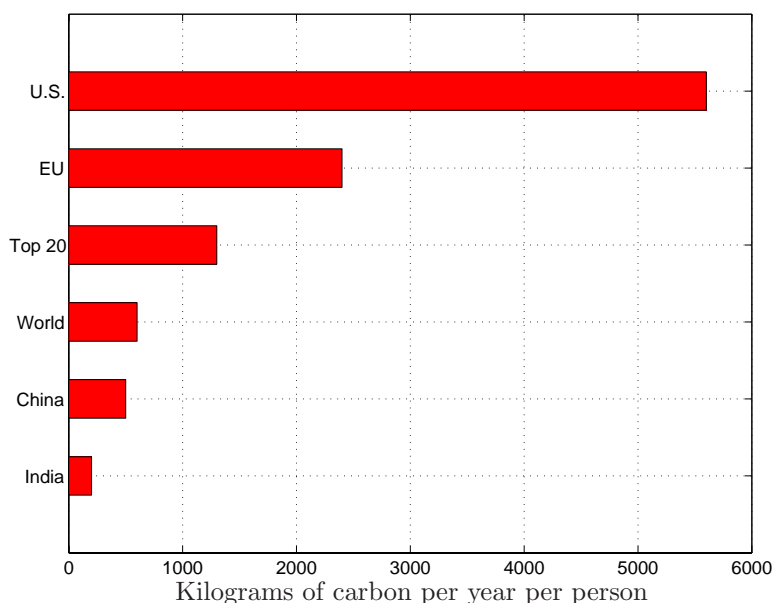


Figure 3.11: The 1999 per capita carbon emission estimates in the U.S., and elsewhere. Source: World Resources Institute, U.S. EIA.

3.7 Agriculture

The following statement is made surprisingly often: “Properly used, [the plants on the earth] can by their reproductive powers supply us indefinitely with the food, the wood, and the other natural products we require.²²” Even though the intensity of sunlight that reaches the earth has not changed appreciably over the human scale of Time, the apparent dominance of the solar energy in agricultural production should not obscure the importance of the *entropic soil degradation* by continuous cultivation. Soil degradation can be severe over a human life span. Even the earliest farmers knew that manuring a soil does not remove its degradation, and to farm always meant to mine, in part, the soil. Clean water is necessary for agriculture. Water is inevitably polluted by agricultural waste; therefore, water too is mined.

It would be a mistake to believe that the practice of fertilizing soil can defeat the Entropy Law and transform food production into an everlasting process. Life feeds not only on the sunlight but also on the low entropy of an *ecosystem*²³.

With time, draft animals, oxen, buffalo and horse, were replaced by machines. A tractor is made of iron, other metals, oil and coal, and it feeds on oil. The natural manure fertilizer from farm animals was replaced by the chemical

²² [10], p. 309.

²³ A process that cycles living organisms. Only the solar energy and waste heat flow across the ecosystem boundary, everything else is recycled, cf. Section 3.10.



Figure 3.12: After the power blackout, people poured onto 8th Avenue, outside the Port Authority, unable to leave the city. The New York Times, August 14, 2003.

fertilizers manufactured from methane, coal, oil, iron, copper, and the earth minerals. The importance of this switch should be plain: the main source of the low entropy that feeds agriculture has been switched from the practically *infinite* solar energy to the very *finite stock of minerals* in the earth's crust. Of course, this switch limits how long and how many people can be fed by the earth. It is no longer the practically unlimited stock of the energy in the sun that limits our survival, but the meager stock of natural minerals mined from the earth crust. If M is the *accessible fraction*²⁴ of this stock, and r is the average rate of its use, then $M = rt$, where t is the corresponding duration of human civilization that depends on the crustal minerals. Depending on the mineral, and its rate of use, this time can be estimated as several tens of years (high quality crude oil), through many hundreds of years (coal), to thousands of years (uranium). So much for sustainable development.

²⁴This fraction may be very small. For example, the vast majority of carbon on the earth is bound in the carbonate rocks. No one in their right mind would dream of extracting this carbon. See also footnote 13.

3.8 Industrial Production

Every car or appliance produced today means fewer human lives in the future. Every styrofoam cup, cell phone or TV set in a landfill now means fewer happy humans later. In industry, just as in agriculture, the price of technological progress has been a shift from the abundant source of low entropy – the sun –, to the earth’s mineral resources. Any time these resources are wasted, we shorten the survival time of humanity. Confronted in the distant future with exhaustion of mineral resources, mankind will be tempted to retrace its steps. It is impossible however, in view of the Entropy Law. The human evolution is *irrevocable* and *cannot be retraced*.

Because of the Entropy Law, the large-scale industrial production of fossil fuels (e.g., ethanol) from the industrial plants *manufactured* [34] by modern agriculture, will only hasten the depletion of mineral resources and the eventual demise of our civilization.

3.9 Waste

The ever-increasing rate of economic activity generates ever more waste. For the earth as whole, this waste cannot be disposed²⁵. Toxic waste once produced is here to stay, unless we will use more free energy to dispose of it. This free energy can only be used once, and will always diminish our future standard of living. Waste cleanup, collection and recycling have begun to interfere with our life and pockets²⁶, and are no longer unimportant to our industrial civilization. The ever accumulating garbage, and the toxic by-products of agriculture and industry are the living proof of the Entropy Law in action.

Incidentally, the process of concentrating the copper atoms, whose entropy efficiency is shown in Figure 3.7, is analogous to the process of fishing out the contaminant molecules dispersed over a huge volume of water and rock. The entropy efficiency of the contaminant cleanup process must be lower than that of the copper production process.

3.10 Sustainability

The opposite of *sustainability* is *irreversibility*, and I define it first after MAX KARL ERNST LUDWIG PLANCK (1858-1947) and AUREL STODOLA (1859-1942):

²⁵Therefore hiding our waste by injecting it into the oceans, aquifers, or burying it in shallow graves - landfills - will always come back to haunt us.

²⁶NYT, August 20, 2003: “Crews have completed the removal of more than 12 metric tons of weapons-grade plutonium from the Rocky Flats (CO) nuclear weapons site as part of a \$7 billion cleanup effort that is expected to be finished in 2006, 12 *years ahead of schedule*. The plant manufactured plutonium triggers for 40 years until it was closed in 1989 for safety violations. The plutonium has been shipped to South Carolina; lower-grade nuclear waste will be sent to New Mexico. The 6,000-acre Rocky Flats site is expected to become a wildlife refuge.” In other words, the cost of picking and sorting the plutonium waste is \$583/g, compared with \$11/g to buy gold.

Definition 3 (Irreversibility) A process is *irreversible* if it can in *no* way be reversed, all other processes are *reversible*. It is impossible, even with the assistance of all agents in nature, to restore everywhere the exact initial state when the irreversible process has once taken place [52].

The essence of an irreversible process is that by no means at our disposal can its consequences be completely eliminated, i.e., so eliminated that in no other body does a change of state persist [62]. \square

Corollary 1 *By the definition above, a linear process that converts the low entropy of fossil fuels into waste is irreversible and cannot be sustainable, see Figure 3.13, and 3.14.* \square

In this process, a finite stock of fossil fuels is rapidly depleted and burned to serve as a collective heat source for all heat engines employed by our civilization, see **Figure 3.16(a)**. In addition, the atmosphere, which acts as a heat sink, becomes polluted by chemical waste from combustion (chemical entropy), as well as by waste heat (thermal entropy). The earth can only export thermal entropy through its atmosphere, see **Appendix A**. In addition to the atmosphere, the earth, which is a part of “the system” in **Appendix B**, also accumulates chemical entropy. As a result, the linear fossil fuel process accumulates chemical entropy in the earth and the atmosphere, and irreversibly degrades our planet on a time scale of our civilization, measured in hundreds of years.

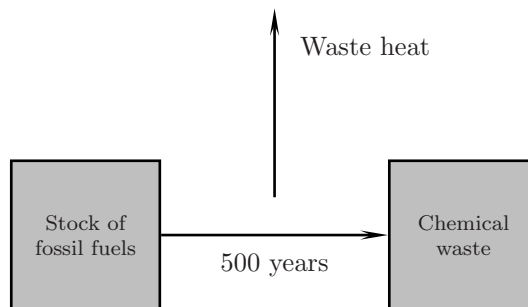


Figure 3.13: A linear process of converting a stock of fossil fuels into waste matter and heat cannot be sustainable. The waste heat is exported to the universe, but the chemical waste accumulates. To possibly replenish some of the fossil fuel stock, it will take another 50-100 million years of photosynthesis, burial, and entrapment.

In contrast, a *cyclic* ecosystem can be sustainable, see **Figure 3.15**. A natural cycle uses the sun as the source of energy and low entropy, and expels only its waste heat into the atmosphere and, ultimately, into the universe, see **Figure 3.16(b)**. Most importantly, *all materials* involved in an ecosystem are *recycled*, and when the natural cycle is completed, only waste heat, or thermal entropy is generated.

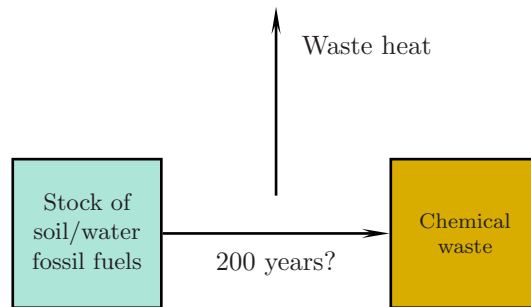


Figure 3.14: Current industrial agriculture is another example of a linear process, which by definition cannot be sustainable.

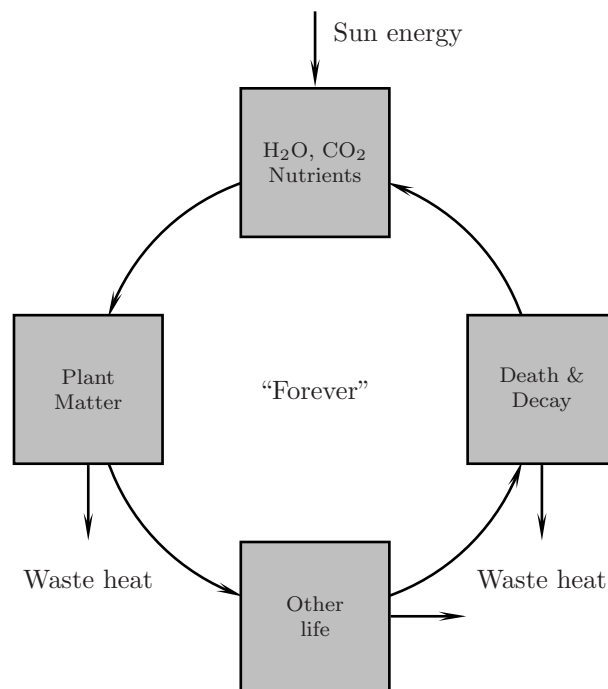


Figure 3.15: An ecosystem transforms the sun energy (low thermal entropy) into waste heat (high thermal entropy). The waste heat is continuously exported to the universe. *Everything* else is completely reused, or recycled.

In order to discuss the existence and constraints on *sustainability*, we need first to define it.

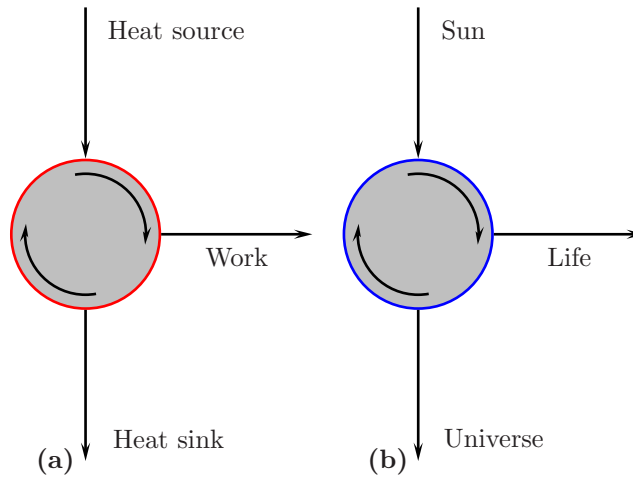


Figure 3.16: Thermodynamic cycles: (a) A heat engine, and (b) An ecosystem.

Definition 4 (Sustainability) A *cyclic* process is *sustainable* if (1) it is capable of being *sustained*, i.e., maintained without interruption, weakening or loss of quality “forever,” and (2) the environment on which this process feeds and to which it expels its waste is also sustained “forever.” \square

Corollary 2 A *cyclic process*, which is also “sustainable,” must not reject chemicals into the environment, i.e., its net mass consumption and production must be “close” to zero.

Corollary 3 A *sustainable cyclic process* must not reject heat into the environment at a rate that is too high for the earth to export this heat to the universe; otherwise, the environment properties will change.

3.10.1 The Earth is an Open System to Heat Flow

Attributes (1)-(2) of a sustainable cyclic process would be a *thermodynamic contradiction* if the earth were approximately a closed system with respect to the infrared radiation (heat). These two attributes would then make a sustainable process a *perpetual machine of the second kind*. Luckily for us, the earth can be treated as an open system with respect to visible and infrared light, and a sustainable cyclic process may generate thermal entropy at a rate per unit area of the earth surface (*specific entropy rate* or *flux*) which is no more than the average flux of entropy export from the earth to the universe, j_S^E , calculated from Eq. (A.1) in **Appendix A**, minus the specific rate of entropy generation

in the atmosphere due to export of the solar energy, calculated from Eq. (A.6) in **Appendix A**.

To quantify sustainability, we first assert that a cyclic process always converts all forms of entropy to thermal entropy. Thermal entropy is the ultimate waste from all processes on the earth, and it should be used for comparisons. Second, per unit area of the earth, we know that (1) the *always positive* specific rate of thermal entropy generation due to everything happening on the earth is $\sigma > 0$, (2) the rate of increase of the specific thermal entropy of the atmosphere due to all these happenings is $\sigma_a > 0$, and (3) the specific rate of thermal entropy generation due to the energy transport from the earth to the universe is σ_t . Then, for cyclic processes, *strong sustainability* can be defined mathematically, see **Appendix B**, as

$$\sigma + \sigma_a \leq j_S^E - \sigma_t \quad (3.3)$$

at every point on the earth, and at all times.

Over an arbitrary time interval $[\tau_1, \tau_2]$, we can write the global condition of sustainability of all cyclic processes on the earth as (Eq. (B.13) in Appendix B)

$$\underbrace{[S_a(\tau_2) - S_a(\tau_1)]}_{\text{Increase of atmospheric entropy}} + \underbrace{[S(\tau_2) - S(\tau_1)]}_{\text{Increase of earth entropy}} - S^E(\tau_1, \tau_2) + S_t(\tau_1, \tau_2) \leq 0 \quad (3.4)$$

where $S^E(\tau_1, \tau_2)$ is the total thermal entropy exported by the earth over the time interval $[\tau_1, \tau_2]$, and S_t is the corresponding thermal entropy generation in the atmosphere due to the solar energy export.

3.10.2 Conclusions

The immediate observations from the above discussion are:

1. To the extent that humans use 80-90% of fossil and nuclear energy to run the heat engines that power the global economy, our civilization is 80-90% unsustainable.
2. If the atmosphere dissipates more energy due to the increased greenhouse gas loading by human (and natural) activities (σ_t increases), there will be less room for all other human activities to remain sustainable. STAHL estimates, [60], Table 1, the specific entropy generation rate in the atmosphere to be $\sigma_t = 0.2 \text{ W/K-m}^2$. So only 1 W/K-m^2 of thermal entropy generation is left to all human and other natural activities.
3. Only energy generation directly from the sun, and the sun-driven wind and water can be sustainable.
4. Burning large quantities of wood or green matter cannot be sustainable to the extent that growing plants mines low entropy from the soil, see Section 3.7.

5. Industrial agriculture can never be sustainable because it relies on the irreversible burning and chemical transformations of fossil fuels, see Section 3.7.

Chapter 4

Part III – Sustainability of Corn-Ethanol Cycle

As pointed out in Part II, our standard of life is maintained by the exploitation of natural resources that have accumulated in the earth over millions of years. A natural resource whose chemical composition *differs most* from the dead states of the elements comprising it, is *most valuable*.

This Part is devoted to the life-cycle analysis of industrial corn and ethanol biofuel produced from it. In my analysis, I will move along the trail charted in the brilliant, albeit incomplete, paper by three Canadian scientists, RICHARD BERTHIAUME, CHRISTIAN BOUCHARD, MARC A. ROSEN [3]. There will important differences, however. I define the industrial corn-ethanol system differently, include more inputs, which are more carefully estimated, and do not require the internal carbon and water cycles to close.

4.1 Available Free Energy

For example, relative to a *datum environment* ($T_0 = 25^0\text{ C}$, $p_0 = 1\text{ atm}$), the quality of heat rejected by a process depends on temperature:

$$\begin{aligned} 1\text{J of heat at } 500^0\text{C} &= 0.614\text{ J of work} \\ 1\text{J of heat at } 50^0\text{C} &= 0.077\text{ J of work} \end{aligned} \tag{4.1}$$

GIBBS, GUOY, STODOLA, and KEENAN's available free energy, see **Appendix B**, is known in chemical and engineering thermodynamics as *exergy*, and is denoted with the symbol B . The concept of exergy and its cumulative consumption in an industrial process has been significantly advanced by the distinguished Polish thermodynamicist, JAN SZARGUT, a professor at the Chemical Engineering Department of my *Alma Mater*, the Silesian Technical University, Gliwice, Poland. His monograph, published in English with DAVID R. MORRIS and FRANK R. STEWARD in 1988 [64] was based on two decades of development

and industrial applications of life-cycle analysis. Today, this monograph still is the most comprehensive source of exergy concepts, data, and examples.

4.1.1 Introduction to Exergy

An easy to understand definition of exergy is due to LUDWIG RIEKERT [55].

Definition 5 Exergy, B , is equal to the shaft work or electrical energy necessary to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged with the environment at constant temperature T_0 . \square

We distinguish the *potential* exergy, B_p , *kinetic* exergy, B_k , *physical* exergy B_{ph} , and *chemical* exergy, B_{ch} :

- **Physical exergy**, B_{ph} is the work obtainable by a reversible physical process from its initial state (T, P) to the environment state (T_0, p_0) .
- **Chemical exergy**, B_{ch} , is the work obtained by taking a substance at the pressure and temperature of the environment to the state of thermodynamic equilibrium with the datum levels of components of the environment.
- **Thermal exergy**, B_{th} , is the sum of physical and chemical exergies:

$$B_{th} = B_{ph} + B_{ch} \quad (4.2)$$

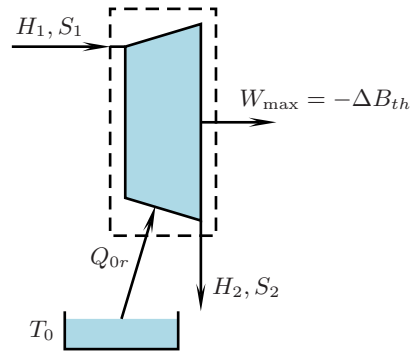


Figure 4.1: Exergy balance in an isothermal, ideal flow machine. The maximum possible shaft work from this machine is equal to the negative change of thermal exergy.

4.1.2 Change of B_{th} between Two States

Consider an ideal (reversible) flow machine, see **Figure 4.1**. An exergy carrier with enthalpy H_1 , and entropy S_1 enters the machine. After physical and/or chemical changes, the effluent has enthalpy H_2 , and entropy S_2 . Heat is transferred between the environment and the working fluid at the ambient temperature T_0 . The first and second law of thermodynamics are simply:

$$\begin{aligned} W_{\text{max}} &= B_{\text{th}_1} - B_{\text{th}_2} = H_1 - H_2 + Q_{0r} \quad (\text{I Law}) \\ S_2 - S_1 - \frac{Q_{0r}}{T_0} &= 0 \quad (\text{II Law}) \\ B_{\text{th}_1} - B_{\text{th}_2} &= -\Delta B_{\text{th}} = H_1 - H_2 - T_0(S_2 - S_1) \quad (\text{I+II Law}) \end{aligned} \quad (4.3)$$

Physical exergy can be calculated immediately from Eq. (4.3)

$$B_{\text{ph}} = H - H_0 - T_0(S - S_0) = H_{\text{ph}} - T_0 S_{\text{ph}} \quad (4.4)$$

4.1.3 An Industrial Flow Process

Consider now an industrial steady-state flow process, which can occur in a heat engine, corn field, or ethanol plant, see **Figure 4.2**. The input to this irreversible process is an exergy carrier with the enthalpy H_1 , and entropy S_1 . The process is also supplied with the quantity of heat Q_1 from the source having temperature $T_1 > T_0$. The process effluent has enthalpy H_2 , and entropy S_2 . The rejected amount of heat Q_0 is transferred to the environment. The useful outcome of the process can be mechanical work W_u or a chemical product having parameters H_u and S_u . The effect of irreversibility is studied by comparing the industrial process with a reversible process with the same inflow and outflow parameters, and the same amount of driving heat. The only difference between these two processes is in the amount of heat rejected to the environment. For the reversible process this heat is Q_{0r} , and for the irreversible one, it is Q_0 .

The first and second law balances for the two processes are:

$$\begin{aligned} H_u &= H_1 - H_2 + Q_1 - Q_0 \quad \text{Real process} \\ H_{ur} &= H_1 - H_2 + Q_1 - Q_{0r} \quad \text{Reversible process} \\ H_{ur} - H_u &= Q_0 - Q_{0r} \end{aligned} \quad (4.5)$$

The increased useful effect of the reversible process causes the amount of rejected heat to be smaller than that in the industrial process, $Q_0 > Q_{0r}$. The sum of all entropy increases in the industrial process is

$$\sum \Delta S = -\frac{Q_1}{T_1} + S_2 - S_1 + \frac{Q_0}{T_0} + S_u > 0 \quad (4.6)$$

while that in the reversible process is

$$\sum \Delta S_r = -\frac{Q_1}{T_1} + S_2 - S_1 + \frac{Q_{0r}}{T_0} + S_{ur} \equiv 0 \quad (4.7)$$

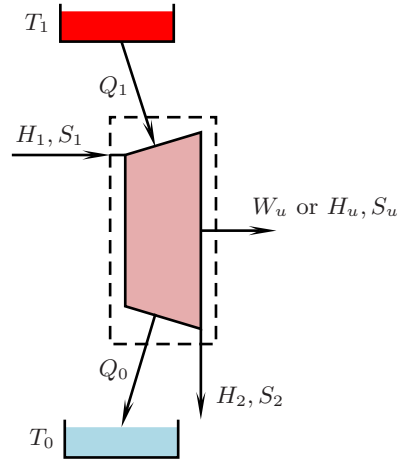


Figure 4.2: Exergy balance in ideal (reversible) and real (irreversible) non-isothermal industrial process.

From Eqs. (4.6) and (4.7) it follows that

$$Q_0 - Q_{0r} = T_0(\sum \Delta S + S_{ur} - S_u) \quad (4.8)$$

and we obtain

$$\underbrace{(H_{ur} - T_0 S_{ur})}_{B_{th,r}} - \underbrace{(H_u - T_0 S_u)}_{B_{th}} \equiv \delta B = T_0 \sum \Delta S \quad (4.9)$$

The left hand-side of Eq. (4.9) represents the difference of the useful thermal exergy in the reversible and industrial process, δB . It therefore expresses the *exergy loss* due to irreversibility of the industrial process under consideration. We have recovered, again, the famous GUOY-STODOLA law, also derived in **Appendix B**.

4.1.4 Cumulative Exergy Consumption (CExC)

All steps of a production process leading from natural resources taken from the environment to the final product result in *exergy losses*.

Definition 6 (CExC) The cumulative exergy consumption (CExC) is the sum of the exergy of all natural resources in all the steps of a production process. \square

The problem of cumulative energy consumption (CEnC), discussed in Part I, is better known, but calculation of CExC is more informative because it accounts for the exergy of non-energetic raw materials (soil, water, air, minerals) extracted from the environment.

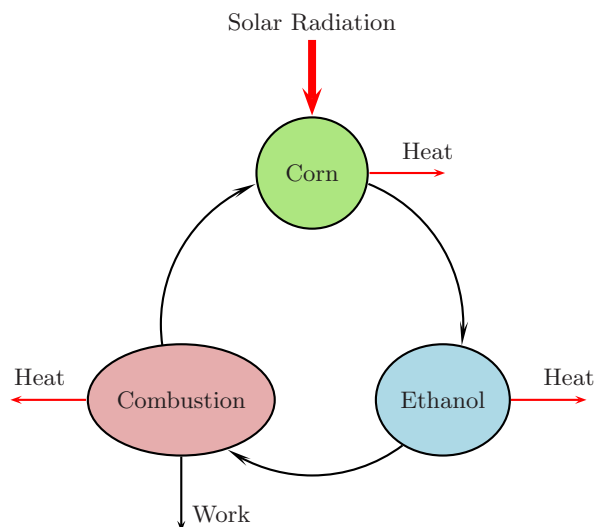


Figure 4.3: The ideal corn-ethanol cycle.

4.2 The Ideal and Real Corn-Ethanol Cycle

Ideally, see **Figure 4.3**, the corn-ethanol system and cycle consist of three parts: (1) Sustainable corn farming, (2) Sustainable ethanol production, and (3) Ethanol combustion to produce useful work.

The cycle is driven *only* by the solar energy, and all chemical by-products are *fully* recycled. Only the low quality heat is rejected by the ideal corn-ethanol cycle into the environment, and this heat is exported through the atmosphere into the universe. All carbon dioxide is recycled, and so is all water. This low-rate ideal cycle *cannot* of course deliver the massive quantities of ethanol fuel from (bi)-annual corn crops.

So, in addition to the current solar energy, we use the ancient solar energy in the form of fossil fuels to *accelerate* the ideal corn-ethanol cycle, see **Figure 4.4**. With massive application of crude oil, methane, natural gas and coal, and their products, nitrogen fertilizer, pesticides and herbicides, we greatly increase the corn yield and the rate of ethanol production, but we also produce massive amounts of chemical waste. In addition, we deplete soil by removing too much plant matter from the fields, and deplete groundwater whenever there is not enough rain. The industrial corn-ethanol cycle relies on the linear processes of mining fossil fuels, soil, water, and air, and in view of Part II, it *cannot* be sustainable. All published statements to the contrary, e.g., [12, 59, 70], and many others, are scientifically indefensible. Below, I will quantify just how unsustainable the industrial corn-ethanol cycle is.

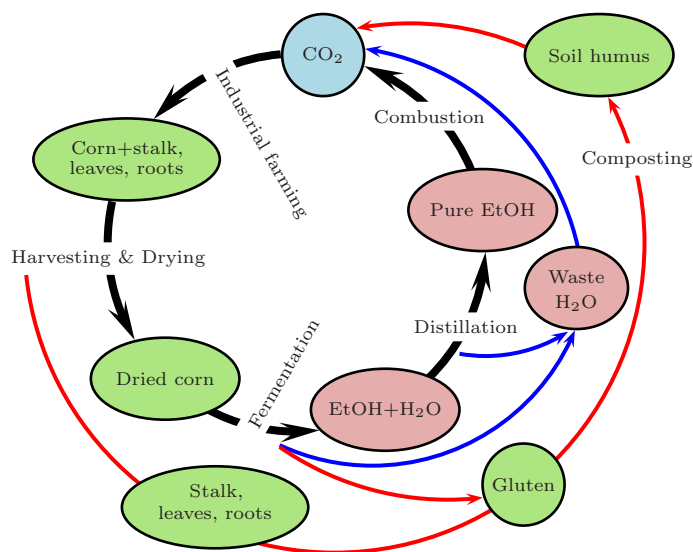


Figure 4.5: The internal carbon cycle in the industrial corn-ethanol cycle can be closed only by recycling most of the corn-plant and corn-grain components.

Remark 2 Most of the biomass must be returned to the field to preserve topsoil. This requirement puts severe restrictions of the various schemes of converting biomass to biofuels. \square

4.4.1 Net CO₂ Emissions

As shown in Figure 4.4, our corn field-ethanol plant-combustion engine system uses fossil fuels as inputs, and outputs *their* combustion products into the environment. Therefore the industrial corn-ethanol cycle generates extra CO₂ and other greenhouse gases, which will all be translated into equivalent CO₂ for simplicity.

The question now is as follows: Does the industrial corn-ethanol cycle generate more equivalent CO₂ from its fossil fuel inputs than the gaseous emissions from replacing the cycle's ethanol with gasoline, methane or diesel fuel? To make this comparison fair, I will account for the cumulative exergy consumption in production of the fossil fuels by adding another 15% to their calorific values, in agreement with [64].

By asking and answering this question, I seek to dispel common misconceptions about the industrially-*manufactured* biofuels, best summarized by the following quotation:

About 70 million barrels¹ of ethanol are included in annual U.S. gasoline consumption after 1992. Because ethanol is a biofuel, the

¹About 11 giga liters.

Table 4.1: Specific CO₂ emissions

NRR	Emission	Units
Electricity	0.322	kg CO ₂ /kWh
Coal	0.089	kg CO ₂ /MJ
Gasoline	0.067	kg CO ₂ /MJ
Diesel	0.069	kg CO ₂ /MJ
LPG	0.059	kg CO ₂ /MJ
Methane	0.050	kg CO ₂ /MJ
Lime	0.785	kg CO ₂ /kg CaO
Nitrogen ^a	2.70	kg CO ₂ /kg N

Sources: Energy Information Administration [14] *Emissions of Greenhouse Gases in the United States 2001*, Table B1

^a G. KONGSHAUG [4]

carbon it contains should not be counted as an emission. Hence, carbon from ethanol is *deducted* from transportation gasoline consumption².

EIA is right, but then the CO₂ emissions associated with the consumption of Non-Renewable Resources (NRRs) in the industrial ethanol-corn cycle should be *added* to the transportation gasoline consumption. The question now is: What is the net balance?

To answer this question, I will use the EIA and the European Fertilizer Manufacturers' Association (EFMA) data on the specific carbon dioxide emissions from the fossil fuel inputs into the industrial corn-ethanol cycle, see **Table 4.1**. These specific emissions, in kg of CO₂ per MJ in a fossil fuel, will be multiplied by the respective energy input fluxes in MJ ha⁻¹ crop⁻¹, established in Part I. Electricity is treated differently, and its specific CO₂ emissions account for the average U.S. efficiency of conversion of thermal energy into electricity.

To convert the NO_x emissions from the industrial corn-ethanol cycle to equivalent CO₂ emissions, I will follow the guidelines of EIA [14], the Intergovernmental Panel on Climate Change (IPCC) [30], and EFMA [4]:

- 1.25% of applied N fertilizer escapes into the air as N₂O.
- 30% of applied N escapes from the field, and 2.5% of that quantity is converted to N₂O in surface water.
- 10% of applied N escapes as NH₃ into the air, and 1% of that becomes N₂O.

²The U.S. Energy Information Agency (EIA) [14], Appendix A, page A3.

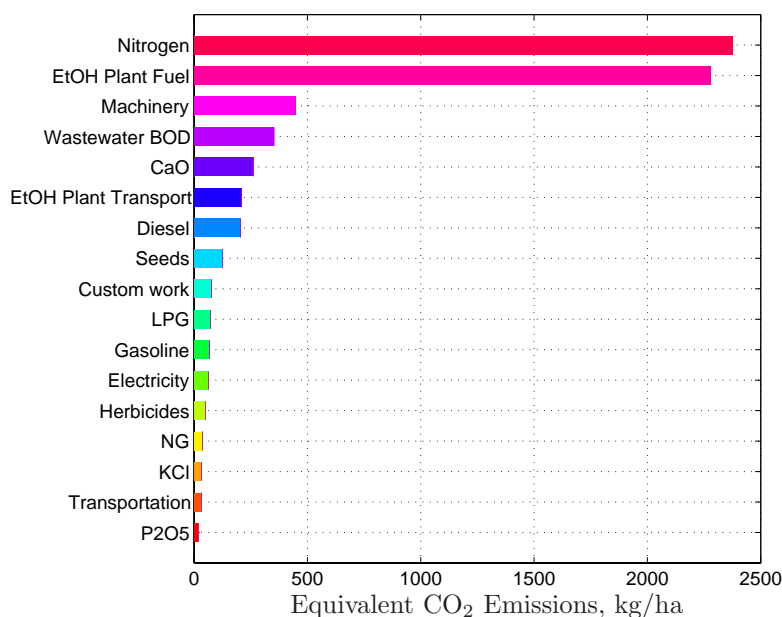


Figure 4.6: Equivalent CO₂ emissions from each major non-renewable resource consumed by the industrial Corn-EtOH cycle.

- Nitrous oxide is 300 times more potent as a greenhouse gas (GHG) than CO₂.
- Equivalent CO₂ emissions are then ~950 kg/ha.
- An average ammonia plant emits 0.03 kg N₂O/kg N in nitric acid, which is used to make ammonium nitrate.
- Equivalent CO₂ emissions from production of ammonium nitrate are then $\sim 150 \times 0.03 \times 300 \times 63/80 = \sim 1000$ kg/ha.
- One may dispute this last number to the extent that ammonium nitrate is not used as fertilizer.

The CO₂ emissions from electricity use in the removal of Biological Oxygen Demand (BOD) in wastewater from ethanol plants, cf. Section 4.5, are also included.

4.4.2 Conclusions

The results of my calculations, shown in **Figures 4.6** and **4.7**, lead to the following conclusions:

1. According to my estimates, 1 ha of industrial corn-for-ethanol generates 6700 kg of CO₂ equivalent from the fossil fuel inputs.

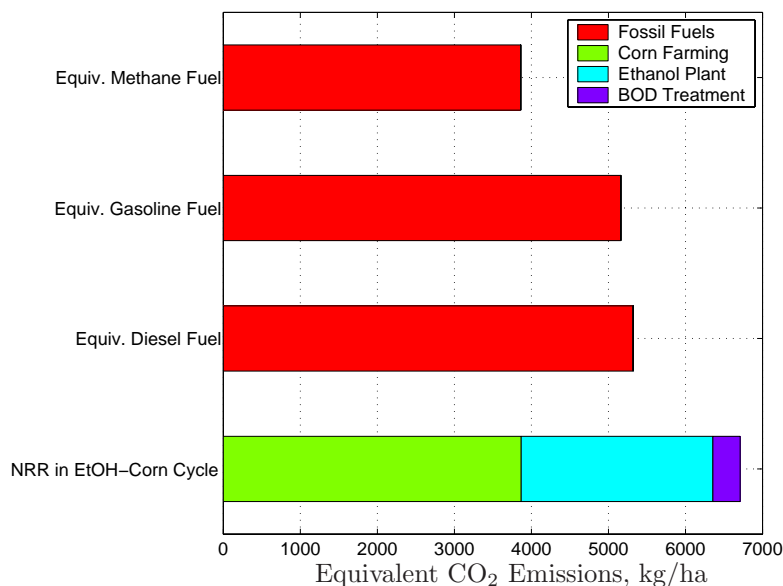


Figure 4.7: The total equivalent CO₂ emissions from the consumption of non-renewable resources by the industrial corn-ethanol cycle. The CO₂ emissions from the energy-equivalent amounts of methane, gasoline and diesel fuel were increased by 15% to account for their recovery, transport, and refinement.

2. If the amount of gasoline with the energy content of 115% of 2170 kg EtOH/ha obtained on the average from corn were burned, it would generate 5100 kg of CO₂.
3. The net CO₂ emissions are then $6700 - 5100 \approx 1600$ kg/ha *above* those of gasoline.
4. Today, the industrial corn-ethanol cycle generates on 4.9 million hectares about 7.9 million metric tonnes of CO₂/year *over and above* the energy-equivalent gasoline.
5. To satisfy 10% of U.S. fuel consumption, the additional CO₂ emissions will be about 65 million metric tonnes per year.

4.5 Water Cycle

The water cycle can be idealized by bringing all necessary water to an imaginary “water tank” at the top of **Figure 4.8**. The water is then dispensed from this tank as rain, irrigation water, and ethanol plant feed water. Water is used by the corn plants, but is also evaporates from the fields, runs off as contaminated surface water, and seeps back into the groundwater, contaminating the under-

lying aquifers as well. Still more water is evaporated by drying the harvested corn in NG/LPG driers.

To estimate the average water requirement by corn plants, I will use Pimentel's [47] average estimate of ~ 100 cm of water per crop³. This translates into 10×10^6 L/ha-crop. About 15% of the water demand [67], 8.1×10^5 L/ha-crop, comes from pumping groundwater and surface water to irrigate corn. For comparison, the average water requirement by corn in Nebraska is 53-71 cm, and roughly 50% of corn acreage is irrigated there [2]. Nebraska sits on top of the most prolific part of the giant High Plains aquifer [56, 68]. Water mining from the High Plains aquifer continues in Texas, Kansas, Oklahoma, New Mexico and Colorado, while the water levels in Nebraska and Wyoming have stabilized or increased, see [68] and the references therein.

To estimate water inputs into a wet-milling ethanol plant I will use the data published in the *Corn Chemistry and Technology Handbook* [73] and by Pimentel [47]. According to [73], one needs the following amounts of process water per 1 liter of ethanol:

- 10-12 liters in corn fractionation (p. 450).
- 20-25 liters in glucose fermentation (p. 697).
- The total amount is 30-37 liters of clean process water per 1 liter of ethanol, or 38-46 liters of water per kilogram of ethanol.
- The average 5-day biochemical oxygen demand (BOD) of waste water is 1000-2000 mg/L.

According to [47], 159 liters of water are needed to produce 1 liter of 95% ethanol, which translates to 190 liters of water per kg of 100% ethanol. Twelve liters of waste-water are generated per 1 liter of ethanol from the separation of industrial beer with 8 percent of ethanol by volume. The wastewater BOD is 18000-37000 mg/L, 10-20 times higher than the previous estimate. This estimate makes sense because the beer wastewater contains dead yeast and unreacted glucose. After mixing with cleaner process water, the overall BOD must go down. BERTHIAUME *et al.* [3], erroneously use 160 L of wastewater per L of EtOH, with BOD of 20000 mg/L.

For the time being, I will go along with 46 L water/kg EtOH with BOD⁴ of 2000 mg/L. Thus, a wet milling ethanol plant needs on average

$$46 \frac{\text{L}}{\text{kg EtOH}} \times 2170 \frac{\text{kg EtOH}}{\text{ha-crop}} = 0.1 \times 10^6 \frac{\text{L}}{\text{ha-crop}}, \quad (4.10)$$

of water, and it generates 200 kg of BOD/ha-crop. This amount of process water is 100 times smaller than the amount of water needed to grow corn in the field.

³The rule of thumb is that corn needs 1000 – 1800 kilograms of water per kilogram of grain produced. This rule translates into 86-150 cm of water requirement, see, e.g., http://www.-jica.go.jp/english/publication/network/-net_vol18/02.html.

⁴A Google search yields BOD values between 600 and 9200 mg/L in the wastewater streams from wet- and dry milling ethanol plants that use different biomass feeds.

Remark 3 The industrial corn-ethanol cycle needs about 10×10^6 liters of water per hectare and per crop. This amount of water must be deposited in the tank. Depending on weather and location, some or most of this water may have to come from mining an aquifer or surface water. \square

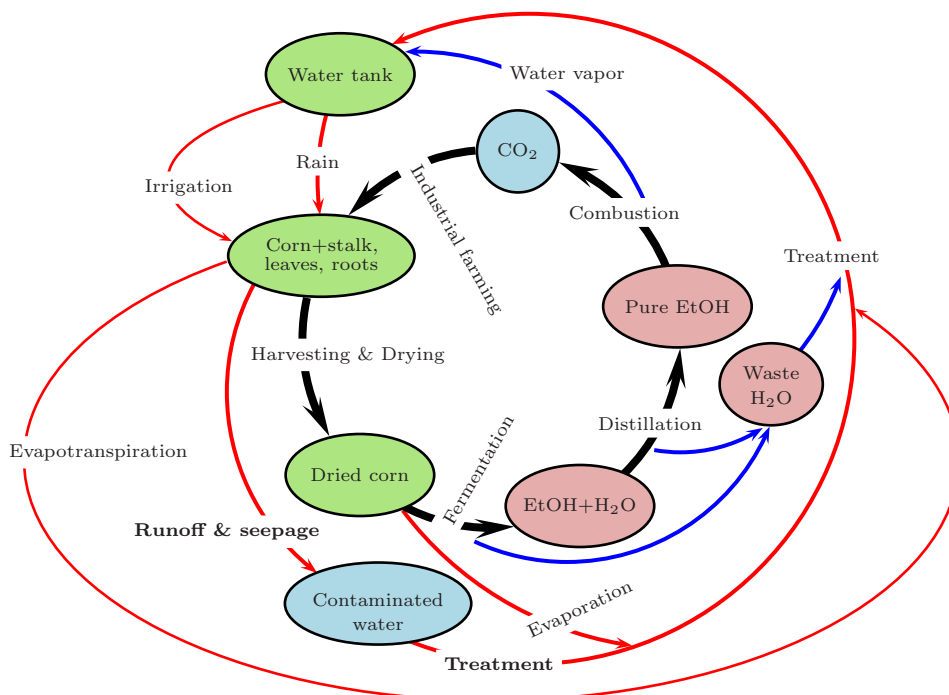


Figure 4.8: The water cycle in corn-ethanol production. Compared with the water requirement by corn plants, the feed water requirement of ethanol plant is small, and the link between the tank and the fermentation stage was not drawn.

Since the volume of process water passing through the ethanol plant is two orders of magnitude smaller than that passing through the field, and all of the process water is readily accessible in holding tanks, ponds, etc., problems with cleaning it up are *insignificant* when compared with the field runoff water.

Remark 4 Industrial agriculture uses a huge land area, and it mines and contaminates huge amounts of soil, water and air. The environmental damage it causes is much more widespread and more difficult to reign in than that from the highly-concentrated industrial sources. In addition, industrial agriculture invades large ecosystems and destroys them. In other words, the twenty first century industrial agriculture poses a more acute threat to life on the earth, than the nineteenth century smoke stacks ever did. \square

Table 4.2: The specific chemical exergies of compounds participating in the ideal corn-glucose-EtOH cycle. Source: [64], Tables I and II in Appendix.

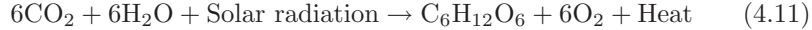
Component	Standard Chemical Exergy MJ/kmol
$C_6H_{12}O_6(s)$	2928.8
$C_2H_5OH(l)$	1363.9
$CO_2(g)$	19.87
$O_2(g)$	3.97
$H_2O(l)$	0.00
$H_2(g)$	236.1

4.6 Exergy Analysis of an Ideal Corn Ethanol Cycle

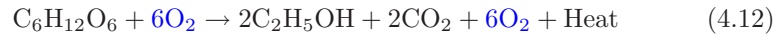
4.6.1 Chemistry of the CO_2 -Glucose-EtOH Cycle

The ideal the CO_2 -Glucose-EtOH cycle consists of three steps:

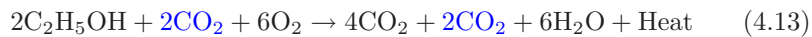
Step 1 Photosynthesis of glucose from atmospheric CO_2 :



Step 2 Production of ethanol from glucose:



Step 3 Combustion of ethanol:



The compounds that appear on both sides of the chemical reactions in Steps 2 and 3 do not participate in these reactions, but appear to close the cycle. The chemical exergies of all compounds are listed in **Table 4.2**. The chemical exergies of the products of each step of the cycle are listed in **Table 4.3**, and the exergy flow is depicted in **Figure 4.9**.

The Maximum Cycle Output per Unit Mass of Corn

To calculate the maximum possible energy output from the ideal CO_2 -Glucose-EtOH cycle, I made the following assumptions:

- Dry corn has 66% glucose (100% hydrolyzed starch) by mass.

Table 4.3: The calculated chemical exergies of the products of steps in Eqs. (4.11 – 4.13).

Step	Product Exergy After Step MJ/kmol C ₆ H ₁₂ O ₆
1	2952.6
2	2791.4
3	119.2
Net	2833

Net chemical exergy per kg of glucose = 15.74 MJ/kg

Exergy of matter after Step 1 per kg of glucose = 16.4 MJ/kg = 3920 kcal/kg

Cycle efficiency = 96%

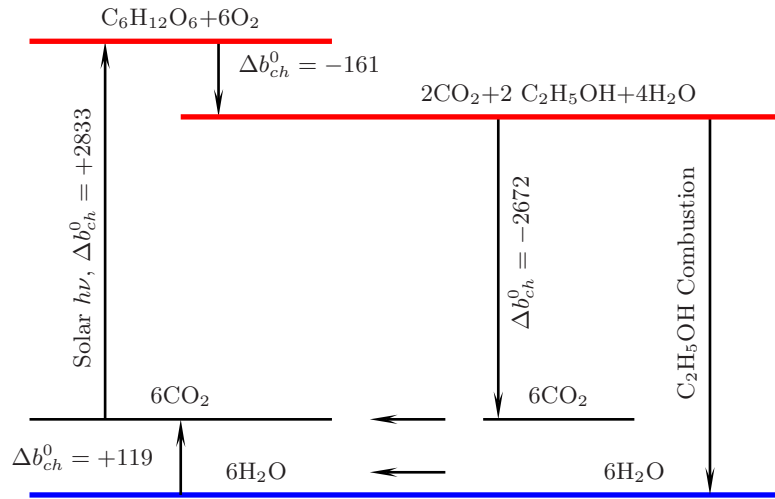


Figure 4.9: Exergy diagram of the ideal CO₂-Glucose-EtOH cycle.

- Starch is converted into ~100% ethanol with 0% losses.
- Corn delivered to an ethanol plant has 15% of moisture.
- The net chemical exergy of an ideal ethanol cycle per kg of moist corn kernels is

$$15.74 \frac{\text{MJ}}{\text{kg glucose}} \times 0.66 \frac{\text{kg glucose}}{\text{kg dry corn}} \times 0.85 \frac{\text{kg dry corn}}{\text{kg wet corn}} = 8.83 \frac{\text{MJ}}{\text{kg wet corn}} \quad (4.14)$$

- At 8600 kg of moist corn per hectare, the chemical exergy from an ideal

ethanol cycle is

$$8.83 \frac{\text{MJ}}{\text{kg wet corn}} \times 8600 \frac{\text{kg wet corn}}{\text{ha}} = \mathbf{75.9 \text{ GJ/ha}} \quad (4.15)$$

- With 88% conversion efficiency of starch into 100% ethanol, the chemical exergy is

$$75.9 \text{ GJ/ha} \times 0.88 = \mathbf{66.8 \text{ GJ/ha}} \quad (4.16)$$

Remark 5 The output of the ideal CO₂-Glucose-EtOH cycle is the chemical exergy of ethanol equal to 66.8 GJ/ha-crop. This exergy can be transformed into useful work (e.g., shaft work or electricity) by different devices. □

For example, efficiency of an excellent internal combustion engine is 35% (usually it is 20%)

$$W_u = 66.8 \times 0.35 = 23 \text{ GJ/ha} \quad (4.17)$$

For fuel cell/electric motor vehicles the efficiency of conversion of chemical exergy to shaft work is higher. Suppose that we could reform ethanol to hydrogen, and use a fuel cell with 60% efficiency [12]

$$W_u = 66.8 \times 0.60 = 40 \text{ GJ/ha} \quad (4.18)$$

to obtain electricity, and shaft work.

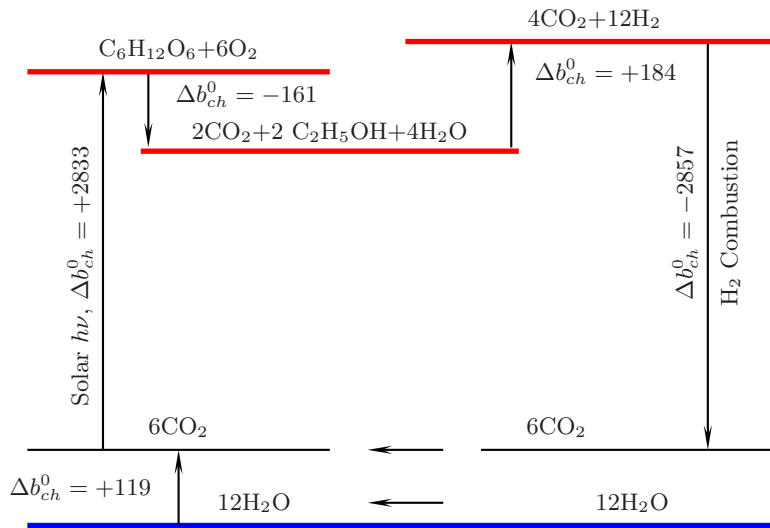


Figure 4.10: Exergy diagram of the ideal CO₂-Glucose-EtOH-H₂ cycle.

4.7 Exergy Analysis of the Modified Ideal Corn-Ethanol Cycle

Now let us look at the useful exergy production in the modified ideal corn-ethanol-**hydrogen** cycle discussed in [12]. This cycle is essentially the same as the cycle described in Eqs. (4.11 – 4.13). The only difference is in Step 3, which is moderately endothermic, and lowers the cycle efficiency by one percent, see **Figure 4.10**. The chemical exergies of the products of each step of the modified cycle are listed in **Table 4.4**.

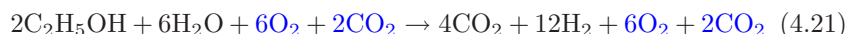
Step 1 Photosynthesis of glucose from atmospheric CO₂:



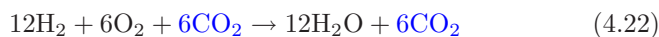
Step 2 Production of ethanol from glucose:



Step 3 Reforming ethanol to hydrogen:

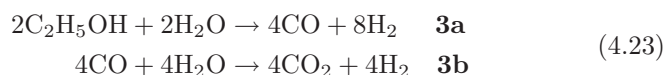


Step 4 Hydrogen combustion:



Step 3, reforming ethanol to hydrogen, is a catalytic variant of water-shift reaction:

Steps 3ab Ethanol oxidation to CO, and then CO₂:



Note that [12] uses a somewhat different stoichiometry with 10H₂ and 10H₂O, but this difference is insignificant.

Remark 6 Practically, the ideal CO₂-Glucose-Ethanol-H₂ cycle discussed in [12] produces the same amount of useful chemical exergy as the ideal CO₂-Glucose-Ethanol cycle. Therefore, all conclusions pertinent to the latter hold for the former. \square

Table 4.4: The calculated chemical exergies of the products of steps (4.19 – 4.23).

Step	Product Exergy After Step MJ/kmol C ₆ H ₁₂ O ₆
1	2952.6
2	2791.4
3	2976.2
4	119.2
Net	2809.8

Net chemical exergy per kg of glucose = 15.61 MJ/kg
 Cycle efficiency = 95%

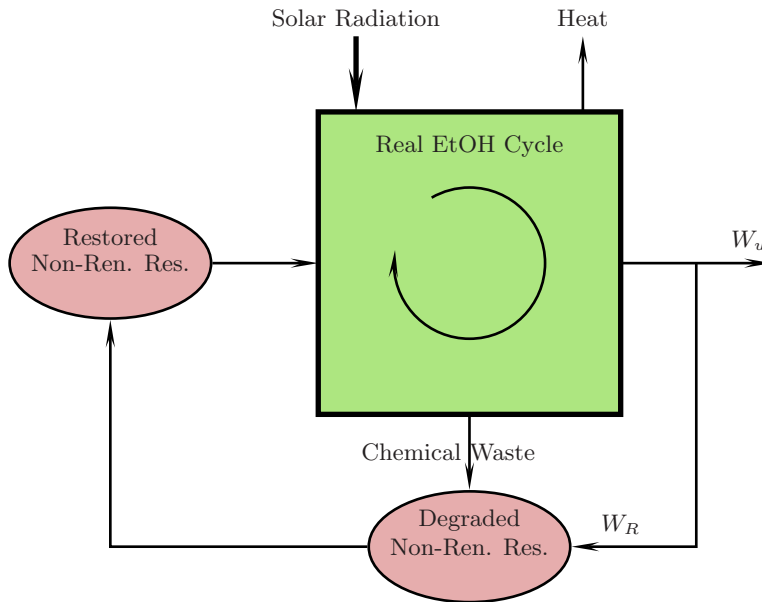


Figure 4.11: A part, W_R , of the useful work, W_u , from the industrial corn-ethanol cycle is diverted to “undo” mining of the environment by this cycle. If $W_u > W_R$, there is net benefit from the ethanol biofuel, otherwise its use should be stopped.

4.8 Resource Consumption and Waste Generation in the Industrial Corn-Ethanol Cycle

Now, I will focus attention on the industrial corn-ethanol cycle depicted in Figure 4.4. In contrast to the sun-driven ideal cycle, the industrial cycle relies

heavily on fossil energy. Therefore, a part W_R of the useful work W_u , must be diverted to restore the non-renewable resources depleted by the cycle, see **Figure 4.11**. As long as the useful work exceeds the restoration work, $W_u > W_R$, the industrial corn-ethanol cycle is beneficial, otherwise it is indefensible.

Remark 7 The depletion of concentrated natural resources is *irrevocable*, cf. Part II. Without causing changes in the environment, we cannot remanufacture the depleted amounts of oil, methane and coal in a reversible process, and put these fuels back into their deposits. Therefore, the reversible restoration work calculation provides the *lowest estimate* of the degree to which the irreversible industrial corn-ethanol cycle is also unsustainable. \square

Table 4.5: CExC of major non-renewable resources used in the industrial corn-ethanol cycle. Sources: Table 5.2 in [64], and calculations by the author.

NRR	Exergy	CExC	Units	Comments
Ammonium Nitrate	10.51	99.6	MJ/kgN	30-years old technology
Phosphate	0.1	10.1	MJ/kg P ₂ O ₅	H ₂ SO ₄ CExC
KCl	0.26	6.09	MJ/kg KCl	Sylvinite ore, 1:1 K:Na
Lime	1.96	10	MJ/kg CaO	Calcinated limestone
Herbicides	261	300	MJ/kg	1.15 exergy
Seeds	104	119	MJ/kg	1.15 exergy
Electricity	3.6	11.83	MJ/kWh	Plant eff. of 34.6%
Diesel	44.4	53.2	MJ/kg	Typical value
Gasoline	48.3	57.5	MJ/kg	Mean value
Natural Gas	50.7	57.9	MJ/kg	Typical value
LPG	48.8	61.6	MJ/kg	Autothermic cracking
Steel	7.1	45.9	MJ/kg	Process ore, blast furnace

From Definition 6, it follows directly that the *minimum* restoration work is equal to the sum of the cumulative exergy consumption (CExC) by all the processes that convert natural resources into inputs to the industrial corn-ethanol cycle. The specific CExC for each such input is listed in **Table 4.5**. For example, the CExC by the production of ammonium nitrate starts from natural gas in the subsurface and nitrogen in the atmosphere, and continues by summing up all intermediate steps. Even though the chemical exergy of ammonium nitrate is only 10.51 MJ/kgN, the cumulative exergy consumption to produce it is almost 10 times larger. The CExC by electricity generation is based on the average exergy efficiency of ten large modern power stations in the U.S. [20,65].

Remark 8 Currently, the fossil fuels are mined from very concentrated deposits and upgraded in very large and efficient plants. Therefore, their CExC's are relatively small. As the rich crude oil and natural gas deposits are depleted, in

part to fuel the extravagant and politically-driven projects such as corn-ethanol in the U.S., the CExC by gasoline, diesel fuel, and clean natural gas will increase dramatically. I will address this looming problem elsewhere. \square

The total CExC for each input is the product of the specific value in Table 4.5 (in MJ/kg) multiplied by the flux (in kg/ha-crop) estimated in Part I. The CExC by cleanup of the water contaminated in the industrial ethanol cycle was not yet considered, and will be discussed now.

4.8.1 Cleanup of BOD in Ethanol Plant Wastewater

The CExC by the cleanup of ethanol plant wastewater is the product of the total biological oxygen demand (BOD) in the wastewater stream in kg O₂/ha-crop, and the specific CExC by BOD removal in MJ/kg O₂. As discussed in Section 4.5, the total BOD is

$$\text{BOD} = 46 \frac{\text{L water}}{\text{kg EtOH}} \times 0.002 \frac{\text{kg O}_2}{\text{L water}} \times 2170 \frac{\text{kg EtOH}}{\text{ha-crop}} = 200 \frac{\text{kg O}_2}{\text{ha-crop}} \quad (4.24)$$

After BERTHIAUME *et al.* [3], I will base the specific CExC of BOD on a survey of energy consumption in municipal wastewater treatment facilities in the Canadian province of Québec. According to reference [5], an average electricity consumption of 4.13 kWh per kg of BOD removal was observed there.

I have used these estimates in the CO₂ emission calculations shown in Figures 4.6 and 4.7.

4.8.2 Cleanup of Contaminated Field Runoff Water

Analysis of the cumulative exergy consumption in the cleanup of contaminated agricultural water that

- Seeps into the aquifers, causing, e.g., the omnipresent nitrate contamination of groundwater in the Corn Belt [42],
- Runs off to streams, rivers, into the Mississippi River, and to the Gulf of Mexico, generating a large anoxic zone there,

is the subject of future research and will not be discussed here.

The Second Law of thermodynamics puts a high price on concentrating and removing dilute contamination, especially from the subsurface. Therefore the restoration work of cleaning up the field runoff water will be at several orders of magnitude larger than that of the ethanol plant runoff water.

Better fertilization practices, and artificial wetlands [24–27] around the corn fields could significantly help in containing and removing the pervasive contamination these fields generate.

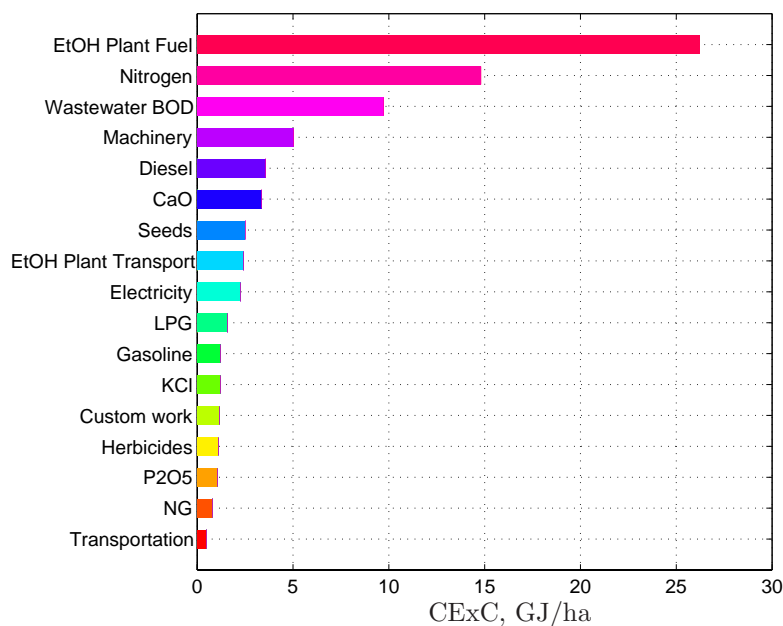


Figure 4.12: The specific cumulative exergy consumption (CExC) by each major non-renewable resource input to the industrial corn-ethanol cycle.

4.8.3 Restoration Work

Now we are ready to estimate the restoration work of the non-renewable resources mined by the industrial corn-ethanol cycle. The results for each major input are shown in **Figure 4.12**. The three main sources of exergy consumption are the ethanol plant fuel, the nitrogen fertilizer, and the removal of biological oxygen demand in the ethanol plant waste water. Note that I have not yet included the potentially huge restoration work of the High Plains aquifer which underlies many of the Corn Belt states, other aquifers, the numerous streams and rivers which drain the field waste water, the Mississippi River, and the Gulf of Mexico at the Mississippi River mouth.

The bottom-line comparison is shown in **Figure 4.13**. Here I compare the yet incomplete cumulative exergy consumption by the industrial corn-ethanol cycle with the cycle's maximum useful work performed by three different machines. This comparison reveals that the corn-ethanol cycle consumes 100-600% more exergy than it replaces.

The lowest deficiency of the cycle, by a factor of 100%, is realized by employing a 60%-efficient, ideal fuel cell to power a car. Such a cell is 2-3 orders more expensive than the car engine, 10 times less reliable, and may never be mass-produced [6,11,13,69]. A 35%-efficient Carnot engine produces 3 times less useful work than the restoration work, and today's car average engine produces 6 times less work.

Remark 9 No matter how efficient is the engine that transforms the industrial corn-ethanol cycle's output into shaft work, the cycle remains utterly unsustainable and unattractive as a source of fossil fuel. \square

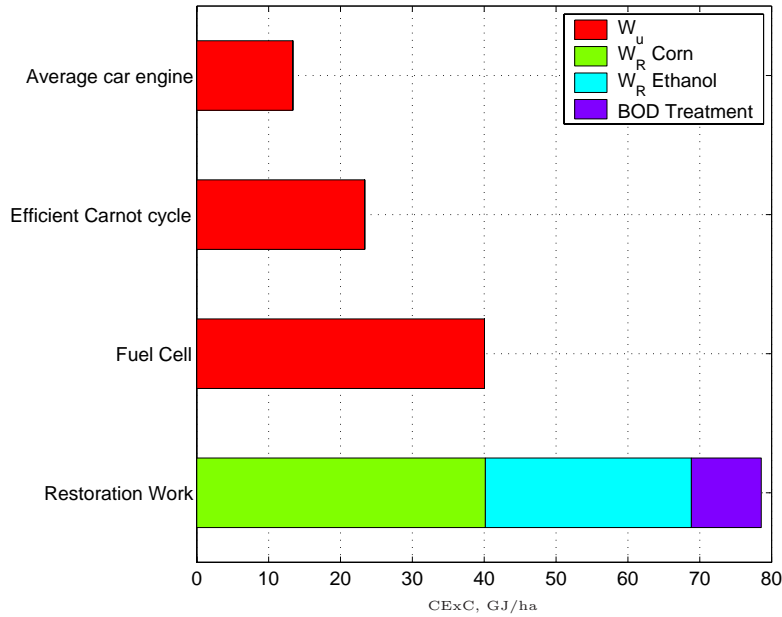


Figure 4.13: The minimum cumulative exergy consumption by the industrial corn-ethanol cycle and its maximum useful work, W_u . For comparison, the cycle's ethanol is burned in an average car engine, an efficient CARNOT engine, and in an ideal fuel cell. This comparison demonstrates that the industrial corn-ethanol cycle is unsustainable by a factor of 100-600%. No adjustment of process parameters I can think of will change this terrible situation.

4.9 Conclusions

- Excluding the restoration work of decontaminating aquifers, rivers, and the Gulf of Mexico, the *minimum* cumulative exergy consumption in restoring the environment polluted and depleted by the industrial corn-ethanol cycle is over 6 times higher than the *maximum* shaft work of a car engine burning the cycle's ethanol.
- This unfavorable ratio decreases to ~ 3 , when an efficient CARNOT engine is used to burn the ethanol, and to 2 when a hydrogen fuel cell is used.
- The industrial corn cycle is not renewable, and is *unsustainable* by a wide margin (100-600%).

- No process changes can make this cycle more viable.
- The corn-ethanol biofuel production is a human assault on the geologic processes and geologic time scale.
- The *limiting factors*, fertilizer-rich humus and water that carries the dissolved nutrients to plant roots are augmented by chemicals obtained in linear fossil processes.
- The natural processes of plant growth, soil and water renewal are accelerated many-fold by industrial mining of non-renewable resources.
- The sun-light is *not* a limiting factor, and could be used to great benefit if we were in less of a hurry.

Chapter 5

Other Problems with Corn-Ethanol

The results obtained in Part I and II can now be used to estimate the annual subsidies to the U.S. corn-ethanol biofuel. These subsidies fall into two categories: (1) the monetary subsidies by the U.S. Federal Government and State Governments to corn and ethanol producers, and (2) the non-monetary contributions of the U.S. population and environment polluted and mined by the industrial corn-ethanol cycle.

The first type of subsidies is easy to estimate:

- U.S. pays its corn farmers \$10 billion a year in subsidies¹ (18% of corn acreage is now devoted to ethanol).
- Federal excise taxes per gallon of fuel²: \$0.184 for gasoline and \$0.132 for EtOH-10 (10 vol% ethanol).
- Relative to gasoline, federal tax breaks per 1 gallon of ethanol are

$$10 \times (\$0.184 - \$0.132) = \$0.52$$

- State excise taxes per gallon of fuel vary widely and are difficult to estimate:
 - Gasoline \$0.075 in Georgia, up to \$0.36 in Connecticut
 - EtOH-10 \$0 in Arizona, up to \$0.2535 in West Virginia
 - Minnesota offers a \$0.20 tax subsidy on EtOH-10. The state's 13 ethanol plants have received up to \$3 million a year³.

¹Corn subsidies, OXFAM.

²Excise Taxes, REUTERS, Washington, Nov. 15, 2003.

³CAT LAZAROFF - ENS, 3 Oct., 2002.

- I will assume that the average state subsidy is only \$0.10/gallon of ethanol. Likely, state subsidies of corn growers, ethanol producers, and EtOH-10 excise tax breaks are several times higher than my estimate.

The second type of subsidies can only be estimated by comparing the maximum useful output of the corn-ethanol cycle with the minimum restoration work necessary to undo the cycle's negative impact on the environment.

Table 5.1: The First Law summary of the U.S. corn-ethanol production in 2004

12.28 GL/yr	of ethanol produced in the U.S.
9.21 GL GE/yr	as ethanol produced in the U.S.
9.25 GL GE/yr	burned to produce this ethanol
1.2 %	of U.S. automobile fuel from ethanol
4.9 million hectares	of U.S. land growing corn for ethanol
17.7 %	of all U.S. corn is farmed for ethanol
40.4 million hectares	for 10% U.S. automobile fuel energy
\$1.69 billion/yr	in federal subsidies for ethanol
\$0.32 billion/yr	in average state subsidies for ethanol
\$1.77 billion/yr	in corn-for-ethanol price subsidies
\$3.78 billion/yr	in total ethanol subsidies

GL = Giga Liter = 10^9 L; GE = Gasoline Equivalent

5.1 First-Law View of Corn-Ethanol Production in 2004

In February 2004, the U.S. ethanol industry set an all-time monthly production record of 212,000 barrels per day (b/d) (12.3 GL/year), according to data released by the U.S. Energy Information Administration (EIA), the Renewable Fuels Association (RFA) reported. The previous all-time record was 211,000 b/d in the previous month. Production was up 25 percent compared to last February when 169,000 b/d (9.8 GL/year) of ethanol were produced.

“U.S. ethanol producers are doing everything they can to add much needed volume and octane to the U.S. gasoline market, thereby helping to hold down gasoline prices,” said RFA President BOB DINNEEN. The ethanol industry is expected to produce more than 3.3 billion gallons in 2004, up from 2.81 billion gallons in 2003. Currently, 75 ethanol plants have the capacity to produce more than 3.2 billion gallons annually. *Thirteen* additional plants under construction will add 500 million gallons of annual production capacity, RFA said.

The highlights of the annualized U.S. corn-ethanol production based on the February 2004 data are listed in **Table 5.1**. Note that the 12.3 GL/yr of

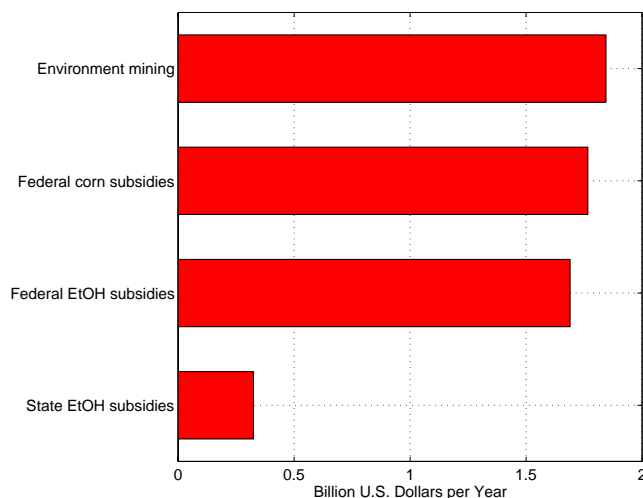


Figure 5.1: The U.S. environment and taxpayers subsidize corn growers and ethanol producers. The U.S. rural population, soil, water, air, plants, fish and wildlife pay the most.

corn-ethanol replace only 9.2 GL/yr of gasoline equivalent (GE), and require 9.3 GL/yr of GE to produce. Corn-ethanol brings *no* energy savings and *no* lessening of the U.S. energy dependency on foreign crude oil, natural gas, and liquified petroleum gas. The opposite happens, we import more methane, LPG, and crude oil. We then burn these fuels to produce corn-ethanol and, finally, we burn the ethanol in our cars at the additional cost of extensive environmental damage. Also note that the ethanol and corn tax-subsidies projected for 2004, will be 12 times higher than the total political contributions of Agribusiness over the last 14 years⁴.

5.2 Second-Law View of Corn-Ethanol Production in 2004

The Second Law exergy analysis brings into the picture the significant contribution of the environment to corporate profits. Depending on which thermodynamic device transforms the chemical exergy of corn-ethanol into useful work, the difference between the minimum restoration work and the maximum useful work by the cycle will vary. This difference in GJ/ha, can be translated roughly into \$/ha, and into the cumulative environmental cost of the industrial

⁴According to the Center for Responsive Politics, <http://www.opensecrets.org/industries/indus.asp?Ind=A>, between 1990 and mid-2004, Agribusiness paid \$320,901,260 to elected officials, 31% to Democrats and 69% to Republicans. The peak donations occurred in the 2000 and 2002 election cycles, exceeding 59 and 54 million dollars, respectively.

corn-ethanol cycle. The hidden cost of environment mining by the industrial corn-ethanol cycle is real, but rarely mentioned. According to the RFA President BOB DINNEEN, ethanol displaces imported crude oil. Therefore, to arrive at an estimate of corn-ethanol's environmental costs, I have assumed that the total exergy deficit will be "paid" with imported crude oil, whose price in the first half of 2004 was close to \$35/barrel. I have assumed that 1 barrel of oil is 136 kg of 35⁰ API oil, with the specific energy content of 45 MJ/kg. The results are listed in **Table 5.2**.

In 2004, the environment will contribute an estimated 2 billion dollars per year by being continuously and irrevocably damaged and depleted. This huge gift to the corporate coffers from the U.S. rural population, soil, water, air, plants, fish and wildlife is as real as the federal tax subsidies. Incidentally, the 60%-efficient fuel cell car does not exist now, and may never exist. But even if in the next 20-years we were to replace all existing cars with the efficient fuel cell cars, the environment's contribution would be still \$1 billion per year. If 10% of the U.S. fuel consumption were supplied by corn-ethanol, the annual contribution of the environment would be \$15 billion.

Again, my current estimate should be viewed as the *lowest* bound on the environmental costs for two reasons: (1) The true restoration work is irreversible and significantly larger than the reversible restoration work, and (2) I have not yet calculated the minimum reversible work of restoring surface and ground water, and soil contaminated by the corn field runoff.

Table 5.2: The Second Law summary of the U.S. corn-ethanol production in 2004

\$ 1.84 billion/yr	Subsidy by the environment with 20% efficient car engine
\$ 1.56 billion/yr	Subsidy by the environment with 35% efficient car engine
\$ 1.09 billion/yr	Subsidy by the environment with 60% efficient car engine
\$ 15.07 billion/yr	10% of U.S. fuel consumption with 20% efficient car engine
\$ 12.75 billion/yr	10% of U.S. fuel consumption with 35% efficient car engine
\$ 8.90 billion/yr	10% of U.S. fuel consumption with 60% efficient car engine

All subsidies to corn growers, ethanol producers and distributors are compared in **Figure 5.1**.

5.3 Public Health Problems

The stated goal of adding ethanol from corn to gasoline was to help in cleaning the air we breath and lessen the U.S. dependance on foreign oil. The opposite is achieved. Air is more polluted, and as much oil and more methane are burned as without the corn-ethanol. At the same time, additional health hazards are

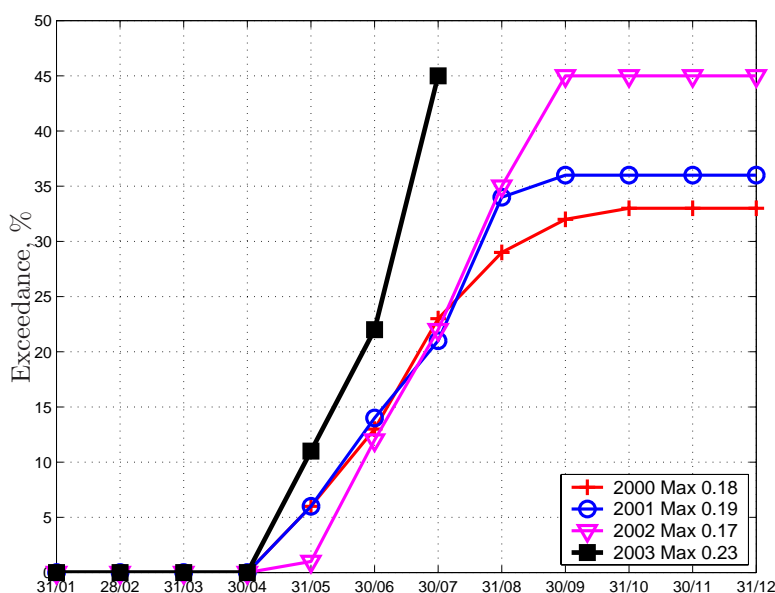


Figure 5.2: The cumulative one-hour exceedances of maximum legal ozone level in Southern California. Source: CAL HODGE, President of A 2nd Opinion, Inc.

created by the agricultural chemicals, fertilizers, insecticides and herbicides, and by the waste water streams.

For example, in 2002, twelve Minnesota ethanol plants agreed to spend \$2 million per plant, pay penalties \$29,000-\$39,000, and limit the following air emissions⁵

- Volatile organic compounds by 2400 - 4000 tons per year,
- Carbon monoxide emissions by 2000 tons per year,
- Nitrogen oxides emissions by 180 tons per year,
- Particulate matter by 450 tons per year,
- Other hazardous air pollutants by 250 tons per year.

Ethanol-in-gasoline seriously pollutes the air. The reactivity of the combined exhaust and evaporative emissions using the ethanol-blended reformulated gasoline is estimated to be about 17% larger than those using the MTBE-blended reformulated gasoline [39]. Ethanol does reduce the carbon monoxide emissions, but increases those of nitrogen oxides (NO_x), acetaldehyde, and peroxy-acetyl-nitrate (PAN) [54]. The negative effects of using gasoline-ethanol blends are clearly seen in Southern California, where ozone levels in the air exceeded the

⁵CAT LAZAROFF - ENS, 3 Oct 2002.

one-hour legal limits more often, see **Figure 5.2**. By 2003, over 70% of gasoline produced in Southern California was blended with ethanol.

Chapter 6

Conclusions

The purpose of this Report was to prove beyond any reasonable doubt that the industrial corn-ethanol cycle accelerates the *irrevocable* depletion of natural resources: fossil fuels, minerals, top soil, surface and subsurface water, and air, while creating a wide-spread environmental damage throughout the continental United States. My arguments relied entirely on the First and Second law of thermodynamics, and on the law of mass conservation.

I have tried to avoid political questions, but at some point one should ask how is it possible that a bad agri-industrial technology, which on its own merit would not stand a chance of competing with other technologies, was allowed to grow explosively in the last four years? The only plausible answer is politics. The recent growth of ethanol production could occur only because of the massive transfer of money from the collective pocket of the U.S. taxpayers to the transnational agricultural cartel, represented most notably by Archer Daniel Midlands Co., Cargill Inc., Monsanto Co., and A. E. Stanley Manufacturing Co. This flow of billions of dollars of public money into few private pockets was accomplished by federal subsidies to corn producers, and the federal and state tax subsidies to ethanol producers. It was spearheaded by many powerful and, I would like to think, thoroughly misinformed politicians.

Even more ominously, as a country, we have diverted our collective attention from the most important issue of this century: energy conservation and increased reliance on the *only* renewable source of energy, the sun, and its weak derivative, the wind, see **Appendix C**. Instead, we have somewhat *accelerated* the rate of depletion of the precious natural gas and crude oil deposits, in exchange for the significantly more wide-spread pollution of water, soil and air over roughly 1/2 of the area of the United States, the incremental carbon dioxide emissions, the substandard ethanol fuel, and the continuous drain of taxpayers' money.

The ethical and moral arguments ought to be developed further, but I will leave this task to others, see e.g., the transcript of an excellent speech by NICHOLAS E. HOLLIS, *Ethics and Agribusiness – In Search of the New Food Security*, given in Newcastle-on-Tyne, United Kingdom, March 15, 2004. Here I will only reiterate the following:

1. Corn-ethanol brings *no* energy savings and *no* lessening of the U.S. energy dependency on foreign crude oil, natural gas, and liquified petroleum gas. The opposite happens, we use more methane, LPG and crude oil. We then burn these fuels to produce corn-ethanol and, finally, we burn the ethanol in our cars at the additional cost of extensive environmental damage.
2. Because of its reliance on fossil energy, the industrial corn-ethanol cycle generates more equivalent carbon-dioxide than would be generated by the energy-equivalent quantity of gasoline or diesel fuel penalized by 15% to account for the cumulative use of free energy in their production. Currently these incremental emissions are 7.9 million tonnes of equivalent CO₂ per year.
3. The taxpayers' subsidies of the industrial corn-ethanol cycle are estimated at \$3.8 billion in 2004. The parallel subsidies by the U.S. environment are estimated at \$1.8 billion in 2004. The latter estimate will probably double when the restoration costs of aquifers, streams and rivers, and the Gulf of Mexico are also included.
4. The rate of sequestration of the unlimited solar energy as organic plant matter is controlled by the availability of water in soil, and the minerals dissolved in this water. For the reasons explained in this Report, water and soil nutrients are finite, easily degradable, and must be replenished by composting all corn plant leftovers, including the byproducts of ethanol production.
5. The mass balance of starch in dry corn grain sets the theoretical efficiency of conversion of corn to ethanol to 0.337 kg EtOH/kg dry kernels (0.423 L EtOH/kg dry kernels), or to 2.85 gallons EtOH/dry bushel = 2.42 gallons EtOH/equivalent bushel of corn with 15% moisture. Therefore, the USDA estimate of the conversion efficiency, 2.66 gallons EtOH/bushel, must be applied to *dry* corn, and not to corn with 15% of moisture.
6. In general, the USDA estimate of 2.66 gallons EtOH/bushel has been multiplied by the moist corn grain yield; this is *incorrect* and leads to an overestimation of the corn-ethanol yield.
7. If used correctly, the USDA estimate is 93% of the theoretical efficiency of corn conversion into ethanol, I have used an 88% efficiency.
8. *All* the published fossil energy inputs into the industrial corn-ethanol cycle [3, 42, 47, 59, 70] have been corrected and/or amended. All the changes to these inputs have been detailed in Part I.
9. With the corrected estimates of the fossil fuel inputs to corn farming and ethanol production, presented in Part I, *all* published estimates predict that production of corn-ethanol is the fossil energy-losing proposition, see **Figure 2.16**.

-
10. In view of Conclusion 4, the robust $\sim 30\%$ energy credits for ethanol production used in [59, 70] are indefensible. In Part II, the Second Law analysis of the industrial corn-ethanol cycle reaffirms this conclusion.
 11. The mere energy balance of the industrial corn-ethanol cycle does not take into account the cumulative consumption of the non-fossil environmental resources: soil, water, air and minerals, and provides an incomplete picture of this cycle.
 12. Because all the published First Law balances of the industrial corn-ethanol cycle are by definition incomplete, their comparison has led to different interpretations, and endless acrimonious debate, see e.g., [42], which served little useful purpose. Worse yet, this debate has diverted our collective attention from the real problems with corn-ethanol and provided cover for the ethanol lobby.
 13. Only when the Second Law of thermodynamics and the concept of available free energy, or *exergy*, are introduced (Parts II and III, Appendix A and B), a definitive analysis of the industrial corn-ethanol cycle is possible.
 14. In the Second Law analysis the *environment* is defined as anything but the top soil of the corn field, the corn plants, the ethanol-producing plants, and the devices that process the ethanol (internal combustion engines and fuel cells). The environment, therefore, is the sun, water, air, nutrients, crude oil, methane, coal, electricity, field chemicals, roads, trucks, etc., and the cold universe to which the heat generated by the cycle's ethanol is rejected. Thus, the environment defined here *cannot* be dismissed summarily as a raving of a green lunatic.
 15. By defining in Section II, Appendix A and B the *irreversibility* and *sustainability*, we can state qualitatively that the industrial corn-ethanol cycle, which relies heavily on mining the environment, is irrevocable and unsustainable. The common references to the cycle sustainability, see e.g., [12] are scientifically indefensible.
 16. In view of Conclusion 4, the recently-advertised ethanol production from "agricultural waste," i.e., from plant leaves, stems, and roots is also unsustainable.
 17. Because the industrial corn-ethanol cycle is irrevocable, the precious natural resources wasted by it disappear forever from the earth, and diminish the wellbeing of our children.
 18. The free energy available on the earth (exergy) is consumed by the industrial corn-ethanol cycle, and its cumulative net consumption is a good quantitative indicator of the degree of unsustainability of this cycle.
 19. The industrial corn-ethanol cycle is compared with the sun-driven ideal corn- ethanol cycle. The maximum useful free energy generated by the

ideal cycle, 67 GJ/ha as corn-ethanol, produces useful shaft work, electricity, or both.

20. When an average car engine (20% efficiency) burns corn-ethanol, it produces 13.4 GJ/ha of useful work. A very efficient car engine (35% efficiency) produces 23 GJ/ha of useful work. An ideal fuel cell/electric motor car with 60% efficiency, produces 40 GJ/ha of useful work.
21. The *maximum* useful work from the ideal corn-ethanol cycle has been compared with the *minimum* reversible work required to undo the environmental damage caused by the industrial corn-ethanol cycle. Of course, this environmental damage cannot be undone in reality, and the minimum reversible restoration work is only a *tool* used to quantify the damage.
22. The cumulative exergy consumption in performing the minimum reversible work of “undoing” the industrial corn-ethanol cycle, exceeds by a factor 6, 3 and 2, respectively, the maximum useful work from a 20% efficient car engine, 35% efficient car engine, and 60% efficient fuel cell car.
23. No process change can improve the very unfavorable ratio of benefits from the industrial corn ethanol cycle to its environmental costs, and I have not yet included the potentially explosive cost of restoring surface and ground water, and soil contaminated by the fertilizer-, pesticide- and insecticide-rich runoff from the corn fields.

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Appendix A

Examples of Entropy Production and Disposal

The Rate of Entropy Export by the Earth

In the simplest model, the earth is in thermal equilibrium; continuously heated by the sun radiation, and cooled by the infrared radiation into the universe.

The *solar constant* is the power collected at the top of the earth atmosphere by a unit area (1 m^2) perpendicular to the light path. This power is remarkably constant, see e.g., [23], and equal to $\dot{q} = 1370 \text{ Watts}^1$ per square meter (W/m^2). The projection of the sun-lit earth hemisphere in the direction perpendicular to the sun light is πr_e^2 , where $r_e = 6371 \text{ km}$ is the mean volumetric earth radius, or $1/2$ of the hemisphere area, and $1/4$ of the earth surface area ($A_e \approx 510 \times 10^6 \text{ km}^2$).

The PLANCK temperature of the sun's radiation is $T_s \approx 5700\text{K}$, and the PLANCK temperature at which the earth radiates its heat is $T_e \approx 254 \text{ K}$. The earth reflects about 30% of the sun radiation, so its surface is reached by only 0.7 of the solar energy. Therefore, the time-averaged flux of entropy exported by the earth into the universe is

$$j_S^E = \frac{\Delta \dot{S}}{4\pi r_e^2} = \frac{4}{3} 0.7 \dot{q} \frac{1}{4} \left(\frac{1}{T_e} - \frac{1}{T_s} \right) = 1.20 \text{ W/K-m}^2 \quad (\text{A.1})$$

where the factor $4/3$ comes from the STEFAN-BOLTZMANN law³. This estimate, incidentally, agrees very well with the $j_S^E = 1.2 \text{ W/K-m}^2$ reported by Prof. ARNE STAHL [60].

¹1 Watt = 1 Joule/second.

²The actual temperature of the earth surface is about 34 K higher due to the greenhouse effect. Therefore there is entropy generation in the atmosphere, see the section below.

³See SZARGUT's one-of-a-kind monograph, [64], page 72, Eq. (2.53).

The Simplest Climate Model

The earth is in thermal equilibrium:

$$\begin{aligned} \text{Rate of energy input from the sun} &= \text{Rate of energy radiation by the earth} \\ \dot{E}_{in} = \dot{E}_{out} = P &= \text{const} \end{aligned} \tag{A.2}$$

Similarly to FRONDEL, OERTEL and RÜBBELKE [17], I assume that the earth's atmosphere is a heat-transporting⁴ gas layer. The surface temperature of the earth is T_0 and the Planck temperature of its radiation is T_e . The stationary heat flow through the atmosphere occurs at a constant rate:

$$P = kA_e(T_0 - T_e) \tag{A.3}$$

where A_e is the surface area of the earth. In this simple model, the steady-state rate of energy export from the earth depends on the mean temperature difference between the earth surface and the uppermost atmosphere. The overall heat transfer coefficient, k , depends on how effectively the atmosphere transports heat. With the increasing concentration of heat absorbers (the greenhouse gases) this coefficient decreases, and the earth temperature must go up.

At steady state, the Second Law of thermodynamics requires the entropy flow rate to satisfy the following equation:

$$P = T_0\dot{S}_0 = T_e\dot{S}_e \tag{A.4}$$

where \dot{S}_0 is the rate of entropy change near the earth surface, and \dot{S}_e is the rate of entropy change at the outer layers of the atmosphere. Therefore, the net rate of entropy generation in the atmosphere due to energy transport is

$$\dot{S}_t = P \left(\frac{1}{T_e} - \frac{1}{T_0} \right) > 0 \tag{A.5}$$

Since both P and T_e are constant, it follows that as the temperature of the earth surface increases, so does the rate of entropy generation in the atmosphere. This *positive feedback* effect, or the *domino effect*, will intensify the impact of human entropy production on the earth climate. The rate of entropy generation in the atmosphere per unit surface area of the earth defines the specific atmospheric entropy generation rate:

$$\sigma_t = \frac{\dot{S}_t}{A_e} \tag{A.6}$$

With the numbers used in Eq. (A.1), this specific rate is equal to 0.11 W/K-m², not bad for such a simplistic model. For comparison, STAHL [60] reports 0.2 W/K-m².

⁴Heat transport through the atmosphere proceeds through turbulent convection and mixing, water evaporation and condensation, thermal conduction, and radiation.

Entropy Generated by a Human

A sedentary human needs about 2400 kcal per day in food to live and work a little. This food consumption translates roughly into an average sustained power of $\dot{Q} = 100$ W, i.e., one man = one 100 W bulb shining infrared light for 24 hours a day. This power is dissipated through work, thermal convection, radiation, excrements, etc., and appears as heat at the ambient temperature $T_0 = 273 + 15 = 288$ K. Thus the entropy generation rate is

$$\dot{S} = \frac{\dot{Q}}{T_0} = 0.35 \text{ W/K} \quad (\text{A.7})$$

per person. At 3500 kcal per day, more representative of the U.S. feeding habits, the rate of entropy generation by one person is $\dot{S} = 0.5$ W/K, in agreement with [60]. This means, that if one crowds 2-3 people per square meter, they will generate more entropy than the earth can export.

Entropy Generated By Fossil Fuels

In the year 2000, the U.S. burned 83 quads (1 quad = 1 quadrillion or 10^{15} BTU⁵) in fossil energy and 2.9 quads in wood, alcohol, etc. For simplicity, I will treat all this energy as the source of heat rejected⁶ into the earth environment at the mean ambient temperature of $T_0 = 288$ K. The U.S. population was $N = 282$ million people in 2000. Therefore, in A.D. 2000, per capita entropy generation rate in the U.S. was

$$\dot{S} = \frac{\dot{Q}}{T_0 N} = \frac{(83 + 2.9) \times 10^{15} \times 1055/365/24/3600}{288 \times 282 \times 10^6} = 36 \text{ W/K} \quad (\text{A.8})$$

per person. My estimate is somewhat higher than the 35 W/K-person calculated in 1996 by STAHL [60]. Incidentally, the whole world produced 400 quads of energy in the year 2000, therefore the U.S. used roughly 1/4 of it. The per capita entropy rate for the whole world excluding the U.S. was 6 W/K-person, or 1/6 of the U.S. rate. This means that where it really counts, in entropy generation rate, the U.S. society is *six times as wasteful* as the world at large, including Europe and Japan.

The U.S. thermal entropy generation rate may also be expressed per unit surface area of the country (9,629,100 km²), resulting in the specific anthropogenic entropy rate $\sigma + \sigma_a = 0.001$ W/K-m², or 0.1% of the net entropy flux exported from the earth. Of course, most of this entropy is generated on a small fraction of the U.S. land area. If all anthropogenic entropy were generated over 0.1% of the U.S. area⁷, roughly the area of Los Angeles, it would overwhelm the

⁵1 BTU = 1055 Joules of energy.

⁶In reality, a portion of the fossil energy, probably 20-30%, generates work, resulting in less heat dumped into the environment. Therefore, this analysis provides the uppermost bound on the entropy generation rate.

⁷A physical impossibility!

entropy export capacity of the earth. This calculation omits the entropy generation rate to “restore” the environment polluted chemically by the fossil fuel by-products. Nevertheless, the anthropogenic entropy generation is still very small when compared with the capacity of the earth to export entropy. Even the transport entropy in the atmosphere is generated at a specific rate 100-200 times higher than the mean generation rate of anthropogenic specific entropy in the U.S.. Note that in his interesting paper RÜBBELKE [57], made a mistake (p. 198), and claimed that the U.S. population produced entropy at the rate of 35 W/K-m², not 35 W/K-person as calculated by STAHL [60]. The consequences of this mistake influenced erroneously his conclusions about sustainability.

What this calculation does not show, is the fast and irreversible exhaustion of the meager stock of high quality crustal materials (low entropy) that feed our civilization.

Appendix B

Availability and Irreversibility in Thermal Systems

Because the earth can export entropy by infrared radiation from the outer layers of the atmosphere, we define any thermodynamic system on the earth as interacting with the atmosphere only. The atmosphere will be treated as being in stable dynamic equilibrium, and characterized by the constant absolute temperature T_0 , volume V_a , and the hydrostatic pressure, $p_0 = 1$ atm, at sea level. By including within the system as much surface land area, surface water, groundwater, minerals, material, plants, machinery, etc.¹, as affected by the process of interest, one is always able to construct the system that interacts with the atmosphere only. For simplicity, chemical entropy generated by the system is not considered here.

GIBBS² showed that for any process which can occur under these circumstances the quantity defined as

$$\Phi = E + p_0V - T_0S \quad (\text{B.1})$$

decreases

$$\Delta\Phi \leq 0 \quad (\text{B.2})$$

where E is the total energy of the system, V its volume, S its entropy, and the increment of Φ , $\Delta\Phi$, is taken in the direction of increasing chronological time.

The process of interest can only occur until the system pressure is uniformly hydrostatic and its uniform temperature is T_0 . Therefore, the state from which no *spontaneous* change can occur is the state in which the system has the hydrostatic pressure (p_0 at sea level) and the atmospheric temperature T_0 , and for which Φ has the smallest possible value, Φ_{\min} . If only one state of the system

¹The entire globe, if necessary.

² [19], p. 40.

results in this minimum value, the system is in *stable equilibrium*. Otherwise, if there are several states corresponding to the minimum value of Φ_{\min} , the system is in *neutral equilibrium* of maximum stability.

GIBBS³ referred to the difference

$$\Phi - \Phi_{\min} \quad (\text{B.3})$$

where Φ is the state in question, as the "...available energy of the body (*our system*) and the medium (*our surroundings*)."

JOSEPH H. KEENAN, [33] later showed that for the system undergoing change from an *earlier* state 1 to a *later* state 2, the amount of useful work W_u is

$$W_u \leq \Phi_1 - \Phi_2 \leq \Phi_1 - \Phi_{\min} \quad (\text{B.4})$$

Therefore, for any state 1, the maximum possible useful work done by the system is $\Phi_1 - \Phi_{\min}$. KEENAN proposed to call this maximum value *availability*, Λ . It may be said⁴ that for any system in the stable atmosphere

$$\Lambda \geq 0 \quad (\text{B.5})$$

and that for the most stable state of the system

$$\Lambda = 0 \quad (\text{B.6})$$

From Eq. (B.4) it also follows that

$$\begin{aligned} \Delta\Lambda &= \Delta\Phi \\ W_u \leq W_{u,\max} &= \Phi_1 - \Phi_{\min} = -\Delta\Phi = -\Delta\Lambda \end{aligned} \quad (\text{B.7})$$

Keenan also quantified the *irreversibility*⁵, I , of a process executed by the system-atmosphere combination:

$$\begin{aligned} I &= W_{u,\max} - W_u \\ &= -\Delta\Phi - W_u \\ &= -\Delta\Lambda - W_u \end{aligned} \quad (\text{B.8})$$

and showed that

$$\begin{aligned} I &= T_0\Delta S + \Delta E_a + p_0\Delta V_a \\ &= T_0\Delta(S_a + S) \end{aligned} \quad (\text{B.9})$$

Of course, KEENAN's irreversibility was discovered much earlier and independently by GOUY [21] and STODOLA [61,62]⁶. Regardless, the process irreversibility is equal to the increase of entropy of everything involved in the process multiplied by the temperature of the atmosphere.

³ [19], p. 53; my comments in italics.

⁴ [33], Eqs. (12) and (13).

⁵ [33], Eqs. (31) - (36).

⁶In particular, Volume II, of [62], pp. 1271-1330, brings a thorough discussion of *The Highest Possible Conversion into Work on the Basis of the Second Law of Thermodynamics*.

One may use Eq. (B.9) in the differential form, and per unit area of the earth surface, by writing

$$\begin{aligned} \frac{1}{A_e} \frac{dI}{dt} &= T_0 \left(\frac{1}{A_e} \frac{dS_a}{dt} + \frac{1}{A_e} \frac{dS}{dt} \right) \\ \sigma_I &= T_0(\sigma_a + \sigma) \end{aligned} \quad (\text{B.10})$$

where σ_I is the specific rate of irreversibility, σ_a is the specific rate of entropy increase in the atmosphere generated by the process, and σ is the specific rate of entropy increase of the system. Note that as the atmospheric temperature increases, so does the irreversibility of any process on the earth.

From Appendix A it follows that we can treat the atmosphere as an open system that exports entropy to the universe with the flux j_S^E calculated from Eq. (A.1). The energy transport through the atmosphere generates entropy at the specific rate of σ_t calculated from Eq. (A.6). Thus, we may rewrite Eq. (B.10) as

$$\sigma_I^{\text{net}}/T_0 = \underbrace{(\sigma_a + \sigma)}_{\text{Thermal entropy from Earth processes}} + \underbrace{(-j_S^E + \sigma_t)}_{\text{Thermal entropy from Solar processes}} \quad (\text{B.11})$$

Using equation (B.11), we can define sustainability as

$$\begin{aligned} \sigma_I^{\text{net}} &\leq 0 \\ \sigma_a + \sigma - j_S^E + \sigma_t &\leq 0 \end{aligned} \quad (\text{B.12})$$

For all places on the earth, and at all times

For *sustainability*, equation (B.12) requires that the net rate of increase of entropy of everything at every place on the earth and for all times be less or equal to zero! Note that the process and energy transport increase the entropy of the earth and the atmosphere, and the low-temperature heat radiation decreases it.

As derived, Eq. (B.12) is quite deceiving. The anthropogenic part of the thermal entropy generation rates, $\sigma + \sigma_a$, can only be sustainable if this entropy is generated in cycles in which all process materials are completely recycled, and all chemical entropy is transformed into thermal entropy. If we rely on a finite stock of fossil energy, then even if the entropy generation rate in a process is much lower than the entropy export flux, the process is *never* sustainable. Therefore, sustainability can only be discussed in the context of *cyclic processes*.

Over an arbitrary time interval $[\tau_1, \tau_2]$, we can write the global condition of *sustainability* of all cyclic processes on the earth as

$$\underbrace{[S_a(\tau_2) - S_a(\tau_1)]}_{\text{Increase of atmospheric entropy from earth processes}} + \underbrace{[S(\tau_2) - S(\tau_1)]}_{\text{Increase of earth entropy}} - S^E(\tau_1, \tau_2) + S_t(\tau_1, \tau_2) \leq 0$$

For the entire earth, and arbitrary τ_1, τ_2

$$(\text{B.13})$$

where $S^E(\tau_1, \tau_2) = j_S^E A_e (\tau_2 - \tau_1)$ is the total thermal entropy exported by the earth over the time interval $[\tau_1, \tau_2]$, and $S_t(\tau_1, \tau_2) = \sigma_t A_e (\tau_2 - \tau_1)$ is the

corresponding thermal entropy generated in the atmosphere by the steady-state energy transport to the universe.

Appendix C

Is Economic Sustainability Possible?

I have already demonstrated that sustainable anything on the earth must involve a closed material loop (a cycle) which is driven by the sun. The solar energy is like fine mist: it dribbles at a constant rate on every square inch of the earth's surface. We cannot increase its flow rate, it dries up overnight, and we cannot store it easily. So one may ask legitimately: is solar power enough to drive the world economy, and if so what constraints does it impose?

The time- and area-average solar energy flux is 240 W/m^2 of the earth surface. At moderate latitudes this flux goes down to about $100\text{-}150 \text{ W/m}^2$, and in tropics it can be as high as 1000 W/m^2 . Thirty percent of the earth's surface, $153 \times 10^6 \text{ km}^2$, is land. Suppose that 1% of land mass on the earth were covered with solar cells that were 10% efficient, and received only 100 W/m^2 of solar energy. The total solar power converted by these cells to electricity would then be 1.5×10^4 gigawatts ($1\text{GW} = 10^9\text{W}$). Currently, the mean world power consumption is about 1.3×10^4 GW. Therefore covering one percent of the earth's land with solar cells would deliver power equal to the mean world power consumption. For the U.S., it would take more like 3% of the land area, $300,000 \text{ km}^2$ (the area of Poland) to replace the entire mean fossil and nuclear power.

There are problems, however, with these calculations:

1. With the necessary infrastructure, the surface area of the solar power plants would probably double or triple.
2. Hot barren areas of the world are where big transmission lines are not.
3. The peak power consumption in the world can be several times the mean power, and power is needed at night.
4. A significant portion of the world power (1/3 in the U.S.) is used by automobiles.

5. At 1 U.S. dollar per watt ($1/7-1/5$ of the current U.S. price), it would take 15 trillion dollars to replace most of the fossil and nuclear energy worldwide with solar cells. This amount would probably double if massive new transmission grids and the required transformers were to be built worldwide.

The first and last item in the list above point out the necessity of decentralization of power generation. With small and micro power plants, one avoids access roads, big transformers, and long transmission lines. Covering big areas with solar cells is also impossible in the mountains and forests.